TECHNICAL ASSESSMENT OF POTENTIAL CONTROL ROD DRIVE MECHANISM THERMAL SLEEVE FAILURE

INTRODUCTION

During a spring outage in 2014, a control rod drive mechanism (CRDM) thermal sleeve wear issue was identified at a U.S. plant when a single thermal sleeve fell from the reactor vessel (RV) closure head at an unrodded CRDM during an inservice inspection (ISI). Examination of the fallen sleeve confirmed that the upper flange, which rests inside the CRDM head adapter tube, had worn through. Industry determined that the wear could be correlated to a change in elevation of the bottom of the thermal sleeve (guide funnel) when compared to the as-designed condition. Measurements of elevations taken showed significant but acceptable wear and all rodded locations had low-to-moderate wear.

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. Belleville is a four-loop, 1300 MW Electricite de France (EdF) plant. 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 worn thermal sleeve flange remnant. Investigation of the incident showed the same wear behavior as was discovered in 2014 in the U.S. plant.

In response to this operational experience (OE) 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. The notification states that while there was no immediate safety concern, 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 technical assessment summarizes the NRC staff's current knowledge regarding CRDM thermal sleeve wear and provides options for U.S. Nuclear Regulatory Commission (NRC) action related to plants in the United States.

This technical assessment is organized into the following sections:

- Section 1 provides background information on the CRDM thermal sleeve flange wear operating experience in the United States and France and a chronology of events.
- Section 2 summarizes the applicable NRC regulatory requirements and indicates changes needed to these regulatory requirements were the operating experience found to be significant in a risk-informed context.
- Section 3 provides an evaluation of the issue using information that is currently available.
- Section 4 described the five principles for making risk-informed decisions. This process is used to evaluate the proposed options, which are described in Section 5.
- Section 5 describes the four options the staff has evaluated to resolve the issue. This evaluation was performed in a manner consistent with the five principles for making risk-informed decisions described in Section 4.
- Section 6 provides the staff's recommended option for management consideration.

1. 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. Figure 1 illustrates a typical Westinghouse PWR closure head assembly. 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.

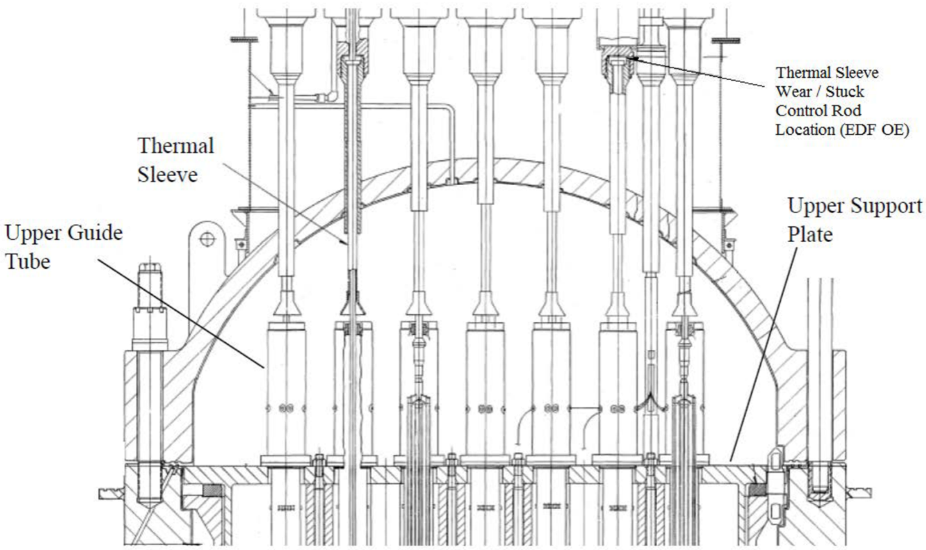

Figure 1: Example Cross-Section of Westinghouse PWR Closure Head assembly, CRDM Thermal Sleeve

An example of the installed thermal sleeve is shown in Figure 2. 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 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).

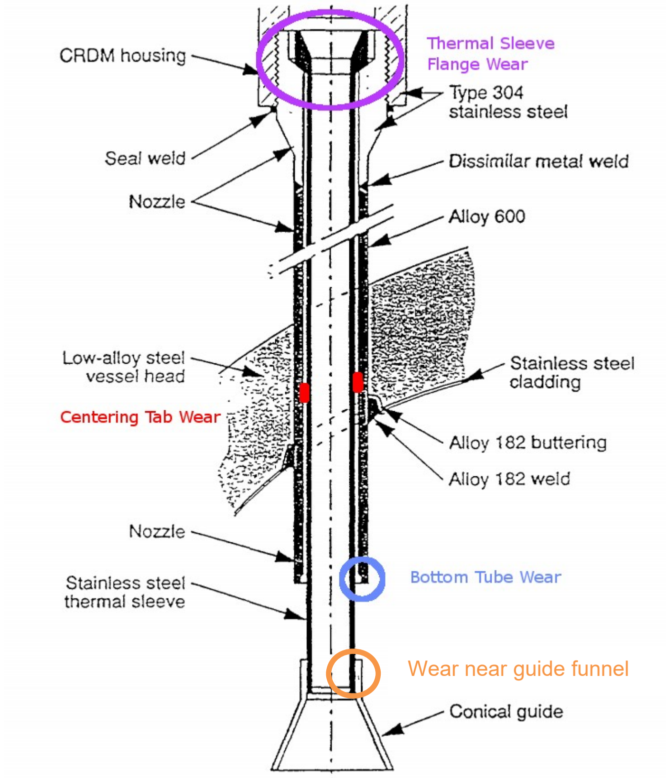

Figure 2: CRDM Nozzle and Thermal Sleeve Example

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 2), 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 3. The end result is a reduced thermal sleeve flange height and a pocket worn into the CRDM housing.

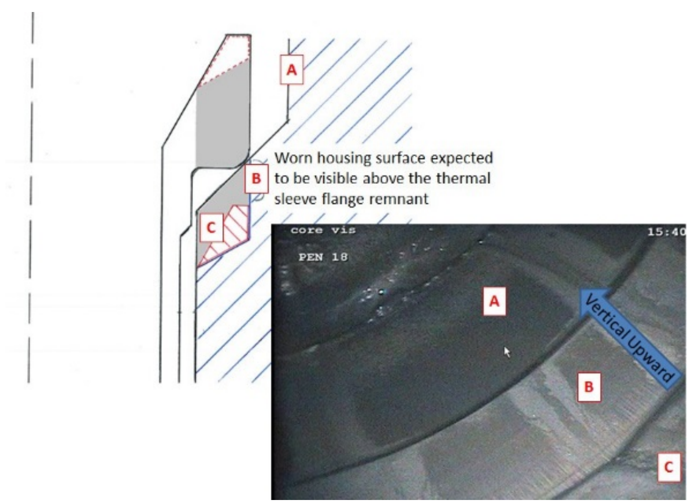

Figure 3: Illustration of CRDM Thermal Sleeve Wear

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 [1]. This technical bulletin provides details related to the operating experience on flange wear and makes associated recommendations. The technical bulletin suggests that certain plants are more susceptible to this wear based on the upper head temperature. In some cases, plants have converted from T-hot head to a T-cold head (by increasing upper head bypass flow) to reduce stress corrosion cracking susceptibility. This conversion causes increased flow in the head region, which has been correlated with increased thermal sleeve wear. 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.

Westinghouse worked with the Pressurized-Water Reactors Owners Group (PWROG) to develop acceptance criteria in PWROG-16003-P [2] which could be used when measuring thermal sleeve wear in accordance with the recommendations in Technical Bulletin TB-07-02. Through these analyses, the PWROG recommended allowable CRDM thermal sleeve drop distances based on several perceived failure modes at the flange location. PWROG-16003-P does allow for plant-specific analysis if measured values failed the PWROG criteria and recommends that for thermal sleeves that do not meet the criteria, licensees should consider possible removal or replacement.

As stated on the first page of this technical assessment, 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 4. Investigation of the incident showed the same wear behavior as was discovered in 2014 in a U.S. plant.

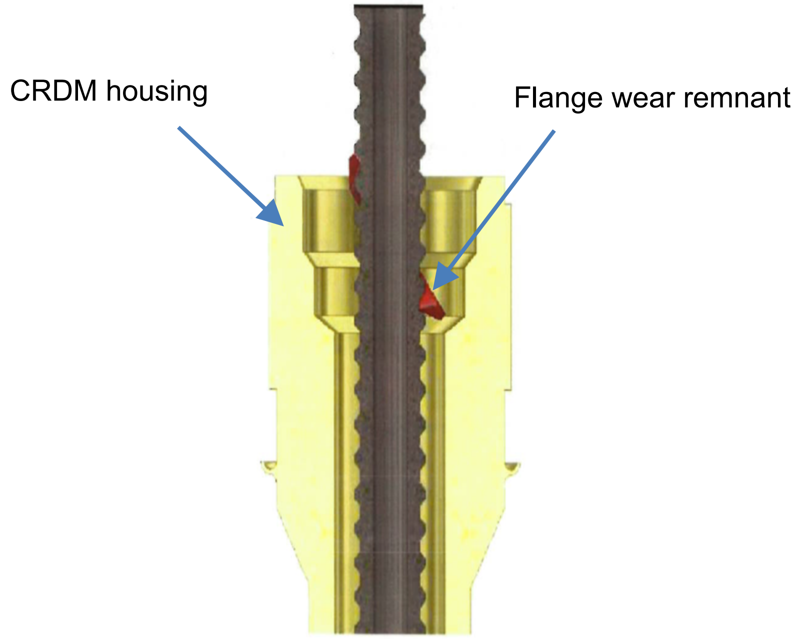

Figure 4: Illustration of Trapped CRDM Flange Remnant

In response to this international operating experience, Westinghouse issued a 10 CFR Part 21 report [3] to provide information on this defect. 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 a nuclear safety advisory letter (NSAL) [4] that provides details on the thermal sleeve flange issue and inspection recommendations. This letter is very similar to the previously discussed documents [1, 2] with more detail on the expected inspections. The technical evaluation contained in this letter suggests that the inspections and evaluations of Technical Bulletin TB-07-2, Revision 3 and PWROG-16003-P may not be sufficiently conservative, and the lack of conservatism could result in a substantial safety hazard. However, the nuclear safety advisory letter 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.

Realizing that Westinghouse plants have different guide tube designs, the nuclear safety advisory letter goes into detail on the expected wear that may occur on the upper guide tubes if the CRDM thermal sleeve were to fail and attached funnel rest on the upper guide tube. The expected difference between the 14x14, 15x15, 16x16, and 17x17 designs rests in how distinct and complete the wear marks may be on the upper tube guide. The nuclear safety advisory letter suggests that all visual inspection start with an inspection of these upper tube guides to determine if any shiny marks indicative of wear exist.

The nuclear safety advisory letter suggests the following inspection actions:

- T-cold[1] plants
    - During the first refueling outage after issuance of the nuclear safety advisory letter, make measurements of thermal sleeve lowering.
    - Use PWROG-16003-P as applicable or use plant-specific acceptance criteria.
    - If acceptance criteria have not been exceeded, determine reinspection frequency
    - If acceptance criteria have been exceeded, perform plant-specific analysis to modify acceptance criteria – if modified criteria are not exceeded determine re-inspection, if modified criteria are exceeded the issue should mitigated.
    - If flange separation has occurred, the issue should be mitigated.
- T-hot plants
    - Monitor industry operating experience.
    - At next refuel outage, visually inspect tops of upper guide tubes according to guidance.
    - During the next under head inspection do the following:
        - Visually inspect bottom of thermal sleeve funnel and funnel elevations.
        - If any measurements are advanced, follow the T-cold head guidance above.

The nuclear safety advisory letter also gives general recommendation on the inspection process but leaves the details to the individual licensees. Table 1 shows the Westinghouse plants identified at Tier 1 plants within the nuclear safety advisory letter that are currently operating with their original upper heads.

Electric Power Research Institute (EPRI) informed the NRC during the May 21–23, 2018 industry ad NRC material program review meetings (ADAMS Accession No. ML18211A380) that it plans to develop interim inspection guidance according to the nuclear safety advisory letter recommendation and incorporate this guidance into the NEI-0308 guidance as a “needed” requirement. EPRI transmitted the interim guidance to the NRC through MRP-2018-033 [5].

[1] Or T-cold capable plants

Table 1: Tier 1 Plants with Original Heads

Plant/Unit	Region	Unit	Years Operating
A. W. Vogtle	**2**	1	31
		2	29
Braidwood	**3**	1	30
		2	30
Byron	**3**	1	33
		2	31
Catawba	**2**	1	33
		2	32
McGuire	**2**	1	37
		2	34
Millstone	**1**	3	32
Seabrook	**1**	1	28
Sequoyah 1 & 2	**2**	1	37
		2	36
Shearon Harris	**2**	1	31
Wolf Creek	**4**	1	33
Watts Bar	**2**	1	22
		2	2

2. APPLICABLE NRC REGULATORY REQUIREMENTS

The regulations at 10 CFR 50.55a “Codes and Standards,” Paragraph (h), “Protection and Safety Systems,” describes the requirements for reactor safety systems, including the ability to rapidly shut down a reactor. The regulations at 10 CFR 50.55a(h)(2) and 10 CFR 50.55a(h)(3), “Safety Systems,” requires licensees with applications under 10 CFR Part 52 or 10 CFR Part 50 dated after May 13, 1999 to meet the requirements for safety systems in IEEE Standard 603-1991, “Standard Criteria for Safety Systems for Nuclear Power Generating Stations,” including the correction sheet dated January 30, 1995.

Additionally, for all U.S. plants, 10 CFR 50.62, “Requirements for Reduction of Risk from Anticipated Transients Without Scram (ATWS) Events for Light-Water-Cooled Nuclear Power Plants,” defines an ATWS event as an “anticipated operational occurrence.” The regulations at 10 CFR Part 50, Appendix A define “anticipated operational occurrence.” General Design Criterion 20 of 10 CFR 50 Appendix A specifies the failure of the reactor trip portion of the protection system.

Appendix A to 10 CFR Part 50 “General Design Criteria for Nuclear Power Plants” defines “anticipated operational occurrences” as those conditions of normal operation which are expected to occur one or more times during the life of the nuclear power unit. These anticipated operational occurrences include, but are not limited to, loss of power to all recirculation pumps, tripping of the turbine generator set, isolation of the main condenser, and loss of all offsite power.

The regulations at 10 CFR Part 50, Appendix A, Criteria 20-29 cover protection and reactivity control systems. These criteria require that the core be protected by two independent systems capable of preventing the fuel from exceeding its design limits and maintaining core cooling capability. These systems must be capable of controlling reactivity under cold conditions, during accidents, and with postulated malfunctions such as stuck control rods.

The facilities' technical specifications, which are part of their operating license, detail how a facility complies with these rules. The technical specifications require that each plant develop a core operating limits report (COLR) prior to each reload cycle and submit the core operating limits report to the NRC. Part of the core operating limits report is a determination of the shutdown margin (SDM) for the new fuel loading. While the specific shutdown margin for each plant is defined in their technical specifications, they are very similar and generally follow the definition found in the NRC glossary:

> The instantaneous amount of reactivity by which the reactor is subcritical or would be subcritical from its present condition assuming all full-length rod cluster assemblies (shutdown and control) are fully inserted except for the single rod cluster assembly of highest reactivity worth that is assumed to be fully withdrawn.

While the exact specifications vary from plant to plant, the plant technical specifications typically state that if one or more rod assemblies become inoperable, or the shutdown margin is otherwise not maintained during plant operation, the plant will enter a limiting condition for operation (LCO). This limiting condition for operation requires that within a set time period, the control rod drive assemblies be made operable, the shutdown margin limits achieved, or the plant shutdown and enter a hot standby condition.

The technical specifications for each PWR require that the mobility of the control rod assemblies be tested depending on the licensee's surveillance program, usually several times a year. In almost all cases, the technical specifications require that the control rod assemblies drop rates be tested prior to achieving criticality after each removal of the reactor pressure vessel upper head, which typically occurs every 18 months.

3. STAFF EVALUATION

3.1. Probability of CRDM flange failure

In evaluating the impacts of CRDM thermal sleeve flange failure on overall reactor risk, the probability of flange failure needs to be calculated. Westinghouse conducted PWR bounding analyses. Using the information from the past pressurized-water reactor CRDM thermal sleeve lowering measurements in the United States, the staff generated a distribution of wear rates (see Figure 5). 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. Note that the wear rate assumption is based solely on the information gathered to date. If future wear measurements from U.S. plants are found to fall outside the bounds of this distribution, they will have a significant impact on the results presented in this section.

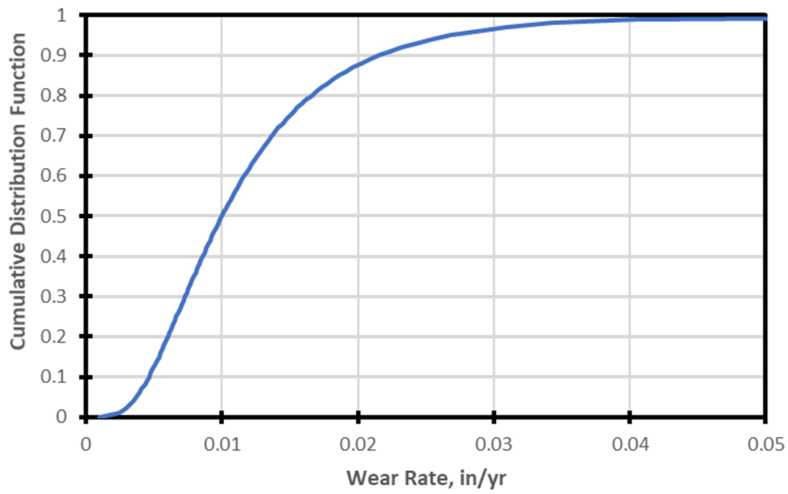

Figure 5: Wear Rate Distribution

Using this wear rate distribution, the staff analyses randomly samples 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. The staff then determined if additional failures would occur within one outage cycle of the first failure. This assumption is based on the fact that the industry will be typically inspecting 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. Relaxing that assumption is considered in a sensitivity study also described below. A Monte-Carlo analysis was conducted using 10,000 realizations and a distribution of failure times was developed. This distribution is shown in Figure 6.

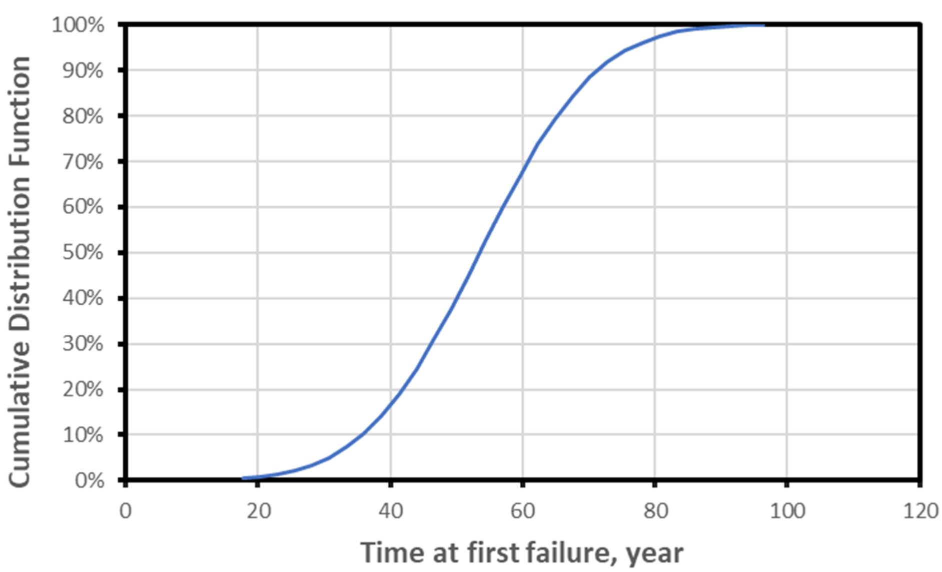

Figure 6: Time at First CRDM Thermal Sleeve Failure

The results in Figure 6 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. Figure 7 shows these probabilities.

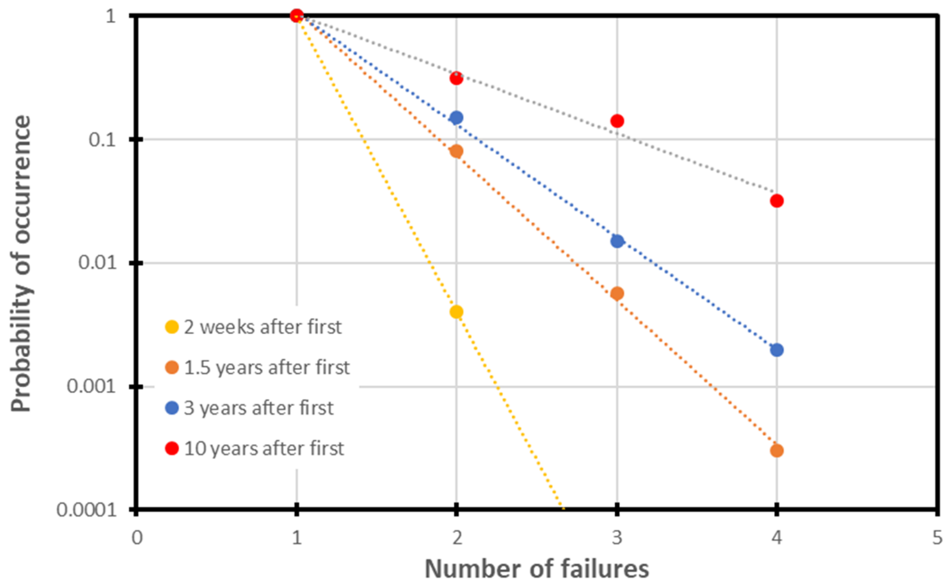

Figure 7: Multiple CRDM Thermal Sleeve Failure Probabilities Conditional on the First Failure

The results from this figure suggest that there is a conditional probability of 3E-4 that four CRDM thermal sleeve failures would occur within one outage cycle from the first failure. That conditional probability increases substantially as the period increases. When the time period is increased from every refueling outage to 10 years, the probability of occurrence of four thermal sleeve failures increases by two orders of magnitude.

Combining Figure 6 and Figure 7, the absolute probability of failure can be estimated (see Figure 8). These results suggest that for a drop of 2 inches, the probability of four thermal sleeve failures occurring within on 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.

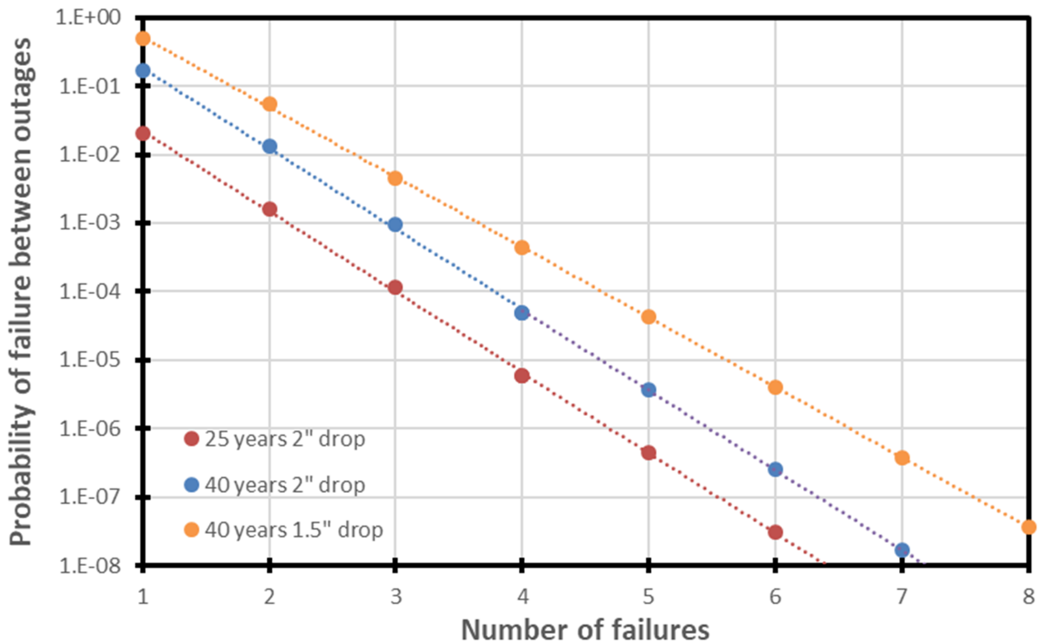

Figure 8: Probability of CRDM Thermal Sleeve Failure within One Outage Cycle

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.

3.2. Impacts of CRDM thermal sleeve failure on plant risk

LIC-504 states that "[f]or the assessment of the acceptability of a change in risk, Regulatory Guide (RG) 1.174…provides appropriate acceptance guidelines." Revision 3 of RG 1.174 [6], is used for making risk-informed decisions to a plant-specific licensing basis.

The NRC staff did not conduct a quantitative analysis of the impact of failure to insert rod cluster control assemblies (RCCAs) on plant risk resulting from severe accidents where reactivity is an important consideration, such as the main steam line break or the RCCA ejection accident. The NRC staff judged that the probability of these accidents, combined with the low probability of several rod failures as discussed above, is sufficiently low that they would not appreciably impact plant risk. The most probable set of initiating events that could result in a reactivity excursion are the steam and feedwater line breaks. For smaller breaks, the initiating event frequency is on the order of 1E-3 per year. However, since these breaks would need several rods to fail to insert (a probability of less than 1E-3 as well) to cause a reactivity excursion, the overall contribution to plant risk is expected to be on the order of 1E-6per year or less. The largest breaks could potentially result in recriticality with only two or three rod failures (approximately 1E-2 or 1E-3 probability), but the initiating event frequency is on the order of 1E-4 per year and thus they are expected to be a similar contributor to plant risk as the smaller breaks. Instead, to assess the impact of thermal sleeve failure on plant risk, the NRC staff performed a bounding analysis assuming that an ATWS results if a certain number of rod cluster control assemblies fail to insert.

An analysis by Westinghouse performed in WCAP-8330, “Anticipated Transients Without Trip Analysis,” [7] reviewed the SRP Chapter 15 transients and determined that the limiting ATWS with regard to shutdown reactivity requirements was the uncontrolled RCCA bank withdrawal at power transient (described in SRP 15.4.2). For this transient, the study found that 2 percent change in reactivity needs to be inserted to bring the core to a subcritical hot zero power condition.

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. Because there is no data to indicate that CRDM thermal sleeve wear is anything other than randomly distributed among CRDM locations, 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,” [8] references a Westinghouse analysis (documented in WCAP-8096 [9]) 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. In addition, the staff did not consider any other mitigative measures that would impact the reactivity of the code, i.e., the analyses assumed only rod insertion would affect reactivity.

NUREG/CR-5500, Volume 2 [10], 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.” This statement is conservative, as many PWRs have more than 53 RCCAs, therefore, for these plants, 10 failed rods is below the 20 percent described in Westinghouse study WCAP-8096.

Based on the discussion in NUREG/CR-5500, the failure of 10 RCCAs to insert due to common cause is currently modeled in the plant Standardized Plant Analysis Risk (SPAR) models. For this analysis, the NRC staff created an additional event in the SPAR model which reduced this number from 10 to 5, adding additional conservatism to account for the following factors: changes in core, fuel and control rod designs since the original analysis was performed in the 1970s, power uprates, and differences in construction and operation between plants. NRC staff analysis also contains the conservative assumption that a failed thermal sleeve also fails the RCCA from functioning and inserting into the core when demanded. The original event representing the failure of 10 rods remained in the model to address other potential causes of mechanical rod failure.

Using the generic failure probabilities developed in Section 3.1, the staff performed a bounding analysis using the SPAR models for a selection of U.S. plants listed in Table 1 of Westinghouse’s May 23, 2018, 10 CFR Part 21 notification. The analysis excludes plants that were known to have replaced their reactor vessel head in the last 10 years. The results are plotted in Figure 10, which was derived from Figure 4 of RG 1.174 for changes (increases) in core damage frequency (CDF) versus the base case. For these analyses, the increase in CDF falls in Region II of the acceptance guidelines defined in RG 1.174 and is considered small (increase in CDF of less than 10^{-5} per reactor years or increase in LERF less than or equal to 10^{-6} per reactor years, when the failure probability for 5 RCCAs due to thermal sleeve failure is set to 4.2E-5).

ATWS sequences are usually not significant contributors to LERF for PWRs. Current risk assessment guidance in IMC-0609, Appendix H (Containment Integrity Significance Determination Process) [11] screens out ATWS sequences in PWRs and states that the risk significance determined by CDF is sufficient.

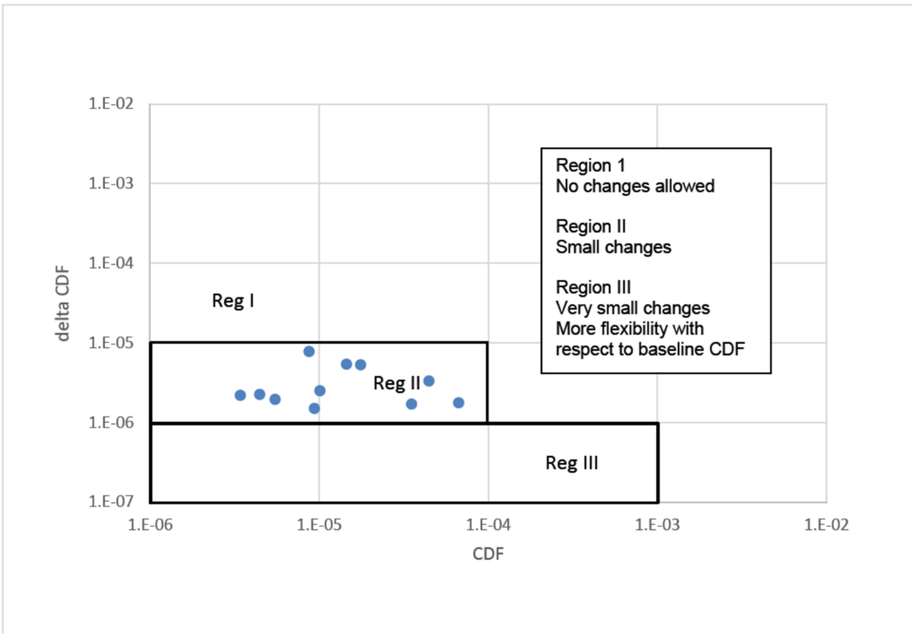

Figure 10: Comparison to RG 1.174 Acceptance Guidelines

4. PRINCIPLES FOR MAKING RISK-INFORMED DECISIONS

NRR Office Instruction LIC-504 [12], "Integrated Risk-Informed Decision-Making Process for Emergent Issues," provides the NRC staff with guidance for evaluating and communicating risk-informed decisions. Risk-informed decisionmaking considers risk insights together with other information (e.g., deterministic evaluations, inspections results, operating experience, and expert knowledge) to reach a determination on the safety significance of a topic. The LIC-504 guidance may be employed when a topic being evaluated does not fit into an existing NRC regulatory process. The LIC-504 instruction explicitly states that the process described for decisionmaking is guidance and not intended to be procedural requirements. Additionally, the LIC-504 instruction recommends that the level of analysis and documentation used in the decisionmaking process should be commensurate with the safety significance of the topic under review. The LIC-504 instruction is intended to be tailored to the specific topic being reviewed to increase NRR efficiency and effectiveness.

The five key principles for making risk-informed decisions are:

1. Compliance with Existing Regulations

2. Consistency with the Defense-in-Depth Philosophy
3. Maintenance of Adequate Safety Margins
4. Demonstration of Acceptable Levels of Risk
5. Implementation of Defined Performance Measurement Strategies

The guidance provided in LIC-504 recommends that the five key principles for making risk-informed decisions be used to differentiate among the options being considered. It is also recognized in the LIC-504 instruction that all of the key principles may not be applicable to each option considered. The five key principles for making risk-informed decisions, as they relate to the current understanding of the CRDM Thermal Sleeve Failure topic, are described below.

4.1. Principle 1: Compliance with Existing Regulations

Determining if the facilities are in compliance with current regulations is complicated by the site-specific requirements for the facilities. The details of how licensees are meeting the current regulations are largely contained in each plant's individual technical specifications. Most plant's technical specifications require that the plant shut down if one CRDM is inoperable and all require a shutdown if more than one CRDM is inoperable. Each set of technical specifications describes a surveillance program to assure that the CRDMs are operable and a drop test every time the head is removed. However, the staff does not know how reliably the rod drop or other surveillance tests would detect the thermal sleeve degradation. As demonstrated by the operating experience at Belleville nuclear power plant in France, a CRDM with a thermal sleeve that has failed could possibly pass one surveillance or rod drop test and fail the next. How often a failed thermal sleeve would cause a CRDM to fail is unknown.

4.2. Principle 2: Consistency with the Defense-in-Depth Philosophy

One factor for assessing how an event might degrade defense in depth is to see how the event affects the balance among the layers of defense. It is useful to consider the following layers of defense (successive measures) when evaluating the impact of CRDM thermal sleeve wear on defense in depth:

1. a robust plant design to survive hazards and minimize challenges that could result in an event occurring
2. prevention of a severe accident (core damage) should an event occur
3. containment of the source term should a severe accident occur
4. protection of the public from any releases of radioactive material (e.g., through siting in low-population areas and the ability to shelter or evacuate people, if necessary)

The likelihood of CRDM thermal sleeve wear severe enough to cause multiple sleeve failures and thus control rod insertion issues during normal operation is low. As discussed earlier, when the sleeve fails, a remnant is left that may get jammed between the CRDM nozzle and the control rod. The movement of this remnant is highly dependent on flow changes within the head, which may occur during a transient/accident event. However, as described above, the probability of multiple failures is low and minimizes any impact to the core safety. Without a robust inspection and mitigation plan, the risk can increase with time.

The thermal sleeve wear is driven by the coolant flow in the RPV head and will not be significantly increased if an accident would occur. However, seismic events or accidents may prematurely cause a worn thermal sleeve to fail, and a control rod to fail to insert.

CRDM flange wear and failure does not affect the containment structure, such that the containment response to these conditions would not be different whether the CRDM thermal sleeves were degraded or not. Finally, the thermal sleeve wear issue has no effect on the emergency preparedness functions, such that the fourth layer of defense is not affected.

Another factor of defense in depth to consider involves the effect of the issue on the fission product barriers (i.e., fuel cladding, RCS pressure boundary, and containment). As stated above, CRDM thermal sleeve flange wear does not affect the containment response. CRDM thermal sleeve flange failures could affect fuel cladding as a result of control rods failing to insert, as previously discussed. This would affect only a small percentage of the cladding. If this occurred during a transient, the damage to the fuel cladding would be isolated due to limited number of control rods that fail to insert. However, as described in Section 3, the probability of this occurrence is low. In addition, the staff assumed that the ATWS event leads directly to core damage, when in reality operators have training and procedures to mitigate an ATWS.

In summary, the CRDM thermal sleeve flange wear issue does not indicate that an imminent safety concern exists from any effect on defense in depth because it does not significantly affect the four layers of defense nor the containment fission product barrier.

4.3. Principle 3: Maintenance of Adequate Safety Margins

Insertion of the control rods during an accident is paramount to ensuring safe shut down of the reactor core. The inability to insert rods for any reason decreases the safety margins associated with the original design. The risk analysis described in Section 3 illustrates that the impacts of CRDM thermal sleeve wear on risk are small and the safety margins are maintained. However, if inspection and mitigations do not occur, the risk would increase, and the safety margins would decrease.

4.4. Principle 4: Demonstration of Acceptable Levels of Risk

As described in Section 3, the probability of CRDM thermal sleeve failure is estimated from the measured wear rates for susceptible U.S. Westinghouse plants. Using a conservative analysis, the probability of five flange failures within one refueling cycle can range between 4E-5 and 7E-7. This analysis assumes 25 and 40 years of operation and that the failures are randomly distributed across the vessel head.

Using past staff positions [8, 10] on the mitigation of an ATWS, the staff estimated five stuck rods as the conservative limit where loss of shutdown capability would occur. Incorporating this scenario into a SPAR analysis, the staff estimated that the increase in CDF would be less than 1E-5 per year and does not surpass the acceptance guidelines documented in RG 1.174 [6]

4.5. Principle 5: Implementation of Defined Performance Measurement Strategies.

Through NSAL-18-1 Rev. 0, Westinghouse has proposed a set of inspections for susceptible plants as described in Section 1 of this document. The NSAL also gives general recommendation on the inspection process but leaves the details to the individual licensees.

Currently, the industry developed interim inspection guidance following the recommendations from NSAL-18-1 and incorporated it into the NEI-03-08 guidance as a “needed” requirement. However, no details about the mitigation strategy or plan has been discussed.

5. STAFF OPTIONS TO RESOLVE THE ISSUE

To address the recent operating experience on CRDM thermal sleeve wear and failure, the staff considered four options for the U.S. fleet of operating nuclear reactors. Table 2 lists the options and describes the staff’s evaluation criteria for each option. In the following paragraphs, each of these options is first described briefly, and then evaluated with respect to the five principles for making risk-informed decisions.

Table 2: Staff Options and Evaluation Criteria

#	Option	Evaluation Criteria
1	Issue Orders Suspending Operation	This option would be required if an imminent safety concern were identified, such as the following: • defense in depth is significantly degraded. • there is significant loss of safety margin. • CDF is greater than or on the order of 1E-3 per year • LERF is greater than or on the order of 1E-4 per year
2	Issue Orders Requiring Inspections and Mitigation	This option would be appropriate if the issue is not an imminent safety concern but one of the following are true: • there is not reasonable assurance that sufficient/adequate defense-in-depth, safety margin, or level of risk is maintained; • the condition is getting progressively worse over a time period relative to the inspection period. • CDF is greater than or on the order of 1E-3 per year • LERF is greater than or on the order of 1E-4 per year
3	Conduct Smart Sample through the Operating Experience Smart Sample Program Issue followed by a Generic Communication if necessary	This option would be appropriate if the issue is not an imminent safety concern and the evaluation determines: • adequate defense-in-depth is maintained; • sufficient safety margin is maintained; • an acceptable level of risk is maintained; • additional information is needed to establish that the aforementioned assessments have an adequate degree of conservatism; • additional information is needed to make a regulatory decision.
4	Monitor and Evaluate	This option would be appropriate if the issue is not an imminent safety concern and the evaluation determines: • adequate defense-in-depth is maintained; • sufficient safety margin is maintained; • an acceptable level of risk is maintained; • the adequacy of defense-in-depth, safety margin, and risk level have a degree of conservatism that provides reasonable assurance that the potential safety impact of CRDM Thermal sleeve failure is bounded.

5.1. Option 1: Issue Orders Suspending Operation

Synopsis: This option consists of shutting down some or all operating reactors through a regulatory process (such as an order) until inspections, analyses, and mitigation are conducted to provide reasonable assurance that the calculated risk levels are acceptable. This option is preferable if there is an immediate safety issue such that the risk to operating plants is clearly demonstrated to be large and immediate. The LIC-504 criterion defines such risk as a CDF above 1E-3 events/year or LERF above 1E-4 events/year.

Principle 1: Immediate shutdown and inspection would find any CRDM thermal sleeve wear issues, and licensees would be required to replace thermal sleeves to ensure design limits would be met for all normal and design-basis operating conditions. With the wear issues mitigated, compliance with the regulations would be ensured.

Principle 2: Option 1 is consistent with the defense-in-depth philosophy because it would ensure CRDM thermal sleeve wear is detected and corrected before the plant starts up. Thus, the likelihood of core damage is minimized with this option and all three barriers to fission product release (fuel cladding, reactor coolant pressure boundary, containment) are intact.

Principle 3: Since CRDM thermal sleeve wear could result in degraded safety margins, immediate shutdown for inspection would determine the extent of degradation. Corrective actions would restore or demonstrate adequate safety margins by the replacement of some or all of the degraded thermal sleeves, combined with an analysis of the as-left condition to demonstrate that safety margins are maintained. Therefore, Option 1 would ensure that adequate safety margins are restored.

Principle 4: The bounding risk assessment of operating with CRDM thermal sleeve wear indicates that this issue does not rise to the level of an imminent safety concern because the estimated CDF is less than 1E-3 per reactor year, as detailed previously. The level of risk for Option 1 would represent no change from the condition of having no CRDM thermal sleeve wear because the susceptible plants would be shut down immediately.

Principle 5: Implementation of Option 1 would allow inspection and mitigation, which are the most effective performance monitoring strategy for CRDM thermal sleeve wear.

5.2. Issue Orders Requiring Inspections and Mitigation

Synopsis: This option encompasses the actions in Option 1 but adds a development effort to require licensees to perform CRDM thermal sleeve inspections, perform subsequent inspections, and develop and conduct mitigation of this issue. The time frame for inspection, subsequent inspections, and mitigation would depend on the plant-specific wear rates and the risk significance of potential failure.

Principle 1: Implementation of this option results in licensees for the most susceptible plants not knowing the physical integrity of the CRDM thermal sleeves until the next scheduled refueling outage. Inspection would identify any degraded CRDM thermal sleeves and licensees would be expected to mitigate the issue. With a robust inspection and mitigation plan in place, the system is restored to a fully qualified condition. Compliance with the regulations would be ensured since these regulations implicitly assume the CRDM assembly is capable of performing its intended function.

Principle 2: Defense-in-depth could potentially be degraded for susceptible plants until the inspections are conducted or mitigation is performed, or both, because fuel cladding damage could occur from a transient due to multiple control rods failing to insert from CRDM thermal sleeve failure. However, based on the determination of acceptable risk for this option, the potential reduction in defense-in-depth is acceptable.

Principle 3: As discussed above, operation with worn CRDM thermal sleeves could mean safety margins are degraded if inspections and mitigations are not performed. However, with the inspection and mitigation efforts in this option, safety margins will be adequately maintained.

Principle 4: As stated in Option 1, operating with worn CRDM thermal sleeves has acceptably low risk levels in the short term, but may increase unless adequate inspections and mitigation are implemented. In addition, CRDM thermal sleeve wear occurs slowly over time; thus, any increase in risk attributable to this wear is judged an acceptable increase for the relatively short-term operation of one fuel cycle or less.

Principle 5: For the susceptible plants, the most effective performance monitoring strategy is for inspection to occur at the next refuel outage with the development of a subsequent inspection schedule and mitigation plan. Without such inspections, no relevant monitoring program exists.

5.3. Conduct Smart Sample Through the Operating Experience Smart Sample Program Issue Followed by a Generic Communication if Necessary

Synopsis: This option is to first conduct a smart sample for those Tier 1 plants that are currently operating with their original upper heads to request information to determine on a plant-specific basis if an adequate degree of conservatism is present in their analyses. The smart sample would request information such as inspection records, wear measurements, inspection and reinspection schedules, calculation packages, condition reports pertaining to this issue, and plans for mitigation. A generic communication may follow if the information provided from the smart sample is insufficient to confirm the conservatism and make a safety determination.

Principle 1: Implementation of this option results in licensees not knowing the physical integrity of the CRDM thermal sleeves for an indeterminate period. Once the licensee performs the inspection and develops a mitigation plan, the CRDM assembly would be restored to a fully qualified condition, and compliance with the regulations would be ensured since these regulations implicitly assume the CRDM assembly is capable of performing its intended function.

Principle 2: Defense-in-depth could potentially be degraded for susceptible plants until the inspections are conducted or mitigation is performed, or both, because fuel cladding damage could occur from a transient due to multiple control rods failing to insert from CRDM thermal sleeve failure. However, based on the determination of acceptable risk for this option, the potential reduction in defense-in-depth is acceptable. However, there is not enough plant-specific information on wear rates, inspection plans or results, or mitigation plans to determine if defense-in-depth is maintained.

Principle 3: As discussed above, operation with worn CRDM thermal sleeves could mean safety margins are degraded if inspections and mitigations are not performed. With a robust inspection, reinspection, and mitigation plan in place, safety margins will be adequately maintained. However, there is not enough plant-specific information on wear rates, inspection plans or results, or mitigation plans to determine if safety margins are maintained.

Principle 4: Even though there is preliminary word from the industry that an inspection plan is under development, it is not clear how long susceptible plants would operate before conducting an initial examination and how subsequent inspections would be defined. NSAL-18-1 suggests that if a plant does an inspection but fails the acceptance criteria, a plant-specific analysis can be completed to extend the inspection interval. The NSAL provides no details or suggestions for mitigation plans for the susceptible plants. Therefore, there is not enough plant-specific information on wear rates, inspection plans or results, or mitigation plans to verify that susceptible plants are bounded by the analyses in Section 3.

Principle 5: Due to the time dependent nature of the CRDM thermal sleeve wear, a robust inspection, reinspection, and mitigation plan is needed to ensure safety. The industry developed interim guidance on CRDM thermal sleeve inspections, but the plant-specific details of these plans are not clear. If analyses can be used to extend or eliminate inspection, the most susceptible plants may not be conducting the most effective and efficient performance monitoring programs.

5.4. Monitor and Evaluate

Synopsis: This option is to continue to monitor and evaluate the industry plans and actions without any additional actions by the NRC. The information to be evaluated will include future CRDM thermal sleeve inspections per the NSAL and interim inspection requirements, analyses to determine acceptability, any plant-specific analyses conducted, and plans and conduct of mitigative measures to slow or halt the wear.

Principle 1: Implementation of this option results in licensees not knowing the physical integrity of the CRDM thermal sleeves for an indeterminate period. Once the licensee performs the inspection and develops a mitigation plan, the CRDM assembly would restored to a fully qualified condition. Compliance with the regulations would be ensured since these regulations implicitly assume the CRDM assembly is capable of performing its intended function.

Principle 2: Defense-in-depth could potentially be degraded for susceptible plants until the inspection or mitigations are performed because fuel cladding damage could occur if multiple control rods stick during a transient due to CRDM thermal sleeve wear. Based on the determination of acceptable risk for this option, the potential reduction in defense-in-depth is acceptable for the short term but may not be acceptable for longer-term operation.

Principle 3: As discussed above, operation with CRDM thermal sleeve wear may degrade safety margins. While it is true that CRDM thermal sleeve wear occurs gradually over time, there could be operating plants with more severe degradation than that observed to date. In addition, the plans for inspection, subsequent inspection, and mitigation are unclear. Increasing the time period between inspections increases the probability of CRDM thermal sleeve failure and decreases the safety margins.

Principle 4: It is not clear how long susceptible plants would operate before conducting an initial examination and how subsequent inspections would be defined. Additional time to resolve this issue increases the uncertainty with how this issue might progress in the future and also increases the associated level of risk. Therefore, the increase in CDF may not be acceptable for longer-term operation.

Principle 5: As discussed above, the industry issued interim guidance on CRDM thermal sleeve inspections, but the plant-specific details of these plans are not clear. If analyses can be used to extend or eliminate inspection, the most susceptible plants may not be conducting the most effective and efficient performance monitoring programs

6. RECOMMENDATIONS

The NRC staff recommends Option 3 since additional information is needed to establish whether the aforementioned assessments have an adequate degree of conservatism. Option 1 and 2 restore margins in a timely manner but the uncertainty in the analyses conducted, which include the assumption of plant specific wear rates, makes it difficult to support these actions. Option 4 is not preferred, in part because of the extended time that plants may operate with CRDM thermal sleeves that continue to degrade. More detailed discussion follows.

Option 1, under which immediate shutdown and inspection or mitigation would be required, is the option that ensures the five key regulatory principles of Regulatory Guide 1.174 are maintained. While Option 1 would ensure that the risk associated with degraded CRDM thermal sleeves is minimized, the calculations presented here demonstrate the risk (CDF) is smaller than the 1E-3 per year LIC-504 guidelines. These results indicate that this issue does not represents an imminent safety hazard. Therefore, an immediate shutdown is not required.

Option 2, which would order inspection or mitigation at the next refueling outage, may result in some degradation in defense-in-depth because of the potential for fuel cladding damage if worn CRDM thermal sleeves cause several control rods to stick during a transient before the inspection. This option could also result in a possible reduction in safety margins because the plant would operate with potentially worn or failed CRDM thermal sleeves. However, the staff's evaluation shows that the immediate risk of core damage from CRDM thermal sleeve failure is two orders of magnitude less than the 1E-3 LIC-504 guidelines. Therefore, the CRDM thermal sleeve wear issue does not warrant a need to issue orders for immediate action.

The industry developed interim inspection guidance, which is incorporated into the NEI-03-08 guidance as a "needed" requirement. The guidance [5] reflects the NSAL-18-1 information, and inspections will be conducted at the next refueling outage for the susceptible plants and reinspection plans will be developed. However, no details about the mitigation strategy or plan has been discussed.

Options 3 and 4, which would involve conducting a smart sample, with possible generic communication, or maintaining the status quo, may also result in degradation of defense-in-depth and reduced safety margins, but the risk change per reactor year is assumed to be the same as for Option 2. However, note that risk-informed decisions should be made with consideration of uncertainty. It is not known, for example, whether there may be currently operating plants with more severe CRDM thermal sleeve degradation than that observed to date (e.g., the French plants have observed wear rates as high as 0.12 inches/year). Additionally, if the inspection results indicate that the thermal sleeve fragility has been adversely affected to the extent that a seismic event within the plant's licensing basis could cause premature failure this risk increase may need to be considered. As a result, the NRC staff does not recommend allowing an indeterminate time period before the inspections and/or mitigations are conducted. The difference is that for Options 3 and 4, the increase in CDF would be for a longer time period than for Option 2.

In addition, Option 3 will allow the NRC staff to gather information on plant-specific issues that would help to determine if the analyses presented in the NSAL and in this document is bounding for the Tier 1 and Tier 2 plants and have an adequate degree of conservatism. Some of the information needed would include the following:

- Plant-specific wear rates. The analyses in both the NSAL and here are based on the wear distributions described earlier. If plants measure wear outside of this distribution, the resulting impact to risk could be larger than anticipated.

- Plant-specific inspection plans and supporting analyses. Currently the NSAL allows the susceptible plants to conduct a plant-specific analyses if their wear extends beyond the generic acceptance criteria in PWROG-16003-P. The results of these analyses may have a significant impact on predicted plant risk.
- Plant-specific mitigation plans. As described in this document, this degradation is driven by the operating behavior of the plants. Without mitigation, the wear will continue and the risk of CRDM thermal sleeve failure increases (see Figure 6).

Therefore, given the risk determination and the uncertainty associated with the plant-specific action, the NRC staff recommends Option 3. The NRC staff will re-evaluate the situation after the NEI-03-08 "needed" inspections are in place and the information from the smart sample is available.

7. REFERENCES

[1] Westinghouse Technical Bulletin, TB-07-2, Revision 3, "Reactor Vessel Head Adapter Thermal Sleeve Wear," December 7, 2015.

[2] Pressurized Water Reactor Owners Group Report, PWROG-16003-P, Revision 1, "Evaluation of Potential Thermal Sleeve Flange Wear," August 2017.

[3] 10 CFR Part 21 Notification, May 23, 2018 (ADAMS Accession No. ML18143B678).

[4] NSAL-18-1, "Thermal Sleeve Flange Wear Leads to Stuck Control Rod," July 9, 2018 (ADAMS Accession No. ML18198A275).

[5] MRP 2018-033, "Transmittal of NEI-03-08 "Needed" Interim Guidance for PWR CRDM Thermal Sleeve Wear," September 5, 2018 (ADAMS Accession No. ML18253A064).

[6] Regulatory Guide 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," Revision 3, U.S. Nuclear Regulatory Commission, January 2018 (ADAMS Accession No. ML17317A256).

[7] Westinghouse Electric Company, "Westinghouse Anticipated Transients Without Trip Analysis," WCAP-8330, August 1974 (ADAMS Accession No. ML061790274).

[8] U.S. Nuclear Regulatory Commission, "Anticipated Transients Without Scram for Light Water Reactors," NUREG-0460, Volume 2, April 1978.

[9] Westinghouse Electric Company, "Anticipated Transients Without Reactor Trip in Westinghouse Pressurized Water Reactors," WCAP-8096, April 1973.

[10] U.S. Nuclear Regulatory Commission, "Reliability Study: Westinghouse Reactor Protection System 1984–1995," NUREG/CR-5500, Volume 2, December 1998.

[11] Inspection Manual Chapter 609, Appendix H, "Containment Integrity Significance Determination Process," May 2004.

[12] NRR Office Instruction LIC-504, Revision 4, "Integrated Risk-Informed Decision-Making Process for Emergent Issues," May 30, 2014 (ADAMS Accession No. ML14035A143).