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## **PREDICTING THE IMPACT OF CRDM THERMAL SLEEVE WEAR IN WESTINGHOUSE PRESSURIZED WATER REACTORS**

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### **ABSTRACT**

In December 2017, a 4-loop 1300 MW Electricite de France (EdF) plant in France, Belleville Unit 2, experienced a complete wear through and separation of one of their thermal sleeves at a rod drive mechanism (CRDM) location. During low power physics testing and rod drop testing, the plant had difficulty stepping the control rod into the core. The rod was freed by exercising the drive rod but was then stopped prior to full insertion during the rod drop test. The failure to insert the rod was caused by the worn thermal sleeve flange remnant.

In response to this Operational Experience (OE), Westinghouse notified the U.S. Nuclear Regulatory Commission (NRC) of this defect pursuant to the requirements of Title 10 of the Code of Federal Regulations (10 CFR) Part 21 and published a nuclear safety advisory letter (NSAL) that provides details on the thermal sleeve flange issue and inspection recommendations. In their notification, Westinghouse determined that there was no immediate safety concern, but a substantial safety concern may be possible in the unlikely event that there is interference with the movement of more than one control rod.

This paper summarizes the NRC staff's safety analysis of this issue. The staff conducted detailed probabilistic and risk analyses and followed up with a smart sample inspection of the industry's thermal sleeve inspection programs to verify the analysis assumptions. The staff found the risk of core damage to be low, their assumptions appropriate, and the industry was following the details of the NSAL appropriately.

### **BACKGROUND**

In typical Westinghouse pressurized-water reactor (PWR) designs, a stainless steel thermal sleeve rests inside each CRDM nozzle and extends beyond the CRDM nozzle to just above the upper guide tube. The thermal sleeves perform the following two design functions:

- Provide a lead-in for the rod cluster control assembly (RCCA) drive rods into the head penetration tubes during reactor vessel head installation.
- Provide shielding of the head penetration tubes from thermal transients produced by varying temperature water that passes through the penetration area during RCCA drive rod stepping movements.

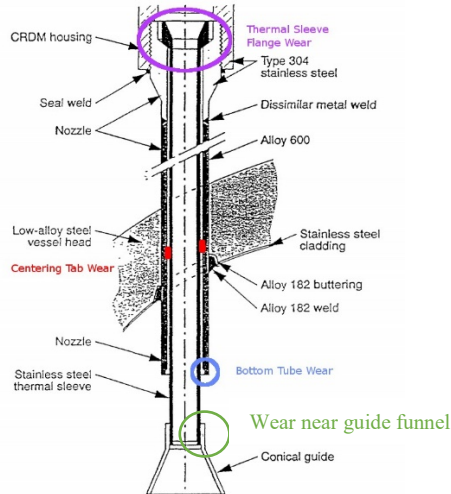


Figure 1: CRDM Nozzle and Thermal Sleeve Example

An example of the installed thermal sleeve is shown in Figure 1. The thermal sleeve is installed in the CRDM housing before the CRDM is welded on, trapping the thermal sleeve. The thermal sleeve is supported by an internal chamfer (ledge) in the CRDM housing. This allows the thermal sleeve freedom to move up, move down, and rotate about its axis.

The industry first identified CRDM thermal sleeve wear in 2007 at several U.S. Westinghouse PWRs. At that time, the wear was located in three places: (1) on the outside diameter of the thermal sleeve where the sleeve exits the CRDM penetration housing, (2) on the inside diameter just above the guide funnel due to contact with the drive rod, and (3) at the centering tab locations within the CRDM nozzle (see Figure 2).

In 2014, the CRDM thermal sleeve flange wear mechanism was identified at one plant when a single, unrodded thermal sleeve fell from the reactor vessel closure head during an inservice inspection. Examination of the fallen sleeve showed that the upper flange, which rests inside the CRDM head adapter tube (Figure 1), had worn through. As the thermal sleeve is rotated or otherwise moved due to water flow within the CRDM, the corner radius of the thermal sleeve upper flange rubs against this chamfered surface and both are worn away over time, as shown in Figure 2. The end result is a reduced thermal sleeve flange height and a pocket worn into the CRDM housing.

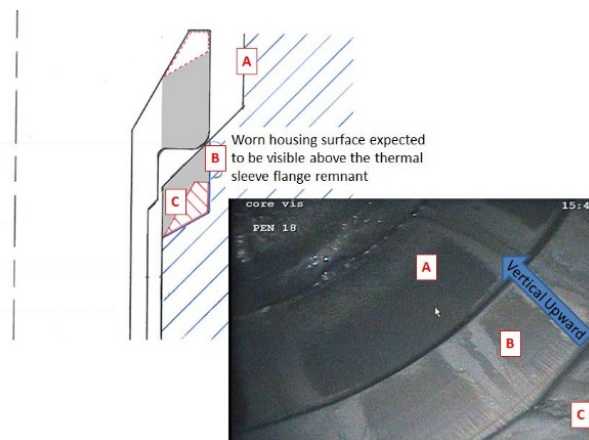


Figure 2: Illustration of CRDM Thermal Sleeve Wear

In response to this operating experience related to wear, Westinghouse issued Technical Bulletin (TB) TB-07-2, Revision 2 followed by Revision 3, which provided further clarification,

see Westinghouse (2015). The technical bulletin recommended that, depending on the plant-specific information, industry conduct thermal sleeve inspections to determine the amount of wear. For the purpose of identifying thermal sleeve flange wear, the technical bulletin suggests that first inspection did not need to occur until after 25 effective full-power years (EFPY) due to the expected wear rate. The technical bulletin concludes that if flange wear occurred, the remnant would remain trapped in the housing or slowly wear away into fine debris and the safety significance of the wear was low.

In December 2017, Unit 2 at Belleville nuclear power plant in France experienced a complete wear through and separation of one of their thermal sleeves at a rodded CRDM location. During low power physics testing and rod drop testing, the plant had difficulty stepping the rod into the core. The rod was freed by exercising the drive rod but was then stopped prior to full insertion during the rod drop test. The failure to insert the rod was caused by the thermal sleeve wear remnant, as shown in Figure 3. Investigation of the incident showed the same wear behavior as was discovered in 2014 in a U.S. plant.

In response to this international operating experience and pursuant to the requirements of Title 10 of the Code of Federal Regulations (10 CFR) Part 21, "Reporting of Defects and Noncompliance," Westinghouse notified the NRC of this defect, see Westinghouse (2108). The report suggests that the current data supports continued operation because the wear rates measured to date in the United States (which excludes the French operating experience) has been moderate for rodDED thermal sleeve locations. From the measurements made, the lowering rates were calculated to be a 95 percent upper bound rate of 0.03 inch/EFPY (inch/effective full-power years) and a 99 percent upper bound rate to be 0.04 inch/EFPY. This rate is significantly lower than the 0.12 inch/EFPY maximum rate measured in France.

Westinghouse's 10 CFR Part 21 report concludes that due to these wear rates, it is extremely unlikely that thermal sleeve wear would result in a condition where more than one control rod is unable to insert within one or two operating cycles. However, Westinghouse did not conduct quantitative analyses to substantiate this conclusion. Based on this conclusion, Westinghouse considered continued operation to be justified. This 10 CFR Part 21 report also included tables of susceptible plants, grouping these plants into the following two tiers:

- Tier 1: T-cold or T-cold capable plants (24 U.S. units)
- Tier 2: T-hot plants (20 U.S. units).

In July 2018, Westinghouse published NSAL18-1, see Westinghouse (2018), that provides details on the thermal sleeve flange issue and inspection recommendations. The technical evaluation contained in this letter suggests that the inspections and evaluations of Technical Bulletin TB-07-2, Revision 3 may not be sufficiently conservative, and the lack of conservatism could result in a substantial safety hazard. However, the NSAL concludes that the sticking of two control rods due to flange remnants is not a credible event prior to the next inspection opportunity for the impacted plants because its unlikely more than one remnant would be present simultaneously. The letter presents no quantitative analysis results to substantiate this claim.

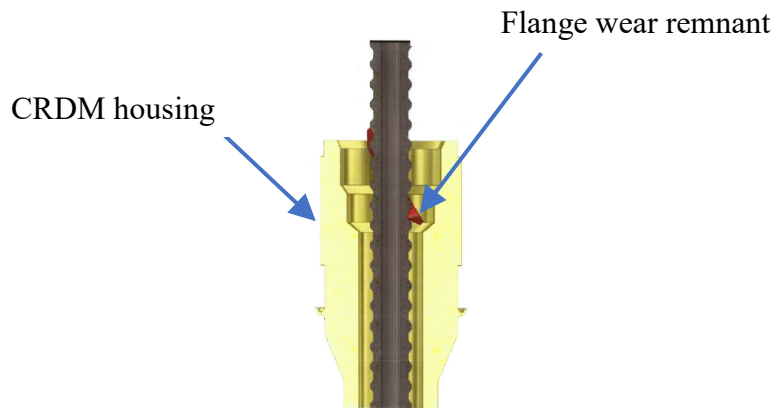


Figure 3: Illustration of Trapped CRDM Flange Remnant

## STAFF EVALUATION

### *Probability of CRDM flange failure*

In evaluating the impacts of CRDM thermal sleeve flange failure on overall reactor risk, the probability of flange failure was calculated, see Rudland (2018). Using the information from the past PWR CRDM thermal sleeve lowering measurements in the United States, the NRC staff generated a distribution of wear rates (see Figure 4). The staff developed this distribution from the information in Westinghouse's nuclear safety advisory letter (95 percent rate = 0.03 inch/year, 99 percent rate = 0.04 inch/year) with the median value at 0.01 inch/year, and the assumption of a log-normal distribution. Even though the wear rates observed in France were higher (up to 0.12 inch/year), the U.S. wear rates were used here to properly reflect the U.S. operating experience.

Using this wear rate distribution, the staff analyses randomly sampled a typical number of rodded CRDM locations (50-70) and calculated the lowest time to rod failure assuming a maximum drop distance of 2 inches<sup>1</sup>. The staff then determined if additional failures would occur within one outage cycle (18-months) of the first failure. This assumption is based on the fact that the industry may inspect every outage, per NSAL 18-1. In addition, most CRDM thermal sleeve failure issues will be found during an outage when the head is removed. A Monte-Carlo analysis was conducted using 10,000 realizations and a distribution of failure times was developed. This distribution is shown in Figure 5.

The results in Figure 5 suggest that a mean time to first failure of 53 years and a 2 percent chance that a failure would occur in 25 years, which is consistent with the recommendation in the NSAL. The analyses also predict the probability of multiple failures conditional on the first failure for different intervals, assuming no mitigative actions were taken.

The absolute probability of failure is shown in Figure 6. These results suggest that for a drop of 2 inches, the probability of four thermal sleeve failures occurring within one outage cycle is about 6E-6 conditional for an inspection after 25 years of operation. Additionally, after 40 years of operation, the probability of first failure increases to 16 percent, and the probability of four failures within one outage cycles increases to 5E-5. Changing the failure criteria from a 2-inch drop to a 1.5-inch drop increases the probabilities by one order of magnitude.

From these results, the probability of occurrence of more than seven CRDM thermal sleeve failures within one outage cycle is less than 1E-6. Conversely, the probability of occurrence of two CRDM thermal sleeve failures within one outage cycle range between 0.16 percent and 5.5 percent.

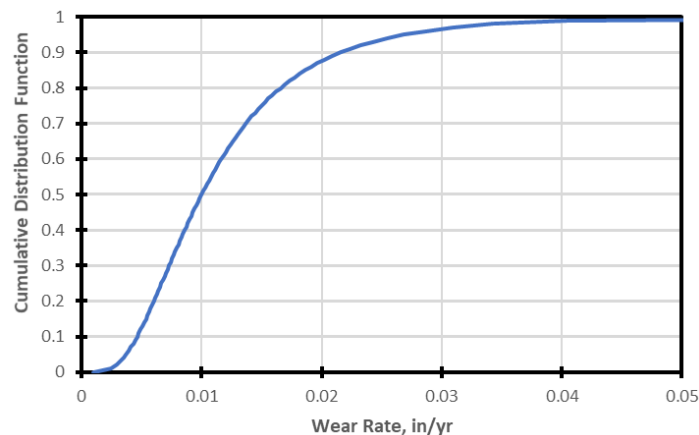


Figure 4: Wear Rate Distribution

<sup>1</sup> This value was varied in sensitivity studies

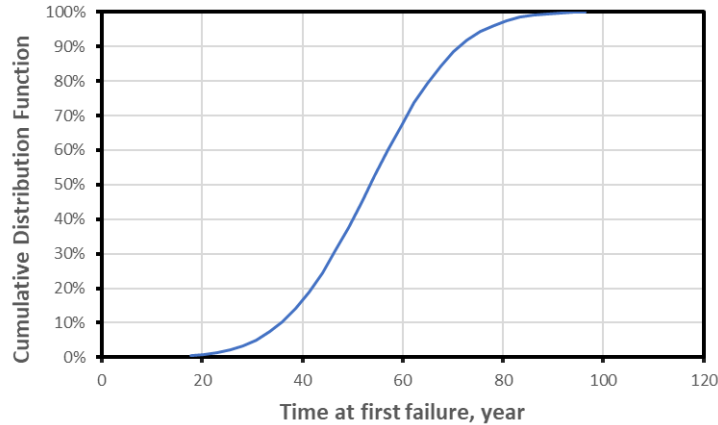


Figure 5: Time at First CRDM Thermal Sleeve Failure

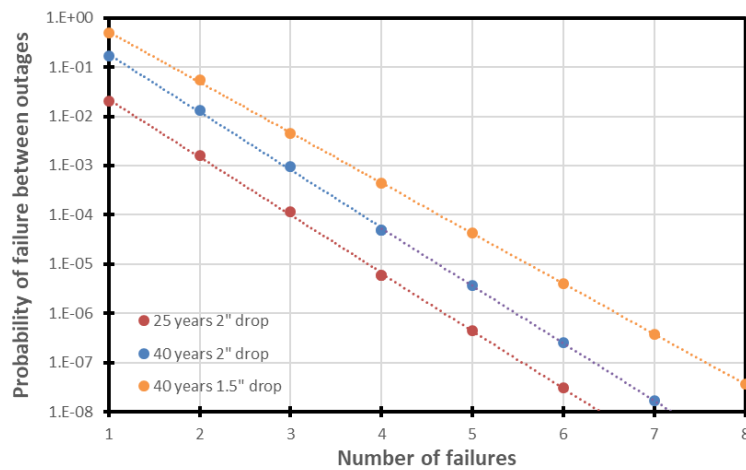


Figure 6: Probability of CRDM Thermal Sleeve Failure within One Outage Cycle

### ***Impacts of CRDM thermal sleeve failure on plant risk***

As will be discussed at the end of this section, the NRC staff performed quantitative studies to assess the impact of thermal sleeve failure on plant risk associated with design basis accidents where reactivity is an important consideration. The staff found these to not be significant contributors to plant risk. Therefore, to assess the impact of thermal sleeve failure on plant risk, the NRC staff performed a bounding analysis assuming that an anticipated transient without scram (ATWS) results if a certain number of rod cluster control assemblies fail to insert.

An analysis by Westinghouse, see Westinghouse (1974), reviewed the NRC-defined transients, all of which are laid out in NRC (2007), and determined that the limiting ATWS with regard to shutdown reactivity requirements was the uncontrolled RCCA bank withdrawal at power transient (which is described in NRC (2007)). The study found that a 2 percent change in reactivity needs to be inserted to bring the core from the transient conditions to a subcritical hot zero power state.

The negative reactivity insertion following a reactor trip, assuming some failed RCCAs, is dependent on the spatial distribution of the RCCAs that fail to insert. Generally, it is expected that a more uniform distribution of the RCCAs results in more negative reactivity insertion on reactor trip. At the time the analysis was performed, there was no data to indicate that CRDM thermal sleeve wear was anything other than randomly distributed among CRDM locations. Therefore, the NRC staff found it reasonable to assume that the locations of RCCAs that fail to insert due to thermal sleeve wear are approximately randomly distributed.

Volume 2 of NUREG-0460, "Anticipated Transients Without Scram for Light Water Reactors," see NRC (1978), references a Westinghouse analysis (documented in Westinghouse (1973)) of the negative

reactivity inserted by certain numbers of RCCAs for a variety of different spatial distributions of the RCCAs that fail to insert. NUREG-0460 states that “if about 10 rods (i.e. 20 percent) do not go in, there will still be inserted greater than 1.5 percent change in reactivity, and greater than 2.0 percent change in reactivity for over 80 percent of distributions.” This analysis was performed for a particular reactor design (one with 53 control rods) and a specific core design; however, NUREG-0460 concludes that the analysis was generally representative of all PWRs. The staff judged based on this analysis that an ATWS would be expected if 10 or more randomly distributed RCCAs failed to insert on a trip signal. In addition, the staff did not consider any other mitigative measures that would impact the reactivity of the core, i.e., the analyses assumed only rod insertion would affect reactivity.

NUREG/CR-5500, Volume 2, see NRC (1998), further defined the number of RCCA failures necessary to cause an ATWS. NUREG/CR-5500 states, “Failure of any 10 rods to insert results in a loss of shutdown capability.”

The staff used the NRC’s Standardized Plant Analysis of Risk (SPAR) models to estimate the potential contribution to plant risk from CRDM thermal sleeve cracking. This was done using the following equation:

$$\Delta CDF = CDF' - CDF_{base} \quad (1)$$

Where CDF’ represents the core damage frequency with assumed CRDM thermal sleeve cracking leading to increased probability of core damage due to an Anticipated Transient without SCRAM (ATWS) and  $CDF_{base}$  represents the nominal, at power, internal events core damage frequency.

The staff conservatively assumed that any rod control cluster assembly (RCCA) with a thermal sleeve experiencing a 1.5” drop would experience mechanical failure when called upon. This was modeled by increasing the probability of mechanical rod failure in the existing SPAR model (nominally about 1E-6 per demand) to approximately 4E-5 per demand as discussed earlier in this paper (see figure 6).

Although insertion of control rods is an important step in mitigating most initiating events, failure of rods to insert does not necessarily lead to core damage. Should rods fail to insert during a transient, there will be a large pressure and temperature increase as the turbine is tripped and the transfer of energy from the primary to the secondary is rapidly reduced. The SPAR models assume that all safety relief valves (SRVs) and power-operated relief valves (PORVs) must successfully open for the reactor coolant system (RCS) to relieve pressure and remain intact. Should the RCS remain intact, prevention of core damage relies on operators establishing emergency boration and injection of either main feedwater or aux feedwater into the steam generators to establish a slow, controlled cooldown.

The assumed CRDM failure impacts all accident sequences where negative reactivity is required. The dominant sequences contributing to  $\Delta CDF$  were general transient sequences, which accounted for ~80% of the change in CDF, primarily due to their high initiating event frequency (approximately .5 per year). The next largest contributors were accident sequences involving loss of main feedwater or the loss of condenser heat sink. These each accounted for about 5% of the change in CDF. The remaining sequences impacting  $\Delta CDF$  (e.g, small-break LOCA) contributed less than 5% and varied from plant to plant.

The  $\Delta CDF$  and base CDF values for the plants that were analysed are shown below in Figure 7.



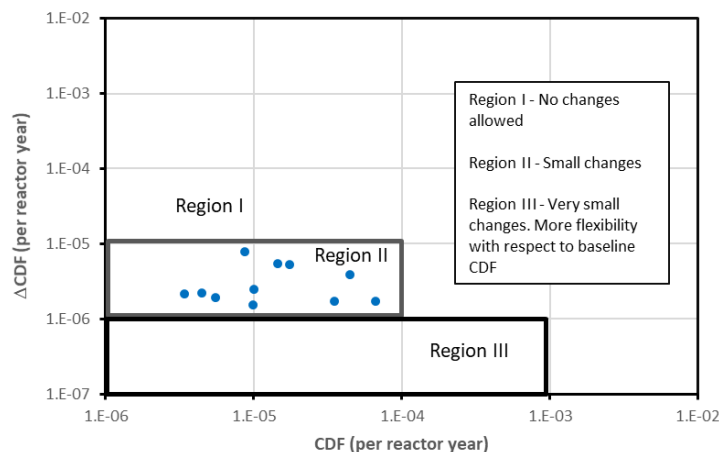


Figure 7 Comparison to RG 1.174 Acceptance Guidelines

### Other considerations

To better understand the potential impact on plant risk associated with a failure to insert rod cluster control assemblies (RCCAs) for accidents where reactivity is an important consideration, the NRC staff performed a study focusing on the main steam line break accident, because it was judged to be the most likely accident resulting in a reactivity excursion if RCCAs failed to insert on demand. The NRC staff judged that a reactivity transient resulting in a challenge to core limits could occur if as few as three RCCAs were to fail to insert on demand. Therefore, the study examined the change in risk associated with a steam line break using an NRC SPAR model assuming the probability of a failure to insert RCCAs on demand was increased to the three-rod failure probability provided in Figure 6 above (approximately 8E-3 per demand). The study considered steam line breaks inside containment (initiating event frequency of approximately 1.5E-4 per year) as a proxy for large steam line break frequency, since smaller breaks were judged to be less of a concern with respect to reactivity insertion. The study found that the  $\Delta$ CDF associated with this accident was on the order of 1E-8 per year, and therefore negligible in comparison to other events.

External events were not explicitly modelled in this analysis but could contribute to the risk significance of this issue. The reason for this is twofold. First, an external event (such as a fire) could cause a transient. As transient sequences were the key drivers of risk in this analysis, the increased transient frequency would lead to a higher delta CDF than would be calculated via internal events alone. Perhaps more significant is that fact that external events (e.g., high winds, seismic) could cause a plant trip coincident with a loss of offsite power (LOOP). The SPAR models assume that offsite power is necessary to mitigate an ATWS. Therefore, any increase in the conditional probability of an ATWS caused by CRDM thermal sleeve cracking would be expected to have a significant risk impact on external event sequences.

Offsetting the omission of external event risk is the fact that 4E-5 was used as the probability of five rods to insert and this is likely a very conservative assumption. Data gathered during the 2018OpESS CRDM Smart Sample indicate wear rates that are lower than originally expected. Using these new wear rates yields a failure probability of approximately 1E-7. This value is a factor of ten lower than the existing assumed probability used for mechanical failure of rods to insert. Therefore, any additional thermal sleeve-cracking-related risk due to external events – while not explicitly calculated – is likely to be bounded by the internal events  $\Delta$ CDF.

### ***OpESS 2018 CRDM Smart Sample***

The recommendation from the NRC staff analyses was to conduct a smart sample of the industry CRDM thermal sleeve inspections that occurred in 2018. The operating experience inspection guidance was issued on November 20, 2018, see NRC (2018). The main purpose of this inspection was to ensure the industry was properly following their inspection guidance per NSAL-18-1, and to gather available measurement data to confirm the wear rate assumptions used in the NRC staff analyses. Out of the population of 16 units which were deemed most susceptible per NSAL-18-1, NRC smart sample inspections

were performed on 10 units. Additionally, all the sites that have susceptible thermal sleeves have either performed the recommended inspections or are scheduled to perform them during the next upcoming outage. Specifically, these inspections consist of determining the relative change in the distance between the end of the thermal sleeve and the top of the guide tube by using a laser scanning technique after the vessel head is removed. The measured values are used to calculate the wear rate, which is then used to determine if the thermal sleeve can remain in service as well as plan for the next subsequent inspection.

### ***Analysis of Results from OpESS 2018***

Through the smart sample, CRDM thermal sleeve measurement data was obtained, see Rudland (2019). This data included either design or as-built CRDM thermal sleeve elevation measurements and to date elevation measurements for each CRDM thermal sleeve in the units. The regional inspection team supplied this data to headquarters in tabular form. Using this data, staff investigated the trends of wear relative to the location of the wear. From the sample of ten Tier 1 plants, two different trends in the data were recognized and illustrated in Figure 8.

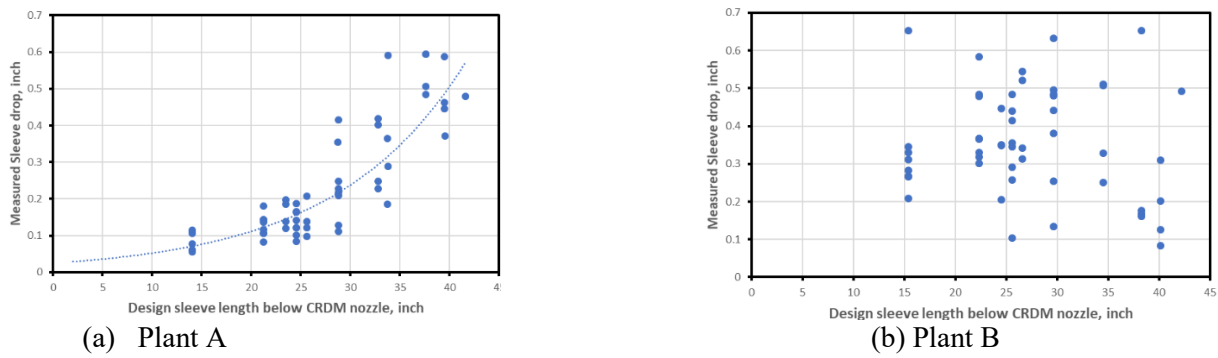


Figure 8 Thermal sleeve wear measurements

The “design sleeve length,” on the above graphs corresponds to the length of the thermal sleeve that is exposed, i.e., the length of the thermal sleeve that hangs below the bottom of the CRDM nozzle. Note that the thermal sleeves near the top of the head have a greater portion of the thermal sleeve exposed to cross flow than those on the periphery of the head. In some plants, a clear trend with location is seen: more wear occurred near the center of the head. In other plants, the wear appeared to be location-independent. It is currently unknown why these differences occurred.

Even though this data only represents one point in time, an average wear rate can be estimated from this data and the design or as-built conditions. These wear rates can then be displayed as a cumulative distribution function and compared against what was used in the NRC analyses, see Rudland (2018) as shown in Figure 2. In this figure, the different symbols represent the data from the sampled plants, while the solid red line represents the distribution assumed in the NRC analyses. Data that falls above and to the left of the red line is considered conservative and that which falls below and to the right is considered non-conservative. It is suspected that the non-conservative values would produce probabilities of failure that are higher than those calculated in the NRC analyses.



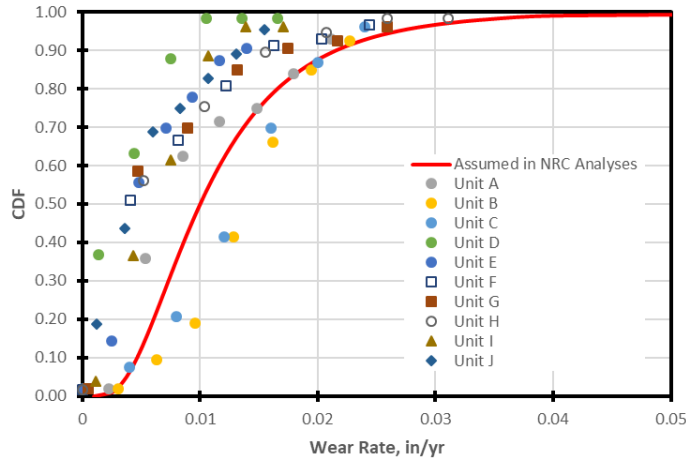


Figure 9 Comparison of smart sample wear rates and assumption in NRC analysis

From Figure 9, most of the collected data falls above the assumption used in the NRC analyses. Of the two plants that fall below the curve, the difference is relatively small.

Taking the worst-case wear data, the staff conducted an analysis to compare the probability of failure results with those in the original NRC analysis. Using the same analysis procedure as in the NRC analyses, see Rudland (2018), staff calculated the probability of failure shown in Figure 10.

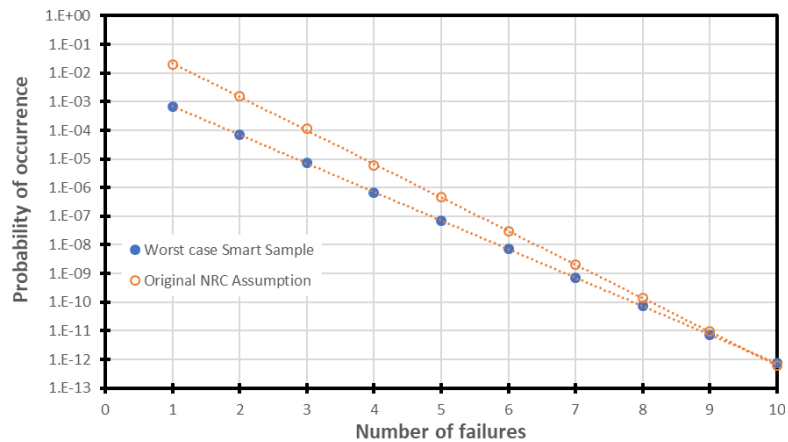


Figure 10 Probability of failure comparison

In these figures, the orange open circles represent the results presented in the NRC analysis, while the blue solid circles represent the results using the worst-case wear rate in Figure 9. Surprisingly, even though the wear-rate data appears to be non-conservative, the probability of failure numbers are conservative compared to those in the original NRC analyses. The reason for this behavior becomes clear when the worst-case data is investigated more closely, as shown in Figure 11.

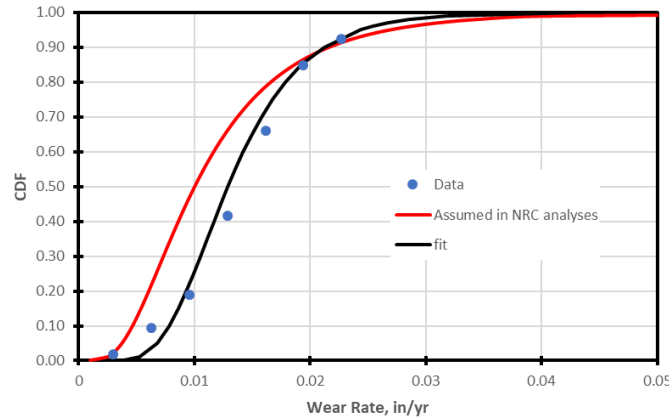


Figure 11 Comparison of worst-case wear rate data with original NRC assumption

Figure 11 shows the worst-case wear data and its fit compared with the assumption used in the original NRC analyses. While most of the data is non-conservative with respect to the wear rate assumed in the NRC analyses, the data at the high wear rates is conservative, i.e., the data above 90% probability falls above the assumption in the original NRC analyses. Since the probability of first thermal sleeve failure is driven by the upper tail of the wear rate distribution, the data and fit shown in Figure 11 would produce probability a first failure greater than that from the original NRC analyses. In looking at the data in Figure 9, the maximum measured wear rate was 0.030 inches/year with all of the high wear rate data falling above the assumption made in the original NRC analyses.

#### ***Impacts on NRC CRDM Thermal Sleeve analysis results***

From the sample of 10 out of 16 most susceptible domestic plants, the CRDM thermal sleeve wear data obtained suggests that the assumptions made in the original NRC analyses are conservative and reasonable for making a safety determination. More than 62% of the most susceptible plants were sampled, the trends are consistent with expectations even though the level of conservatism is small.

The smart sample results also suggest that the licensees are following the details of the NSAL appropriately and have taken steps to perform additional measurements at future outages and/or repair CRDM thermal sleeves as needed.

Using the results generated in this effort, the staff recommends that no further smart sample inspections are needed.

#### **SUMMARY**

Based on the potential for the thermal sleeve wear resulting in a nuclear safety issue, the Westinghouse NSAL-18-1 recommended that the most susceptible plants (those with T-cold upper heads) perform inspections during the first refueling outage following issuance of the NSAL, if they have exceeded 25 EFPY. The recommendations suggested establishing acceptance criteria to prevent thermal sleeve separation, and perform baseline inspection, and establish a re-inspection frequency based on the observed wear.

Using a risk-informed process, the NRC staff determined that the immediate safety significance of the CRDM thermal sleeve wear issues was low. However, the staff recommended a smart sample of the industry inspections to verify the assumptions in the staff analyses. Based on the inspection results of 10 of 16 most susceptible units, the domestic T-Cold plants are performing the NSAL recommended inspections. Consequently, the staff is satisfied that the thermal sleeve flange wear assumptions made in their analyses are bounding and the issue is properly being addressed by the affected plants. The NRC staff will continue to monitor the CRDM thermal sleeve wear industry operating experience.

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