REACTOR COOLANT PUMP SEAL ISSUES AND THEIR APPLICABILITY TO NEW REACTOR DESIGNS

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ABSTRACT

Reactor Coolant Pumps (RCPs) of various types are used to circulate the primary coolant through the reactor in most reactor designs. RCPs generally contain mechanical seals to limit the leakage of pressurized reactor coolant along the pump drive shaft into the containment. The relatively large number of RCP seal and seal auxiliary system failures experienced at U.S. operating plants during the 1970's and early 1980's raised concerns from the U.S. Nuclear Regulatory Commission (NRC) that gross failures may lead to reactor core uncovery and subsequent core damage. Some seal failure events resulted in a loss of primary coolant to the containment at flow rates greater than the normal makeup capacity of Pressurized Water Reactor (PWR) plants. This is an example of RCP seal failures resulting in a small Loss of Coolant Accident (LOCA).

This paper discusses observed and potential causes of RCP seal failure and the recommendations for limiting the likelihood of a seal induced small LOCA. Issues arising out of the research supporting these recommendations and subsequent public comments by the utility industry on them, serve as lessons learned, which are applicable to the design of new reactor plants.

BACKGROUND - GENERIC ISSUE 23

Preliminary risk analyses by the NRC indicated that the overall probability of a core melt due to small break LOCAs could be dominated by RCP seal failures. Industry actions have reduced the seal failure rate (during the last 10 years) for normal operations, so that the Core Melt Frequency (CMF) from this type of LOCA is likewise reduced. However, the potential for seal failures from off-normal conditions, which result in a loss of all seal cooling, has not yet been fully addressed by industry.

The preliminary risk analysis coupled with the high rate of RCP seal failures experienced from the mid 1970's to the early 1980s led to seal failure being categorized as a high priority issue in 1983 by the NRC. This issue, Generic Issue 23 (GI-23) "Reactor Coolant Pump Seal Failure," addresses failures of RCP seals that challenge the makeup capability of the Emergency Core Cooling Systems (ECCS) in PWR nuclear power plants (NPPs). The objective of the issue was to evaluate the adequacy of current licensing requirements relating to RCP seal integrity and to determine if further NRC action is necessary to assure that seal and seal auxiliary system failures do not pose an unacceptable risk to the public.

Operating experience indicates that PWRs and Boiling Water Reactors (BWRs) experience roughly the same number of seal failures. However, the technical investigations carried out for GI-23 have primarily considered the safety concerns of seal failures in PWR plants. BWR plants exhibit significantly lower leak rates from seal failures than PWR plants, primarily due to the lower system pressure in BWRs. The smaller leak rate, the larger makeup capabilities of a BWR, and the presence of isolation valves in the reactor recirculation loops in BWRs reduces the potential of significant leak rates as a result of pump seal failures. Therefore, BWRs were initially not considered as part of the definition of GI-23.

RCP SEAL DESIGN

The RCP seals limit the leakage of high pressure primary reactor coolant from the Reactor Coolant System (RCS) along the RCP shaft into the primary containment, directing the majority of this flow back to the Chemical and Volume Control System (CVCS) with most, if not all, of the remainder being directed to the Reactor Coolant Drain Tank (RCDT) or equivalent. A small amount goes to the containment sump in some cases. These seals consist of primary seals, which limit the leakage between rotating and stationary pump elements, and secondary seals, which limit leakage between pump elements having only slight motion relative to one another. Therefore, the seals are physically part of the RCS pressure boundary, although they have not always been fully treated as an RCS pressure boundary component. Both the primary and secondary seals require continuous cooling

*Work performed under the auspices of the U.S. Nuclear Regulatory Commission.

during RCP operation and at hot shutdown conditions with RCPs stationary. This seal cooling is required to prevent overheating of the seals by high temperature reactor coolant water and consequent failure.

There are three major RCP designs in U.S. PWRs: Westinghouse, Byron Jackson, and Bingham International, (formerly Bingham-Willamette). Although there are variations among seal designs, the general behavior of the seals is similar. The seal assembly is made up of three or four stages. A simplified representation of a single stage is shown in Figure 1.[1] Some designs allow the rotating seal ring to move axially, instead of the non-rotating seal ring as shown in the figure. Seal stage connections also vary by design, with some designs directing the seal leakoff flow to the next stage rather than collecting it separately and some designs divide the pressure drop across several stages by control of the seal bypass flow.

Water (CCW) system is capable of removing heat. One vendor design provides seal cooling only via a thermal barrier.

SEAL FAILURE SCENARIOS

RCP seal failure scenarios which can result in a LOCA can be divided into two categories: (1) those resulting during normal operations from mechanical-induced or maintenance-induced failures, and (2) those resulting from a loss of all seal cooling during off-normal conditions such as station blackout (SBO), loss of CCW or loss of Service Water (SW).

During normal operation RCP seal failures have occurred from many causes[2] including maintenance errors, wear out, vibration, corrosion, contamination, abnormal pressure staging, overheating of the seal cavity, operator error, improper venting, and defective parts. The resulting seal leakage has varied from very low rates up to 500 gallons

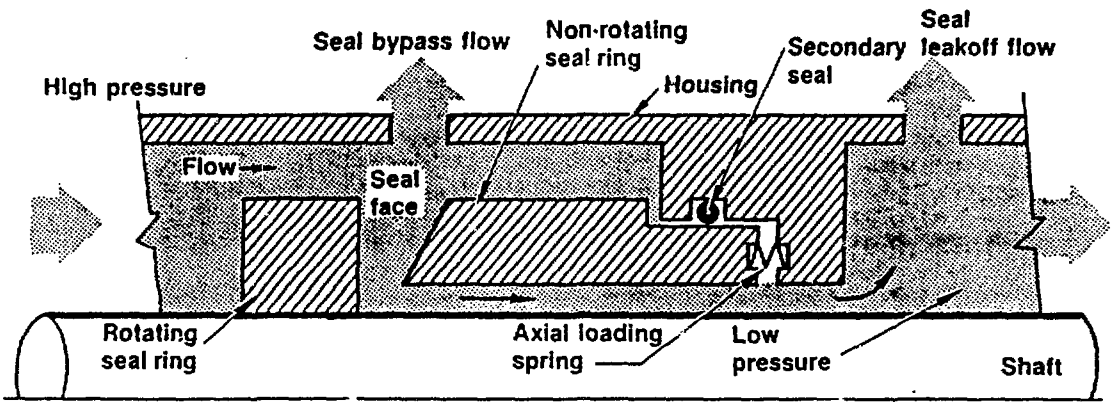

Figure 1. Simplified single stage of a RCP shaft seal

The gap between the rotating and non-rotating seal rings is the primary hydraulic seal which determines the leakage flow. One seal ring can move axially to maintain a virtually constant gap while the shaft is subject to thermal and pressure induced expansions. The gap between the seal rings is determined by a balance of forces on the movable seal ring. The hydrostatic pressure on the back side of the movable seal ring and the spring load (if present) act to close the gap. The leakage flow passing through the restricted flow area of the gap produces a distributed pressure load across the seal face, which tends to open the gap. Polymer secondary seals prevent leakage between the movable seat ring and the housing while allowing relative axial motion between them.

In normal power operation at most PWRs, the seals are cooled by continuously injecting a small amount of makeup water using either the charging or high pressure injection pumps. A portion of this relatively cold injected flow passes down along the shaft to the RCS and the remainder passes upward through the seal assembly, thereby cooling the seals. Seal cooling is also provided by a thermal barrier, where an internal heat exchanger cooled by the Component Cooling

per minute ($\sim$115 m^3/hr). Further, when such failures occur, there is no way to isolate the seal. Plant shutdown and depressurization are necessary to control the leak, and partial draindown of the system is often necessary to stop the leak.

Components that are part of the reactor coolant pressure boundary (RCPB) should meet the requirements for Class 1 components in Section III of the ASME Boiler and Pressure Vessel Code. However, Section III of the ASME Boiler and Pressure Vessel Code has included specific exemptions for seal components under NB-3411.2 and NB-2121(b). As a result, the RCP seal has not always been treated as important to safety in the pressure boundary and based on operating experience, its failure probability is considerably higher than that of the passive elements of the primary system boundary.

Although RCP seal failures are only important from a risk perspective when the seal leakage exceeds the capacity of the normal makeup systems and proactive actions by industry have reduced the rate and magnitude of seal failure in the last 10 years, improving quality control over seal materials and fabrication, installation, and maintenance, as well as seal operations could be expected to decrease the current failure rate for the RCP seals. Improving instrumentation and monitoring capabilities in order to identify degraded seal performance early enough to take corrective action to mitigate seal failure could also reduce seal failure rates during normal operation. Treating the seals as part of the RCPB would serve to improve quality control and to improve instrumentation monitoring and procedural coverage.

Loss of seal cooling scenarios such as SBO, loss of CCW or SW, represent a potential common cause failure for all RCP seals. These scenarios also illustrate that the resolution of GI-23 is related to resolution of Unresolved Safety Issue A-44 (station blackout). In fact, the expected magnitude and timing of seal leakage determined under GI-23 directly effect the strategies used to comply with the station blackout rule.

For off-normal conditions certain common mode dependencies could both cause an RCP seal LOCA and render the mitigating systems inoperable, and thus lead to core melt. In addition to station blackout, another such scenario involves the complete loss of the CCW system, which provides cooling water to the seal thermal barrier heat exchanger. In some PWRs, reactor coolant makeup system pumps or CVCS charging pumps that supply RCP seal injection flow are also cooled by the CCW system. Furthermore, in some plants, the reactor coolant makeup pumps are used as the high pressure safety injection pumps. Other plants may have separate high pressure safety injection pumps, but these may also be cooled by CCW. Therefore, for some plants, complete loss of CCW could result in the equivalent of a small-break LOCA caused by seal degradation, with no high pressure safety injection pumps available for emergency core cooling. Another potential common mode scenario involves the complete loss of all SW. Essentially, all PWRs rely on the SW system, either directly or indirectly via the CCW system, for cooling the CVCS charging pumps and the high head safety injection pumps. For plants with this common mode vulnerability, loss of all SW could result in a sequence of events that could lead to core melt. Recent work on GI-23 has shown that the risk from seal failures as a result of loss of SW is greater than that from SBO or loss of CCW.

During off-normal conditions, which lead to loss of all seal cooling, seal system components begin to be exposed to high temperature reactor coolant fluid approximately 10 minutes after cooling is lost. This is when the cold volume of fluid in the seal inlet cavity and lower pump volute is purged. The presence of high temperature fluid in the seal system creates the possibility of the loss of seal integrity by "popping open" instability or degradation of secondary seal materials. Restoration of seal cooling later than 10 minutes after it is lost will not ensure that seal integrity will be restored once it has been compromised and may actually cause seal failure if it has not already occurred.

Industry and NRC analyses[3,4] of PWR RCP seal leak rates for loss of cooling conditions have indicated that seal leakage rates will remain less than 25 gpm (~6m^3/hr) per pump, based on reactor coolant system (RCS) density, if there are no seal failures of any type. The same analyses determined a worst case PWR leakage rate of 480 gpm (~110m^3/hr) per pump, based on RCS density, if all seal stages fail.

The high temperature survivability of the polymers is reflected by their high temperature extrusion resistance and *any increase in frictional* drag forces *due to degradation* at high temperatures. An NRC-sponsored test evaluation[5] of the extrusion resistance of polymer seal materials of the three pump manufacturers indicated that a blowout was probable with the O-rings used by two vendors. The third vendor's polymer seals experienced degradation which tends to increase fractional drag forces and impact seal stability.

Seal instability can result from the off-design temperatures and subsequent flashing which occur during a loss of seal cooling, and which can affect the pressure distribution of the flow through the gap between the primary seal rings. Increased pressure loading on the seal face has the potential of causing the primary seal to open to a large gap or to pop open completely, resulting in substantially increased leakage. In general, unstable behavior can be expected if seal inlet fluid conditions are near saturation and the seal rings are exposed to low back pressure (unless the seal faces are divergent and are not worn or warped enough to allow significant leakage). NRC sponsored analytic and experimental studies[1,5] have indicated that all RCP seal assemblies are at risk of popping open under two-phase flow conditions.

Even if no seal failure occurs during a loss of seal cooling, the seal leak rate will increase substantially. This is due to the decrease in water viscosity (~ a factor of four between 100°F or 37.8°C and 550°F or 287.8°C) thermal distortion of seal components, and increased gap width in response to seal face pressure re-distribution resulting from flashing.

Reference 6 is a summary of the technical findings of the NRC staff's studies of the RCP seal issue.

POTENTIAL RECOMMENDATIONS

Based on information available in 1990 and 1991 the NRC staff developed potential recommendations for an approach to resolve GI-23. These potential recommendations were included in Draft Regulatory Guide DG-1008.[7] This document, together with a draft Regulatory Analysis[8] and supporting information, were issued for public comment in April 1991.

Briefly, for normal operations, the approach recommended treating the RCP seals of PWRs as part of the safety-related RCS pressure boundary by applying appropriate QA programs to the seal components, ensuring adequate operating procedures, and ensuring adequate instrumentation to assess seal integrity.

For off-normal conditions, which could lead to a loss of seal cooling and the potential for a common mode seal

LOCA coincident with the loss of makeup functions due to plant specific common dependencies, it was recommended to either evaluate and eliminate these dependencies or provide additional seal cooling which is independent of normal seal cooling and the support systems to the extent practical. Some existing seal cooling piping runs may be shared if the probability of failure of the piping is shown to be acceptably low or if, upon piping failure, the leak can be isolated and other seal cooling can be maintained. To accommodate station blackout events the additional cooling should be independent of AC power supply. Full QA requirements were not considered to be cost beneficial for the independent cooling system, and since the system was designed primarily to accommodate station blackout conditions, criteria consistent with the criteria in the station blackout rule were applied. An example arrangement of such a real cooling system is given in Figure 2.

An alternative recommendation, rejected because of the high degree of uncertainty associated with development and installation costs, involved an emergency backup seal stage on each RCP to preclude excessive leakage in the event of loss of seal cooling.[8] The design would have take advantage of and depended on fixed shaft position (no rotation) and limited seal leakage to less than 3 gpm (~0.7m^3/hr). Activation of such an emergency seal would have precluded the requirement for an alternate seal cooling system.

BWR SEAL FAILURES

The ensuing public comments brought forward some interesting issues. One issue has resulted in reconsideration of the applicability of GI-23 to BWRs for loss of seal cooling events, and the relationship between GI-23 technical findings and current compliance with the station blackout (SBO) rule

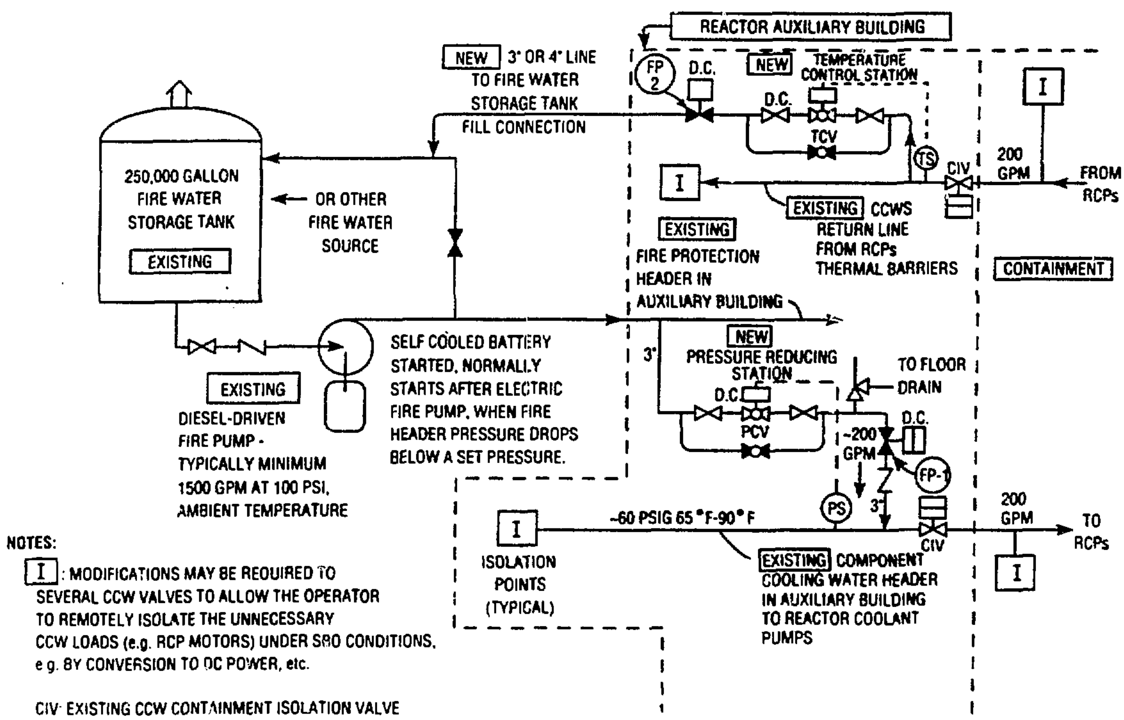

Figure 2. Example of independent seal cooling

Providing an engineering solution to the loss of cooling seal problem by providing an alternative source of cooling, that would be available during all postulated loss of cooling events, such as station blackout and loss of CCW/SW, would resolve the unknowns associated with hydraulic instability, high temperature performance of secondary seal materials, engineering judgment associated with seal failure modeling, and the duration of loss of seal cooling events. If implemented in PWRs these potential recommendations would limit seal leakage to the values used in station blackout coping analyses.

by BWRs. Most current SBO coping strategies for BWRs are based on an expected 18 gpm (~4 m^3/hr) per pump seal leakage rate, which assumes that no seal failures of any type occur. Investigations for GI-23 predict maximum seal leak rates from loss of seal cooling failure mechanisms of about 100 gpm (22.7 m^3/hr) per pump, or 200 gpm (45.4 m^3/hr) total, for a typical two loop BWR, assuming that the seals in both pumps fail. For station blackout, isolation of the recirculation loops is not possible because the motor-operated isolation valves depend on AC power. Manual reactor depressurization is available, but the rate of depressurization is limited by reactor vessel design criteria. Therefore, significant makeup inventory will be required to cope with SBO events. Several sources of high pressure makeup, namely normal feedwater, condensate, and control rod drive (CRD) systems are not available during an SBO due to their dependence on AC power. This leaves the DC dependent reactor core isolation cooling (RCIC) system with steam driven pumps and other independently powered emergency vessel water supply systems; high-pressure coolant injection (HPCI), high-pressure core spray (HPCS), or diesel-driven fire pumps, to supply makeup.

It was originally thought that these emergency vessel water supply systems would be able to mitigate seal leakage of 200 gpm (45.4 m^3/hr) during SBO. However, the public comments indicated that guaranteed BWR makeup capacity may be smaller than originally expected during off-normal conditions. Other comments indicated that BWR station blackout coping analyses may have to be redone because GI-23 investigations predict maximum seal leak rates which are much greater than those used in the BWR SBO coping analyses. Accounting for this larger leakage will likely require somewhat extensive plant specific analyses to overcome problems related to the operation of high pressure makeup systems and challenges to containment temperature and pressure limits.[9]

These problems involve heat up of the suppression pool due to: the seal leakage accumulation, reactor vessel boil-off due to decay heat, initial safety relief valve (SRV) opening, and RCIC/HPCI steam exhaust. The condensate storage tank (CST) inventory probably will not be sufficient to supply the necessary makeup via the emergency vessel water supply systems, requiring an automatic switchover to draw from the suppression pool. Use of heated suppression pool water by these systems may cause their pump design temperature limits to be exceeded. Also the suppression pool heat capacity temperature limit (HCTL) may be violated. In addition, the RCIC system flow rate may not be adequate to provide the required makeup during an SBO with worst case seal leakage. Other parameters which must be managed during an SBO include:

- Reactor water level
- Suppression pool level
- Reactor pressure
- Containment pressure
- Drywell temperature

Complex calculations, requiring detailed plant computer codes may be necessary to ensure that any potential SBO coping strategy maintains all these parameters within their limits.

One possible solution to these issues is for BWR plants to re-perform their SBO coping analyses taking into account the bounding seal leakage of 200 gpm (45.4 m^3/hr) per plant. The re-coping strategies would depend on plant specific considerations and may be somewhat complex.

For non-blackout loss of seal cooling events, BWRs should be able to mitigate any inventory loss from seal leakage by isolation of the reactor recirculation loops and also possible manual depressurization of the reactor. Implementation of these strategies will probably require some analysis and changes to procedures.

The final development of a rule for resolution of GI-23 for PWRs during off-normal conditions is nearing completion. Presently, seal issues related to normal operations and BWR station blackout rule compliance are being handled separately.

APPLICATION TO ADVANCED REACTOR DESIGN

The experience with RCP seal failures in operating NPPs and the lessons learned from the studies for GI-23 should be carefully considered at the design stage of new reactor plants. Appropriate design selections could ensure that these failures and concerns are eliminated or at the least minimized. Issues for design consideration of new plants are:

1. Elimination of RCP seals by use of canned rotor pumps or natural circulation.
2. Design of RCP seals as quality components of the RCS pressure boundary.
3. Backup seal stage to ensure leak-tight integrity in case of failure of main stages.
4. Comprehensive instrumentation and procedures for seals.
5. Diverse cooling/seal support systems.
6. Mitigation systems that consider a common mode seal LOCA.

Appropriate consideration of these issues would be expected to eliminate the seal LOCA event as a concern in new reactors.

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