DEVELOPMENTS IN REACTOR COOLANT PUMP SEAL ENHANCEMENTS INCLUDING POST-FUKUSHIMA SOLUTIONS

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ABSTRACT

Westinghouse reactor coolant pump seal (RCP) technology is used by approximately 50% of the global nuclear fleet. Since developing the first hydrostatic RCP seals in the 1960s, Westinghouse has developed innovative solutions to improve seal performance, reliability, and safety. Recent enhancements such as the SHIELD® Passive Thermal Shutdown Seal and Extended Life High Temperature O-rings improve plant safety by mitigating the risk of excessive seal leakage during Station Blackout events while providing greater operational flexibility and lower operating costs. An optimized seal designed to offer improved reliability and greater service life is currently under development to provide a comprehensive sealing solution for today. This paper provides an overview of these innovations.

Keywords

Reactor coolant pump; Westinghouse; RCP seals; Post-Fukushima

1. Background

Westinghouse pressurized water reactors (PWR) generate power via the Rankine cycle by utilizing steam generators to transfer heat between a pressurized primary loop and a secondary steam system. The primary system consists of a reactor vessel containing the nuclear core and several circulating pumps and steam generators, while the secondary loop contains feed pumps, turbines, and a condenser. A pressurizer in the primary loop maintains the reactor coolant system in a subcooled state at a temperature and pressure of approximately 300°C and 155 Bar. Single stage vertical reactor coolant pumps circulate water through the core and transfer heat to the secondary system, where a turbine generator converts thermal energy to electricity. Mechanical seals between the pump and motor isolate the process fluid. The severe operating conditions and high reliability demanded of such seals necessitate the use of precision mechanical seals that must provide stable operation over an extended range of temperatures, pressures, and chemical environments. For over 50 years, Westinghouse reactor coolant pumps have utilized hydrostatic mechanical seals (Figure 1), which offer a number of desirable characteristics including limited wear, tolerance of foreign material, and controlled leakage.

In pursuit of greater nuclear safety, Westinghouse has developed innovative seal technologies such as the SHIELD® Passive Thermal Shutdown Seal and Extended Life High Temperature O-rings. These innovations are Post-Fukushima solutions to improve reactor safety by mitigating the risks associated with loss of seal cooling events (i.e., seal loss of coolant accident). Westinghouse is also pursuing an optimized reactor coolant pump seal, which offers improved reliability and service life, helping to lower the operating costs of reactor coolant pumps. This paper provides an updated perspective on the developments first discussed in [5].

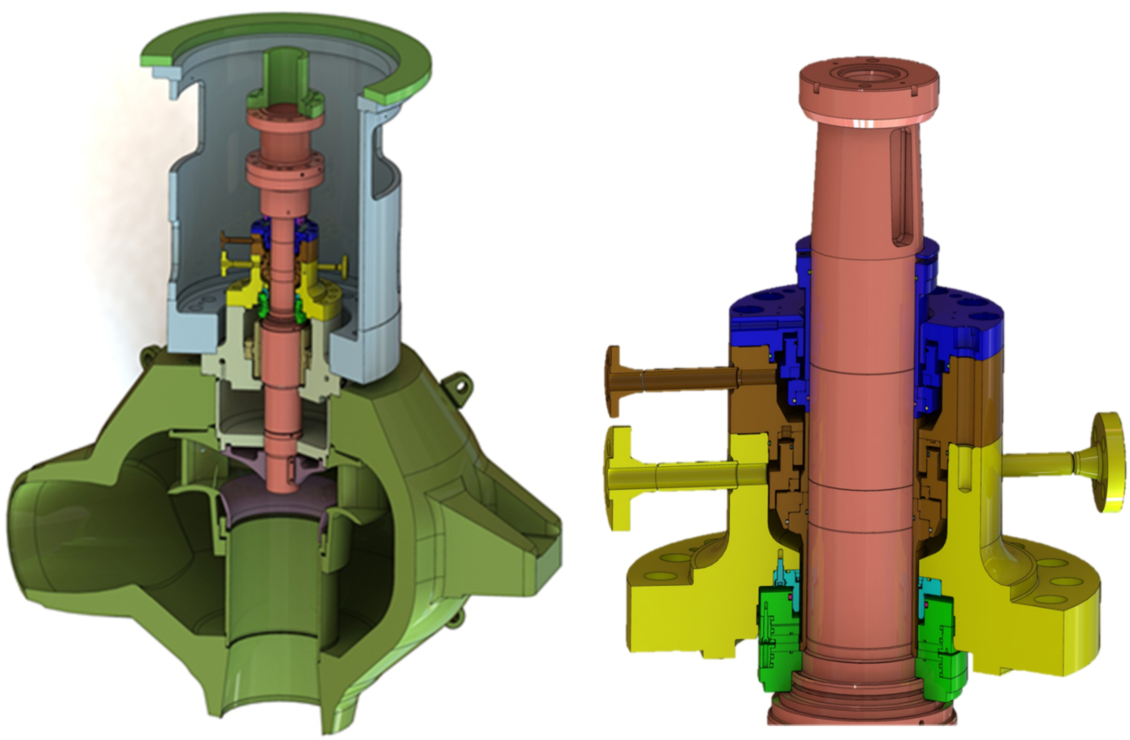

Fig 1. Westinghouse Model 93D Reactor Coolant Pump and Seal Package

2. Westinghouse Seal Innovations

2.1. SHIELD® Passive Thermal Shutdown Seal

Westinghouse reactor coolant pumps are designed to circulate water through the reactor coolant system at approximately 300°C and 155 bars. While the hydraulic section of the pump is designed for operating in this environment, the bearing and seal package must be maintained at lower temperatures for continuous operation. This requirement is established due to material limitations and the desire to avoid two-phase flashing flow across the seal faces. Westinghouse reactor coolant pumps are typically restricted to operation with bearing and seal temperatures below 110-115°C, which is maintained by a continuous flow of buffer water from the chemical and volume control system.

During normal operation, the chemical and volume control system provides a continuous flow of cool, filtered water at a rate of nominally 1800 l/h. Approximately 600 l/h travels through the seal package, and the remainder travels downward through the pump into the reactor coolant system. Buffer water entering the seal package passes through the first stage seal, drops in pressure to approximately 3 bars, and is returned to the chemical and volume control system via dedicated return piping. The second and third seal stages each experience significantly lower differential pressure and negligible leakage rates.

Redundant cooling capability is provided to the upper pump internals via an integral heat exchanger connected to the independent component cooling water system. Acceptable seal operating temperatures can be maintained by either the injection of cool buffer water (i.e., seal injection) or by cooling reactor cooling system leakage with the thermal barrier heat exchanger. If both seal injection flow and thermal barrier cooling are simultaneously interrupted, then leakage from the reactor coolant system can reach the seal package at elevated temperatures. In such conditions, high temperature water causes a thermo-elastic warping of the first stage seal that allows for elevated seal leakage [1]. In the worst case, seal leakage from the reactor coolant pumps can accumulate to a significant volume of reactor coolant system inventory loss leading to uncovering the core and fuel damage. Probabilistic risk assessments (PRA) have shown that such “loss of seal cooling events” commonly represent a major contributor to the overall risk of core damage at many plants.

To mitigate this risk, Westinghouse has developed the SHIELD® Passive Thermal Shutdown Seal. The SHIELD® shutdown seal is a passive, thermally-actuated device that limits seal leakage to negligible levels in the event of a total loss of seal cooling. Designed as a drop-in replacement to an existing seal component, the shutdown seal replaces the number 1 seal insert and includes a thermal actuator and sealing mechanism that is activated by elevated seal leak off temperatures. The shutdown seal is located immediately downstream of the first stage seal such that, when deployed, both the seal return piping and second stage seal are completely protected (Figure 2).

The shutdown seal assembly consists of a thermal actuator, a split piston ring, a solid polymer sealing ring, and a wave spring fit into a modified number 1 seal insert and contained by a shrink-fitted retaining ring (Figure 3). If seal cooling is interrupted, the thermal actuator is activated at approximately 150°C by a phase change of a thermally-sensitive element. The actuator retracts from between the butt ends of a split piston ring, allowing the piston ring to snap closed and form an initial seal against the pump shaft or sleeve. The piston ring creates a hydraulic resistance, which in turn compresses the solid polymer sealing ring against the pump shaft creating the final leak tight seal. In this condition, the shutdown seal limits leakage to below 227 l/h, typically to below 1 l/h.

The SHIELD® shutdown seal is proven by extensive testing and operating experience. Qualification testing performed in Westinghouse laboratories has included over 100 successful full-scale actuation tests, and has demonstrated that the design is compatible with all environmental factors including reactor water chemistry, radiation, corrosion product deposition, seismic loading, vibration loading, and temperature and pressure fluctuations.

Endurance testing totaling over 10,000 hours has demonstrated that the shutdown seal reliably limits seal leakage to negligible levels for 168 hours at temperatures and pressures up to 300°C and 155 bar, respectively. In October 2015, a shutdown seal was removed from Beaver Valley Unit 2 nuclear power plant near Pittsburgh, Pennsylvania, USA and successfully tested at the Westinghouse Science and Technology Center, further proving the seal's robust design and compatibility with the installed environment [2].

A survey of three Westinghouse-designed PWRs was performed to quantify the safety improvement rendered by installation of the SHIELD® shutdown seal. Utilities were asked to provide results of their probabilistic risk assessment models, namely the calculated core damage frequency (CDF) expressed in units of events/reactor year of operation. The survey results reveal the safety benefits of the SHIELD by providing a comparison of CDF before and after the SHIELD was installed. Survey results for three plants are provided in Figure 4. Plants A and B are both four loop PWRs and experienced reductions in CDF of approximately 61% and 58%, respectively. Plant C is a three loop PWR and experienced a reduction in CDF of approximately 27%. The difference in CDF reduction is due to the relative contribution of seal-related loss of coolant accidents to the overall risk profile of the plant, which is dependent upon plant-specific backup equipment, operator response procedures, and other factors. Differences in the PRA methodologies among the three plants surveyed may also contribute to the difference in CDF reduction. However, in all cases it is observed that installation of the SHIELD® yielded a considerable improvement in plant safety.

The SHIELD® Passive Thermal Shutdown Seal has been endorsed by the United States Nuclear Regulatory Commission [3] and has accrued more than 1 million hours of successful operation in over 80 reactor coolant pumps worldwide.

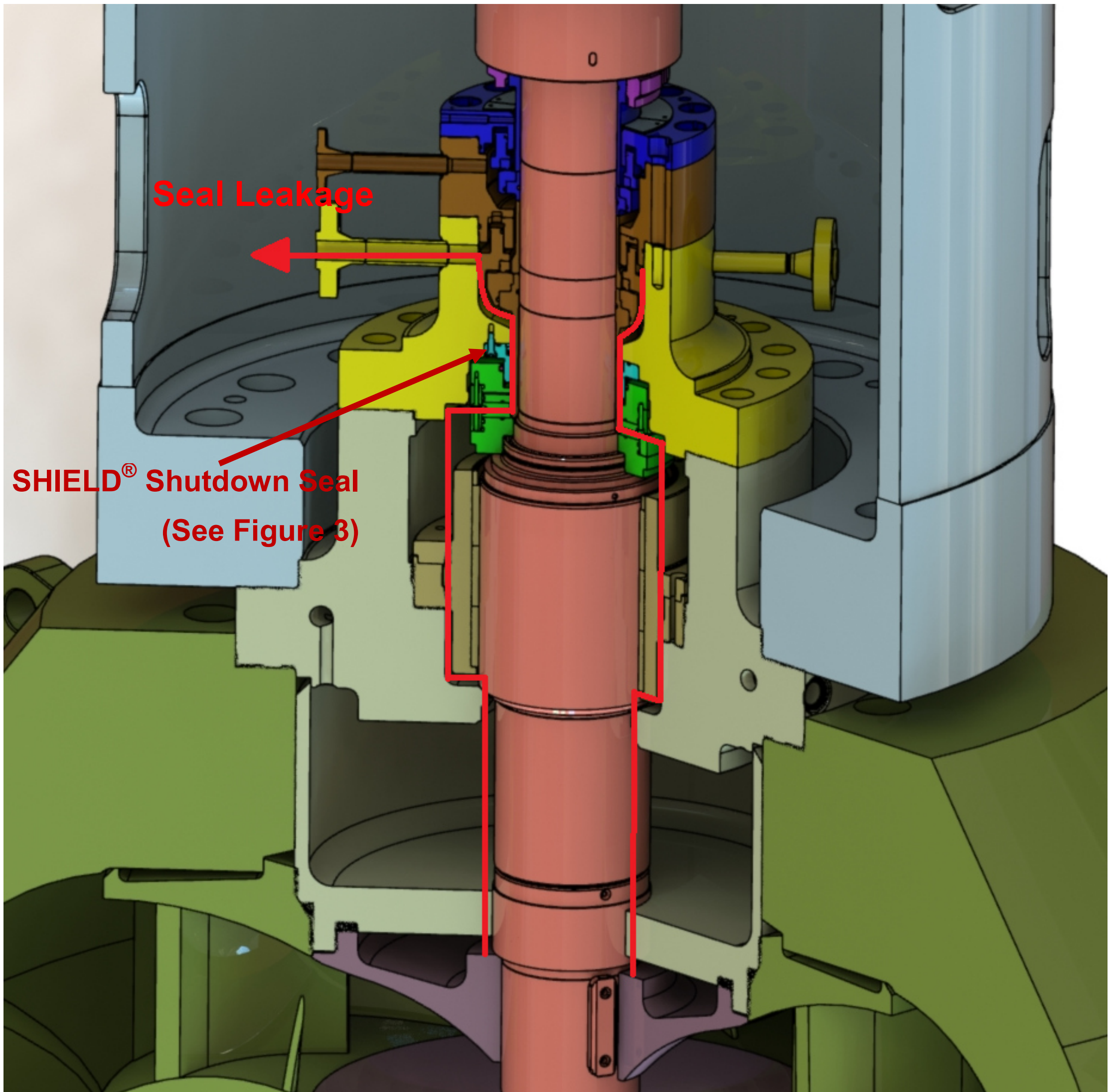

Fig 2. SHIELD® Shutdown Seal Location
(Thermal Barrier Heat Exchanger Coils not Shown)

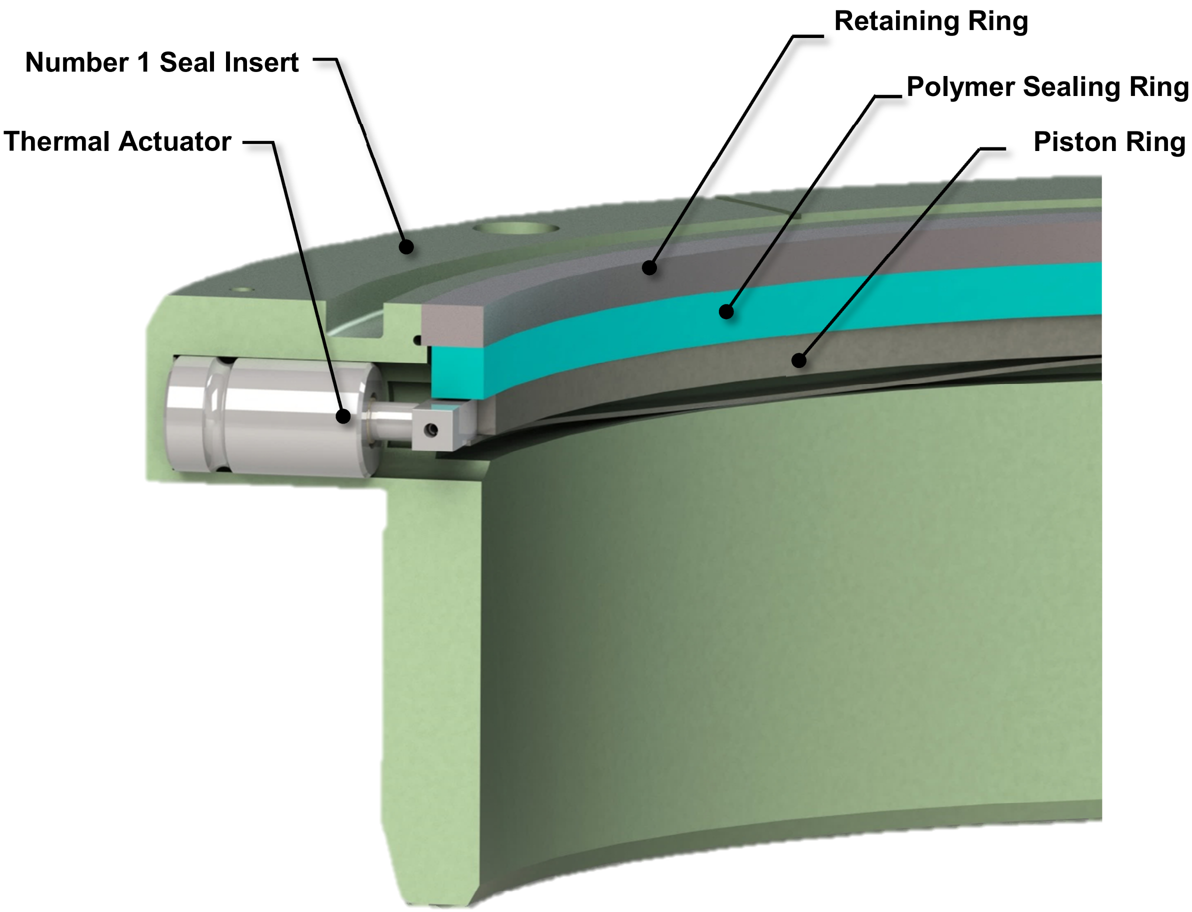

Fig 3. SHIELD® Shutdown Seal Diagram

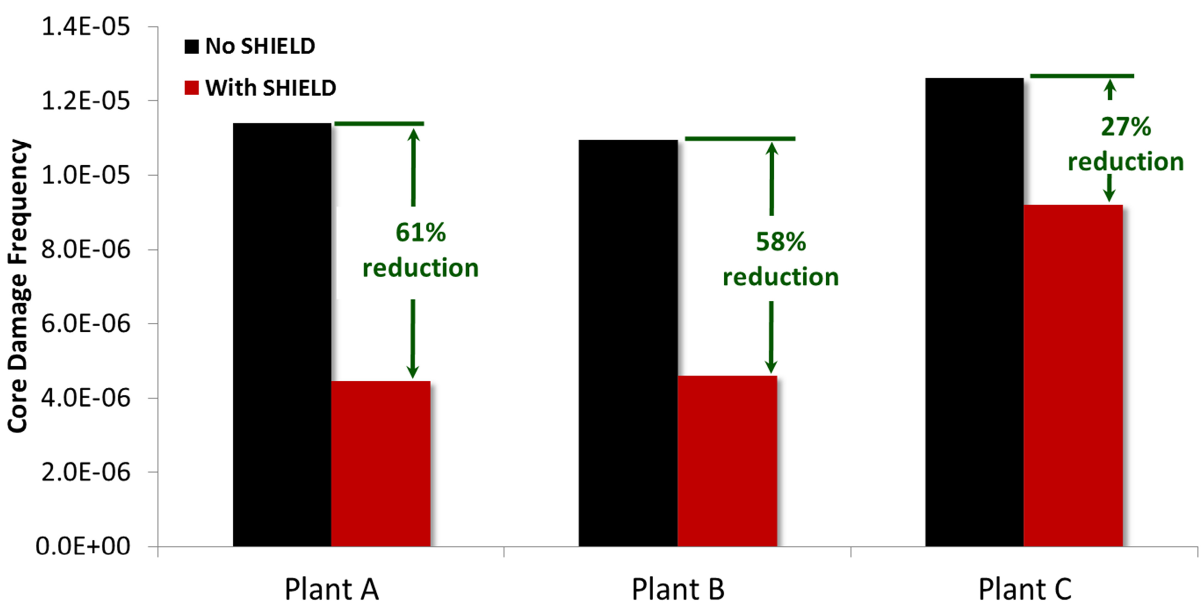

Fig 4. CDF Improvement Rendered by SHIELD® Shutdown Seal

2.2. Extended Life High Temperature O-Rings

Reactor coolant pumps employ elastomer secondary seals to seal static joints such as those between flange faces and shaft sleeves. Due to the severe conditions inside the reactor coolant system, secondary seals used in the reactor coolant pump seal package must be specially qualified for normal operating conditions, transients, radiation and a range of chemical environments. Further, secondary seals must be extensively tested to develop statistically-significant reliability estimates used for PRA modeling.

Westinghouse has completed the development and qualification of a new O-ring compound suitable for 12 years of service. Compound 7228-D O-rings were tested at the Westinghouse Churchill Site, where they demonstrated satisfactory thermal and radiation resistance as well as compatibility with system chemistry in the reactor coolant pump. The O-rings were also subjected to challenging station blackout testing, in which they performed successfully at temperatures and pressures up to 305ºC and 155 bar for limited durations.

Westinghouse Compound 7228-D O-rings have a qualified service life of 12 years, doubling the maximum time between seal maintenance, and providing utilities with greater flexibility for outage management and lower maintenance costs without compromising safety. Westinghouse is currently supporting plants worldwide in transitioning to Compound 7228-D O-rings.

2.3. Enhanced Hydrostatic Seal

While Westinghouse reactor coolant pump seals have provided reliable service for decades, amassing nearly 100 million hours of successful operation, demands for improved reliability and increased service life have necessitated a dedicated innovation program incorporating a thorough evaluation of the proven design and implementation of new technologies.

Upon surveying seal performance at a large number of nuclear power plants across different markets, utility operators, and geographic locations, several key issues were identified for improvement. One common observation at many sites is significant wearing of the Double Delta Channel Seal (DDCS) and fretting of the sealing surface on the first stage seal insert. Because this dynamic seal is necessary both for allowing unrestricted axial motion of the seal ring and for providing a seal against 155 bar pressure, the integrity of the dynamic seal is essential for proper operation of the reactor coolant pump.

Significant efforts were dedicated towards understanding the tribological behavior of a variety of dynamic seal materials (dry lubricants) and their tolerance to environmental conditions, such as radiation and chemistry, through empirical methods. Characterization of wear, friction and dry film formation were performed as part of a parametric sensitivity study to determine the best overall combination of dynamic seal design, material selection, and wear surface properties.

These laboratory test results [4] demonstrated that a significant reduction in wear rate is achievable when utilizing the state of the art materials coupled with an appropriate sealing surface interface (Figure 5). A considerable reduction in wear was achieved both by altering the material selection and fine-tuning the wear surface properties. The most significant reduction in wear was observed when both the DDCS material and wear surface properties were optimized (Figure 5, Material C, Surface Y). The considerable reduction in wear rate was accompanied by a corresponding reduction in the coefficient of friction. These tribology sensitivity studies provided an improved understanding of the DDCS wear behavior and determined the ideal characteristics for an optimized DDCS design.

Considering that the DDCS is one of the only wear components within the Westinghouse reactor coolant pump seal package, the optimized DDCS design will prolong reactor coolant pump seal life and reduce maintenance frequencies significantly, positively affecting the operating cost of the utility. In addition, DDCS optimization is expected to mitigate installation problems that can contribute to refueling outage delays.

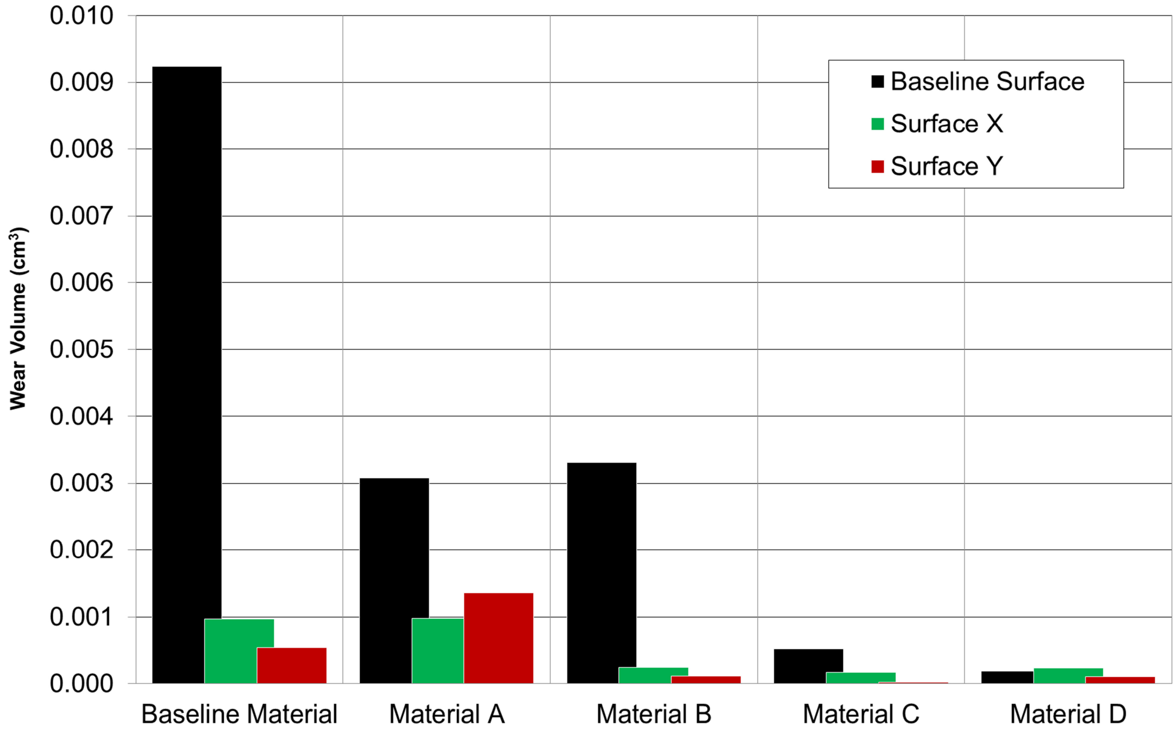

Fig 5. Sensitivity Study of Dry Lubricants Volumetric Wear Data

Another common issue that impacts the lifespan of reactor coolant pump seals is encroachment upon the upper or lower operating limits due to thermal sensitivity, electrophoresis, momentary contact during startup, or other unidentified causes.

Westinghouse seals are typically designed to operate with a continuous first stage leakage of approximately 230 l/h to 1130 l/h, and if leakage departs from this range, plants face the possibility of a forced outage to perform seal maintenance. To provide greater operating margin and enhanced reliability, Westinghouse has developed an optimized number 1 seal that offers improved thermal stability, more stable startup and transient performance, and a simpler design with fewer components and failure modes. Furthermore, the design is a drop-in replacement to the existing seal and will not require any modification of pump, piping, or instrumentation and control system. Development testing of the optimized seal demonstrates that it provides improved stability, more predictable leakage behavior, and reduced thermal sensitivity (Figure 6).

Another common issue observed is the variability of number 1 seal leakage between reactor coolant pump seals within in a common operating plant. This variability is often assumed to be influenced primarily by the operating parameters. However, manufacturing tolerances, inter-component contact behavior, and material changes over time also have a significant impact on seal leakage variability.

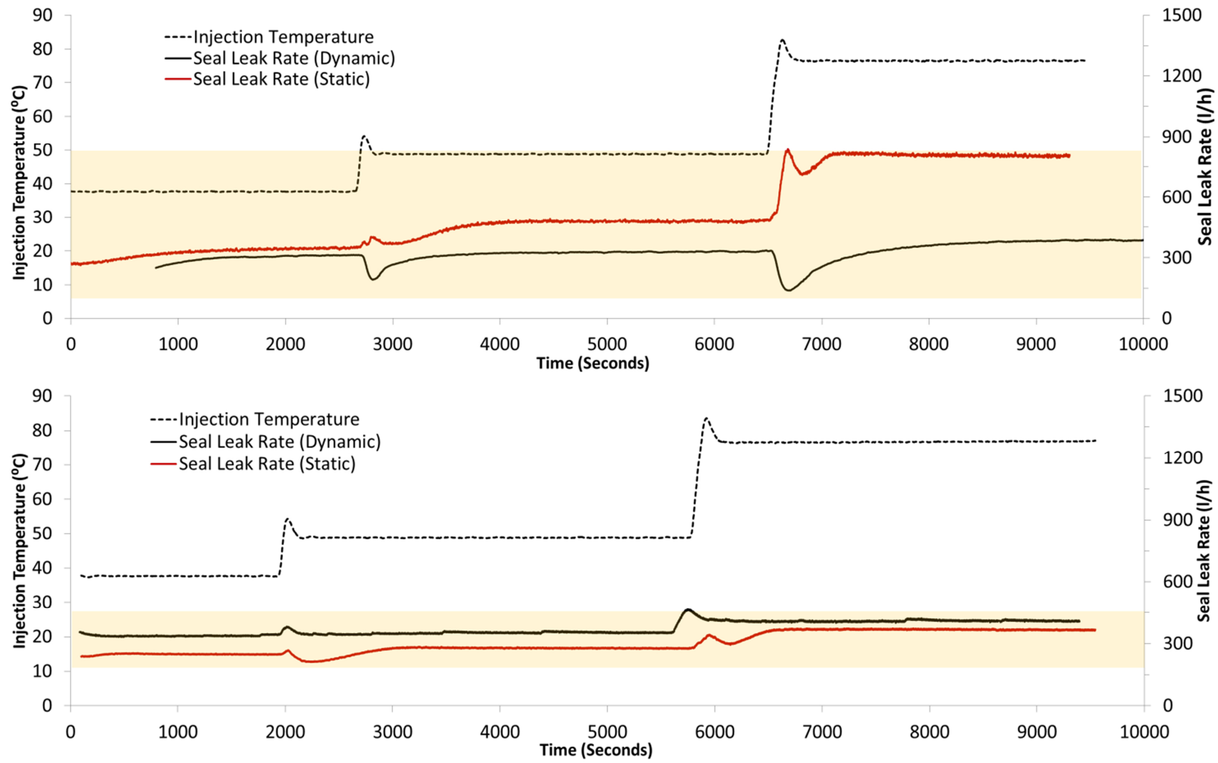

Fig 6. Improved Performance of Optimized Seal Comparison

The optimized number 1 seal was developed to eliminate design and operational sensitivity by removing or modifying unnecessary features that impact the seal leak rate. To quantify the degree to which the optimized seal reduces design sensitivity, a statistical leak rate analysis was performed for both the optimized seal and the conventional seal. The analysis consisted of a Monte Carlo simulation to generate a large number of random combinations of the key design parameters within the prescribed tolerances followed by a physics simulation of each case to determine the resultant leak rate. The key design parameters including seal face shape dimensions, film profile dimensions, and interfacing forces were assumed to vary within their prescribed tolerance ranges corresponding to three standard deviations. Equivalent assumptions and methodology were used for the conventional seal and optimized seal, and performance calculations were conducted at representative inlet conditions of 155 bars and 38°C.

Results from the Monte Carlo analysis are provided in Figure 7. It is readily observed that the leak rate of the optimized seal is distributed more closely to its mean than is that of the conventional seal. Overall, the theoretical calculations suggest an approximate 65% reduction in seal leak rate variability relative to the conventional design.

For qualitative verification of the methodology, data from two plants in the US are included. The plant data set consists of six total pumps in two three loop PWRs with approximately 1 data point for each pump on a weekly basis over a two year period. The wider distribution of plant data (conventional seal) relative to the theoretical calculations (conventional seal) is due variability in operating parameters and additional sources of design variability that are not captured in the statistical sampling method or physics simulation model.

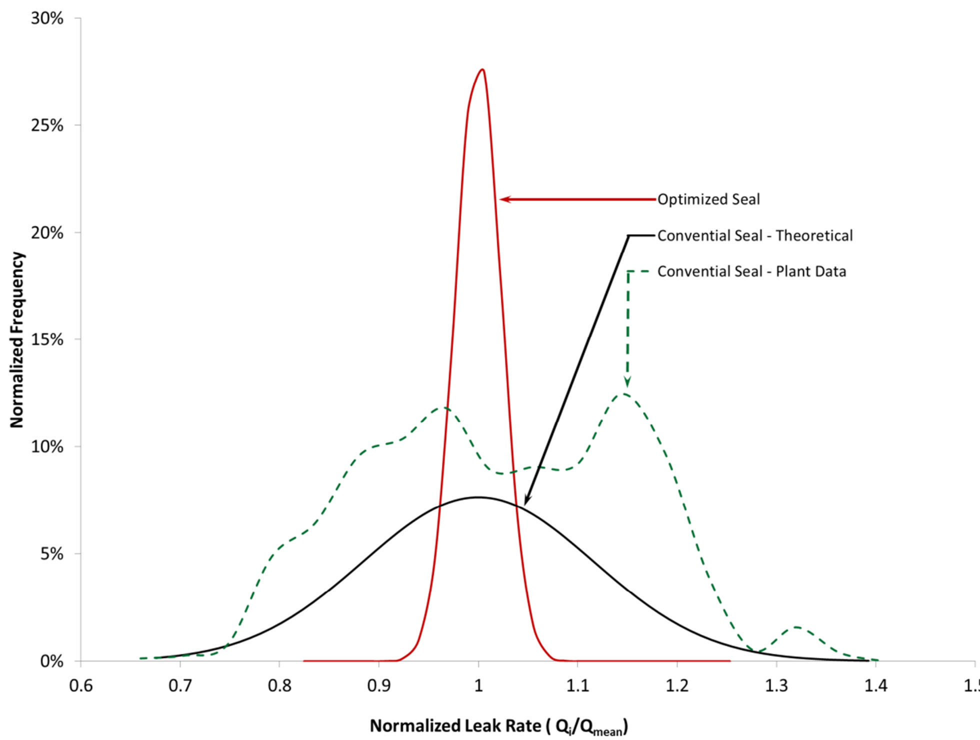

Fig 7. Theoretical and Empirical Variability of Seal Leak Rate Performance

3. Conclusions

Westinghouse reactor coolant pump seals have provided reliable service for over 50 years and in nearly half of the world's nuclear power plants. Recent Post-Fukushima innovations, such as the SHIELD® Passive Thermal Shutdown Seal, enhance plant safety by mitigating the risk of seal LOCA. Westinghouse is continuing to pursue further improvement with a state-of-the-art optimized number one seal design (patent pending) qualified with today's nuclear industry in mind, reducing operating cost and improving plant safety.

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