Failures of Reactor Coolant Pump Seals

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Abstract

Failures of reactor coolant pump (RCP) seals that could result in a loss-of-coolant accident (LOCA) are of current concern. This could occur either where leakage through the seals exceeded the capacity of the normal makeup systems, as has occurred in operating plants, or under station blackout conditions where loss of seal cooling represents a common mode failure for all RCPs.

Experience from loss of seal cooling events as well as mechanical and maintenance induced seal failures in operating reactors are used to determine the potential risk for a seal induced loss-of-coolant accident. Seal component test results which relate to the station blackout type failures are also presented.

1. Introduction

Reactor coolant pump seals limit the leakage of reactor coolant along the pump shaft, directing the majority of this flow back to the chemical and volume control system with the remainder being directed to the reactor coolant drain tanks. In limiting the reactor coolant leakage to containment, the RCPs use a series of primary and secondary seals. Therefore, these seals become part of the reactor coolant system pressure boundary. The primary seals (metallic oxides, carbides and graphite) limit the leakage of reactor coolant across the interface between rotating and stationary RCP elements. The secondary seals (elastomer O-rings, U-cups and teflon channel seals) prevent leakage between stationary mechanical elements of the RCP seal or those elements which have only a slight relative motion. Both the primary and secondary seals require continuous cooling during pump operation and at hot shutdown conditions with RCPs stationary.

Excessive leakage resulting from RCP seal failures can occur as a result of loss of seal cooling or mechanical failures. In addition to the mechanical failures caused by the lack of adequate seal cooling, mechanical failures may result from excessive pump vibration, defective parts, introduction of contaminants, high frictional torque, secondary seal failure, pressure, temperature or flow transients, improper maintenance, faulty assembly, installation or adjustment and others. The RCP seal failures which have occurred to date have not resulted in a direct threat to health and safety of the public, however, the potential does exist for seal failures which could have significant safety consequences. Seal failures have occurred in which the loss of primary coolant to the containment was greater than the normal makeup capacity of the plant. The potential, therefore, exist for seal failures which can result in a small LOCA.

In all of the seal failures that have occurred to date, emergency makeup capability was available to replenish reactor coolant lost through seal leakage. However, none of these incidents involved complete loss of the component cooling water (CCW) system which provides cooling water to the seal cooling heat exchangers. On some plants, the high pressure coolant injection pumps are also cooled by the CCW system and cannot operate with the CCW system inoperable. Therefore, on complete loss of CCW, the equivalent of a small-break LOCA could occur, due to seal degradation, with no high pressure coolant injection pumps available for reactor coolant system makeup. This sequence of events could lead to core melt. Station blackout can also lead to core melt since station blackout results in a common mode failure of the RCP seal cooling systems through the loss of all A/C power.

NRC initiated Generic Issue 23, "Reactor Coolant Pump Seal Failures," to evaluate the potential safety consequences of failures in PWR primary coolant pump seals and BWR recirculating pump seals. The overall objective of Generic Issue 23 is to determine the need for additional regulatory guidance to assure greater reliability of RCP seals and seal cooling systems.

In support of Generic Issue 23, which includes the NRC concerns regarding loss of all seal cooling due to station blackout, NRC has initiated several studies. The studies to date include the following:

(1) Brookhaven National Laboratory (BNL), "Evaluation of Reactor Coolant Pump Seal Cooling Reliability." The objectives of this study are: to assess the reliability of three representative component cooling water system designs currently in use and identify the major contributors to seal cooling function unreliability; to determine the contribution to core melt frequency caused by seal failures resulting from loss of all component cooling water.

(2) Brookhaven National Laboratory (BNL), "Assessment of the Effect of Mechanical and Maintenance Induced Reactor Coolant Pump Seal Failures on Risk." The objectives of this study are: to evaluate the failure rate and resulting expected leak rate of the three major RCP seal systems (Byron-Jackson, Bingham-Willamette and Westinghouse) from the standpoint of mechanical and maintenance induced failures and to determine the contribution to core melt frequency caused by mechanical and maintenance induced seal failures.

(3) Brookhaven National Laboratory (BNL), "Evaluation of the Adequacy of Current Reactor Coolant Pump Seal Instrumentation and Operator Responses to Possible Reactor Coolant Pump Seal Failures." The objectives of this study are: to evaluate the adequacy of current RCP seal and seal cooling system instrumentation to detect RCP seal degradation and failures; to evaluate the adequacy of current automatic actions and manual operator responses to prevent RCP seal LOCAs or other unacceptable events and to propose possible instrumentation changes, automatic actions or manual operator responses which could improve the current RCP seal safety procedures.

(4) Idaho National Engineering Laboratory (INEL) "Reactor Coolant Pump Shaft Seal Behavior During Station Blackout." The objectives of this study are: to provide fundamental

information and test data that pertains to the behavior of RCP shaft seals during station blackout. This work includes elastomer/polymer seal extrusion tests in high temperature water, taper face seal blowdown tests, and station blackout considerations and analysis.

(5) Energy Technology Engineering Center (ETEC), "Leak Rate Analysis of the Westinghouse Reactor Coolant Pump." The objectives of this study is to determine leakage rates for the Westinghouse reactor coolant pump during a station blackout, without consideration to predicting seal failure or identifying the failure mechanism.

At present these studies are in various stages of completion. However, the preliminary results have yielded some valuable information regarding potential seal failures under normal operation and station blackout conditions.

2. Assessment of the Effects Mechanical and Maintenance Induced Reactor Coolant Pump Seal Failures on Risk

This BNL study is limited to evaluating the core melt frequency resulting from mechanical and maintenance induced failures of the RCP seals. The failures of RCP seals due to either the extended loss of component cooling system or station blackout were not considered as part of this study.

To assess the frequency of core melt induced by pump seal leakage, two major steps are involved. The first is determination of the frequency of pump seal failure and the expected range of leak rates. The second is to evaluate the conditional core melt probability given various sizes of primary coolant leakage. Phase one of the study deals with the data collection and statistical analysis, while phase two of the study deals with a probabilistic approach to evaluate the core melt frequency induced by pump seal leakage.

A data survey of the pump seal failures for existing nuclear power plants in the U.S. from five available data sources was performed. These data sources were Nuclear Safety Information Center (NSIC) files, Licensee Event Reports (LER's), Nuclear Power Experience (NPE), Nuclear Plant Reliability Data System (NPRDS), data collected during prioritization of RCP seal failure issue, and EPRI-NP-351 report.

For the PWR plants, a total of 118 events were collected in which 173 RCP seal failures are noted, indicating that some events involved the failure of more than one pump. Seven of these events resulted in leak rates greater than 25 gallons per minute. Out of the 118 events, 46 events are for Westinghouse plants with Westinghouse (W) pumps, 31 events are for Combustion Engineering (CE) plants with Byron Jackson (BJ) pumps, 28 events are for Babcox and Wilcox (B&W) plants with pre-1974 Bingham Willamette (Bingham) two stage seal design pumps, and 4 events are for B&W plants with Bingham post-1974 three stage seal design pumps. Forty percent of the seal failures were attributed to mechanical seal failures; twenty percent of failures were judged to be maintenance induced; and, the remaining were considered to be result of plant transients, seal surface contamination, etc. Regardless of the pump design, the data shows a statistical indication of slow degradation of pump seals after a service life of about 2 years for PWRs and 16 months for BWRs. The hazard rate (failure intensity per month) for RCP seal failure, with exception of the pre-1974 Bingham pumps, seems to be constant with a service life less than 20 months for PWRs and 16 months for BWRs. The seal failures in this range are expected to be caused by random failures. The best estimates of the hazard rate for the first 18 months of seal life in PWR plants are: W plants with W pumps 1.7 x 10^{-2}; B&W plants with Bingham pumps 2.0 x 10^{-2}; B&W plants with old design Bingham pumps 10.2 x 10^{-2}; B&W plants with BJ pumps 3.6 x 10^{-2}; and CE plants with BJ pumps 3.6 x 10^{-2}. The best estimate of the hazard rate for a service life less than 16 months in the BWR plants is 1.4 x 10^{-2}.

The second phase of the study entails the estimation of the annual core melt frequencies induced by various sizes of LOCAs, which are induced by RCP seal failures in three representative nuclear power plants. The three representative plants chosen were: Indian Point 3, Calvert Cliffs 1 and Arkansas Nuclear One-1 (ANO-1). The available documentation for the PRAs of these plants seems to be complete enough for estimating the core melt frequency. Preliminary results from the second phase of the study are available for ANO-1, but not for the other representative plants.

The dominant accident sequences for ANO-1 which are initiated by a small LOCA induced by RCP seal leakages have been determined. The frequency estimated for the initiating event is based on the leak rate distribution for a B&W plant with four BJ RCPs. The median value estimated for RCP LOCAs, in excess of normal makeup capacity of the plant is 2.1 x 10^{-3}, with an error factor of three. The accident sequences are quantified based on the median failure rates and recovery probabilities estimated in the ANO-1 Interim Reliability Evaluation Program (IREP). The dominant minimal cut sets for each accident sequence then were determined based on their contribution to the core melt frequency.

The total contribution of RCP seal induced LOCA to annual core melt frequency of ANO-1 is estimated to be 7.8 x 10^{-6} per year. Considering the core-melt frequency estimated for the ANO-1 plant excluding the RCP seal induced LOCA is 3.5 x 10^{-5}, the increment in core melt frequency caused by RCP seal induced LOCA would be less than 23%. The five major dominant cutsets from the overall accident sequences contribute about 60% of the total core melt frequency induced by RCP seal induced LOCAs.

3. Leak Rate Analysis of the Westinghouse Reactor Coolant Pump

ETEC conducted this independent analysis of the leakage rates from the primary coolant system through the Westinghouse RCP shaft seals and associated downstream piping for a postulated station blackout condition. A station blackout is the loss of all A/C power in the plant and therefore causes loss of component cooling water and injection cooling flow to the RCP seal system. This results in subjecting the seals to full reactor coolant temperature and pressure of 550°F and 2250 psia. The safety concern is that leakage of reactor coolant through the uncooled RCP seal system would cause core uncovery if a lengthy station blackout occurs.

Three computer models were developed. The seal model determined the gap and pressure distribution between the faceplates of the No. 1 film riding seal for various flow conditions. The flow model calculated the pressure drop for single and two phase flow through the constant area leak paths such as the labyrinth seal and the leakoff lines. The structural model determined the rotation of the seal faceplates due to thermal and pressure gradients across the seals. Results of the three models were integrated to obtain the final leakage rates.

The Westinghouse RCP has three seals. The No. 1 seal is a film riding, controlled leakage seal whereas the Nos. 2 and 3 seals are rubbing face type seals. The leakage across the No. 1 seal cools the seal assembly. The high pressure, subcooled leakage is supplied by an injection system upstream of the No. 1 seal. Backup cooling is provided by a water to water heat exchanger parallel to the labyrinth seal. During the proposed station blackout, both injection and cooling water would be lost. High temperature reactor coolant water would then flow into the seal system. This off-design condition will affect the angle between the faceplates of the RCP seals and the gap between the faceplates of the No. 1 film riding seal. The seal model calculates this gap and the pressure distribution across the No. 1 seal. The gap between the No. 1 seal faceplates is determined by a force balance. The model calculates the pressure distribution along the seal face. The included angle between the seal faceplates is determined by the structural model based on the thermal and pressure gradients across the seal. The seal model incorporates the two phase flow correlations used for the flow model.

The reactor coolant water is subcooled under nominal conditions. As it flows through the RCP seal system, the pressure drop causes the fluid to enter the two phase region. Two phase flow correlations were used to calculate pressure gradients in this region. The correlations were based on the Dukler constant slip model, which assumes that the ratio of the phase velocities to the average velocity is constant across a cross section. The flow model also assumes thermodynamic equilibrium between phases and adiabatic, steady state, one dimensional flow in the axial direction. The flow path is along the pump shaft through the labyrinth seals, through the cartridge seal internals, and either through one of the three seal leakoff lines or out the top of the pump casing. The flow rate estimate is modified until the downstream pressure condition is reached or until choked flow occurs. The downstream pressure conditions for the No. 1 leakoff line was 165 psia, the set pressure for the No. 1 seal leakoff line pressure relief valve.

Finite element structural models were developed for all three seals to predict thermal and pressure distortions on the structures. The model of the No. 1 seal is particularly important in determining the angle between the seal faceplates.

The results of the analysis indicate an initial leakage rate of 19.6 gpm for the case where all three seals perform as designed. This leakage rate decreases to 16.9 gpm as the reactor is depressurized (2250 psia to 1250 psia). An initial leakage rate of 64.7 gpm was predicted for the case with No. 1 seal failure and Nos. 2 and 3 seals operational. This leakage rate decreases to 33.7 gpm with depressurization. An initial leakage rate of 422 gpm was calculated for the case with all three seals failed.

3. Reactor Coolant Pump Shaft Seal Behavior During Station Blackout

As challenged by station blackout conditions, the hydrostatic type seal with its No. 1 seal withstanding almost all the pressure drop appears to be more vulnerable to seal failure than the other hydrodynamic multi-staged seal arrangements. The test program conducted under the INEL study was therefore focused on the hydrostatic seal arrangement. More than twenty elastomer (or elastomer/polymer) seals are used in the three stages of the hydrostatic RCP seal. On loss of seal injection cooling and component cooling water flow to the thermal barrier, the elastomer seals would be exposed to high temperature water. Entry of hot water to the seal cavity accompanied by localized cooling due to flashing could lead to thermal gradients and large temperature variations between seal components. The clearance gaps at certain elastomer seal locations could greatly exceed the as-machined values. Both increased temperature and increased clearance gaps have the effect of lowering the elastomer seal's resistance to extrusion. Blowout type failures of an elastomer seal by extrusion would result in additional main coolant leakage and could contribute to opening of the seal faceplates.

The objective of the elastomer seal tests was to determine the ability of the seal materials to maintain a leaktight pressure seal during 18 hours of exposure to combinations of temperature, pressure and clearance gaps that could occur during a loss of seal cooling event such as station blackout. Due to the variation in gap dimensions, pressure differential and temperatures to which the elastomers would be exposed during station blackout, the test program covered a range of plausible clearance gaps at two different temperatures. The aim was to define a limiting pressure differential above which failure by blowout of the seal will occur, for each gap and temperature condition. Both O-rings and channel seals were tested.

The results of the test program show that Parker Seal Company ethylene propylene compound E515-80 is likely to experience blowout type failures when subjected to clearance gaps, temperatures and pressure differentials representative of station blackout conditions. It is also probable that channel seals backed with this compound would also fail under the predicted conditions. Tests of an alternate material, Parker Seal Company ethylene propylene compound E740-75, appears suitable for 18 hours or less exposure to the predicted conditions. The test results indicate that channel seal material Tetralon 720 backed with E740-75 in place of E515-80 O-rings may be suitable for the predicted conditions. However, further testing of the channel seal and O-ring configuration in larger cross-sections will be required.

The tests indicated cause for concern about the ability of the materials to withstand the predicted conditions. The study, however, was not sufficiently comprehensive to permit reliable prediction of time to failure for in-service seals. Possible effects of seal lubrication, of small movements of the sealed components, and of prior aging (radiation, etc.) of the polymeric materials were not addressed in this study.

Within a particular class, elastomer compounds can vary widely in resistance to a given set of conditions. This is shown explicitly by the large difference in high temperature extrusion reistance of the two ethylene propylene compounds investigated in this study. When a compound has been qualified for this service, the only way to verify the adequacy of all future seals for the high temperature event would be to subject at least one seal from every elastomer batch to a high temperature extrusion test marginally on the safe side of the limits established in this study.