February 12, 2007

Mr. Gordon Bischoff, Manager
Owners Group Program Management Office
Westinghouse Electric Company
P.O. Box 355
Pittsburgh, PA 15230-0355

SUBJECT: FINAL SAFETY EVALUATION FOR PRESSURIZED WATER REACTOR OWNERS GROUP (PWROG) TOPICAL REPORT WCAP-16175-P, REVISION 0, (CE NPSD-1199, REVISION 1) “MODEL FOR FAILURE OF RCP SEALS GIVEN LOSS OF SEAL COOLING IN CE NSSS PLANTS” (TAC NO. MB5803)

Dear Mr. Bischoff:

By letter dated January 22, 2004,the PWROG (formerly known as the Westinghouse Owners Group and Combustion Engineering Owners Group), submitted Topical Report (TR) WCAP-16175-P, Revision 0, “Model for Failure of RCP [reactor coolant pump] Seals Given Loss of Seal Cooling in CE NSSS [Nuclear Steam Supply Systems] Plants” (also referred to as CE NPSD-1199, Revision 1) to the U.S. Nuclear Regulatory Commission (NRC) staff. By letter dated January 19, 2006, an NRC draft safety evaluation (SE) regarding our approval of WCAP-16175-P was provided for your review and comments. By letter dated March 6, 2006, the PWROG commented on the draft SE. The NRC staff’s disposition of PWROG’s comments on the draft SE are discussed in the attachment to the enclosed final SE.

The NRC staff has found that WCAP-16175-P is acceptable for referencing in licensing applications for CE designed pressurized water reactors to the extent specified and under the limitations delineated in the TR and in the enclosed final SE. The final SE defines the basis for our acceptance of the TR.

Our acceptance applies only to material provided in the subject TR. We do not intend to repeat our review of the acceptable material described in the TR. When the TR appears as a reference in license applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this TR will be subject to a plant-specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that PWROG publish accepted proprietary and non-proprietary versions of this TR within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed final SE after the title page. Also, they must contain historical review information, including NRC requests for additional information and your responses. The accepted versions shall include an "-A" (designating accepted) following the TR identification symbol.

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, the PWROG and/or licensees referencing it will be expected to revise the TR appropriately, or justify its continued applicability for subsequent referencing.

Sincerely,

/RA/

Ho K. Nieh, Deputy Director
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 694

Enclosure: Final SE

cc w/encl:

Mr. James A. Gresham, Manager
Regulatory Compliance and Plant Licensing
Westinghouse Electric Company
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Pittsburgh, PA 15230-0355

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT WCAP-16175-P, REVISION 0, (CE NPSD-1199, REVISION 1)

"MODEL FOR FAILURE OF RCP [REACTOR COOLANT PUMP] SEALS

GIVEN LOSS OF SEAL COOLING IN CE [COMBUSTION ENGINEERING]

NSSS [NUCLEAR STEAM SUPPLY SYSTEMS] PLANTS"

PRESSURIZED WATER REACTOR OWNERS GROUP

PROJECT NO. 694

1.0 INTRODUCTION

By letter dated January 22, 2004, the Pressurized Water Reactor Owners Group (PWROG), formerly known as the Westinghouse Owners Group and CE Owners Group (CEOG), submitted Topical Report (TR) WCAP-16175-P, Revision 0, "Model for Failure of RCP Seals Given Loss of Seal Cooling in CE NSSS Plants" (also referred to as CE NPSD-1199, Revision 1) to the U.S. Nuclear Regulatory Commission (NRC) staff for review. This TR establishes a model for estimating the probability of failure of a RCP seal given loss of all cooling to the RCP seal. This model is intended for use in the individual CE plant's probabilistic risk/safety assessments (PRAs/PSAs) to quantify the risk of an RCP seal loss-of-coolant accident (LOCA), given the occurrence of a loss of seal cooling (LOSC) event.

As part of the close-out of Generic Safety Issue 23 (GSI-23), "Reactor Coolant Pump (RCP) Seal Failure" (Reference 1), the NRC staff stated that, until better models are developed to support future risk-informed licensing decisions, the NRC staff will use the "Rhodes model," in determining the contribution to core damage frequency (CDF) from RCP seal LOCAs. The Rhodes model is described in Appendix A of NUREG/CR-5167, "Cost/Benefit Analysis for Generic Issue 23: Reactor Coolant Pump Seal Failure," (Reference 2). The NRC staff also recommended that the Rhodes model be used in the American Society of Mechanical Engineers standards. Within the nuclear industry, there are several different models currently used in licensees' PRAs/PSAs[1] for RCP seal leakage following a LOSC event. These differences generate a level of modeling inconsistency across the industry and raise modeling issues when these models are used to support risk-informed regulatory initiatives and applications by specific licensees.

The PWROG has been actively involved in the development of RCP seal failure models for over a decade, with initial efforts dating back to 1992. These initial efforts were later extended in 1996 with the issuance of CE NPSD-755, Revision 01, "Reactor Coolant Pump Seal Failure Probability Given a Loss of Seal Injection" (Reference 3). Given the interest in the RCP seal

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[1]PRA and PSA are used interchangeably in WCAP-16175-P, Revision 0 (CE NPSD-1199, Revision 1) and this safety evaluation.

failure models used in plant-specific PSAs, the CEOG authorized a project to develop an RCP seal failure model for LOSC conditions.

This model was developed for CE plants as WCAP-16175-P (Reference 4), to use in estimating the probability of failure of an RCP seal, and to quantify the risk of an RCP seal LOCA, given the occurrence of a LOSC event.

As stated in WCAP-16175-P, Revision 0, the model:

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

The WCAP-16175-P, Revision 0, RCP seal failure model quantification is based on a combination of operating experience data, the results from past RCP seal tests, analytic models, and expert opinion. However, the TR did not include any new, additional tests nor did it include the development of any new analytic models to evaluate the physical response of the RCP seals. Thus, the TR was developed from previously existing information.

This safety evaluation (SE) addresses WCAP-16175-P, Revision 0, as modified by the PWROG letter dated March 6, 2006 (Reference 5), and identifies specific conditions, limitations, and modifications for its application. Unless otherwise stated, the conditions, limitations, and modifications imposed are in addition to, or replacements for, specific modeling-related aspects presented in WCAP-16175-P, Revision 0.

Plant-specific information provided in the TR is limited to CE plants. The NRC staff recognizes that the RCP seal failure model may be applicable to other plant types that use the same, or similar, RCP seal packages (i.e., seal packages with individual seal stages that are made of the same type materials, have the same type design, and have the same operational and performance characteristics). However, caution must be used in applying this model to non-CE plants to ensure that the model accurately reflects the operation, experience, and knowledge of the specific plant with these RCP seal packages. This caution is particularly important for the assumptions applied in developing the model and the associated failure rates. Additional conditions, limitations, and modifications are provided in this SE to address some of the issues that must be addressed by application of TR WCAP-16175-P, Revision 0, RCP seal failure model to non-CE plants.

2.0 REGULATORY EVALUATION

The NRC's final policy statement on the use of PRA methods in nuclear regulatory activities (Reference 6) encourages greater use of PRA methods to improve safety decisionmaking and improve regulatory efficiency. Elements of risk-informed decisionmaking are currently used in several areas, including: reactor oversight process (including the significance determination process), implementation of the maintenance rule, backfit and generic safety issue analyses, and individual plant licensing basis changes. The NRC's policy statement also states that the PRAs used in support of regulatory decisions should be as realistic as practicable. With the issuance of WCAP-16175-P, Revision 0, as modified by the NRC staff conditions, limitations, and modifications identified in this SE, an alternative RCP seal failure model will be recognized by the NRC staff for CE plants.

3.0 TECHNICAL EVALUATION

This section provides the NRC staff's evaluation of the technical elements of WCAP-16175-P, Revision 0. In performing the evaluation, the NRC staff also relied upon a guidance document developed by Brookhaven National Laboratory (BNL), entitled "Guidance Document for Modeling of RCP Seal Failures" (Reference 7). The NRC staff's technical evaluation addresses the following elements:

- Seal Designs and Principles of Operation (Section 3.1)
- Seal Failure Mechanisms (Section 3.2)
- Plant Operating Conditions that Affect Seal Performance (Section 3.3)
- Applicable Tests of RCP Seals and Operating Experience (Section 3.4)
- RCP Seal Failure Model and Quantification (Section 3.5)
- Implementation of RCP Seal Failure Model (Section 3.6)

The conditions, limitations, and modifications identified in this section are listed in Section 4.0 of this SE.

3.1 Seal Designs and Principles of Operation

Chapter 3 of WCAP-16175-P, Revision 0, describes the CE RCP seal designs, with additional information on the RCP seal designs used in CE plants provided in Appendix A. This chapter also describes how the CE RCP seals operate, including a discussion on CBO and the importance of elastomer materials.

As stated in WCAP-16175-P, Revision 0, CE plants use two basic types of RCP seal designs. Prior to the CE System 80® design, the CE plants employed RCP seals designed by BJ (now Flowserve). The BJ RCPs incorporate 4-stage "SU"-type shaft seal cartridges. Seal cartridge cooling is accomplished via the component cooling water (CCW) system. CE System 80® design plants (i.e., Palo Verde Nuclear Generation Station (PVNGS), Units 1, 2, and 3) use CE-Klein, Schanzlin, and Becker (KSB) pumps which originally used 3-stage seals made by KSB in Germany, but now use 3-stage seals designed by Sulzer Pumps (formerly Bingham Willamette Company (BWC)). The CE-KSB design utilizes seal cooling via seal injection and the CCW system (referred to as the nuclear cooling system at PVNGS).

The original seal designs did not explicitly consider station blackout (SBO) conditions. Pump manufacturers developed more robust seals as operating experience was gained, harsh operating environments were better understood, and analysis technology improved. The newer seals are specifically designed to cope with SBO conditions. The improved BJ seal is marketed as the N-9000 seal design (an N-7500 seal design is also used, which is equivalent to the N-9000, with a slightly smaller diameter) and Sulzer offers improved 3-stage and 4-stage seal designs.

The TR notes that the seal design improvements included use of high temperature-resistant elastomers throughout the seal and an improved seal face design that includes thermally-superior materials to increase seal hydrostatic stability and predictability during events leading to high temperature exposure. Furthermore, the tungsten carbide used in the improved seal designs has superior thermal conductivity and heat capacity compared to earlier “hard” face materials, resulting in markedly reduced susceptibility to thermally-induced surface damage (e.g., heat checking) under reduced cooling operation. All CE plants currently use the improved RCP seal designs.

The TR describes the operation of the RCP seals, addressing both the 4-stage and 3-stage designs. The TR further provides a brief description of the operation of the CBO in controlling reactor coolant system (RCS) leakage and makes the following points with regard to CBO line pressure relief:

- CBO relief valve design flow and set pressure are such that a challenge to the relief valve will not occur unless the first three stages of more than one RCP seal has failed, and

- CBO relief valve may be isolated from the seal flow should it become necessary to terminate a high pressure discharge or an inadvertent opening of the relief valve.

The TR also identifies the importance of the elastomer materials used in the RCP seal designs. In particular, the TR states that the early RCP seal designs were selected based primarily on normal seal operating conditions and not on long-term survivability at elevated temperatures. As a result, the materials used in early RCP seal designs (e.g., nitrile compounds of BJ SU-type RCP seals) are less likely to survive exposure to a harsh environment than the materials used in current RCP seal designs (i.e., ethylene-propylene compounds of N-9000 RCP seals). The TR concludes that the materials used in current RCP seal designs have improved performance and are likely to survive prolonged exposures at high temperatures.

Based on the NRC staff review, the NRC staff finds that the TR adequately describes the design and operation of the CE RCP seals. The NRC staff further finds that the CE plants are using improved seal designs that are less susceptible to failure. These NRC staff findings are based on the materials information provided in the TR. Changes in materials would require plant-specific evaluations and/or testing to verify the acceptable performance of the RCP seal design and applicability of the CE RCP seal failure model for these designs.

Further, if a plant uses the older seal designs (e.g., BJ SU-type), materials that are not “qualified,” as defined in the BNL guidance document, or has a plant design that is different from that addressed in the TR (e.g., different CBO design, alignments, or flow capacities), the plant must modify the RCP seal failure model to reflect the plant-specific RCP seal design, including the potential for the increased likelihood of RCP seal failure, and justify the appropriateness of this plant-specific model in risk-informed licensing activities.

3.2 Seal Failure Mechanisms

Chapter 4 of WCAP-16175-P, Revision 0, provides a qualitative discussion of the potential CE RCP seal failure mechanisms associated with a LOSC event. The TR states that operational experience with various seal designs indicates that extended LOSC events are the only initiating events that can threaten seal integrity. In the early years, following initial plant startups for CE plants, numerous seal stage failures occurred. The root cause analyses of these failures indicate that the vast majority of the failures were the result of faulty design, assembly, or maintenance. Several RCP seal stage failures were also attributed to a LOSC event to one or more RCP seals. As experience with the RCP seals increased, the plants learned how to treat the seals in such a way (both in maintenance and operation) as to maximize their useful life. Based on the experience from the early years of CE plant operations, the TR categorizes the operational failure mechanisms into three broad categories:

- System-related failure causes, including: RCS fluid contaminated with metal chips, corrosion products, or other solid particles; thermal or pressure transients; low system pressure; faulty valve lineups; improper venting; and loss of cooling (and/or loss of seal injection for PVNGS RCPs).

- Design-related and manufacturing-related failure causes, including: excessive wear; improper seal and face materials; heat checking; improper balance ratios; poor arrangement of elastomer seals resulting in deformation of shaft sleeve; arrangement of seals such that reverse pressure (as during venting) could displace the seal from its intended orientation; sharp edges that cut the seals during installation; and manufacturing defects such as out-of-design-tolerance parts, poor quality assurance, and poor quality control.

- Maintenance-related failure causes, including: lack of proper training; lack of proper maintenance, inspection, and testing tools; defective parts; wrong parts; missing parts; replacement parts from uncertified suppliers; wrong materials; improper lubricants; introduction of contaminants; lack of receipt inspection; improper instructions; poor drawings; performing maintenance under severe time constraints; and lack of quality control.

Of the above categories, the CE RCP seal failure model only explicitly addresses the system-related failure causes associated with LOSC events. The design-related, manufacturing-related, maintenance-related, and other system-related failure causes are not explicitly modeled as they are expected to be addressed by the improvements and maturing of the designs, manufacturing, and plant maintenance and operational controls resulting from the experiences during the early years of CE plant operations.

Chapter 4 of WCAP-16175-P, Revision 0, specifically discusses the failure mechanisms identified in the BNL guidance document, which are:

- Binding failure of the seal ring for the stage,

- Extrusion failure of secondary seal elastomers (referred to as O-ring extrusion failure) for the stage,

- Opening of stage seal faces due to hydraulic instability caused by fluid flashing (referred to as “pop-open” failure).

The TR states that since temperature and pressure may vary at each seal stage, the above failure mechanisms affect each individual stage differently. Thus, the CE RCP seal failure model addresses each seal stage individually.

For the binding failure mechanism, the TR states that binding occurs when the secondary seals exhibit premature extrusion induced by sustained high-temperature conditions. The potential for binding failure of a seal stage is stated as a function of the following factors:

- Temperatures reached in each seal stage,

- Elastomer material,

- Extent of the postulated extrusions,

- Seal restorative forces (i.e., hydraulic and mechanical) that would act to offset the additional frictional forces associated with seal degradation, and

- Degree and timing of shaft motion.

The TR also refers to a LOSC test and an actual LOSC plant event involving BJ SU-type seals in which a seal stage appears to have failed due to the binding failure mechanism. The NRC staff notes, as is also stated in the TR, that the BNL guidance document considered binding failure of the RCP seal to be a concern only for low-temperature (“unqualified”) elastomers. As identified in Section 3.1 of this SE, all CE plants are currently using the improved RCP seal designs that are less susceptible to this type of failure.

For the O-ring extrusion failure mechanism, the TR states that the failure characteristics of O-rings depend upon temperature, differential pressure across the seals, and the seal geometry. The potential for extrusion failure is stated as a function of the following factors:

- Material properties,

- Seal component gaps,

- Temperatures experienced, and

- Pressure differential.

The TR further states that the current RCP seal designs in CE plants utilize O-rings with superior temperature performance and are consistent with the BNL guidance document “qualified” O-rings. Similar to the discussion on the binding failure mechanism, O-ring extrusion failure of qualified O-rings is considered unlikely during a LOSC event. In the BNL guidance document, qualified O-rings are assumed not susceptible to failure under full system pressure.

For the hydraulic instability (“pop-open”) failure mechanism, the TR states that the hydrodynamic response of RCP seals is influenced by several operational and design parameters. The TR further states that analyses have shown that the face seal will remain stable (i.e., not pop-open) when the following conditions exists:

- Inlet fluid is sufficiently subcooled (> 50 °F), or
- Backpressure (P_b) acting on the seal is greater than half the saturation pressure (P_{sat}) at the inlet temperature (T_{inlet}) (i.e., $P_b > ½ P_{sat}(T_{inlet})$).

The TR also refers to BJ SU-type seal tests in which intermittent and sustained seal stage pop-open events were observed and states that evidence of local seal stage pop-open failure has been noted in operational LOSC events at various CE plants when BJ SU-type seals were used. As identified in Section 3.1 of this SE, all CE plants currently use the improved RCP seal designs and, with the improved materials, are less susceptible to this type of failure.

Based on the NRC staff review, the NRC staff finds that the TR adequately describes the seal failure mechanisms of concern. The NRC staff further finds that the CE RCP seal failure model explicitly addresses the system-related failure causes associated with LOSC events, but does not explicitly address the design-related, manufacturing-related, maintenance-related, and other system-related (non-LOSC) failure causes. These other (not modeled) causes are expected to be addressed by the improvements and maturing of the design, manufacturing, and plant maintenance and operational controls that resulted from the plant-specific experiences during the early years of CE plant operations. This expectation is demonstrated for the current CE plants by the reduction in seal stage failure events attributed to design, manufacturing, maintenance, and non-LOSC system-related causes. As the CE RCP seal failure model assumes that the RCP seals are designed, manufactured, maintained, and operated properly, plants using the CE RCP seal failure model should review the CE early operating experiences for associated lessons learned; verify the adequacy of their design, manufacturing, and plant maintenance and operational controls (specifically ensuring that the CE operating experiences are addressed); and modify the plant-specific RCP seal failure model to address potentially new failure mechanisms, when appropriate.

However, plants that convert their RCP seal packages to the CE RCP seal packages or similar packages (i.e., seal packages with individual seal stages that are made of the same type materials, have the same type design, and have the same operational and performance characteristics), will initially not have the plant-specific experience and lessons learned from the initial CE plant operations. Therefore, the experiences during the early years of CE plant operations should be reviewed and considered by such a plant in developing the design, manufacturing, and plant maintenance and operational controls. Furthermore, as part of the RCP seal design conversion, the plant should consider and model the potential for additional failure modes, beyond those reflected in the CE RCP seal failure model, to address the early years of operation with the new RCP seals. This modeling consideration should be used until stable and predictable operations of the RCP seals are established for an operating cycle (i.e., predicted normal operating pressures, temperatures, and flow rates associated with the RCP seals are maintained as expected throughout a plant operating cycle).

In addition, if a plant uses the older seal designs (e.g., BJ SU-type) or materials that are not “qualified,” as defined in the BNL guidance document, the plant must modify the RCP seal failure model to reflect the plant-specific RCP seal design, including the potential for increased likelihood of binding, O-ring extrusion, and pop-open failure, and justify the appropriateness of this plant-specific model in risk-informed licensing activities.

3.3 Plant Operating Conditions that Affect Seal Performance

Chapter 5 of WCAP-16175-P, Revision 0, provides information on the operating conditions that affect seal performance. This chapter highlights the aspects of normal and abnormal RCP seal operation and post-accident response of the plant to LOSC events that influence specific seal stage failure probability and leakage potential. Specifically, this chapter addresses:

- Pressure staging of RCP seals,
- Seal leakage,
- Seal conditions following LOSC events,
- Impact of RCP shaft motion,
- Impact of RCP operation following LOSC events, and
- Impact of RCP motor failure.

Based on the discussion presented in the TR, the designs of the CE RCP seals are considered very robust. As stated in the TR, provided that at least one hydrodynamic seal stage remains intact, the increased RCS leakage flow will be controlled to small levels by the non-bypassed pressure control devices internal to the RCP seal package and if a lower stage (i.e., not the vapor stage) is intact, the seal leakage may be controlled by the normal chemical and volume control system (CVCS). When the vapor stage is intact, any increased flow will be primarily directed towards the CBO line. Otherwise, seal leakage will be noted and the excess flow will be sensed in the containment. It should also be noted that if the CBO line is isolated, any leakage due to RCP seal stage failures will be directed past the vapor stage to the containment. A similar response would occur if the leakage is greater than the CBO relief capacity and excess flow check valves fail to seat. The maximum leakage (for the typical 4-stage RCP seal design) is bounded by the RCP thermal barrier flow area, which limits the total discharge rate. Based on the discussion on seal leakage it is concluded in the TR that RCP seal packages, with at least one of the internal seal stages not failed, are considered functional (i.e., not failed) for purposes of averting an RCP seal-induced LOCA.

Chapter 5 of WCAP-16175-P, Revision 0, also describes the three main means of causing a LOSC event:

- SBO (i.e., a loss-of-offsite power and the inoperability of all plant emergency alternating current power sources - typically provided by diesel generators), which causes a LOSC to all RCP seal packages, but also causes the RCPs to stop,
- Loss of CCW (LOCCW) affecting RCP seal heat exchanger heat removal, which typically causes a LOSC to all RCP seal packages, but does not automatically stop the RCPs, and

- LOSC to one or more RCP seals due to the inoperability of one or more RCP seal heat exchanger cooling control valve(s), which is limited to the affected RCP seal package(s) and does not stop the RCP.

The discussion in Chapter 5 of the TR describes the conditions and required operator actions in response to a LOSC event. Many of the operator actions are different among the plants due to differences in plant procedures (e.g., if CBO is isolated or not) and differences in plant responses to different plant conditions (e.g., isolating CBO for SBO, but not isolating CBO for LOCCW). These differences impact the plant-specific RCP seal failure model. Therefore, the plant personnel that use the WCAP-16175-P, Revision 0, RCP seal failure model need to ensure that they implement the model consistent with their plant procedures and include appropriate operator errors (e.g., failure to isolate CBO early when directed by procedures). In particular, the plant-specific procedures vary on the establishment of RCS subcooling and CBO isolation. The RCP seal failure model uses an RCS subcooling of > 50 °F to define the condition in which the pop-open failure mode will not occur. In addition, the data used in the RCP seal failure model differentiates between early and late CBO isolation and its effect on seal stage temperatures.

For purposes of the RCP seal failure model, the NRC staff interprets early CBO isolation as being within 10 minutes of the LOSC event. Late CBO isolation is also established within the TR. Beyond the time established within the TR for late CBO isolation, the RCP seal failure model should consider the CBO as not being isolated. A similar time limit is established in the RCP seal failure model condition event tree (in Chapter 6 of WCAP-16175-P, Revision 0) for stopping the RCP(s) affected by a LOSC. Beyond the established time, the RCP seal packages are assumed to fail catastrophically in the affected RCP(s). The following conditions and assumptions within the RCP seal failure model should be confirmed on a plant-specific basis, or alternative assumptions be justified.

- RCPs are assumed not to be restarted if a LOSC event has existed for more than 30 minutes. Instead, cooling is assumed to be restored as soon as possible and a plant cool down is initiated followed by an outage to refurbish all RCP seals.

- RCP motors are assumed not to fail on an LOCCW or other LOSC events that do not automatically stop the RCPs. Tests and plant events have shown that these motors can survive without cooling for a substantial length of time. Thus, operator actions should be modeled for turning RCPs off within the time limit established in the RCP seal failure model condition event tree (in Chapter 6 of WCAP-16175-P, Revision 0), following LOSC events that do not automatically stop the RCPs, to avoid catastrophic failure of the RCP seals.

- Seal cooling is assumed not to be restored if a LOSC event has occurred for any significant length of time, to avoid further damage to the RCP seals due to thermal shock, according to vendor guidance regarding plants using BJ SU-type seals (i.e., old seal design) and seal injection (e.g., PVNGS). The TR notes that the BJ N-9000 seals are thermal-shock resistant and restoration of CCW following a LOSC event is unlikely to cause further damage.

In addition, the NRC staff notes that there may be additional means of causing a LOSC, especially for a single RCP. For example, RCP seal heat exchanger plugging or plugging of one or more pressure breakdown devices internal to the RCP would effectively cause a LOSC event to the affected RCP seal package. The LOSC event needs to be fully developed consistent with good PRA practices; recognizing that it can be the initiating event itself or be a subsequent failure of some other initiating event.

Based on the NRC staff review, the NRC staff finds that the TR adequately describes the plant conditions that affect seal performance. The NRC staff further finds that the CE RCP seal failure model explicitly considers the plant and operator responses to the LOSC events. As identified in the discussion above, the plant procedures vary widely in their response to specific events. Thus, the plant-specific RCP seal failure models must address the specific plant and operator responses, including operator errors in responding according to the plant procedures in the time interval established by the WCAP-16175-P, Revision 0, RCP seal failure model.

3.4 Applicable Tests of RCP Seals and Operating Experience

Chapter 7 of WCAP-16175-P, Revision 0, discusses applicable tests and test results, while Chapter 8 describes operating experience involving LOSC events at CE plants. However, the TR did not include any new, additional tests nor did it include the development of any new analytic models to evaluate the physical response of the RCP seals. Thus, the TR was developed from previously existing information.

The TR organized the test programs into the following three categories:

- LOSC with Operating RCPs - These tests were conducted at nominal RCS operating conditions. The tests verified RCP seal leakage during heat up following a limited duration of LOSC for a period of about 30 minutes. One BJ SU-type seal design confirmation test and one BWC test on a smaller scale RCP seal were performed in this category with satisfactory results.

- LOSC with Static RCPs - These tests were conducted at conditions expected when a LOSC event occurs and the RCPs trip (reflecting SBO or other transient conditions). These tests were intended to verify the robustness of the seals to a long duration high temperature, high pressure exposure. These tests included a 50-hour SBO simulation on the BJ SU-type seal design, and an 8-hour SBO simulation on the BJ N-9000 seal. The results of these tests indicated that the seals performed as predicted.

- Elastomer Performance Experiments - The purposes of these tests were to understand the degradation mechanism with RCP seal elastomers and to gain confidence that seal materials can withstand a locally harsh environment for extended periods. One test was performed to investigate the San Onofre Nuclear Generating Station seal arrangement. During this test the seals in the facility were exposed to 650 °F environment until seal failure occurred. One of the two elastomer O-rings failed approximately 2.5 hours after the seal temperature reached 500 °F. The second seal failed approximately 5.5 hours after the seal temperature reached 500 °F.

In Chapter 8, the TR presents events that have occurred over the past 25 years, involving 21 LOSC events at CE plants. Most of the events occurred in the early years of operation. The LOSC events varied in duration from very short (i.e., under 10 minutes) to greater than 4 hours and several included extended RCP operation. However, no LOSC event at a CE plant has resulted in a failure of a single RCP seal (i.e., failing all four RCP seal stages).

The information provided in Chapters 7 and 8 of the TR are used in supporting the development of the RCP seal failure model and the data associated with specific failure modes. Based on the NRC staff review, the NRC staff finds that the TR adequately describes the testing and test results used in supporting the development of the RCP seal failure model and the associated failure data.

3.5 RCP Seal Failure Model and Quantification

Chapter 6 of WCAP-16175-P, Revision 0, describes the RCP seal failure model, while Chapter 9 provides quantification of this model, depending on the plant operating conditions and plant operating staff response to these conditions following any LOSC events at CE plants.

The RCP seal failure model presented in Chapter 6 of WCAP-16175-P, Revision 0, is an assimilation of information from several sources, including: the BNL guidance document (Reference 7), data obtained from RCP seal tests and operating events, RCP seal vendor operational manuals, and analytical predictions of seal performance. The RCP seal failure model consists of three elements:

- Environmental conditions event tree (common to all CE seal designs),
- RCP seal fault tree for 4-stage RCP seal designs, and
- RCP seal fault tree for 3-stage RCP seal designs.

The environmental conditions event tree is used to establish RCP seal stage conditions for use in estimating the RCP seal stage failure conditions. It is constructed to represent the impact of a LOSC event on local seal conditions. The RCP seal fault trees assess the potential for, and magnitude of, an RCP seal failure. As stated above in Section 3.3 of this SE, an RCP seal LOCA does not occur (i.e., leakage greater than makeup capability of CVCS), unless all seal stages of an affected RCP are failed at a CE plant. Thus, the fault tree models assume an RCP seal LOCA only if all seal stages of an affected RCP are failed.

The RCP seal failure model predicts the probability of RCP seal failure, given an initiating event and the success or failure of various operator actions. Consequently, the model has been developed to be sufficiently flexible to accommodate various seal designs and operating procedures. Furthermore, the TR recognizes that additional factors (e.g., capability and availability of mitigating systems and inventories, recovery actions, etc.) must be considered, beyond the RCP seal failure model, when the RCP seal failure model is incorporated into a plant-specific PRA. As a result, properly considering potential for RCP seal failure can be complex and complicated.

Based on the NRC staff review, the NRC staff finds the RCP seal failure model is adequately developed using appropriate information derived from guidance documents, data obtained from RCP seal tests and operating events, RCP seal vendor operational manuals, and analytical predictions of seal performance. As such, the RCP seal failure model can be integrated into the plant-specific PRA and can be quantified, as demonstrated in Chapter 9 of WCAP-16175-P, Revision 0. Further, the NRC staff finds that the specific plant responses and operator actions, as stated previously in this SE, need to be developed (including appropriate human error probabilities for operator errors) and incorporated into the model on a plant-specific basis.

However, the NRC staff notes that the quantified results tables in Chapter 9 of WCAP-16175-P, Revision 0, could be misleading if used in isolation (and not in concert with the RCP seal failure model condition event tree inputs). Some operating strategies and plant conditions artificially appear to be slightly better (i.e., have lower quantitative values) than other strategies and plant conditions that are expected to actually have better performance. These counter-intuitive results are primarily due to limited test and operational data, the conservative approach used in addressing this limited data, and the limitations in PRA modeling techniques. An example of this counter-intuitive result is with the CBO isolated versus CBO not isolated results. Isolating CBO is expected to be a better response strategy than not isolating CBO and yet the quantified results tables in Chapter 9 of WCAP-16175-P show that not isolating CBO has slightly lower conditional RCP seal failure probabilities than isolating CBO. Recognizing this limitation in data and modeling conservatisms, the NRC staff finds that plants should not change their operations or plant procedures to obtain slightly better (i.e., lower) quantitative results, but rather, should ensure that the RCP seal failure model adequately addresses and reflects their plant procedures and operations (i.e., the model should reflect operations - not have operations reflect the model).

3.6 Implementation of RCP Seal Failure Model

Chapter 10 of WCAP-16175-P, Revision 0, provides two sample case calculations for three seal designs to demonstrate the implementation of the CE RCP seal failure model. The two sample case calculations address:

- SBO with subsequent RCP seal induced small LOCA and
- LOCCW event that results in RCP seal induced small LOCA.

The focus of these calculations is to show how the conditional RCP seal failure probabilities can be incorporated into typical LOSC event sequences. The NRC staff notes that these sample calculations are simplistic examples that do not reflect all of the modeling aspects that must be considered in developing a complete integrated PRA model for the CE RCP seals (e.g., addressing all of the event tree branches of the RCP seal failure model condition event tree presented in Chapter 6). To fully integrate the model into the plant-specific PRA will require the use of unique basic event identifiers to address and differentiate between the specific RCP stage failures.

The NRC staff recognizes that plants may chose to develop simplified approaches instead of developing and quantifying an integrated RCP seal failure model directly in the plant-specific PRA (e.g., developing a single RCP seal failure model and applying it to all pumps or using representative basic events in the PRA based on the plant-specific tabular results similar to Chapter 9 for each of the modeled plant conditions). If simplified approaches are used, the simplifications must be documented and justified as appropriate for the PRA and as utilized in risk-informed licensing activities.

Based on the NRC staff review, the NRC staff finds that the TR adequately demonstrates how the RCP seal failure model may be implemented for specific issues, but does not present a complete integrated PRA model. Plants must ensure a fully integrated model is developed and utilized considering the conditions, limitations, and modifications identified in this SE. Model and quantification simplifications must be documented and justified as appropriate for the PRA and as utilized in risk-informed licensing activities.

4.0 LIMITATIONS AND CONDITIONS

The following conditions, limitations, and modifications apply to approval of this TR:

- CE plants are using the improved seal designs that are less susceptible to failure. These NRC staff findings are based on the materials information provided in the TR. Changes in materials would require plant-specific evaluations and/or testing to verify the acceptable performance of the RCP seal design and applicability of the CE RCP seal failure model for these design/material changes.

- The CE RCP seal failure model explicitly addresses the system-related failure causes associated with LOSC events, but does not explicitly address the design-related, manufacturing-related, maintenance-related, and other system-related (non-LOSC) failure causes. These other (not explicitly modeled) causes are assumed to be addressed by the improvements and maturing of the design, manufacturing, and plant maintenance and operational controls that resulted from the plant-specific experiences during the early years of CE plant operations. This expectation is demonstrated for the current CE plants by the reduction in RCP seal stage failure events attributed to design, manufacturing, maintenance, and non-LOSC system-related causes. As the CE RCP seal failure model assumes that the RCP seals are designed, manufactured, maintained, and operated properly, plants using the CE RCP seal failure model must review the CE early operating experiences for associated lessons learned; verify the adequacy of their design, manufacturing, and plant maintenance and operational controls (specifically ensuring that the CE operating experiences are addressed); and modify the plant-specific RCP seal failure model to address potentially new failure mechanisms, if appropriate.

- The CE RCP seal failure model must explicitly consider the plant and operator responses to the LOSC events. As identified in Section 3.3 of this SE, the plant procedures vary widely in their responses to specific events. Thus, the plant-specific RCP seal failure model must address the specific plant and operator responses, including operator errors in responding according to the plant procedures in the required time interval established by the WCAP-16175-P, Revision 0, RCP seal failure model. Critical operator responses identified in the TR include:

    - Isolating CBO early, late, or not isolating CBO within the times established in the TR.

    - Achieving RCS subcooling > 50 °F.

  - Stopping affected RCPs (consistent with the timing established within the TR RCP seal failure model) following a LOSC event, if they are not automatically stopped by the event.

  - For those plants using seal injection or using BJ SU-type seals, not restoring seal cooling if any significant amount of time (consistent with the timing established within the TR) has elapsed following a LOSC event.

  Further, it should not be assumed that the RCP motors fail on a loss of cooling, unless the plant has definitive documented analyses that this will occur (consistent with the timing established within the TR RCP seal failure model) following a LOSC event.

- There may be additional means of causing a LOSC event, especially for a single RCP, that were not explicitly identified in the TR. The LOSC event must be fully developed, consistent with good PRA practices, on a plant-specific basis; recognizing that it can be the initiating event itself or be a subsequent failure of some other initiating event.

- The quantified results tables in Chapter 9 of WCAP-16175-P, Revision 0, could be misleading if used in isolation (and not in concert with the RCP seal failure model condition event tree inputs). Therefore, plants should not change their operations or plant procedures to obtain slightly better (i.e., lower) quantitative results, but rather, should ensure that the RCP seal failure model adequately addresses and reflects their plant procedures and operations (i.e., the model should reflect operations - not have operations reflect the model). (See discussion in Section 3.5 of this SE).

- Plants must ensure a fully integrated model is developed and utilized, including the development of unique basic event identifiers to distinguish seal stage failure events between affected RCPs. Model and quantification simplifications must be documented and justified as appropriate for the PRA and as utilized in risk-informed licensing activities.

Though the identified scope of application and the specific information provided in WCAP-16175-P, Revision 0, is limited to CE plants, the model may be applicable to other plant types that use the same type of RCP seal packages or similar RCP seal packages (i.e., seal packages with individual seal stages that are made of the same type materials, have the same type design, and have the same operational and performance characteristics). However, caution must be used in applying this model to non-CE plants to ensure that the model accurately reflects the operation and experience of the specific plant. This caution is particularly important for the assumptions applied in developing the model and the associated failure rates. Additional conditions, limitations, and modifications are provided below to address some of the issues that must be addressed by application of the CE RCP seal failure model to non-CE plants.

Any of the following conditions indicate the need to modify the CE RCP seal failure model:

- Plant uses older seal designs (e.g., BJ SU-type),

- Plant uses materials that are not “qualified,” as defined in the BNL guidance document,

- Plant design is different from that addressed in the TR (e.g., different RCP gaps that effect flow through failed seals such that fewer stage failures result in leakage above CVCS makeup, CBO design, alignments, or flow capacities), or

- Plant procedures or required operator actions are different from those addressed in the TR.

The plant must modify the RCP seal failure model to reflect:

- Plant-specific RCP seal design and

- The potential for the increased likelihood of RCP seal failure, including increases in binding, O-ring extrusion, and pop-open, and other types of failures that are not explicitly included in the CE RCP seal failure model.

The plant must justify the appropriateness of this plant-specific model in risk-informed licensing activities.

Further, plants that convert their RCP seal packages to the CE RCP seal packages or similar packages (i.e., seal packages with individual seal stages that are made of the same type materials, have the same type design, and have the same operational and performance characteristics), will initially not have the plant-specific experience and lessons learned from the initial CE plant operations. Therefore, the experiences during the early years of CE plant operations must be reviewed and considered by such a plant in developing the design, manufacturing, and plant maintenance and operational controls. Furthermore, as part of the RCP seal design conversion, the plant must consider and model the potential for additional failure modes, beyond those reflected in the CE RCP seal failure model, to address the early years of operation with the new RCP seals. This modeling consideration must be used until stable and predictable operations of the RCP seals are established for an operating cycle (i.e., predicted normal operating pressures, temperatures, and flow rates associated with the RCP seals are maintained as expected throughout a plant operating cycle).

Finally, in its March 6, 2006, letter, the PWROG proposed to incorporate additional information in the TR to specifically address the Waterford-3 RCP seal design, (i.e., N-9000 seal design for the lowest three stages with a BJ-SU type vapor stage). Because of the NRC staff's acceptance, the approved version of this TR must reflect this additional information and the related changes. Furthermore, at a minimum, the following editorial comments must be addressed in the approved version of this TR, as they may influence the quantified model results:

- Transfer gate naming error and a transfer gate paging error in the RCP seal failure model fault tree for 3-stage RCP seals in Chapter 6,

- Exponent error in one of the summary table entries for the Byron-Jackson (BJ) N-9000 and Sulzer 4-stage seal designs with CBO isolated in Chapter 9,

- Inconsistency for the timing of late CBO isolation between the text in Chapter 6 and the summary results tables of Chapter 9, and

- A “No” entry for elastomer failure for an event that involved a stage failure due to thermal expansion and seal face cracking.

5.0 CONCLUSIONS

The WOG TR WCAP-16175-P, Revision 0, (also referred to as CE NPSD-1199, Revision 1) establishes a model for estimating the probability of failure of an RCP seal given a LOSC event. This model is intended for use in the individual CE plant’s PSAs to quantify the risk of an RCP seal LOCA, given the occurrence of a LOSC event.

The NRC staff finds that the RCP seal leakage model as documented in the WCAP-16175-P, Revision 0, is acceptable for use in plant-specific PSAs and can be used in support of risk-informed applications for CE plants, provided it is used within the conditions, limitations, and modifications listed in Section 4.0 of this SE.

6.0 REFERENCES

1. Letter from Ashok C. Thadani, Director, Office of Nuclear Regulatory Research, to William D. Travers, Executive Director of Operations, “Closeout of Generic Safety Issue 23, ‘Reactor Coolant Pump Seal Failure,’” November 8, 1999, ADAMS Accession No. ML993370509.

2. Scientech, Inc., “Cost/Benefit Analysis for Generic Issue 23: Reactor Coolant Pump Seal Failure,” NUREG/CR-5167, April 1991.

3. Combustion Engineering, Inc. “Reactor Coolant Pump Seal Failure Probability Given a Loss of Seal Injection,” CE-NPSD-775, Revision 01, May 1988.

4. Westinghouse Electric Company LLC, “Model for Failure of RCP Seals Given Loss of Seal Cooling in CE NSSS Plants,” WCAP-16175-P, Revision 0 (also referred to as CE NPSD-1199, Revision 1), January 2004, ADAMS Accession No. ML040340226.

5. Letter from T. Schiffley, Chairman, PWROG, to USNRC, “Westinghouse Owners Group Comments and Resolution of Comments on the NRC’s Draft Safety Evaluation on WCAP-16175-P, Rev. 0, ‘Model for Failure of RCP Seals Given Loss of Seal Cooling in CE NSSS Plants’ (PA-RMSC-0103),” March 6, 2006, ADAMS Accession No. ML060680071.

6. U.S. Nuclear Regulatory Commission, “Final Policy Statement ‘Use of Probabilistic Risk Assessment (PRA) Methods in Nuclear Regulatory Activities,’” August 16, 1995, ADAMS Accession No. ML051610044.

7. Brookhaven National Laboratory, “Guidance Document for Modeling of RCP Seal Failures,” W6211-08/99, August 1999.

Attachment: Resolution of Comments

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Date: 2/12/07

RESOLUTION OF COMMENTS

ON DRAFT SAFETY EVALUATION FOR

PRESSURIZED WATER REACTOR OWNERS GROUP (PWROG)

TOPICAL REPORT (TR) WCAP-16175, REVISION 0, "MODEL FOR FAILURE OF

RCP [REACTOR COOLANT PUMP] SEALS GIVEN LOSS OF SEAL COOLING IN

CE [COMBUSTION ENGINEERING] NSSS [NUCLEAR STEAM SUPPLY SYSTEMS] PLANTS"

By letter dated March 6, 2006, the PWROG provided comments on the draft safety evaluation (SE) for the PWROG TR WCAP-16175, Revision 0, "Model for Failure of RCP Seals Given Loss of Seal Cooling in CE NSSS Plants." The following is the NRC staff's resolution of those comments.

PWROG Comment 1:

> The draft safety evaluation could be misinterpreted to mean that Waterford does not use an improved RCP seal design and that the hybrid seal design may exhibit failure data in excess of that shown in the topical report for non-hybrid designs. To resolve this concern, Westinghouse has prepared Waterford specific RCP seal failure fault tree probabilities tables that will be added to Section 9 of the topical. These tables, attached, show that the seal failure data for Waterford remains consistent with that of the CE fleet and are provided for staff review. It is intended that these Waterford-specific tables will be incorporated into the accepted version of the report. Thus the WOG requests that specific parenthetical comments regarding the hybrid Waterford seal design be deleted from the final SE.

NRC Resolution:

The NRC staff agreed to the change and deleted the parenthetical comments regarding the hybrid Waterford seal design.

PWROG Comment 2:

> WCAP-16175-P, Rev. 0 identifies as proprietary certain controlled bleed-off (CBO) isolation times....

NRC Resolution:

The NRC staff agreed to the changes and removed the proprietary CBO isolation times.

ATTACHMENT