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

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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

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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

Materials Reliability Program: Reevaluation of Technical Basis for Inspection of Alloy 600 PWR Reactor Vessel Top Head Nozzles (MRP-395). EPRI, Palo Alto, CA: 2014. 3002003099. [Freely downloadable at www.epri.com]

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

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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

Materials Reliability Program Inspection Plan for Reactor Vessel Closure Head Penetrations in U.S. PWR Plants (MRP-117), EPRI, Palo Alto, CA: 2004. 1007830. [Freely downloadable at www.epri.com]

Materials Reliability Program Probabilistic Fracture Mechanics Analysis of PWR Reactor Pressure Vessel Top Head Nozzle Cracking (MRP-105NP), EPRI, Palo Alto, CA: 2004. 1007834. [ML041680489]

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

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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 $$K_{\mathrm{I}} = \sigma_0 i_0 \sqrt{\pi a}$$
  - Temperature effect $$f_{temp} = e^{-\frac{Q_g}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)}$$
  - Material variability $$\dot{a} = f_{temp}\alpha\left(K_{\mathrm{I}} - K_{\mathrm{I},th}\right)^{\beta}$$

Example Crack Growth Calculation
Temperature Effect

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

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

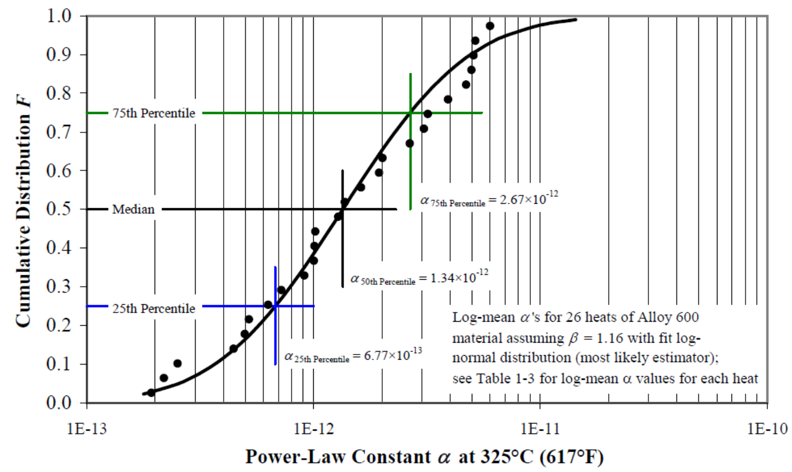
  – For Alloy 600, the widely accepted thermal activation energy for PWSCC growth is 130 kJ/mole (31 kcal/mole)

- 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

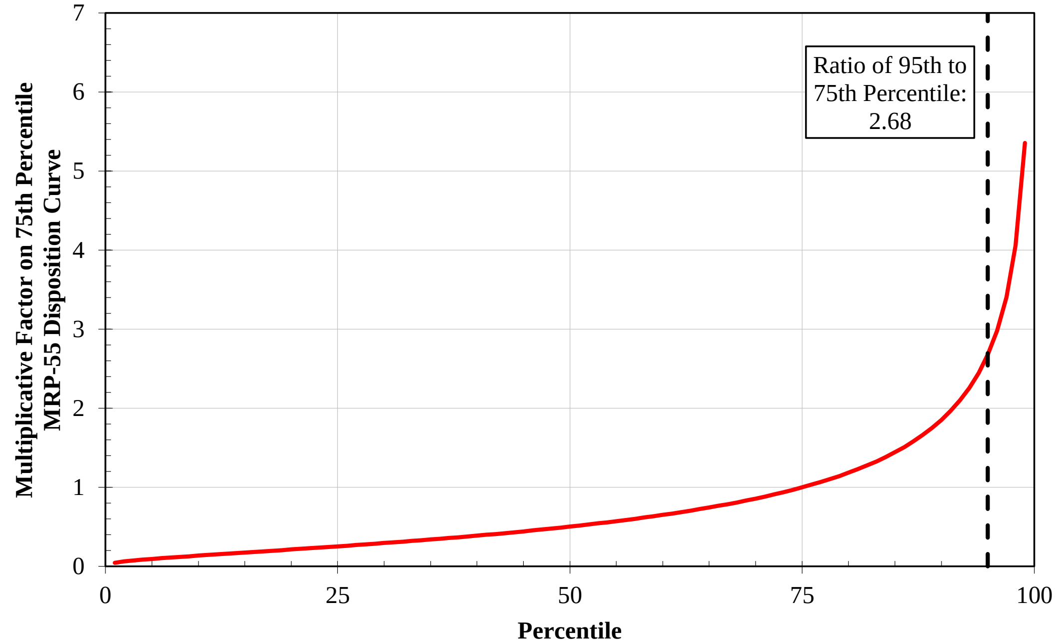
Example Crack Growth Calculation

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



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:

$$\Delta a = 18 \text{ months} \times 0.98 \times \frac{da}{dt} \quad \left(\text{using } K_{\mathrm{I}} \text{ for deepest point}\right)$$

$$\Delta c = 18 \text{ months} \times 0.98 \times \frac{dc}{dt} \quad \left(\text{using } K_{\mathrm{I}} \text{ for surface point}\right)$$

σ_0 [ksi]	75%ile da/dt [m/s]	75%ile Δa [mm]	75%ile dc/dt [m/s]	75%ile Δc [mm]
35.0	1.5E-11	0.7	1.0E-11	0.5
50.0	2.8E-11	1.3	1.9E-11	0.9
65.0	4.1E-11	1.9	3.0E-11	1.4

σ_0 [ksi]	95%ile da/dt [m/s]	95%ile Δa [mm]	95%ile dc/dt [m/s]	95%ile Δc [mm]
35.0	4.1E-11	1.9	2.7E-11	1.3
50.0	7.4E-11	3.4	5.2E-11	2.4
65.0	1.1E-10	5.1	7.9E-11	3.7

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

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

[1] *Byron Unit 2 - Technical Basis for Reactor Pressure Vessel Head Inspection Relaxation*, AM-2007-011 Revision 1, Exelon Nuclear, 2007.
[2] *Technical Basis for RPV Head CRDM Nozzle Inspection Interval - H. B. Robinson Steam Electric Plant, Unit No. 2*, R-3515-001-NP, Dominion Engineering, Inc., 2003.

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

Case Name and Table Reference Number	Flaw Orientation and Location	Penetration Angle (°)	Initial Aspect Ratio	End Condition	Operating Temperature (°F)	Time for Growth from Initial to End Conditions (Fuel Cycles) (75th %ile)	Time for Growth Adjusted to 558°F (Fuel Cycles) (75th %ile)	Time for Growth from Initial to End Conditions (Fuel Cycles) (95th %ile)	Time for Growth Adjusted to 558°F (Fuel Cycles) (95th %ile)
MRP-105 Deterministic Calculations [3]	Circumferential Crack along the J-groove Weld (Downhill)	38	N/A	300°	600	15	45	5.6	17
		43.5	N/A	300°	600	7.3	22	2.7	8.2
		48.8	N/A	300°	600	6.3	19	2.4	7.1
		49.7	N/A	300°	600	13	38	4.8	14
Inspection Interval Technical Basis [2]		27.1	N/A	300°	599.7	5.7	17	2.1	6.3
Deterministic Calculation of this Report		~20	N/A	300°	600	9.2	27	3.4	10
Conservative Time Between Leakage and Stability Risks (Median of Cases)							**25**		**9.2**

[2] *Technical Basis for RPV Head CRDM Nozzle Inspection Interval - H. B. Robinson Steam Electric Plant, Unit No. 2*, R-3515-001-NP, Dominion Engineering, Inc., 2003.
[3] *Materials Reliability Program: Probabilistic Fracture Mechanics Analysis of PWR Reactor Vessel Top Head Nozzle Cracking (MRP 105)*, EPRI, Palo Alto, CA: 2004. 1007834.

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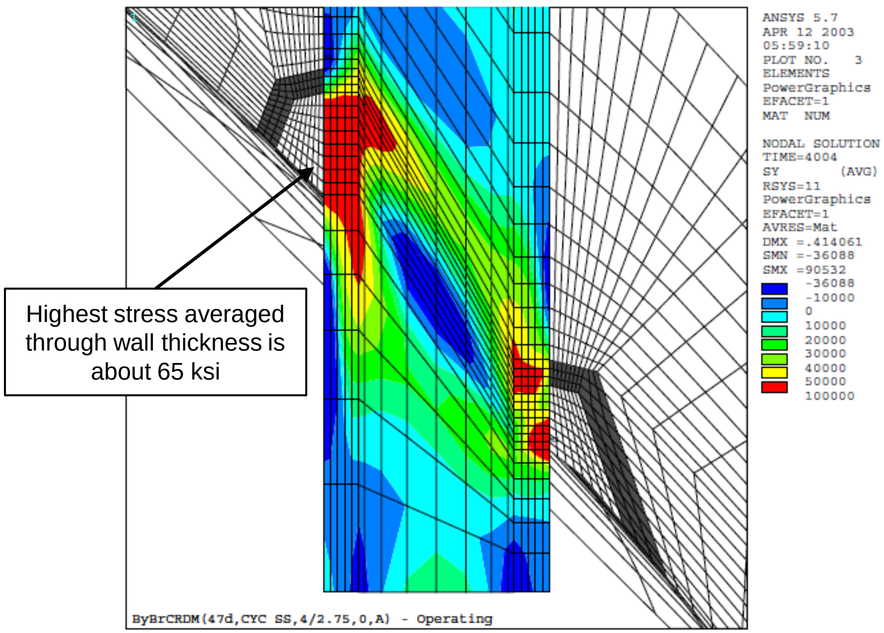
Byron 2 Inspection Frequency Relief Request
Summary

- 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

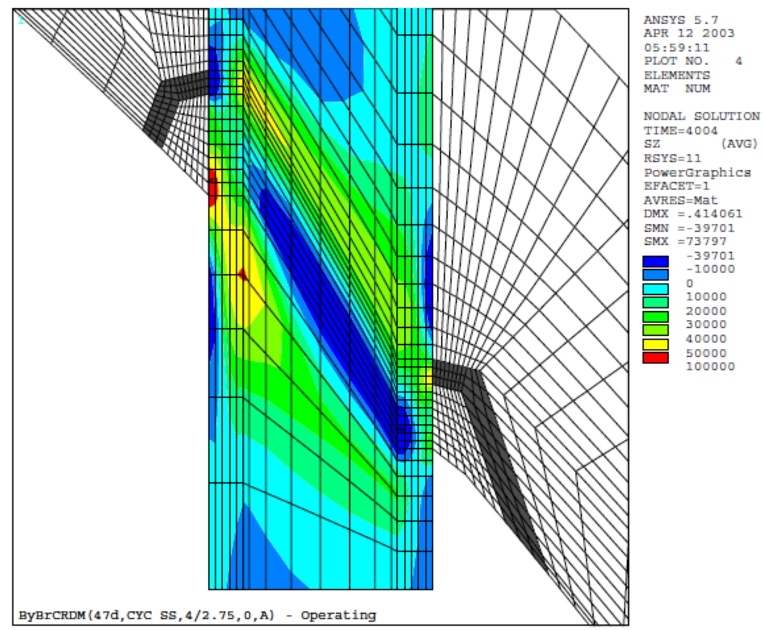
Previous Byron 2 Relief Request – Crack Growth Calculation

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)



Typical Operating Plus Residual Hoop Stress Field Used for Crack Growth RPV Head 47° Nozzle (psi)



Typical Operating Plus Residual Axial Stress Field Used for Crack Growth RPV Head 47° Nozzle (psi)

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

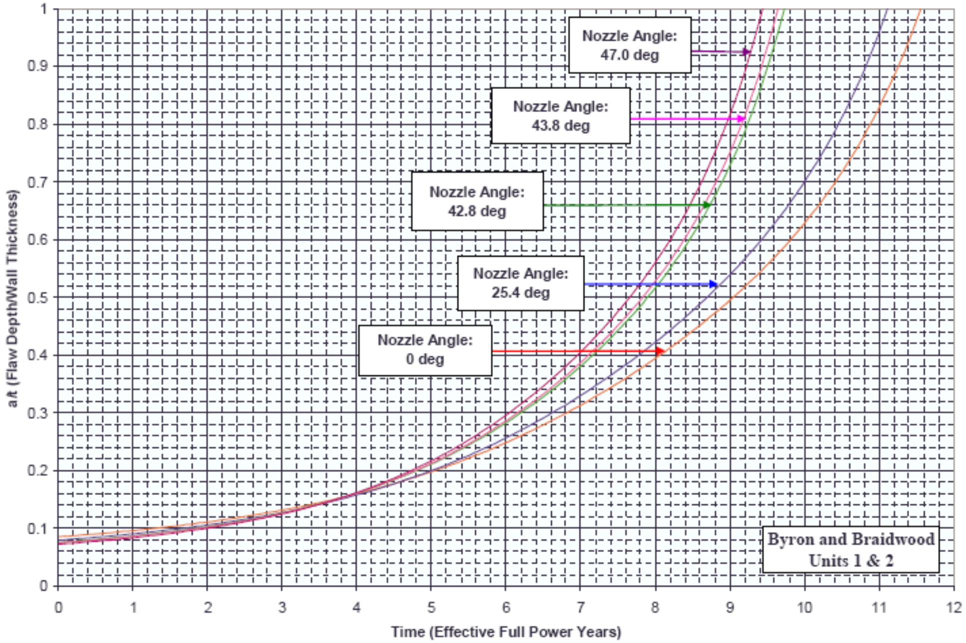
Operating Time for A Postulated Axial Flaw at the J-groove Weld to Grow to Its Leakage Limit		
Nozzle Group & Location	**Available Operating Window (75th Percentile CGR) (Fuel Cycles)[1]**	**Available Operating Window (95th Percentile CGR) (Fuel Cycles)[1]**
0.0° Nozzle	7.3	2.72
25.4° Nozzle; Downhill	9.05	3.38
25.4° Nozzle; Uphill	6.06	2.26
42.8° Nozzle; Downhill	11.69	4.36
42.8° Nozzle; Uphill	6.37	2.38
43.8° Nozzle; Downhill	12.26	4.57
43.8° Nozzle; Uphill	6.42	2.40
47.0° Nozzle; Downhill	13.75	5.13
47.0° Nozzle; Uphill	6.67	2.49

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 75th percentile crack growth rate curve)
- Time to through-wall growth from ~10% TW is at least ~2.9 EFPY (2.0 cycles) (using 95th 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

Unit	CRDM Nozzles Repaired
Byron 1	2011 – Four nozzles (31, 43, 64, 76)
Byron 2	2007 – One nozzle (68) †2014 – One nozzle (6)
Braidwood 1	2012 – One nozzle (69)
Cold Head A	2012 – Four nozzles 2014 – Five nozzles
Cold Head B	2012 – Four* nozzles *One additional nozzle repaired during mid-cycle outage 2013 – One nozzle †2015 – Three nozzles

Operating Experience

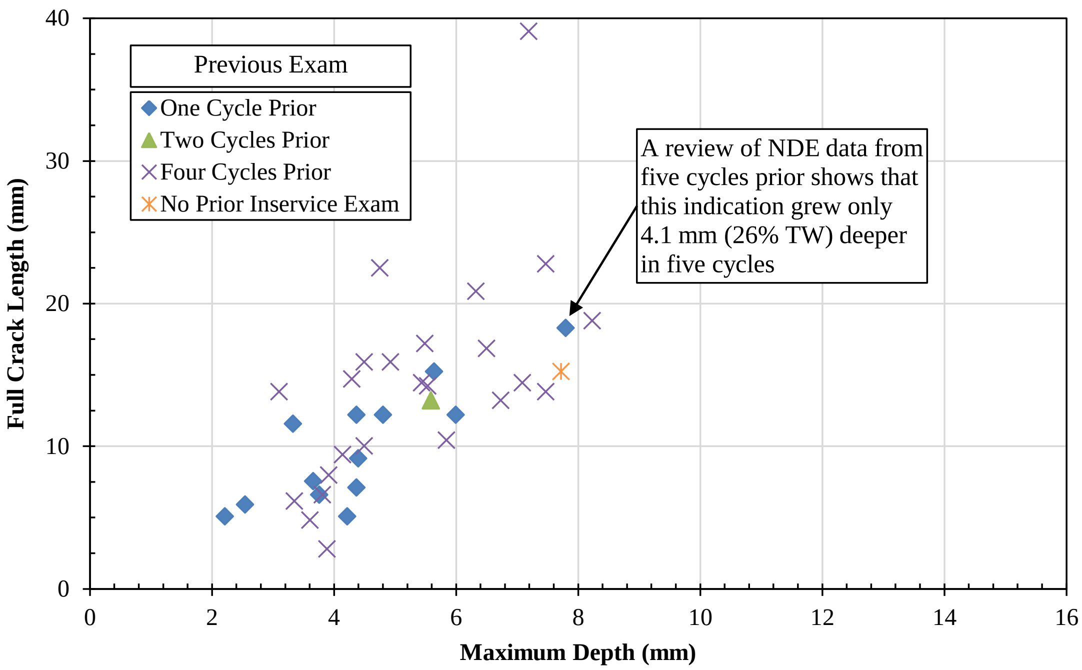
Example Cold Head Experience of Interest

- 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 (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_{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



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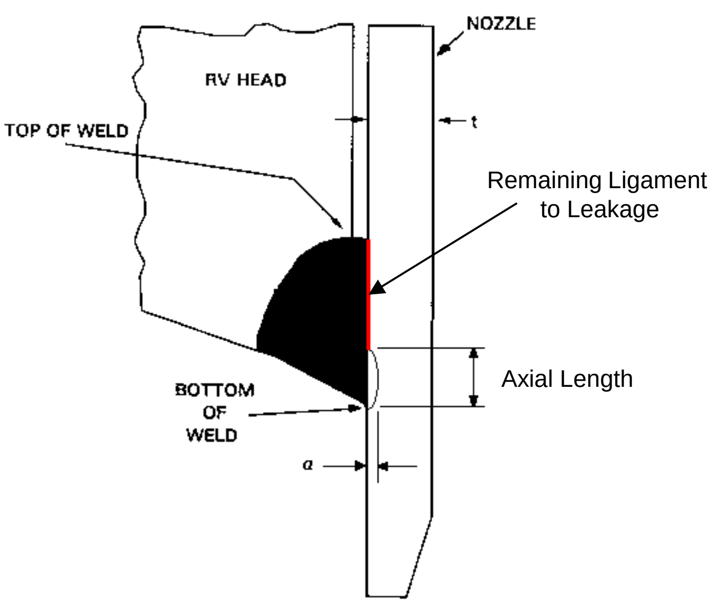
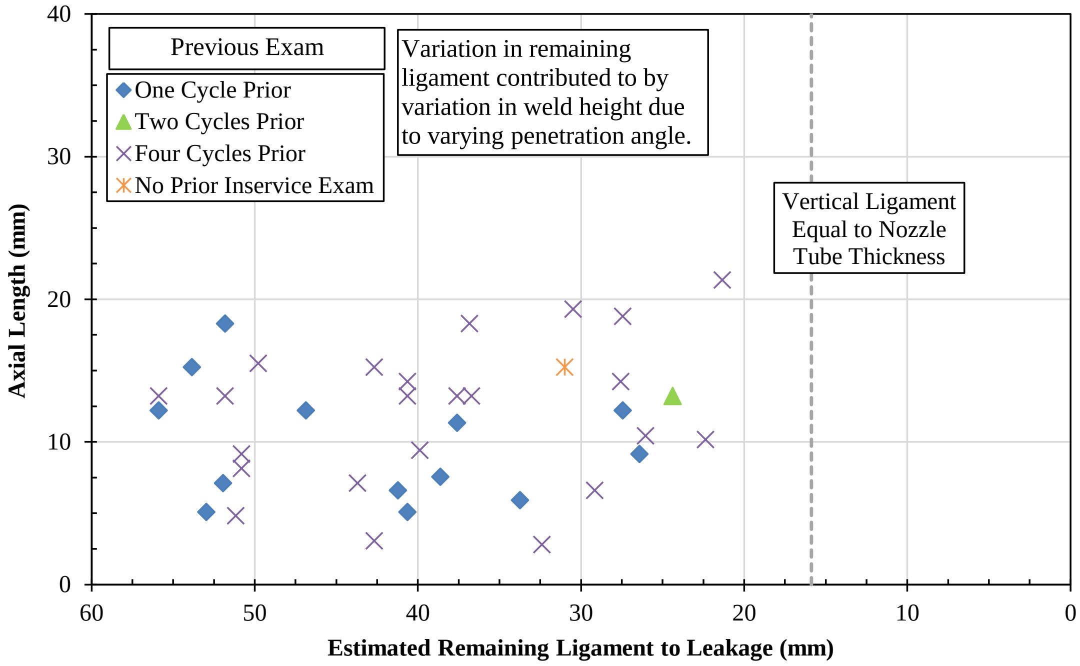
Operating Experience

T_{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



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Operating Experience

T_{cold} PWSCC Indication Sizes Adjusted to Hypothetical Two-Cycle Exam Frequency

- 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

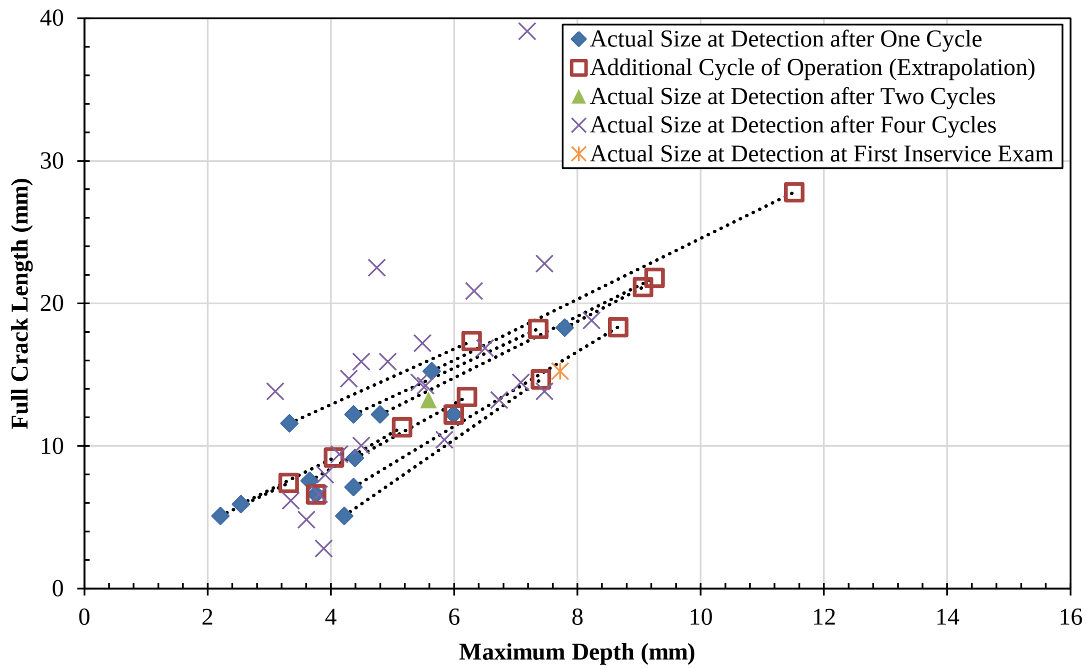

Figure extrapolates flaw size using an assumed stress of 70 ksi and using a CGR percentile based on the assumed or estimated prior size

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

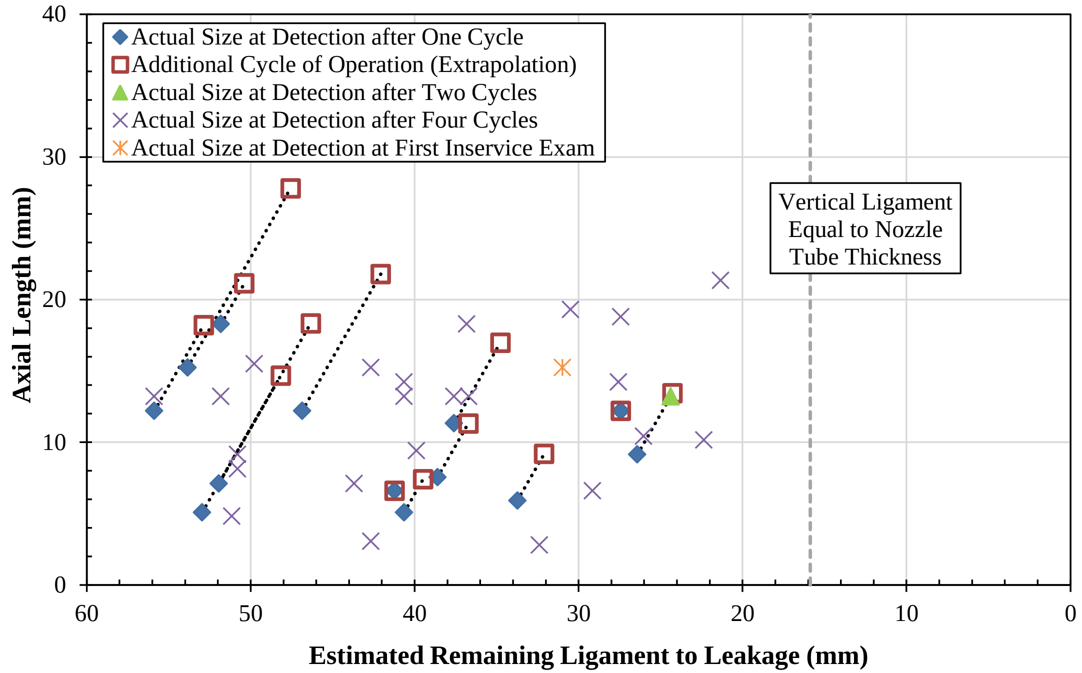

Figure extrapolates flaw size using an assumed stress of 70 ksi and using a CGR percentile based on the assumed or estimated prior size

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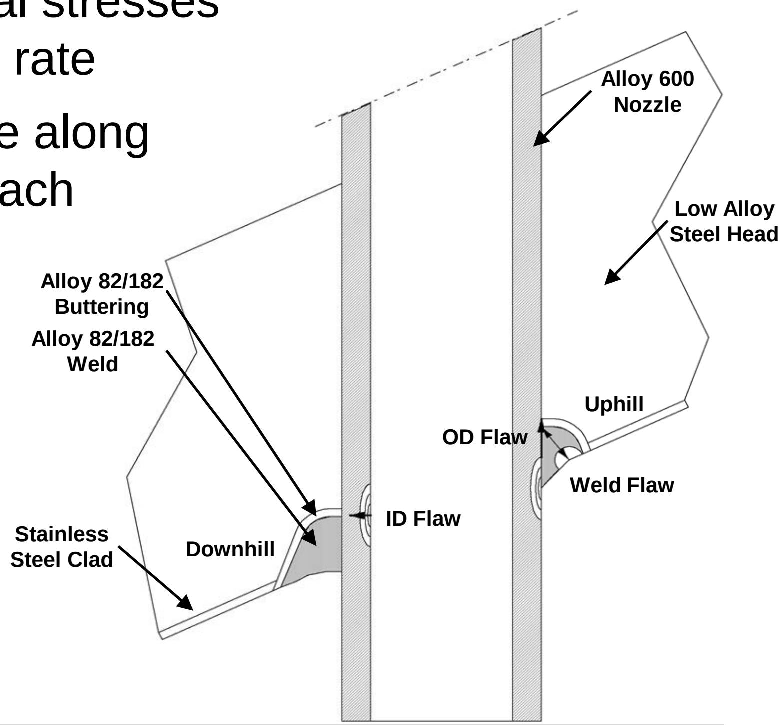
Operating Experience
Conclusions

- 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_{cold} including BMNs corroborates a low frequency of PWSCC in Alloy 600 top head nozzles operating at T_{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°)



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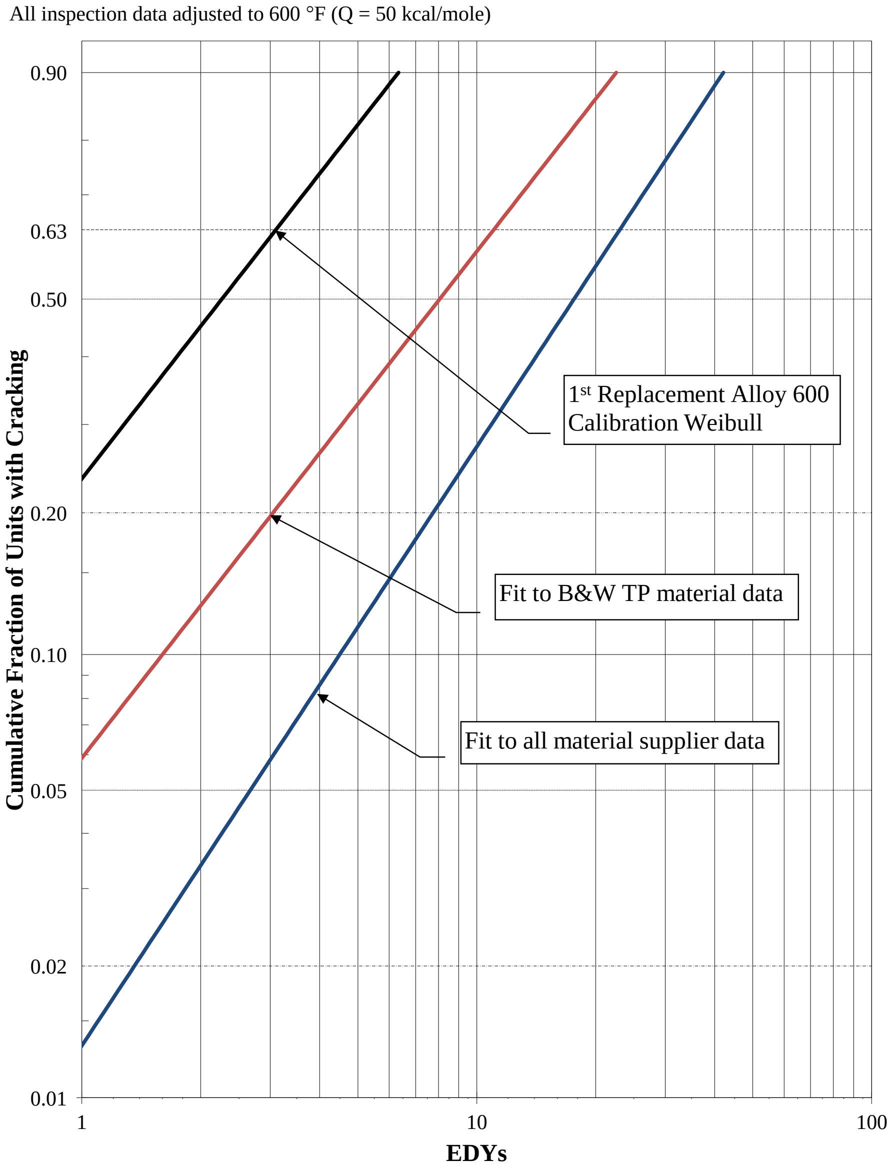
Weibull Initiation Model
Models Used in MRP-395

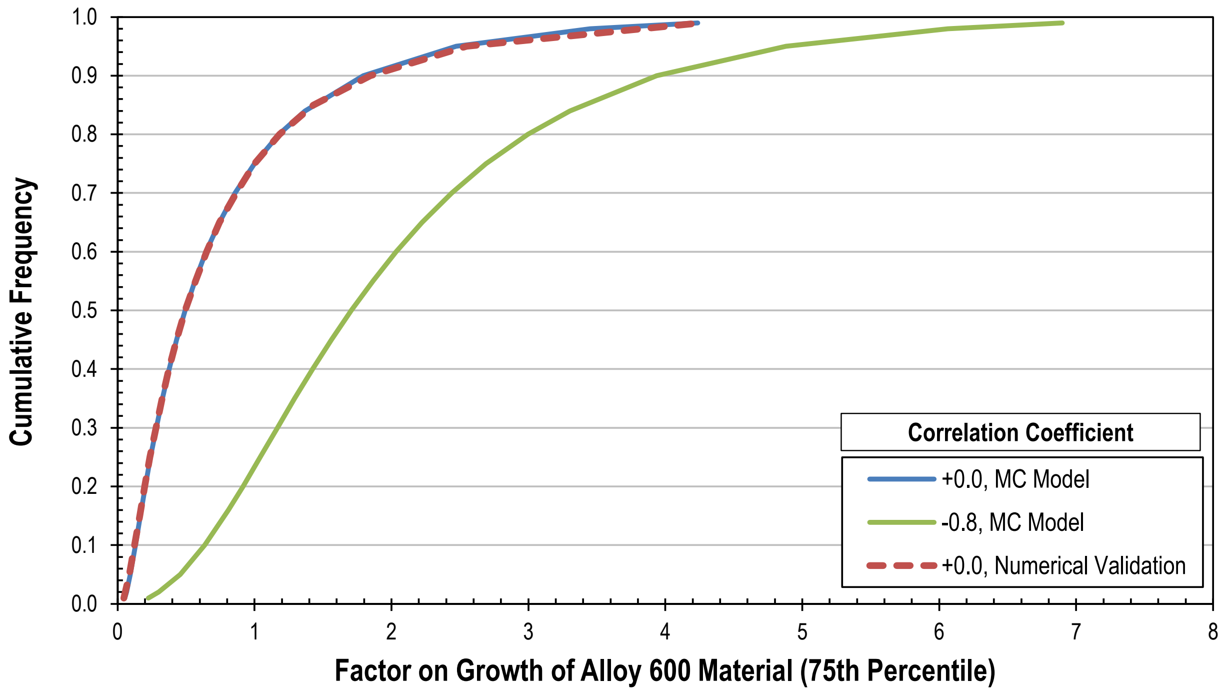
- Three crack initiation Weibull cases are used to bound the range of PWSCC susceptibility observed in U.S. heads due to material and fabrication differences
  - Bounding Weibull case calibrated to “Alloy 600 replacement head” experience
    - Applied in main probabilistic assessment cases to ensure 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



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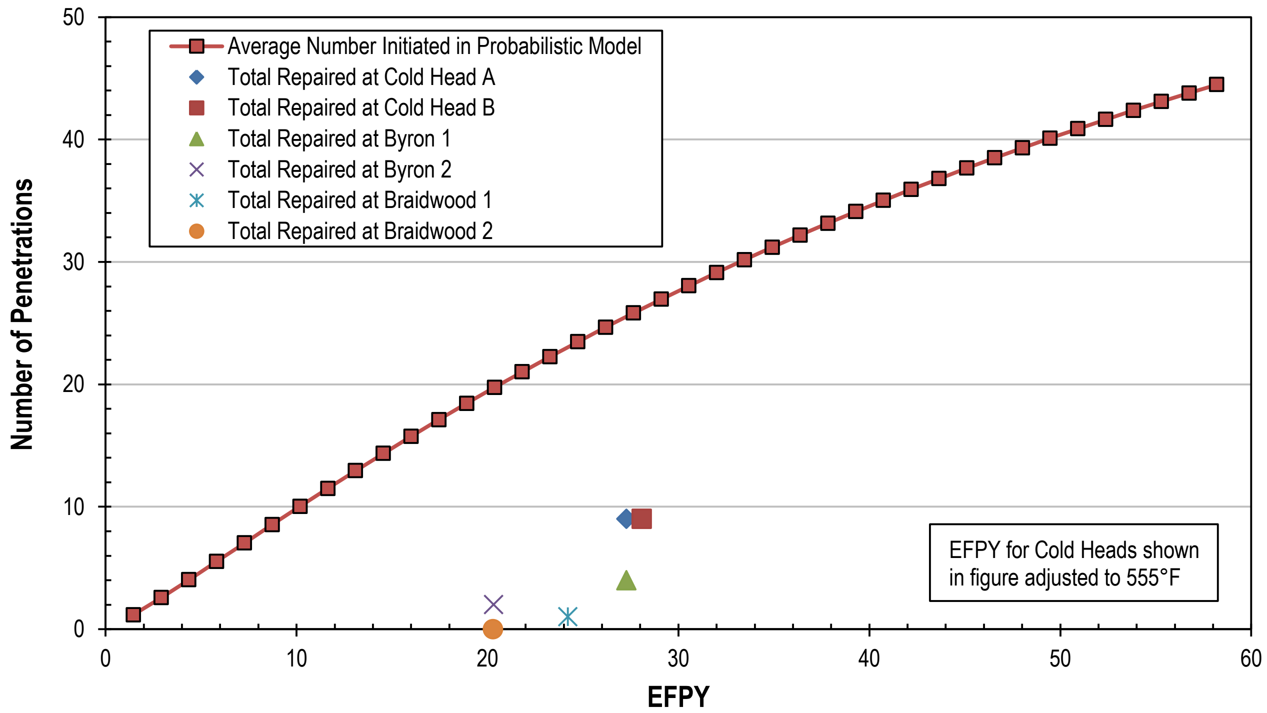
Probabilistic Initiation Model

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



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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_{cold}

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Conclusions

Acceptability of Performing Volumetric or Surface Examination Every Other Refueling Outage for Heads Operating at T_{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_{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_{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 95^{th}%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

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