February 27, 2017

Mr. Brian Thomas, Director
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Office of Research
Mail Stop T10-A36
Nuclear Regulatory Commission
Washington, DC 20555-0001

Subject: Comments Regarding Future NRC Consideration of ASME Code Case N-729-5 and N-729-6 with Regard to Re-Examination Interval for Reactor Vessel Heads Operating at Cold Leg Temperature and having Previously Detected Primary Water Stress Corrosion Cracking (PWSCC)

References:


Dear Sir:

The NRC mandates that operating pressurized water reactors (PWRs) perform periodic examinations of reactor vessel top head penetration nozzles (RPVHPNs) in accordance with 10 CFR 50.55a(g)(6)(ii)(D). This NRC regulation requires the use of ASME Code Case N-729-1 (Reference 1), subject to specific NRC conditions. The NRC condition specified in 10 CFR 50.55a(g)(6)(ii)(D)(5) requires that the interval for volumetric or surface examinations be each refueling outage in the case that flaws attributed to primary water stress corrosion cracking (PWSCC) have previously been identified, whether acceptable or not for continued service. In 2012, ASME incorporated this NRC condition into N-729-5 (Reference 3) for the purpose of simplifying future implementation of the code case by licensees, and not as the result of concurrence on the technical merits of the condition.

In October 2015, ASME reinstated a reexamination interval of every other refueling outage for heads operating at reactor cold-leg temperature (Tcold) and having previously detected PWSCC. Specifically, Note (8) of Table 1 of N-729-5 (Reference 3) states in part, “For reactor vessel heads with operating temperatures less than 570°F (300°C), the reinspection frequency shall be at least once every 36 months of operating time.” Thus, N-729-5 would permit heads operating at Tcold with previously detected PWSCC and operating on a nominal 18-month fuel cycle to be examined every other refueling outage. ASME adopted this change to the code case on the basis of EPRI report MRP-395 (Reference 4). MRP-395, which assessed the latest available plant experience using deterministic and probabilistic approaches, concluded that the interval of 36 operating months is sufficiently conservative for heads operating at Tcold and having previously detected PWSCC. The latest version of the code case published by ASME, N-729-6 (Reference 5), maintains this interval.

In October 2014, Exelon submitted a relief request (Reference 6) to NRC requesting an extension of the volumetric reexamination interval to every second refueling outage (i.e., 36
operating months) for the RPVHPNs at three PWRs on the basis of MRP-395 (Reference 4). PWSCC indications have previously been reported for the T_{cold} heads at these PWRs. In July 2015, EPRI presented (Reference 7) a summary of the MRP-395 technical basis at an NRC public meeting regarding this relief request. In December 2015, the NRC issued a response (Reference 8) to the relief request finding that the request was not sufficient to justify the proposed alternative.

The NRC periodically considers revisions to 10 CFR 50.55a, which incorporates standards, as part of its rulemaking process. ASME understands that the NRC considers in that rulemaking versions of code cases issued by ASME more recent than the versions previously incorporated into 10 CFR 50.55a. Considering that Reference 6 proposed an alternative interval that would be permitted by ASME Code Cases N-729-5 and N-729-6, ASME is writing to ensure that the NRC is aware of the supplemental deterministic technical basis published as an ASME Pressure Vessels & Piping (PVP) conference paper in 2016 (Enclosure 1). The contents of the PVP paper were previewed at the May 2016 meeting of the ASME Section XI Task Group High Strength Nickel Alloys Issues in Orlando, Florida (Enclosure 2).

ASME believes that Enclosure 1 addresses the concerns expressed by the NRC staff in Reference 8 regarding the MRP-395 technical basis (Reference 4) and thus that the NRC should consider this PVP paper when considering ASME Code Case N-729-5, N-729-6, or later versions for incorporation into 10 CFR 50.55a. Specifically, the NRC staff concerns expressed in Reference 8 are addressed as follows:

- **Results of deterministic crack growth analyses.** The NRC expressed the concern that “the apparent influence of material specific issues and fabrication and weld processing issues” “are not addressed in the time/temperature cracking model.” The MRP-395 technical basis (Reference 4) applies the standard deterministic PWSCC crack growth rate equation included in Appendix C of ASME Section XI. The supplemental deterministic calculations of the PVP paper address this concern through application of the 95th percentile of material variability, bounding the range of material susceptibility to PWSCC growth for reactor vessel head penetrations in U.S. PWRs. As discussed in the PVP paper, this approach bounds the laboratory crack growth rate data for the heat of head penetration nozzle material with the highest incidence of cracking observed in U.S. PWRs, and the approach also bounds the crack growth rates that can be deduced from plant experience for head penetration nozzles in U.S. PWRs. In this manner, the deterministic technical basis explicitly considers a bounding material condition for the range of applicable material processing and component fabrication practices.

- **Results of probabilistic crack growth analyses.** The purely deterministic approach presented in the PVP paper provides a sufficient technical basis without considering probabilistic analyses. It is unnecessary for the NRC staff to consider the probabilistic analyses of MRP-395 (Reference 4) when considering the acceptability of the alternative interval that would be permitted by ASME Code Cases N-729-5 and N-729-6.

- **Implications of boric acid corrosion.** As stated in Reference 8, the NRC found that the requirement to continue bare metal visual examinations every refueling outage “to address the concern for potential boric acid corrosion is acceptable as part of a comprehensive inspection program.” Thus, this item is addressed by the existing requirements.

- **Prior issuance of a similar proposed alternative.** The NRC noted that approval of a previous similar alternative was terminated when additional cracking was detected. This
NRC concern is not relevant to the technical basis presented in the PVP paper, which applies deterministic crack growth analyses assuming that one or more additional instances of PWSCC initiation have occurred.

- **Incorporation of NRC condition into Code Cases N-729-3 and N-729-4.** The NRC also noted in Reference 8 that “the ASME code has found the NRC’s position [on its requirement to inspect heads in which cracking has occurred every outage] to be persuasive as the Code adopted the NRC’s required inspection interval in ASME Code Case N-729-4.” ASME responds that the NRC Condition 10 CFR 50.55a(g)(6)(ii)(D)(5) was incorporated into Code Case N-729-3 solely for the purpose of simplifying future implementation of the code case by licensees and not on technical merits. Once the additional supporting technical information in Reference 4 and 7, and Enclosure 1, was presented to the ASME Code Committee, the reexamination frequency was returned to an interval of every other outage in ASME Code Case N-729-5.

- **Effectiveness of NRC condition to prevent leakage and/or structural failure.** The PVP paper clearly demonstrates that the alternative interval (36 operating months) that would be permitted by ASME Code Cases N-729-5 and N-729-6 is sufficiently conservative to prevent leakage and/or structural failure. The PVP paper assesses the dimensional data for the cold head indications, clearly showing that an interval of two cycles would have been sufficient to detect the PWSCC prior to leakage, with substantial margin.

In summary, ASME requests that the NRC consider the supplemental deterministic technical basis published as Paper PVP2016-64032 (Enclosure 1) in its future 10 CFR 50.55a rulemaking regarding periodic examinations of RPVHPNs in PWRs. ASME believes that this PVP paper addresses the NRC concerns expressed regarding the alternative interval for T_{cold} heads with previously detected PWSCC that would be permitted by ASME Code Case N-729-5 or N-729-6.

If you have any questions in regards to the contents of this letter, please direct them to Mr. Christian Sanna, Director, ASME Nuclear Codes & Standards by telephone (212) 591-8513 or by e-mail SannaC@asme.org.

Very Truly Yours,

Ralph Hill III, Chair
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cc: Members, ASME Board on Nuclear Codes and Standards
Members, ASME Standards Committee on Operation and Maintenance of Nuclear Power Plants
Members, ASME BPV Committee on Nuclear Inservice Inspection (XI)
Enclosure 1
DETERMINISTIC TECHNICAL BASIS FOR RE-EXAMINATION INTERVAL OF EVERY SECOND REFUELING OUTAGE FOR PWR REACTOR VESSEL HEADS OPERATING AT T\textsubscript{COLD} WITH PREVIOUSLY DETECTED PWSCC

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ABSTRACT
Plant operating experience with Alloy 600 reactor pressure vessel top head penetration nozzles in U.S. PWRs shows that the inspection intervals prescribed by ASME Code Case N-729-1 have been successful in managing the PWSCC concern. No through-wall cracking has been observed in the U.S. after the first in-service volumetric or surface examination was performed on all CRDM or CEDM nozzles in a given head. The current inspection intervals have facilitated identification of any PWSCC in its early stages, with small numbers of nozzles affected and substantial margins to leakage at the five affected heads operating at T\textsubscript{cold}. MRP-395 demonstrated through both deterministic and probabilistic analyses that the inspection intervals of Code Case N-729-1 remain valid to conservatively address the PWSCC concern.

This paper supplements MRP-395 with additional deterministic crack growth analyses coupled with assessments of the PWSCC indications detected in heads operating at T\textsubscript{cold}. The supplemental deterministic assessments presented in this paper demonstrate the acceptability of a 36-month volumetric or surface inspection interval for heads with previously detected PWSCC and that operate at T\textsubscript{cold}. Until Code Case N-729-5 is approved by U.S. NRC, use of the 36-month interval in the U.S. for such heads would require review and approval by U.S. NRC of a relief request submitted by the licensee.

INTRODUCTION
Inspection requirements for Alloy 600 reactor pressure vessel top head penetration nozzles including CRDM/CEDM nozzles are defined by ASME Code Case N-729-1 [1], which is mandated in the U.S. by the Nuclear Regulatory Commission (NRC) and subject to conditions in 10 CFR 50.55a. Periodic volumetric (UT) or surface (ET or PT) examinations for indications of cracking must be performed every 8 calendar years or before the Re-Inspection Years (RIY) defined by the code case equals 2.25, whichever is less. For cold heads, which operate at reactor cold-leg temperature (T\textsubscript{cold}), the RIY = 2.25 requirement equates to an interval of 4 or 5 18-month fuel cycles. For non-cold heads, the resulting interval is typically 1 or 2 fuel cycles.

Periodic direct visual examinations (VE) of the outer surface of the head to detect evidence of pressure boundary leakage, including the intersection of each nozzle with the head, are required every refueling outage. However, if the head has been in service for less than 8 Effective Degradation Years (EDY) as defined by the code case (which is currently the case for all U.S. cold heads) and no flaws unacceptable for continued service have been detected, the VE interval is every 3rd refueling cycle or 5 calendar years, whichever is less. In this case, a VT-2 visual examination (per IWA-2212 of ASME Section XI) of the head must be performed under the insulation through multiple access points in refueling outages that the more rigorous VE is not completed.

For reactor vessel heads with previously detected primary water stress corrosion cracking (PWSCC), Note (8) of Code Case N-729-1 Table 1 requires volumetric or surface examinations every other refueling outage (if permitted by the RIY = 2.25 requirement). The NRC condition in 10 CFR 50.55a(g)(6)(ii)(D)(5) modifies this interval to be every refueling outage if PWSCC has been previously detected. Code Case N-729-3 [2], which was approved by ASME on April 4, 2012, adopted this NRC condition for the purpose of simplifying future implementation of the code case by licensees.
of two fuel cycles for heads with previously detected PWSCC reaffirmed that a volumetric or surface reexamination interval head material due to pressure boundary leakage. MRP-395 also conservatively address the PWSCC concern, including the as conditioned by 10 CFR 50.55a(g)(6)(ii)(D) remain valid to that the current inspection requirements of Code Case N-729-1 probabilistic analyses, the updated technical basis concluded so that PWSCC as a function of operating time adjusted for temperature). On the basis of both deterministic and probabilistic analyses, the updated technical basis concluded that the current inspection requirements have been effective in detecting any PWSCC degradation in its relatively early stages. Over the period from 2002 to early 2008, a baseline volumetric or surface examination of all original heads in the U.S. with Alloy 600 nozzles was performed. All heads still in service with Alloy 600 nozzles are now in a program of periodic repeat volumetric examinations.

No nozzle leaks have been detected after the outage of the first in-service volumetric or surface examination of all nozzles in a given head. The only occurrence of nozzle leakage since 2004 was in 2010, during the first in-service inspection of a replacement head from a cancelled plant (see [10], [11]). This head had been operating for 6 calendar years, for the equivalent of 5.5 EPY, EDY = 9.2, and RIY = 7.5. Hence this experience is not directly relevant to the re-inspection interval requirement for cold heads. Since 2004, no circumferential PWSCC indications in the nozzle tube near or above the top of the weld have been detected. This type of flaw could produce a nozzle ejection if it were to grow to encompass a very large fraction of the nozzle region subject to weld residual stresses, and the critical length of through-wall circumferential flaws in the nozzle tube is a large fraction of the circumference. In addition, FEA calculations have shown that ASME Code primary membrane and membrane plus bending stress requirements are still met even assuming a substantial volume of head material is lost.

EFFECTIVENESS OF CURRENT REQUIREMENTS

The current inspection requirements have been effective in providing protection against pressure boundary leakage, circumferential nozzle cracking and nozzle ejection, the generation of loose parts, and significant boric acid corrosion of the low-alloy steel head. Critical flaw size calculations [4] have shown that top head nozzles are highly flaw tolerant. The critical axial crack length is much greater than the height of the nozzle region subject to weld residual stresses, and the critical length of through-wall circumferential flaws in the nozzle tube is a large fraction of the circumference. As will be shown below, this conclusion does not depend on performing the probabilistic fracture mechanics analysis included a Weibull statistical model for PWSCC initiation based on industry operating experience and a crack growth model applying the MRP-55 [6] PWSCC crack growth rate equation for Alloy 600. The analysis was calibrated to the plant experience available at that time (2004), which demonstrated distinctly lower probabilities of cracking and leakage for cold heads [4].

In September 2014, EPRI published MRP-395 [7], re-evaluating the technical basis for the inspection requirements of Code Case N-729-1 [1]. MRP-395 considered the latest set of Alloy 600 head nozzle experience, including the PWSCC detected for five U.S. cold heads since 2007. MRP-395 assessed the growth rates implied by this additional experience and updated the Weibull statistical model for PWSCC initiation (probability of at least one nozzle in a head having detectable PWSCC as a function of operating time adjusted for temperature). On the basis of both deterministic and probabilistic analyses, the updated technical basis concluded that the current inspection requirements of Code Case N-729-1 as conditioned by 10 CFR 50.55a(g)(6)(ii)(D) remain valid to conservatively address the PWSCC concern, including the potential concern for boric acid corrosion of the low-alloy steel head material due to pressure boundary leakage. MRP-395 also reaffirmed that a volumetric or surface reexamination interval of two fuel cycles for heads with previously detected PWSCC that operate at $T_{cold}$ would provide a sufficient level of conservatism and that the NRC condition 10 CFR 50.55a(g)(6)(ii)(D)(5) is overly conservative. On the basis of the MRP-395 evaluation, Code Case N-729-5 [8], which was approved by ASME on October 7, 2015, reinstates a volumetric or surface examination frequency of two fuel cycles, specifically every 36 months of operating time, in this circumstance. ASME Code Case N-729-5 also maintains the requirement for direct visual examinations (VEs) for evidence of leakage each refueling outage if flaws unacceptable for continued service under the code case have been detected. However, in December 2015 NRC [9] concluded that a relief request for implementation of this change in inspection interval for volumetric or surface examination was not acceptable.

The current inspection program is intended to provide protection against pressure boundary leakage, circumferential nozzle cracking and nozzle ejection, the generation of loose parts, and significant boric acid corrosion of the low-alloy steel head. Critical flaw size calculations [4] have shown that top head nozzles are highly flaw tolerant. The critical axial crack length is much greater than the height of the nozzle region subject to weld residual stresses, and the critical length of through-wall circumferential flaws in the nozzle tube is a large fraction of the circumference. In addition, FEA calculations have shown that ASME Code primary membrane and membrane plus bending stress requirements are still met even assuming a substantial volume of head material is lost.

### NOMENCLATURE

- CEDM: Control Element Drive Mechanism
- CRDM: Control Rod Drive Mechanism
- EDY: Effective Degradation Years
- EFFY: Effective Full Power Years
- ET: Eddy Current Testing
- FEA: Finite-Element Analysis
- NDE: Non-Destructive Examination
- NRC: U.S. Nuclear Regulatory Commission
- PT: Liquid Penetrant Testing
- PWSCC: Primary Water Stress Corrosion Cracking
- RIY: Re-Inspection Years
- $T_{cold}$: Reactor Cold-Leg Temperature
- TW: Through-Wall
- UT: Ultrasonic Testing
- VE: (Bare Metal) Visual Examination

### INSPECTION REQUIREMENTS TECHNICAL BASIS

The original technical basis for ASME Code Case N-729-1 [1] is documented in MRP-117 [3], and is supported by the MRP-110 [4] safety assessment and the MRP-105 [5] probabilistic assessment. The probabilistic fracture mechanics analyses of MRP-105 were performed to determine the frequencies of nozzle ejection and leakage versus time for inputs including operating temperature, inspection types, and inspection intervals. The analysis included a Weibull statistical model for PWSCC initiation based on industry operating experience and a crack growth model applying the MRP-55 [6] PWSCC crack growth rate equation for Alloy 600. The analysis was calibrated to the plant experience available at that time (2004), which demonstrated distinctly lower probabilities of cracking and leakage for cold heads [4].

In September 2014, EPRI published MRP-395 [7], re-evaluating the technical basis for the inspection requirements of Code Case N-729-1 [1]. MRP-395 considered the latest set of Alloy 600 head nozzle experience, including the PWSCC detected for five U.S. cold heads since 2007. MRP-395 assessed the growth rates implied by this additional experience and updated the Weibull statistical model for PWSCC initiation (probability of at least one nozzle in a head having detectable PWSCC as a function of operating time adjusted for temperature). On the basis of both deterministic and probabilistic analyses, the updated technical basis concluded that the current inspection requirements of Code Case N-729-1 as conditioned by 10 CFR 50.55a(g)(6)(ii)(D) remain valid to conservatively address the PWSCC concern, including the potential concern for boric acid corrosion of the low-alloy steel head material due to pressure boundary leakage. MRP-395 also reaffirmed that a volumetric or surface reexamination interval of two fuel cycles for heads with previously detected PWSCC that operate at $T_{cold}$ would provide a sufficient level of conservatism and that the NRC condition 10 CFR 50.55a(g)(6)(ii)(D)(5) is overly conservative. On the basis of the MRP-395 evaluation, Code Case N-729-5 [8], which was approved by ASME on October 7, 2015, reinstates a volumetric or surface examination frequency of two fuel cycles, specifically every 36 months of operating time, in this circumstance. ASME Code Case N-729-5 also maintains the requirement for direct visual examinations (VEs) for evidence of leakage each refueling outage if flaws unacceptable for continued service under the code case have been detected. However, in December 2015 NRC [9] concluded that a relief request for implementation of this change in inspection interval for volumetric or surface examination was not acceptable.

The current inspection program is intended to provide protection against pressure boundary leakage, circumferential nozzle cracking and nozzle ejection, the generation of loose parts, and significant boric acid corrosion of the low-alloy steel head. Critical flaw size calculations [4] have shown that top head nozzles are highly flaw tolerant. The critical axial crack length is much greater than the height of the nozzle region subject to weld residual stresses, and the critical length of through-wall circumferential flaws in the nozzle tube is a large fraction of the circumference. In addition, FEA calculations have shown that ASME Code primary membrane and membrane plus bending stress requirements are still met even assuming a substantial volume of head material is lost.

### EFFECTIVENESS OF CURRENT REQUIREMENTS

The current inspection requirements have been effective in detecting any PWSCC degradation in its relatively early stages. Over the period from 2002 to early 2008, a baseline volumetric or surface examination of all original heads in the U.S. with Alloy 600 nozzles was performed. All heads still in service with Alloy 600 nozzles are now in a program of periodic repeat volumetric examinations.

No nozzle leaks have been detected after the outage of the first in-service volumetric or surface examination of all nozzles in a given head. The only occurrence of nozzle leakage since 2004 was in 2010, during the first in-service inspection of a replacement head from a cancelled plant (see [10], [11]). This head had been operating for 6 calendar years, for the equivalent of 5.5 EPY, EDY = 9.2, and RIY = 7.5. Hence this experience is not directly relevant to the re-inspection interval requirement for cold heads. Since 2004, no circumferential PWSCC indications in the nozzle tube near or above the top of the weld have been detected. This type of flaw could produce a nozzle ejection if it were to grow to encompass a very large fraction of the nozzle cross section. The periodic volumetric examinations of non-cold heads have discovered modest numbers of nozzles affected by part-depth cracking, often below the weld where the nozzle tube is not part of the pressure boundary [7].

Five of the 19 operating cold heads with Alloy 600 nozzles have shown indications of PWSCC, all of which have been part-depth. This plant experience demonstrates a low probability of nozzle leakage in the cold heads given the examinations being performed [7]. As will be shown below, this conclusion does not depend on performing the examinations each refueling outage after the initial PWSCC detection. For a limiting cold head operating at $561°F$ ($294°C$),
performing an examination every other refueling outage (i.e., 36 months) leads to no more than RY = 1.07, which is far more frequent than the RY = 2.25 interval for heads without previously detected PWSCC.

The MRP safety assessments ([5], [7]) show that the RY = 2.25 interval maintains an acceptably low effect on nuclear safety for cold heads, even for probabilistic cases assuming (1) frequencies of PWSCC crack initiation at the most susceptible end of the range of plant experience and (2) negative correlation of the material susceptibility to crack growth and the time to PWSCC initiation. The MRP probabilistic analyses show that periodic volumetric examinations of the nozzle tube base metal with a frequency corresponding to RY = 2.25 are effective in maintaining a low probability of leakage due to PWSCC of the nozzle tube, and plant experience has demonstrated that there is a low probability of leakage overall including consideration of possible through-weld cracking. The lower incidence and extent of PWSCC observed in cold heads relative to the experience for non-cold heads is consistent with the relatively large sensitivities of the time to PWSCC initiation and the PWSCC crack growth rate to temperature [7].

Thus, the 36-month interval for cold heads with previously detected PWSCC represents a large conservatism.

**DETERMINISTIC CRACK GROWTH METHODOLOGY**

PWSCC growth rates for Alloy 600 material are commonly modeled as a function of two physical parameters, operating temperature of the cracked component and the crack-tip stress intensity factor. Operating temperatures are adjusted to a reference temperature, \( T_{\text{ref}} \), of 325°C (598.15 K, 617°F) using an Arrhenius equation, as shown in Eqn. (1):

\[
    f_{\text{temp}} = e^{-Q_g / (RT_{\text{ref}})}
\]

\( f_{\text{temp}} \) is the calculated temperature factor. \( Q_g \) is the thermal activation energy for Alloy 600 PWSCC growth, and is taken as the widely accepted value of 130 kJ/mol (31 kcal/mol) [6]. \( R \) is the universal gas constant, 0.008314 kJ/mol-K (0.001103 kcal/mol-R). \( T \) is the absolute operating temperature of the component. For cold heads with reported PWSCC, 292°C (558°F) is a bounding operating temperature. The difference in temperature between a cold head operating at 292°C and a non-cold head operating at 318°C (605°F) yields a temperature factor of 3.4, meaning that a crack on a cold head operating at 292°C would grow 3.4 times slower than an identical crack on a head operating at 318°C.

Mode-I stress intensity factors, \( K_i \), for pipes with part-through-wall semielliptical flaws are given in Eqn. (2) [12] assuming a uniform membrane stress, \( \sigma_0 \), that represents the combined effects of operating and weld residual stresses:

\[
    K_i = \sigma_0 i_0 \sqrt{2a}
\]

where \( a \) is the crack depth, and \( i_0 \) is a geometry factor parametrized as a function of flaw aspect ratio, flaw depth, pipe radius, and wall thickness. Typical driving stresses, \( \sigma_0 \), for cracks in Alloy 600 CRDM or CEDM nozzle tube material range from 207 to 483 MPa (30 to 70 ksi) [7].

The temperature factor and stress intensity factor are then applied in the MRP-55 [6] Alloy 600 crack growth rate equation, which is defined in Eqn. (3):

\[
    \dot{a} = f_{\text{temp}} \alpha \left( K_i - K_{\text{th}} \right)^\beta
\]

The stress intensity factor threshold parameter, \( K_{\text{th}} \), per MRP-55 is 9 MPa-m\(^{0.5}\). Values for given percentiles of the power law constant, \( \alpha \), which incorporates heat-to-heat variation in material susceptibility to PWSCC, are provided in Figure 1. This power law constant has a 75th percentile value of 2.67×10\(^{-12}\) for crack growth rate, \( \dot{a} \), in units of m/s and \( K_i \) in units of MPa-m\(^{0.5}\), and can be scaled using factors given in Figure 2 to obtain values at other percentiles of material susceptibility. For example, the 95th percentile power law constant is a factor of 2.68 greater than that for the 75th percentile. The power law exponent, \( \beta \), is 1.16 and does not vary with temperature [6].

In both deterministic and probabilistic approaches, the MRP-55 crack growth rate equation is applied in a forward Euler integration scheme to simulate crack growth. A given crack is grown in sufficiently small discrete time-steps, in which \( K_i \) is calculated for each time step based on the crack length and depth at that time step.
This standard crack growth calculation methodology is applied below to address the potential for PWSCC degradation of Alloy 600 nozzles in cold heads.

**MARGIN TO LEAKAGE FOR POSTULATED FLAWS IN COLD HEADS**

MRP-395 [7] tabulated crack growth calculation results from various sources for a representative set of CRDM/CEDM nozzle cases. For axial flaws, an initial flaw depth at the UT detectability limit (~10% TW) was applied, and all cases assumed the 75th percentile power law constant. The standard approach per MRP-55 and ASME Section XI is to apply the 75th percentile of the power law constant for deterministic calculations. The 75th percentile may be interpreted as the mean of the upper half of the distribution describing the variability in crack growth rate due to material heat [6]. In this manner, the MRP-55 curve addresses the concern that heats that are more susceptible than average to PWSCC crack initiation tend to have higher crack growth rates than average. In the ASME Section XI approach, conservatism in the growth analysis is provided by applying structural factors to the loads when determining the end-of-evaluation-period flaw size. Growth of an axial flaw to the critical size causing unstable rupture is not conservative to prevent leakage in the case of a cold head with previously detected PWSCC. It is noted that the limiting case in Table 1 is for an axially oriented flaw on the inside surface of the nozzle. This flaw location is unlikely as the large majority of head nozzle flaws have been observed to be located on the penetration outer surface at or just below the weld [7].

This paper converts the times reported in MRP-395 to reflect 18-month fuel cycles (rather than EFPY) assuming a limiting operating capacity factor of 98%, and presents results for a cold head temperature of 292°C (558°F) and the 95th percentile of material susceptibility. Under these conditions, the time required for an axial flaw to grow from a detectable depth (~10% TW) to leakage is shown in Table 1. As shown by plant experience and laboratory testing for the heat of head penetration nozzle material with the highest incidence of cracking observed in U.S. PWRs, the 95th percentile of the power law constant is understood to represent the upper end of material susceptibility for head nozzles in U.S. PWRs [7].

The deterministic results in Table 1 show at least 36 months of operating time for a crack at the UT detectability limit to grow to cause leakage, even if the 95th percentile of material susceptibility to PWSCC crack growth is applied. All of these calculations conservatively determine stress intensity factors using stress profiles that are bounding of those predicted in the vicinity of the location of interest, with no credit taken for the drop in tensile stress as flaws grow in length away from the area of maximum stress. Given the dominant roles of operating temperature and variability due to material heat on the crack growth rate, these results demonstrate that a 36-month interval between examinations is conservative to prevent leakage in the case of a cold head with previously detected PWSCC. It is noted that the limiting case in Table 1 is for an axially oriented flaw on the inside surface of the nozzle. This flaw location is unlikely as the large majority of head nozzle flaws have been observed to be located on the penetration outer surface at or just below the weld [7].

**Table 1. Deterministic Crack Growth Analysis Results for Surface Axial Cracks**

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Flaw Orientation and Location</th>
<th>Penetration Incidence Angle (°)</th>
<th>Initial Aspect Ratio (2c/a)</th>
<th>End Condition</th>
<th>Operating Temperature (°F)</th>
<th>Time for Growth from Initial to End Conditions (Fuel Cycles) (75th % ile)</th>
<th>Time for Growth from Initial to End Conditions (Fuel Cycles) (95th % ile)</th>
<th>Time for Growth Adjusted to 558°F (Fuel Cycles) (75th % ile)</th>
<th>Time for Growth Adjusted to 558°F (Fuel Cycles) (95th % ile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Head Examination Frequency Relief Request</td>
<td>ID Axial Crack (Uphill)</td>
<td>42.8</td>
<td>6</td>
<td>100%TW</td>
<td>558</td>
<td>5.2</td>
<td>2.0</td>
<td>5.2</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>OD Axial Crack (Uphill)</td>
<td>42.8</td>
<td>2</td>
<td>to nozzle OD annulus</td>
<td>558</td>
<td>6.4</td>
<td>2.4</td>
<td>6.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Non-Cold Head Inspection Interval Technical Basis</td>
<td>ID Axial Crack (Downhill)</td>
<td>27.1</td>
<td>6</td>
<td>100%TW</td>
<td>599.7</td>
<td>1.9</td>
<td>0.7</td>
<td>5.7</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>OD Axial Crack (Downhill)</td>
<td>27.1</td>
<td>2</td>
<td>to nozzle OD annulus</td>
<td>599.7</td>
<td>3.5</td>
<td>1.3</td>
<td>10</td>
<td>3.8</td>
</tr>
<tr>
<td>MRP-395 Deterministic Calculations</td>
<td>ID Axial Crack (Downhill)</td>
<td>~20</td>
<td>4.5</td>
<td>100%TW</td>
<td>600</td>
<td>3.6</td>
<td>1.3</td>
<td>11</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>OD Axial Crack (Downhill)</td>
<td>~20</td>
<td>4.5</td>
<td>to nozzle OD annulus</td>
<td>600</td>
<td>2.8</td>
<td>1.0</td>
<td>8.3</td>
<td>3.1</td>
</tr>
</tbody>
</table>

**Table 2. Deterministic Crack Growth Analysis Results for Through-Wall Circumferential Cracks**

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Penetration Incidence Angle (°)</th>
<th>End Condition</th>
<th>Operating Temperature (°F)</th>
<th>Circumferential Through-Wall Crack Environmental Factor</th>
<th>Time for Growth from Initial to End Conditions (Fuel Cycles) (75th % ile)</th>
<th>Time for Growth from Initial to End Conditions (Fuel Cycles) (95th % ile)</th>
<th>Time for Growth Adjusted to 558°F (Fuel Cycles) (75th % ile)</th>
<th>Time for Growth Adjusted to 558°F (Fuel Cycles) (95th % ile)</th>
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<tr>
<td>MRP-105 Deterministic Calculations</td>
<td>38</td>
<td>300°</td>
<td>600</td>
<td>2.0</td>
<td>15</td>
<td>5.6</td>
<td>45</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>43.5</td>
<td>300°</td>
<td>600</td>
<td>2.0</td>
<td>7.3</td>
<td>2.7</td>
<td>22</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>48.8</td>
<td>300°</td>
<td>600</td>
<td>2.0</td>
<td>6.3</td>
<td>2.4</td>
<td>19</td>
<td>7.1</td>
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<tr>
<td></td>
<td>49.7</td>
<td>300°</td>
<td>600</td>
<td>2.0</td>
<td>13</td>
<td>4.8</td>
<td>38</td>
<td>14.0</td>
</tr>
<tr>
<td>Non-Cold Head Inspection Interval Technical Basis</td>
<td>27.1</td>
<td>300°</td>
<td>599.7</td>
<td>2.0</td>
<td>5.7</td>
<td>2.1</td>
<td>17</td>
<td>6.3</td>
</tr>
<tr>
<td>MRP-395 Deterministic Calculations</td>
<td>~20</td>
<td>300°</td>
<td>600</td>
<td>2.0</td>
<td>9.2</td>
<td>3.4</td>
<td>27</td>
<td>10.0</td>
</tr>
</tbody>
</table>
The details of the calculation case set identified as “Cold Head Examination Frequency Relief Request” in Table 1 were first provided in a 2009 relief request [13] submitted to NRC. The operating times calculated included that for a postulated axial flaw on the nozzle tube OD at the J-groove weld toe to grow upward to leakage. Assumptions included a range of nozzle incidence angles (0.0° to 47.0°), uphill and downhill initiating locations, an initial flaw depth of 1.9 mm (12% TW), an initial flaw length of 3.8 mm, 75th percentile crack growth rate behavior, 18-month fuel cycles, and a 98% plant capacity factor. These calculations showed an available operating window between 6.06 and 13.75 fuel cycles prior to leakage. If the 95th percentile crack growth rate behavior were applied instead, this available operating window would range from 2.26 to 5.13 fuel cycles. Similarly, this relief request included calculations showing at least 2.0 fuel cycles from UT detectability to leakage for flaws assumed to initiate on the nozzle ID surface, adjusting for 95th percentile crack growth rate behavior. Thus, for the same reasons cited in the previous paragraph, this submittal further supports a 36-month interval between volumetric or surface examinations for cold heads with previously detected PWSCC.

Crack growth calculations were also documented in MRP-395 [7] for through-wall circumferential cracks located in the nozzle tube. An initial through-wall circumferential flaw with a circumferential extent of 30° centered at the limiting downhill side of the nozzle was assumed in all cases. The final circumferential extent of 300° is conservatively below the 330° critical size for net section collapse typical of CRDM and CEDM nozzles [4]. Again, for this paper the MRP-395 reported cases have been adjusted to reflect a 95th percentile crack growth rate and the results converted from EFPY to 18-month fuel cycles assuming a limiting 98% plant capacity factor. The results, as shown in Table 2, demonstrate that the examination schedule of Code Case N-729-1 conservatively addresses the nuclear safety concern for nozzle ejection. Note that, as recommended by MRP-55 [6], these results conservatively apply a factor of 2 to the crack growth rate to address potential environmental uncertainties in the nozzle OD annulus.

Typically UT volumetric examinations from the nozzle ID are applied to meet the requirement for periodic non-visual NDE. These examinations are not qualified to detect part-depth cracks located in the J-groove weld. The concern for weld cracking is addressed through periodic external visual examinations for evidence of leakage and UT leak path examinations that interrogate the interference fit between the nozzle and head. These examinations provide protection against significant boric acid corrosion and wastage of the low-alloy steel head due to nozzle leakage. For cold heads without previously detected PWSCC, either a bare metal visual examination (VE) or an ASME IWA-2212 VT-2 visual examination under the insulation through multiple access points is performed every refueling outage. Plant experience has shown that visual examinations performed at appropriate intervals under the insulation are highly effective in detecting any leakage prior to significant boric acid corrosion occurring [14]. For cold heads with previously detected PWSCC, the requirement is for a VE every refueling outage. ASME Code Case N-729-5 [8] maintains this existing requirement that all heads with Alloy 600 nozzles be examined visually for evidence of leakage every refueling outage.

Thus, the nuclear safety concerns of nozzle ejection and structurally significant boric acid corrosion, as well as the leakage concern for defense in depth, are conservatively addressed under the alternative of a 36-month interval between volumetric or surface examinations for cold heads with previously detected PWSCC.

**ASSESSMENT OF PWSCC OPERATING EXPERIENCE FOR HEADS OPERATING AT Tcold: AS-FOUND MARGIN TO LEAKAGE**

There are currently 24 reactor vessel top heads with Alloy 600 penetration nozzles and Alloy 82/182 J-groove welds operating in the U.S., of which 19 operate at Tcold. Of these 19 cold heads, five have reported indications of PWSCC in the CRDM nozzle tube. Table 3 lists the number of affected nozzles for each of these five heads. All of the cold head indications were connected to the nozzle tube OD within or below the elevation of the J-groove weld. A nozzle OD flaw would need to grow axially upward through the weld elevation before causing a leak. The lack of nozzle ID flaws detected in cold heads remains consistent with overall industry operating experience, where PWSCC has been detected on the nozzle ID for only 15 of 184 CRDM/CEDM nozzles at only 3 of 23 U.S. PWRs with reported PWSCC indications in CDRM/CEDM nozzles as of the end of 2015.

All the PWSCC indications detected in heads operating at Tcold have been in nozzles fabricated using Alloy 600 material supplied by a single material producer. This material category, which has shown the highest incidence of PWSCC in the U.S. fleet, represents the upper end of material susceptibility for head nozzles [7]. NRC-sponsored laboratory tests [15] have shown that the 95th percentile of crack growth rate material heat-to-heat variability assessed in MRP-55 [6] bounds this level of material susceptibility.

**Table 3. PWSCC Indications at U.S. Cold Heads by Outage**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Number of CRDM Nozzles with Reported PWSCC Indications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Head A</td>
<td>2012 - Four nozzles</td>
</tr>
<tr>
<td></td>
<td>2014 - Five nozzles</td>
</tr>
<tr>
<td></td>
<td>2012 - Four* nozzles</td>
</tr>
<tr>
<td>Cold Head B</td>
<td>2013 - One nozzle</td>
</tr>
<tr>
<td></td>
<td>2015 - Three nozzles</td>
</tr>
<tr>
<td>Cold Head C</td>
<td>2011 - Four nozzles</td>
</tr>
<tr>
<td>Cold Head D</td>
<td>2007 - One nozzle</td>
</tr>
<tr>
<td></td>
<td>2014 - One nozzle</td>
</tr>
<tr>
<td>Cold Head E</td>
<td>2012 - One nozzle</td>
</tr>
</tbody>
</table>

* Occurred after MRP-395 was published
† Occurred after MRP-395 was published
Figure 3 plots the as-found length and depth of all U.S. cold head PWSCC indications reported to date, as documented in Licensee Event Reports and Relief Requests. In general, flaws detected during an examination one refueling outage after the prior examination tended to be smaller than those found four cycles after the prior examination, given the difference in time available to grow subsequent to initiation.

Figure 4 plots the as-found total axial crack length versus the estimated remaining ligament to leakage (distance from the top of the flaw to the top of the J-groove weld, shown in Figure 5). Axial position information was available for all of the cold head indications. Figure 4 shows that all PWSCC indications detected at U.S. cold heads had a remaining vertical ligament to leakage greater than the nozzle tube thickness, which represents 100% of the margin available for growth of hypothetical nozzle ID flaws prior to leakage. In one case, size data were available for an indication examined during a refueling outage and a second time during a mid-cycle outage 12 months later. The earlier examination took place four cycles after the previous examination. The remaining vertical ligament was only 2% shorter and the depth was only 0.7 mm greater after the additional year of operation, reflecting the slow-growing nature of PWSCC in cold head nozzles. Per the standard activation energy for PWSCC crack growth [6], a crack at the bounding cold head temperature of 561°F (294°C) grows 3.1 times slower than a crack at a temperature of 605°F (318°C), which corresponds to RIY = ~2.25 for a 24-month fuel cycle. This benefit of reduced crack growth rate for cold heads, as confirmed through the plant head experience, directly supports the alternative interval of 36 months of operating time subsequent to first detection of PWSCC in a cold head, compared to the single fuel cycle (i.e., 18-24 months) currently required by 10 CFR 50.55a for all heads including heads operating near 600°F. It is important to note that even if an OD flaw below the J-groove weld were to grow through-wall in the nozzle tube, the flaw would still need to grow axially to the top of the weld prior to leakage occurring (Figure 5).

Figure 3. Tcold PWSCC Indication Sizes

Figure 4. Tcold PWSCC Indication Remaining Ligament

Figure 5. CRDM Nozzle Schematic Illustrating the Remaining Ligament to Leakage for OD PWSCC

**ASSESSMENT OF PWSCC OPERATING EXPERIENCE FOR HEADS OPERATING AT Tcold: MARGIN TO LEAKAGE FOR TWO-CYCLE INTERVAL**

NDE dimensional data for PWSCC indications detected in heads operating at Tcold were also applied to calculate the additional crack growth that would have occurred under the alternative interval of 36 months of operating time subsequent to first detection of PWSCC in a head. This simulated growth (‘extrapolation’) for an assumed additional cycle of operation was based on the assumption that the initial flaw depth was at the limit of detectability at the previous examination (all for UT, assumed to be 10-15% TW). However, in some cases, the PWSCC indication was found to correspond to an indication reported during a previous outage but dispositioned as not service-related. In such cases, the depth of the earlier indication was applied to project the growth for an additional 18 months of service. The crack growth calculation considers stress intensity factors calculated both at the deepest and surface points on a semi-elliptical crack front, i.e. the calculation does not assume a constant crack aspect.
ratio. Crack growth is extrapolated forward in time by conservatively assuming a constant driving stress of 483 MPa (70 ksi) and using a crack growth rate percentile reflecting the elapsed time for growth from the assumed initial flaw depth to the detected depth, reflecting crack growth rate percentiles as high as 94th percentile. Typically, the driving stress in a J-groove nozzle for an OD axial crack tends to decrease prior to the crack reaching the nozzle OD annulus ([16], [17]).

Figure 6, which is the counterpart to Figure 3, plots the as-found length and depth for all detected cold head PWSCC indications, as well as the size of flaws detected after one cycle extrapolated to an additional cycle of operation. Figure 7, which is the counterpart to Figure 4, shows the remaining vertical ligament including the extrapolated results. Note that two of the indications detected after one cycle were reported to not have grown over the prior cycle based on information for corresponding indications at the previous UT examination.

**CONCLUSIONS**

In 2004, the two-cycle interval for volumetric or surface examinations of cold heads with previously detected PWSCC was established as a conservative measure [3]. The corresponding interval for cold heads without previously detected PWSCC is typically 4 or 5 fuel cycles, while the interval for heads operating near 600°F (316°C) is every refueling outage whether or not PWSCC was previously detected in that head. In 2014, MRP performed a comprehensive reevaluation of the inspection technical basis [7] that reaffirmed the large conservatism associated with the 36-month interval for cold heads with previously detected PWSCC. On the basis of that work ASME reinstated this interval within ASME Code Case N-729-5 [8], which was approved by ASME in October 2015. However, in December 2015 NRC [9] concluded that a relief request for implementation of this 36-month interval for a cold head with previously detected PWSCC was not acceptable.

This paper presents a purely deterministic analysis approach that demonstrates the acceptability of the 36-month interval. This new analysis, which does not rely in any way on the probabilistic analysis in MRP-395 [7], extends the deterministic analysis in that report by applying the 95th percentile factor describing the material variability in crack growth rate, rather than the standard 75th percentile recommended by ASME Section XI. As demonstrated by plant experience and laboratory crack growth rate testing, use of the 95th percentile ensures that the crack growth analysis conservatively bounds the influence of material PWSCC susceptibility. In addition, detailed dimensional data are assessed for the U.S. cold head PWSCC indications that have been reported, including extension of indications detected a single fuel cycle after the previous examination to account for an assumed additional cycle of crack growth. The assessment of plant indications shows large margins against crack sizes that would penetrate to the nozzle OD annulus and causing a small leak. As illustrated in Figure 7, under the alternative interval for cold heads with previously detected PWSCC, the remaining margin for vertical growth significantly exceeds the nozzle tube thickness, which again represents 100% of the margin available for growth of hypothetical nozzle ID flaws prior to leakage.

Under the alternative, the nozzle indications detected after one operating cycle would still have been detected in the early stages of nozzle degradation, with substantial margins against leakage. The plant experience with cold head PWSCC indications demonstrates the conservative nature of the deterministic crack growth results presented in Table 1. Thus, plant operating experience directly supports the conclusion that volumetric or surface examinations every 36 months of operating time is sufficiently conservative for cold heads with previously detected PWSCC to maintain defense in depth.
interval for volumetric or surface examinations of cold heads with previously detected PWSCC. This interval would continue to ensure that the nuclear safety concern and the leakage concern (for defense in depth) are conservatively addressed. The analyses and conclusions of this paper cover all cold heads with Alloy 600 nozzles in the U.S. fleet.

ACKNOWLEDGMENTS

The authors would like to thank Duke Energy, Exelon, and South Carolina Electric & Gas Company for their support of this work.

REFERENCES


[9] Letter from J. C. Poole (Nuclear Regulatory Commission) to B. C. Hanson (Exelon Generation), “Byron Station, Unit Nos. 1 and 2, and Braidwood Station, Unit 1 – Relief from the Requirements of the ASME Code (CAC Nos. MF1530, MF1531, and MF1532),” dated December 3, 2015. [NRC ADAMS Accession No.: ML15323A486]


Enclosure 2
Technical Basis for Re-examination Interval of Every Second Refueling Outage for PWR Reactor Vessel Heads Operating at $T_{\text{cold}}$ with Previously Detected PWSCC

Craig Harrington, EPRI
Glenn White, Dominion Engineering, Inc.

NRC Public Meeting with Exelon Re: Relief Requests Byron Station I3R-27 (Units 1 and 2) and Braidwood Station I3R-14 (Unit 1)
Rockville, Maryland
July 27, 2015
Presentation Outline

- Technical Basis for Inspection Requirements
- Understanding of NRC Concerns
- Effectiveness of Current Inspection Requirements
- Deterministic Crack Growth Calculations
  - Crack growth rate for axial flaw with $a/t = 0.25$ and $2c/a = 4$
  - MRP-395 tabulation of deterministic results
  - Deterministic calculation specific to Braidwood and Byron heads
- Margin to Leakage for Flaws Detected in Cold Heads
- Probabilistic Approach of MRP-395 to Bound Most Susceptible Nozzle Material
  - Calibration to most susceptible heats of Alloy 600 nozzle material
  - Bounding of number of nozzles with PWSCC indications
  - Correlation of crack growth rate to crack initiation time to bias crack growth rates high
- Conclusions
Technical Basis for N-729-1

Introduction – Summary of Current Inspection Requirements

- The current inspection requirements are defined by ASME Code Case N-729-1, which is mandated by NRC subject to conditions in 10 CFR 50.55a(g)(6)(ii)(D)

- Periodic volumetric or surface exams for indications of cracking:
  - Every 8 calendar years or before Re-Inspection Years (RIY) = 2.25
    - **Cold heads**: usually every 4 or 5 18-month fuel cycles
    - **Non-cold heads**: usually every one or two fuel cycles
  - If PWSCC has previously been detected, NRC condition requires the exam every refueling outage (rather than the N-729-1 requirement of every other refueling outage, if permitted by RIY = 2.25)

- Periodic visual exams of outer surface of head for evidence of pressure boundary leakage:
  - Direct visual exam (VE) of the entire outer surface of the head, including essentially 100% of the intersection of each nozzle with the head, every RFO
  - Except if EDY < 8 and no flaws unacceptable for continued service have been detected, the VE interval is every 3rd refueling outage or 5 calendar years, whichever is less
    - An IWA-2212 VT-2 visual examination of the head is performed under the insulation through multiple access points in outages that the VE is not completed
Note 8 of Code Case N-729-1 Table 1 and NRC Condition

- ASME Code Case N-729-1 Table 1 (Examination Categories) [Note (8)] states:
  - If flaws have previously been detected that were unacceptable for continued service in accordance with -3132.3 or that were corrected by a repair/replacement activity of -3132.2 or -3142.3(b), the reexamination frequency is the more frequent of the normal reexamination frequency (before RIY = 2.25) or every second refueling outage, and [Note (9)] does not apply. Additionally, repaired areas shall be examined during the next refueling outage following the repair.

- 10 CFR 50.55a(g)(6)(ii)(D)(5) states:
  - If flaws attributed to PWSCC have been identified, whether acceptable or not for continued service under Paragraphs -3130 or -3140 of ASME Code Case N-729-1, the re-inspection interval must be each refueling outage instead of the re-inspection intervals required by Table 1, Note (8) of ASME Code Case N-729-1.
Technical Basis (MRP-117) for ASME N-729-1 Inspections

- Protection against pressure boundary leakage
  - Inspections provide additional defense in depth by maintaining a low probability of leakage
- Protection against circumferential nozzle cracking and nozzle ejection
  - Critical flaw size calculations showing that top head nozzles are highly flaw tolerant
  - Deterministic crack growth calculations for circumferential flaws
  - Sufficiently small effect on core damage frequency for RIY ≤ 2.25 based on probabilistic calculations
    - The RIY parameter is a measure of the re-examination interval length normalized for differences in operating temperature based on the temperature dependence of the crack growth rate
    - Thus RIY is a measure of the potential for crack extension between exams
    - Reducing the interval to two 18-month cycles in the case of previously detected PWSCC in a cold head represents a substantial conservatism relative to the interval of RIY = 2.25 supported by the assessments of MRP-105 and MRP-395
- Protection against generation of loose parts
- Protection against significant boric acid wastage of the low alloy steel head
  - Bare metal visual exams still to be performed each RFO for cold heads with previously detected PWSCC
Understanding of NRC Concerns

Introduction

- The next two slides summarize relevant NRC concerns as understood by EPRI MRP
- MRP responses are provided
- More detailed responses are provided in the backup slides to the concerns expressed by NRC staff in 2008 in its response to public comments on NRC rulemaking for revision of 10 CFR 50.55a (NRC-2007-0003-0025)
Understanding of NRC Concerns

Operating Experience with Crack Growth Rates Above the 75th Percentile

**NRC Concern:** NRC staff have questioned whether material factors such as microstructure variability and cold work are adequately addressed in the MRP analyses

- The deterministic crack growth rate equation contained in the MRP-395 technical basis does not bound industry operating experience for observed crack growth rates
- Under sponsorship of NRC, ANL performed laboratory PWSCC crack growth rate testing of ex-service Alloy 600 CRDM nozzle tube material, concluding that the crack growth rates for the heat of material tested approximately corresponded to the 95th percentile of material variability for the MRP-55 crack growth rate model [NUREG/CR-6921, NRC ADAMS Accession No.: ML063520366]

**MRP Response:**

- The ASME Section XI approach to deterministic crack growth calculations is to use a conservative mean for the crack growth rate (75th percentile):
  - For piping flaws, conservatism is applied through structural factors applied to the piping loads when determining the end-of-evaluation-period flaw size
  - For CRDM nozzle flaws, conservatism for axial flaws is based on rupture due to axial cracking not being credible considering the extent of the high stress region driving crack growth
- Nevertheless, deterministic calculations provided in this presentation include predictions using the 95th percentile crack growth rate equation, addressing the concern for plant-specific factors such as microstructure and cold work
- The probabilistic modeling addresses the most susceptible heats of nozzle material through calibration to the bounding plant experience, with bias to high crack growth rates through correlation of the crack growth rate with the time to crack initiation
Understanding of NRC Concerns

**PWSCC Detections in Consecutive Outages**

- **NRC Concern:** In some cases, new UT indications have been observed in consecutive refueling outages

- **MRP Response:**
  - Defense in depth is demonstrated by showing that the probability of leakage is low. To demonstrate a low probability of leakage, it is not necessary to apply bounding crack growth rates in a deterministic crack growth rate calculation
  - As described in MRP-395, the nuclear safety and leakage concerns are addressed through periodic volumetric or surface exams performed on a schedule in accordance with the RIY = 2.25 criterion, supplemented by periodic direct visual exams for evidence of leakage
  - Reducing the interval to two 18-month cycles in the case of previously detected PWSCC in a cold head is sufficiently conservative and maintains defense in depth
    - Performing UT every refueling outage in this case is overly conservative and unnecessary to maintain defense in depth
  - Defense in depth does not require detection of every indication at the first refueling outage when flaw becomes detectable via UT
Effectiveness of Current Inspection Requirements

- The current requirements have been effective in detecting the PWSCC reported in a timely fashion, well before the degradation produces flaws of direct safety significance
  - No nozzle leaks have been detected via visual exams after the outage of the first in-service volumetric/surface exam of all CRDM/CEDM nozzles
  - Since 2004, no circumferential PWSCC indications located near or above the top of the weld have been detected
  - The only occurrence of nozzle leakage since 2004 was detected in 2010 during the first in-service volumetric NDE inspection performed of a replacement Alloy 600 head from a cancelled plant
    - Leakage detected after 6 calendar years, 5.5 EFPY, EDY = 9.2, and RIY = 7.5
  - The cold head exams and the repeat exams performed on non-cold heads have been effective in detecting the PWSCC reported in its early stages and in a timely fashion
    - This conclusion does not depend on performing the volumetric or surface exam each refueling outage after PWSCC has first been detected in the head
    - Cold head exam every other refueling outage is no more than RIY = 1.07
Example Crack Growth Calculation

Introduction

- The following slides provide an example, simplified crack growth calculation for the purpose illustrating the magnitude of the crack growth rate for cold heads with nozzle material at the upper end of material susceptibility

- Additional details are provided in the backup slides

- Analysis steps:
  - Stress intensity factor
    \[ K_1 = \sigma_0 i_0 \sqrt{\pi a} \]
  - Temperature effect
    \[ f_{\text{temp}} = e^{\frac{Q_g}{R} \left( \frac{1}{T} - \frac{1}{T_{\text{ref}}} \right)} \]
  - Material variability
    \[ \dot{a} = f_{\text{temp}} \alpha \left( K_1 - K_{1,\text{th}} \right)^\beta \]
Example Crack Growth Calculation

Temperature Effect

- Crack growth rate temperature dependence follows an Arrhenius relationship, as PWSCC growth is a thermally activated process

\[ f_{\text{temp}} = e^{\frac{Q_g}{R} \left( \frac{1}{T} - \frac{1}{T_{\text{ref}}} \right)} \]

- For Alloy 600, the widely accepted thermal activation energy for PWSCC growth is 130 kJ/mole (31 kcal/mole)

- The difference in temperature between a head operating at 605°F (which corresponds to RIY < 2.25 for a 24-month cycle) and a typical cold head of 558°F leads to a temperature factor of 3.4

  - Identical cracks subject to identical conditions (other than temperature) would grow 3.4 times faster in a component at 605°F than in a component at 558°F
  
  558°F bounds the reactor vessel head temperature of all Byron and Braidwood units, as well as all cold head units that have detected PWSCC indications
Example Crack Growth Calculation

**Multiplicative Factor on 75th Percentile Crack Growth Rate Curve**

- **MRP-55 distribution of variability in crack growth rate due to material variability**

- **Ratio of crack growth rate power law constant to 75th percentile power law constant when accounting for heat-to-heat variability**

![Graph showing crack growth rate distribution with 75th percentile and MRP-55 disposition curve.](image)
Example Crack Growth Calculation

**Crack Growth Rate**

- Assuming a constant crack growth rate for 18 months (assuming a thermal power capacity factor of 0.98), change in crack depth and length after 18 months can be evaluated:

\[
\Delta a = 18 \text{ months} \times 0.98 \times \frac{da}{dt} \quad \text{(using } K_1 \text{ for deepest point)}
\]

\[
\Delta c = 18 \text{ months} \times 0.98 \times \frac{dc}{dt} \quad \text{(using } K_1 \text{ for surface point)}
\]

<table>
<thead>
<tr>
<th>σ₀ [ksi]</th>
<th>75%ile da/dt [m/s]</th>
<th>75%ile Δa [mm]</th>
<th>75%ile dc/dt [m/s]</th>
<th>75%ile Δc [mm]</th>
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</thead>
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<td>1.5E-11</td>
<td>0.7</td>
<td>1.0E-11</td>
<td>0.5</td>
</tr>
<tr>
<td>50.0</td>
<td>2.8E-11</td>
<td>1.3</td>
<td>1.9E-11</td>
<td>0.9</td>
</tr>
<tr>
<td>65.0</td>
<td>4.1E-11</td>
<td>1.9</td>
<td>3.0E-11</td>
<td>1.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>σ₀ [ksi]</th>
<th>95%ile da/dt [m/s]</th>
<th>95%ile Δa [mm]</th>
<th>95%ile dc/dt [m/s]</th>
<th>95%ile Δc [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>35.0</td>
<td>4.1E-11</td>
<td>1.9</td>
<td>2.7E-11</td>
<td>1.3</td>
</tr>
<tr>
<td>50.0</td>
<td>7.4E-11</td>
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<tr>
<td>65.0</td>
<td>1.1E-10</td>
<td>5.1</td>
<td>7.9E-11</td>
<td>3.7</td>
</tr>
</tbody>
</table>
Deterministic Crack Growth Rate Analysis

**MRP-395 Table 3-1 (Surface Cracks)**

- Assumes an initial flaw size of ~10% TW for all cases
- Results provide confidence that inspection intervals are sufficient to prevent leakage
- Bounding case shown below is for geometries and operating conditions specific to Braidwood and Byron
  - The case for axial cracking on the nozzle OD shows greater time to leakage compared to the case for ID PWSCC, which has not been detected in any cold heads
- A fuel cycle was conservatively assumed to be 18 months with 98% capacity factor

<table>
<thead>
<tr>
<th>Case Name and Table Reference Number</th>
<th>Flaw Orientation and Location</th>
<th>Penetration Angle (°)</th>
<th>Initial Aspect Ratio</th>
<th>End Condition</th>
<th>Operating Temperature (°F)</th>
<th>Time for Growth from Initial to End Conditions (Fuel Cycles) (75th %ile)</th>
<th>Time for Growth Adjusted to 558°F (Fuel Cycles) (75th %ile)</th>
<th>Time for Growth from Initial to End Conditions (Fuel Cycles) (95th %ile)</th>
<th>Time for Growth Adjusted to 558°F (Fuel Cycles) (95th %ile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examination Frequency Relief Request [1]</td>
<td>OD Circumferential Crack (Downhill)</td>
<td>42.8</td>
<td>6</td>
<td>100%TW</td>
<td>558</td>
<td>5.6</td>
<td>5.6</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>ID Axial Crack (Uphill)</td>
<td>42.8</td>
<td>6</td>
<td>100%TW</td>
<td>558</td>
<td>5.2</td>
<td>5.2</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>OD Axial Crack (Uphill)</td>
<td>42.8</td>
<td>2</td>
<td>to top of weld</td>
<td>558</td>
<td>6.4</td>
<td>6.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Inspection Interval Technical Basis [2]</td>
<td>ID Axial Crack (Downhill)</td>
<td>27.1</td>
<td>6</td>
<td>100%TW</td>
<td>599.7</td>
<td>1.9</td>
<td>5.7</td>
<td>0.7</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>OD Axial Crack (Downhill)</td>
<td>27.1</td>
<td>2</td>
<td>to top of weld</td>
<td>599.7</td>
<td>3.5</td>
<td>10</td>
<td>1.3</td>
<td>3.8</td>
</tr>
<tr>
<td>Deterministic Calculation of this Report</td>
<td>ID Axial Crack (Downhill)</td>
<td>~20</td>
<td>4.5</td>
<td>100%TW</td>
<td>600</td>
<td>3.6</td>
<td>11</td>
<td>1.3</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>OD Axial Crack (Downhill)</td>
<td>~20</td>
<td>4.5</td>
<td>to top of weld</td>
<td>600</td>
<td>2.8</td>
<td>8.3</td>
<td>1.0</td>
<td>3.1</td>
</tr>
</tbody>
</table>

**Conservative Time Between Detectable Flaw and Leakage (Median of Cases)**

| 6.4 | 2.4 |

**Deterministic Crack Growth Rate Analysis**

**MRP-395 Table 3-1 (Through-Wall Circumferential Cracks)**

- Assumes an initial through-wall flaw with circumferential extent of 30° for all cases
- Results demonstrate large margins to preclude possibility of nozzle ejection
- A fuel cycle was conservatively assumed to be 18 months with 98% capacity factor

<table>
<thead>
<tr>
<th>Case Name and Table Reference Number</th>
<th>Flaw Orientation and Location</th>
<th>Penetration Angle (°)</th>
<th>Initial Aspect Ratio</th>
<th>End Condition</th>
<th>Operating Temperature (°F)</th>
<th>Time for Growth from Initial to End Conditions (Fuel Cycles) (75th %ile)</th>
<th>Time for Growth Adjusted to 558°F (Fuel Cycles) (75th %ile)</th>
<th>Time for Growth from Initial to End Conditions (Fuel Cycles) (95th %ile)</th>
<th>Time for Growth Adjusted to 558°F (Fuel Cycles) (95th %ile)</th>
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<tbody>
<tr>
<td>MRP-105 Deterministic Calculations [3]</td>
<td>Circumferential Crack along the J-groove Weld (Downhill)</td>
<td>38</td>
<td>N/A</td>
<td>300°</td>
<td>600</td>
<td>15</td>
<td>45</td>
<td>5.6</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>43.5</td>
<td>N/A</td>
<td>300°</td>
<td>600</td>
<td>7.3</td>
<td>22</td>
<td>2.7</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48.8</td>
<td>N/A</td>
<td>300°</td>
<td>600</td>
<td>6.3</td>
<td>19</td>
<td>2.4</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>49.7</td>
<td>N/A</td>
<td>300°</td>
<td>600</td>
<td>13</td>
<td>38</td>
<td>4.8</td>
<td>14</td>
</tr>
<tr>
<td>Inspection Interval Technical Basis [2]</td>
<td></td>
<td>27.1</td>
<td>N/A</td>
<td>300°</td>
<td>599.7</td>
<td>5.7</td>
<td>17</td>
<td>2.1</td>
<td>6.3</td>
</tr>
<tr>
<td>Deterministic Calculation of this Report</td>
<td></td>
<td>~20</td>
<td>N/A</td>
<td>300°</td>
<td>600</td>
<td>9.2</td>
<td>27</td>
<td>3.4</td>
<td>10</td>
</tr>
<tr>
<td>Conservative Time Between Leakage and Stability Risks (Median of Cases)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Byron 2 Inspection Frequency Relief Request

Summary

- Relief Request for Byron Station Unit 2 I3R-16: “Previous Relief Request”
  - Submitted to extend the inspection period following repair of nozzle 68 in 2007
  - Relief was granted by the NRC for non-visual NDE examination of every other outage
    - Approval of the original Byron 2 relief request was predicated on no additional instances of detected PWSCC
    - Supported by detailed deterministic crack growth calculations [NRC ADAMS Accession No. ML091030445]
- Relief Request Byron Station I3R-27 and Braidwood Station I3R-14: “Current Relief Request”
  - The current relief request is based on analyses that explicitly bound the range of material PWSCC susceptibility observed in the U.S. fleet
Previous Byron 2 Relief Request – Crack Growth Calculation

Weld Residual Stress Model

- To perform PWSCC crack growth calculations, operating plus weld residual stresses are calculated using finite-element analysis (FEA).
- Results shown below apply a stress-strain curve based on cyclic stress-strain data.
  - Produced similar or greater stresses in most cases than an alternate method developed for the U.S. NRC (ASME PVP Paper 2007-26045).

Highest stress averaged through wall thickness is about 65 ksi.
Previous Byron 2 Relief Request – Crack Growth Calculation

Postulated Time to Nozzle Leakage

- Table below extends the Relief Request I3R-16 crack growth calculation results [NRC ADAMS Accession No.: ML091030445] to an assumed 95th percentile CGR
- These calculations assume an initial flaw depth of 0.075 in. (1.9 mm) (12% through-wall) and an initial flaw length of 0.15 in. (3.8 mm) with stress intensity factors calculated using FEA
- The available operating window before leakage, when applying the 95th percentile crack growth rate, is above two operating cycles

<table>
<thead>
<tr>
<th>Nozzle Group &amp; Location</th>
<th>Available Operating Window (75th Percentile CGR)</th>
<th>Available Operating Window (95th Percentile CGR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Fuel Cycles)¹</td>
<td>(Fuel Cycles)¹</td>
</tr>
<tr>
<td>0.0° Nozzle</td>
<td>7.3</td>
<td>2.72</td>
</tr>
<tr>
<td>25.4° Nozzle; Downhill</td>
<td>9.05</td>
<td>3.38</td>
</tr>
<tr>
<td>25.4° Nozzle; Uphill</td>
<td>6.06</td>
<td>2.26</td>
</tr>
<tr>
<td>42.8° Nozzle; Downhill</td>
<td>11.69</td>
<td>4.36</td>
</tr>
<tr>
<td>42.8° Nozzle; Uphill</td>
<td>6.37</td>
<td>2.38</td>
</tr>
<tr>
<td>43.8° Nozzle; Downhill</td>
<td>12.26</td>
<td>4.57</td>
</tr>
<tr>
<td>43.8° Nozzle; Uphill</td>
<td>6.42</td>
<td>2.40</td>
</tr>
<tr>
<td>47.0° Nozzle; Downhill</td>
<td>13.75</td>
<td>5.13</td>
</tr>
<tr>
<td>47.0° Nozzle; Uphill</td>
<td>6.67</td>
<td>2.49</td>
</tr>
</tbody>
</table>

Note 1. A fuel cycle was assumed to be 18 months with a 98% capacity factor. Hot operating time conversion is 1.5 years/fuel cycle.
Previous Byron 2 Relief Request – Crack Growth Calculation

Postulated Time to Through-Wall Growth

- Time to through-wall growth from ~10% TW is at least ~7.9 EFPY (5.4 cycles) (using 75\textsuperscript{th} percentile crack growth rate curve)
- Time to through-wall growth from ~10% TW is at least ~2.9 EFPY (2.0 cycles) (using 95\textsuperscript{th} percentile crack growth rate curve)
- Bounding case in MRP-395 Table 3-1 is for an inside surface, axially oriented indication, which has not been reported for cold heads to date

PWSCC Growth Projections for an Inside Surface, Axially Oriented Flaw on the Uphill Side at the J-groove Weld
Operating Experience
List of PWSCC Indications at U.S. Cold Heads by Outage

- Cases indicated with † occurred after MRP-395 was published
  - The “replacement Alloy 600 head” calibration case remains the bounding probabilistic analysis case and is insensitive to additional reports of cold head PWSCC

- All PWSCC indications detected in the nozzle tube in cold heads were connected to the nozzle tube OD at or below the J-groove weld:
  - Plant experience has demonstrated a low frequency of PWSCC on the nozzle ID, even for the most susceptible temperature and material conditions
  - PWSCC has been detected on the ID of CRDM/CEDM nozzles for only 3 of the 23 heads in the U.S. with reported PWSCC. Only about 15 of the approximate 184 CRDM/CEDM nozzles with detected PWSCC in the U.S. were reported to have PWSCC that originated on the nozzle ID

<table>
<thead>
<tr>
<th>Unit</th>
<th>CRDM Nozzles Repaired</th>
</tr>
</thead>
<tbody>
<tr>
<td>Byron 1</td>
<td>2011 – Four nozzles (31, 43, 64, 76)</td>
</tr>
<tr>
<td>Byron 2</td>
<td>2007 – One nozzle (68) †2014 – One nozzle (6)</td>
</tr>
<tr>
<td>Braidwood 1</td>
<td>2012 – One nozzle (69)</td>
</tr>
<tr>
<td>Cold Head A</td>
<td>2012 – Four nozzles 2014 – Five nozzles</td>
</tr>
<tr>
<td>Cold Head B</td>
<td>2012 – Four* nozzles *One additional nozzle repaired during mid-cycle outage 2013 – One nozzle †2015 – Three nozzles</td>
</tr>
</tbody>
</table>
Operating Experience
Example Cold Head Experience of Interest

- 2013 Mid-Cycle Repair at a Cold Head Plant
  - NRC report [NRC ADAMS Accession No.: ML13192A154]
  - Indication was identified during pre-outage review of the UT inspection data from the prior refueling outage
    - About 13 months after the prior inspection
  - Flaw did not measurably grow in depth
    - Depth reported to be 4.0 mm (0.16 in.)
  - Flaw length grew from 6.6 mm (0.260 in.) in spring 2012 to 8.0 mm (0.314 in.) in spring 2013
    - Average crack growth rate \( \frac{dc}{dt} \) of about 0.63 mm/yr at each surface tip

- 2014 Indication Detected After UT Every Other Outage
  - Indication was about 35% through-wall at time of repair
  - Indication was axial and at the weld toe
  - Ligament above flaw to nozzle annulus estimated as 24 mm (0.96 in.)
Operating Experience

$T_{\text{cold}}$ PWSCC Indication Sizes

- Figure below shows the as-found length and depth of all U.S. cold head PWSCC indications as reported in Licensee Event Reports (LERs) and Relief Requests (RR) to date
  - All indications located on nozzle OD

- As expected, in general, flaws detected during an examination one refueling cycle after the prior exam tend to be smaller than those found four cycles after the prior exam given the difference in time available to grow subsequent to initiation
Operating Experience

\( T_{\text{cold}} \) PWSCC Indication Remaining Ligament Length

- In all cases, the remaining ligament to leakage (distance from the top of the flaw to the top of the J-groove weld) is at least as long as the axial length of the detected flaw and longer than the thickness of a nozzle tube
  - Indication position information was available for all cold head indications except one indication detected four cycles after the previous exam
- Even if a flaw below the J-groove weld grows through-wall in the nozzle tube, it must still grow axially to the top of the weld before leakage occurs

RPV Head Nozzle Schematic with Example Flaw Location
Flaws detected after one refueling cycle can be simulated to grow for an additional refueling cycle using extrapolation of available information.

In some cases, the indication was correlated with previous UT information to estimate the size of the indication at the time of the previous exam.

Extrapolation based on assumption that initial flaw depth was at:

- Limit of detectability at previous exam, or
- Reported size of corresponding indication at previous exam.

Extrapolation forward in time considers $K$ calculated at deepest and surface points on crack front:

- Driving stress is conservatively held constant as crack extends even though actual stress field often tends to decrease in the direction of growth.

Two of the indications detected after one cycle were reported not to have grown over the prior cycle based on information for corresponding indication at previous exam.

Figure extrapolates flaw size using an assumed stress of 70 ksi and using a CGR percentile based on the assumed or estimated prior size.
Operating Experience

$T_{cold}$ PWSCC Indication Remaining Ligament Length – Adjusted for Interval

- The adjusted flaw sizes at time of detection show substantial margin remaining prior to a crack extending to the nozzle annulus and causing a small leak.

- The plant experience supports the conclusion that UT every other refueling outage is sufficiently conservative for cold heads with previously detected PWSCC to maintain defense in depth.

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**Figure** extrapolates flaw size using an assumed stress of 70 ksi and using a CGR percentile based on the assumed or estimated prior size.
Operating Experience

Conclusions

- Lower incidence and extent of PWSCC in nozzles on cold heads is consistent with the large sensitivity to operating temperature

- Inspection experience for other locations operating at $T_{\text{cold}}$ including BMNs corroborates a low frequency of PWSCC in Alloy 600 top head nozzles operating at $T_{\text{cold}}$

- The experience for colds heads with PWSCC shows that a two cycle volumetric or surface exam interval would still have detected indications in the early stages of nozzle degradation, including with substantial margins against leakage
Probabilistic Approach
Component Modeling

- Alloy 600 Reactor Pressure Vessel Head Penetration Nozzles (RPVHPNs)
  - Multiple penetration nozzles per top head
  - Flaws can initiate on ID, OD below weld, and J-groove weld wetted surfaces on uphill or downhill side
    - Initiation time is sampled from a multiple flaw initiation Weibull model for these six locations

- Operational loads are superimposed with residual stresses to calculate the stress intensity factor and growth rate

- Growth of circumferential flaws in the nozzle tube along the weld contour modeled using a 3D FEA approach

- Leakage criterion is satisfied if a flaw reaches the OD nozzle annulus
  - Assumed to immediately initiate a 30° through-wall circumferential flaw

- Ejection criterion is satisfied if circumferential through-wall cracking along the J-groove weld contour reaches critical size (~300-330°)
Weibull Initiation Model
Models Used in MRP-395

- Three crack initiation Weibull cases are used to bound the range of PWSCC susceptibility observed in U.S. heads due to material and fabrication differences
  - Bounding Weibull case calibrated to “Alloy 600 replacement head” experience
    - Applied in main probabilistic assessment cases to ensure that results cover all operating cold heads
      - Weibull fit to nozzle material supplied by B&WTP
      - Weibull fit to all material suppliers
Probabilistic Initiation Model

Initiation-Growth Correlation on Growth Rate of Active Flaws

- A negative correlation coefficient between initiation and growth simulates that a material more susceptible to PWSCC initiation is more susceptible to PWSCC growth
- In this approach, the sampled crack growth rates are substantially biased upwards as shown in this figure.
Probabilistic Initiation Model

Average Number of Penetrations with PWSCC Initiation per Cycle

- The MRP-395 “Alloy 600 Replacement Head Weibull” models approximately one new nozzle with initiated PWSCC every cycle
  - The initiation model is conservative with respect to operating experience
  - Continued PWSCC initiation in susceptible material is consistent with this bounding initiation model applied in MRP-395
Acceptability of Performing UT Every Other Refueling Outage
Requirements for Previously Repaired Nozzles

- It is justified that the NDE specific to repaired areas also be performed every other refueling outage in cases where an interval of two cycles is justified for the general volumetric or surface examination of N-729-1 per MRP-395
  - “Embedded flaw repair” with application of a weld overlay
    - Periodic UT checks for potential growth of an embedded flaw and addresses the potential for new flaws initiating on the nozzle ID
    - Repair technique has been applied in over 45 instances throughout the world, and the flaw being repaired has never come into contact with water after repair
  - ID temper bead mid-wall repair
    - Relocates the pressure boundary from the original J-groove weld to a new weld using PWSCC-resistant material at the mid-wall of the head
    - Periodic UT of the repaired region is required to monitor the integrity of the repaired area
    - Surface conditioning is applied along the entire region from above the nozzle section that was roll-expanded during the repair to below the Alloy 52 mid-wall weld toe
    - No cases have been identified in which new leaks or cracks were detected
  - NDE every other refueling outage is appropriate given the substantial favorable plant experience and the substantial PWSCC benefit of operating at $T_{\text{cold}}$
Conclusions

Acceptability of Performing Volumetric or Surface Examination Every Other Refueling Outage for Heads Operating at $T_{\text{cold}}$ with Prior PWSCC (1/2)

- Updated plant experience and analyses show that volumetric or surface examination of a cold head every other refueling outage is sufficiently conservative:
  - The experience for cold heads with PWSCC shows that this proposed change would still have detected indications in the early stages of nozzle degradation, including with substantial margins against leakage
  - As was the case for MRP-105, the MRP-395 probabilistic calculations support applying the RIY = 2.25 interval to heads with previously detected PWSCC (4 or 5 18-month cycles for cold heads)
    - The probabilistic analyses assume a high likelihood that many PWSCC flaws are initiated in the head over life
  - Performing the volumetric exam every other refueling outage is a substantial conservatism vs. RIY = 2.25 (at least a factor of 2)
  - Performing UT every refueling outage in this case is overly conservative and unnecessary to maintain defense in depth
  - Plant experience confirms large benefit of operation at $T_{\text{cold}}$ on crack growth rates
  - All currently operating cold heads in U.S. have a nominal 18-month fuel cycle
- A reexamination interval of two 18-month cycles is also justified for the periodic NDE required for individual nozzles that have been repaired using either of the two main methods that have historically been used
Conclusions
Acceptability of Performing Volumetric or Surface Examination Every Other Refueling Outage for Heads Operating at $T_{\text{cold}}$ with Prior PWSCC (2/2)

Performing reexamination of the RPV head penetrations per Code Case N-729-1 defined frequency provides an acceptable level of quality and safety

- Defense in depth is maintained with volumetric or surface exams performed every other refueling outage:
  - Effectiveness of current inspection intervals in preventing leakage as demonstrated by:
    - Deterministic crack growth calculations for axial part-depth flaws conservatively assuming 95th%tile behavior for the range of material susceptibility
    - Cold head experience with adjustment of the detected flaws sizes to an interval of two cycles
  - Low probability of leakage per plant experience and probabilistic calculations assuming PWSCC susceptibility bounding range of Alloy 600 nozzle material heat susceptibility

- Nozzle ejection, head wastage, and loose parts concerns are conservatively addressed as described in MRP-395

- These conclusions bound all cold heads with Alloy 600 nozzles in the U.S. fleet, including the Braidwood and Byron units
Together...Shaping the Future of Electricity