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Update of Technical Basis for Inspection of Alloy 600 PWR Reactor Vessel Top Head Nozzles

NRC Public Meeting, Rockville, MD

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Purpose

- Fulfill EPRI MRP commitment to provide NRC an update on the implications of plant experience for the inspection basis for PWR top heads
- Provide recommendations
  - Allow two-cycle volumetric or surface exam interval for cold heads with previously detected PWSCC
  - Maintain current visual exam intervals

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Topics

MRP-395 was published on September 30, 2014, and is freely downloadable at www.epri.com:
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.

- Introduction
  - Status of U.S. Fleet
- Original Technical Basis for ASME Code Case N-729-1
- Updated Technical Basis (MRP-395)
  - Assessment of Plant Experience
  - Deterministic Analyses
  - Probabilistic Analyses
  - Assessment of Concern for Boric Acid Corrosion
  - Conclusions
- Recommendations

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Introduction

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Inspection Results Summary

Timeline

- First leak on CRDM penetration at Bugey 3 in France in 1991
- Between 1991 and 2000, surface examinations of the CRDM nozzle ID were performed at several U.S. PWRs
  - A 43% through-wall axial flaw was detected
- In November 2000, leaks due to PWSCC were discovered for the first time in the U.S. on reactor pressure vessel head (RPVH) penetrations
- In Spring 2001, circumferential flaws discovered above the J-groove weld on the outside surface of two leaking nozzles
- In Spring 2002, CRDM nozzle leaks were detected on one head that led to significant boric acid wastage of the low-alloy steel top head material requiring replacement of the head in 2003
- NRC Order EA-03-009, dated February 11, 2003
  - Established High, Moderate, and Low susceptibility categories based on effective degradation years (EDYs)*

*measure of cumulative operating time normalized to a head temperature of 600°F using the temperature dependence for PWSCC crack initiation

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Inspection Results Summary

Timeline (cont'd)

- By December 2003, all the original heads in service were inspected by bare metal visual examination and/or volumetric/surface NDE techniques
- NRC First Revised Order EA-03-009, dated February 20, 2004
- By Fall 2005, all 46 plants with > 8 EDYs completed baseline volumetric/surface exams or head replacement
- By February 2008, all the original heads in service were inspected by volumetric/surface NDE techniques
- December 31, 2008, Implementation Date for ASME Code Case N-729-1
  - Established requirement for repeat volumetric/surface exams based on Re-Inspection Years (RIYs)*
- First repeat volumetric/surface exams in heads operating at T_{cold} (i.e., cold heads) generally started in 2011

*measure of operating time normalized to a head temperature of 600°F using the temperature dependence of the PWSCC crack growth rate

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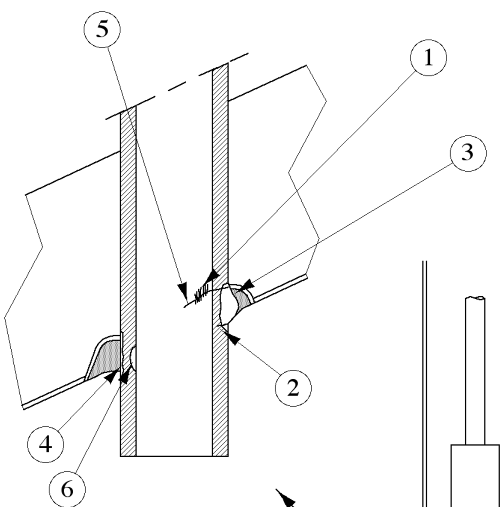
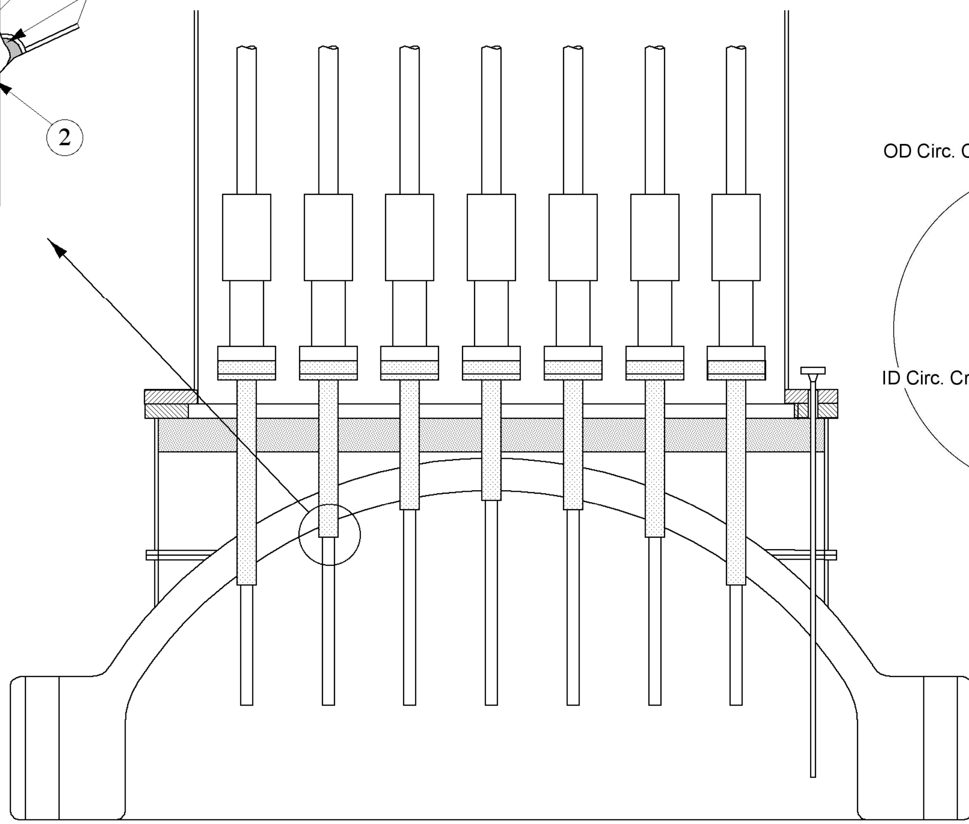
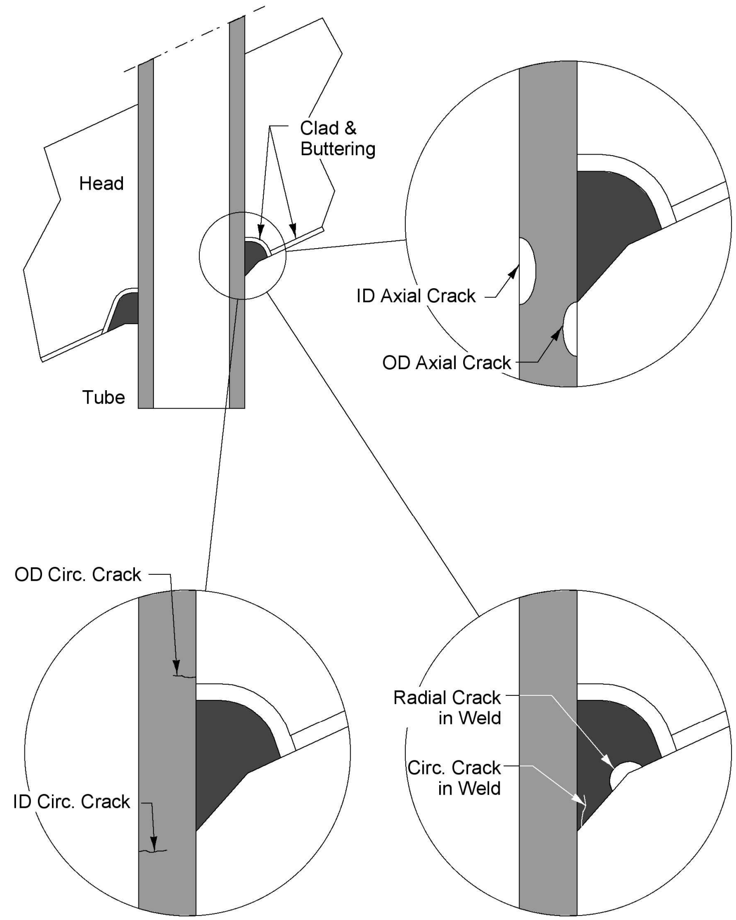
Introduction

Types of PWR RV Head Nozzle PWSCC



1. Craze cracks on ID surface
2. Circ crack below weld
3. Deep axial crack through weld
4. Shallow axial crack at nozzle OD
5. Deep circ crack above weld
6. Deep axial crack on ID surface





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Introduction

U.S. Fleet Status – Summary

- 63 heads with Alloy 600 nozzles have been inspected by non-visual NDE
- 24 heads with Alloy 600 nozzles remain in-service
  - 1822 CRDM/CEDM nozzles remain in-service and 46 other J-groove top head nozzles
  - 19 of these heads operate at T_{cold} (1483 of the Alloy 600 J-groove nozzles)
  - There are plans for replacement or peening mitigation for some of the heads now in service
- Seven heads remaining in-service have detected PWSCC
  - Five of these heads operate at T_{cold}
- 41 heads with replacement materials (Alloy 690 nozzles and Alloy 52/152 attachment welds) are now in service

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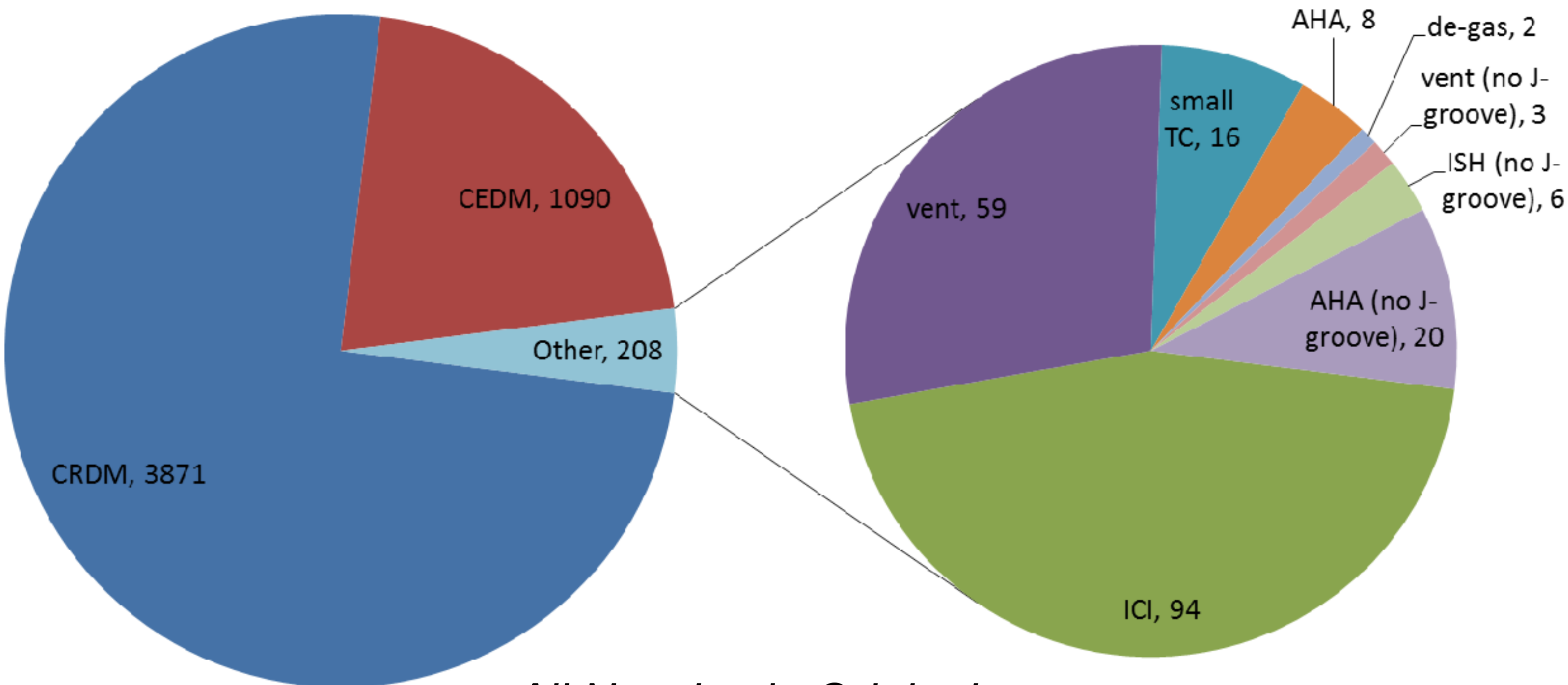
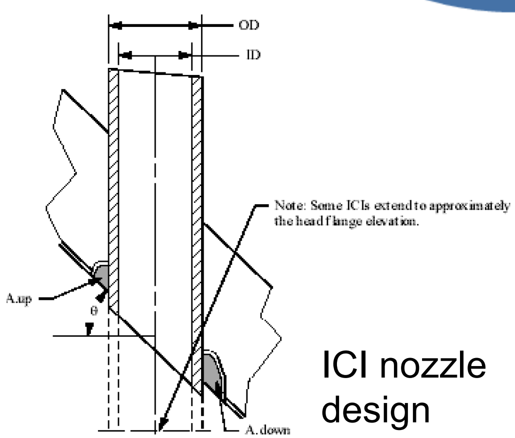
Introduction

Penetration Nozzle Types in Original Heads (per MRP-48)

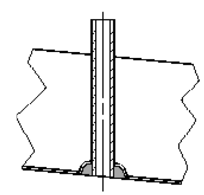


All Nozzles in Original Heads included Alloy 600

Key:
CRDM – control rod drive mechanism nozzles
CEDM – control element drive mechanism nozzles
ICI – in-core instrument (ICI) nozzles
small TC – small-bore thermocouple nozzles
AHA – auxiliary head adapters nozzles
ISH – internals support housing nozzles



ICI nozzle design



J-groove vent nozzle design

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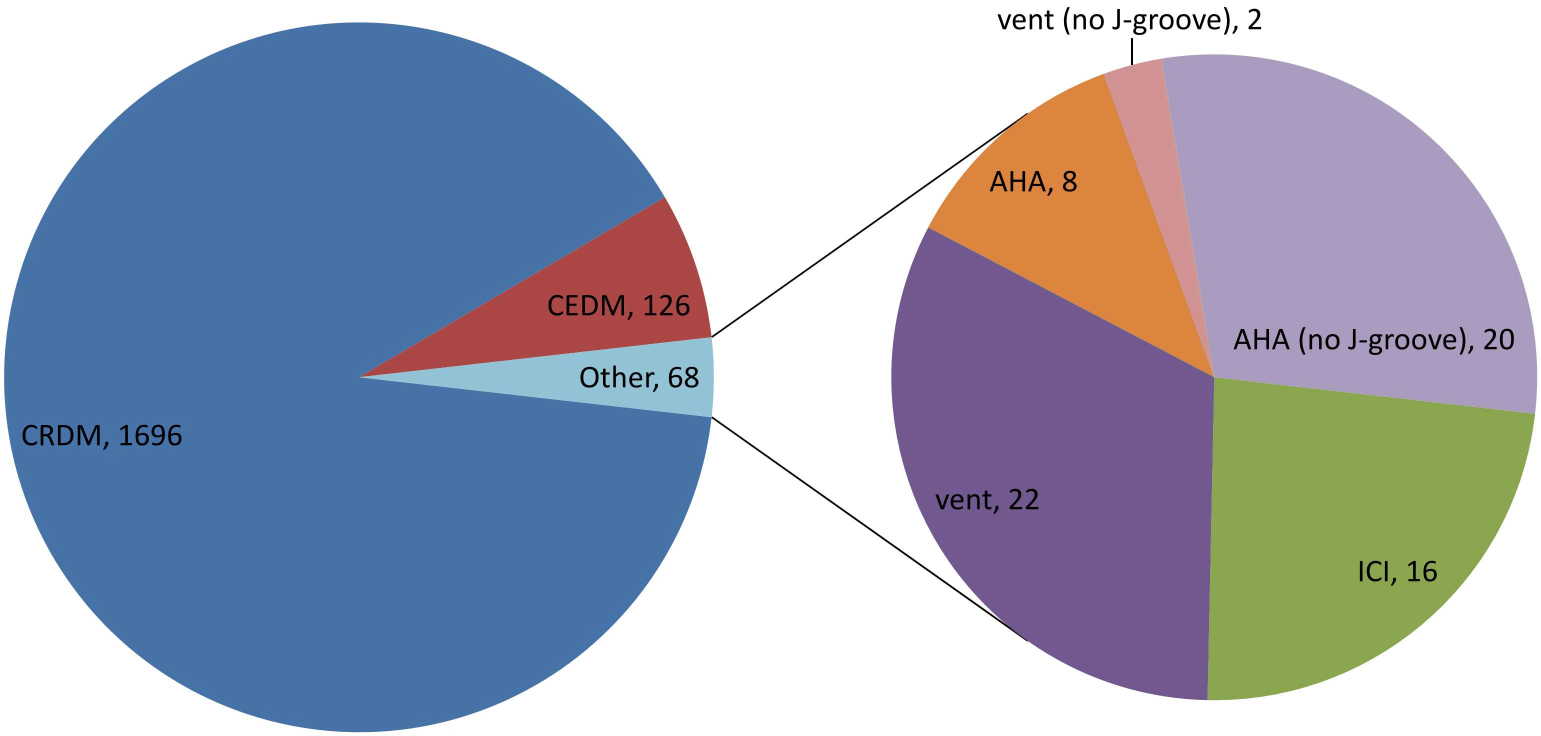
Introduction

Nozzle Types in Heads Still in Service with Alloy 600 Nozzles



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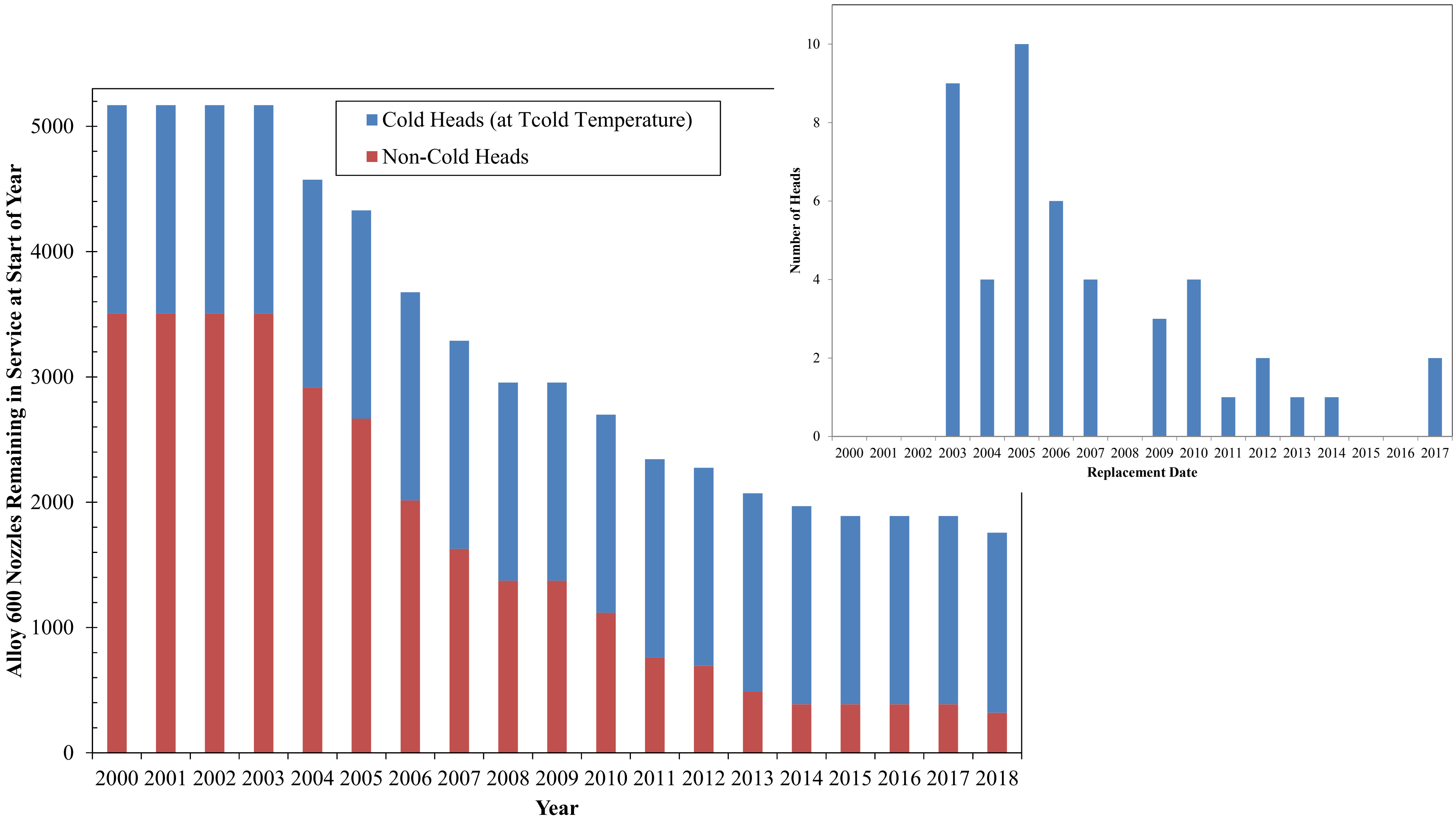
Introduction

U.S. Fleet Status – Number of Nozzles In-Service



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Original Technical Basis for ASME Code Case N-729-1

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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 Reinspection 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

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Technical Basis for N-729-1

Introduction – Technical Basis Documents and Public Meetings

- The original technical basis for ASME Code Case N-729-1 was developed by EPRI MRP in 2001-04:
  - MRP-117: Technical Basis Summary
  - MRP-110: Top Level Safety Assessment Report
  - MRP-105: Probabilistic Assessments
  - MRP-95R1: Basis for Volumetric or Surface Inspection Coverage
  - MRP-103 and MRP-104: Supporting Safety Assessments
  - MRP-48: Tabulations of Head-Specific Info
  - MRP-55 and MRP-115: PWSCC Crack Growth Rate Studies
  - EPRI 1007842: Visual examinations for leakage
  - MRP-89: Demonstrations of vendor equipment and procedures for NDE
- The technical basis was discussed at a series of NRC public meetings:
  - June 12, 2003
  - March 2, 2004
  - April 14, 2004
  - September 8, 2004

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Technical Basis for N-729-1

MRP-110 Table of Contents

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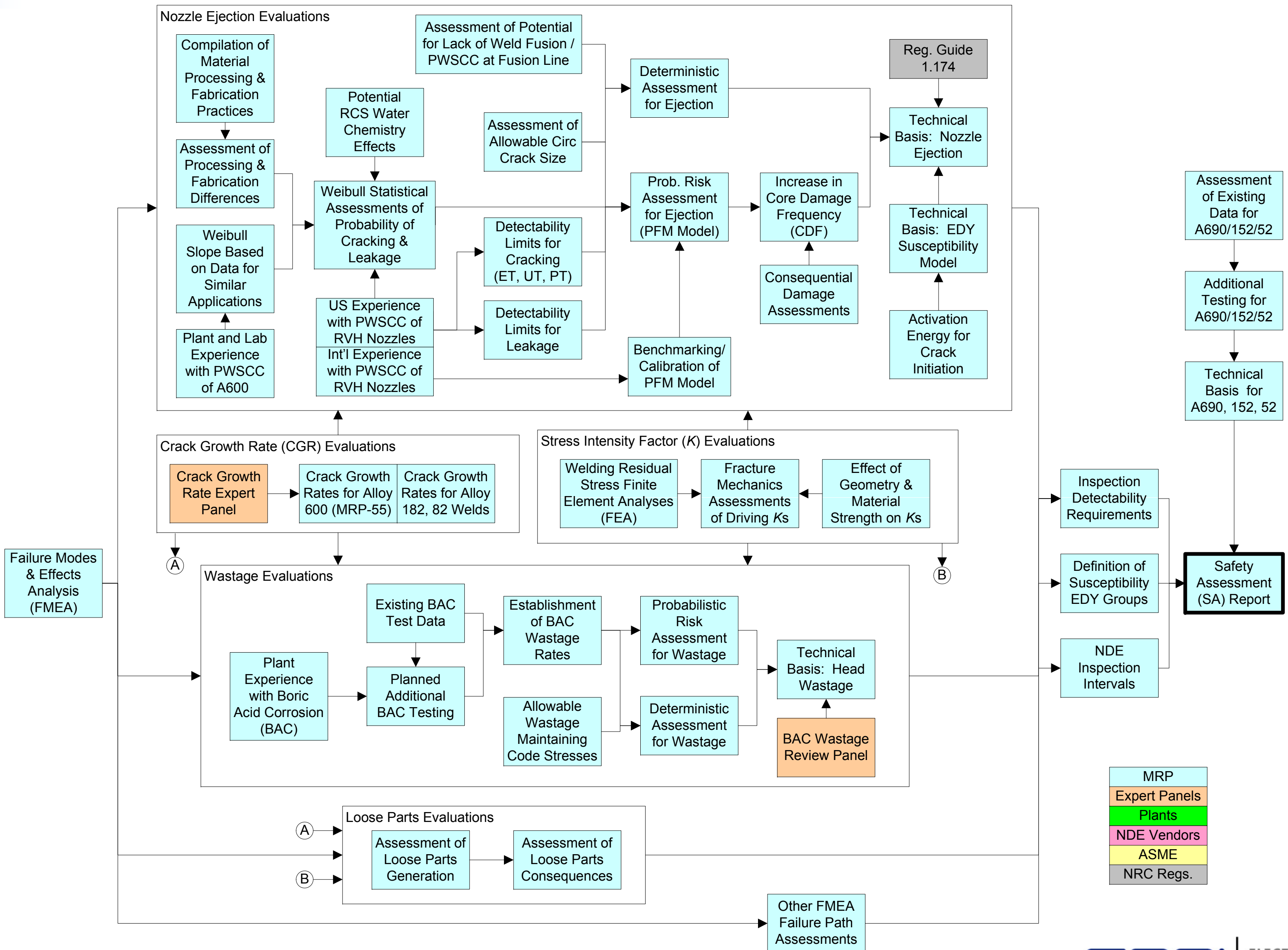
Technical Basis for N-729-1

2001-04 Safety Assessment Process



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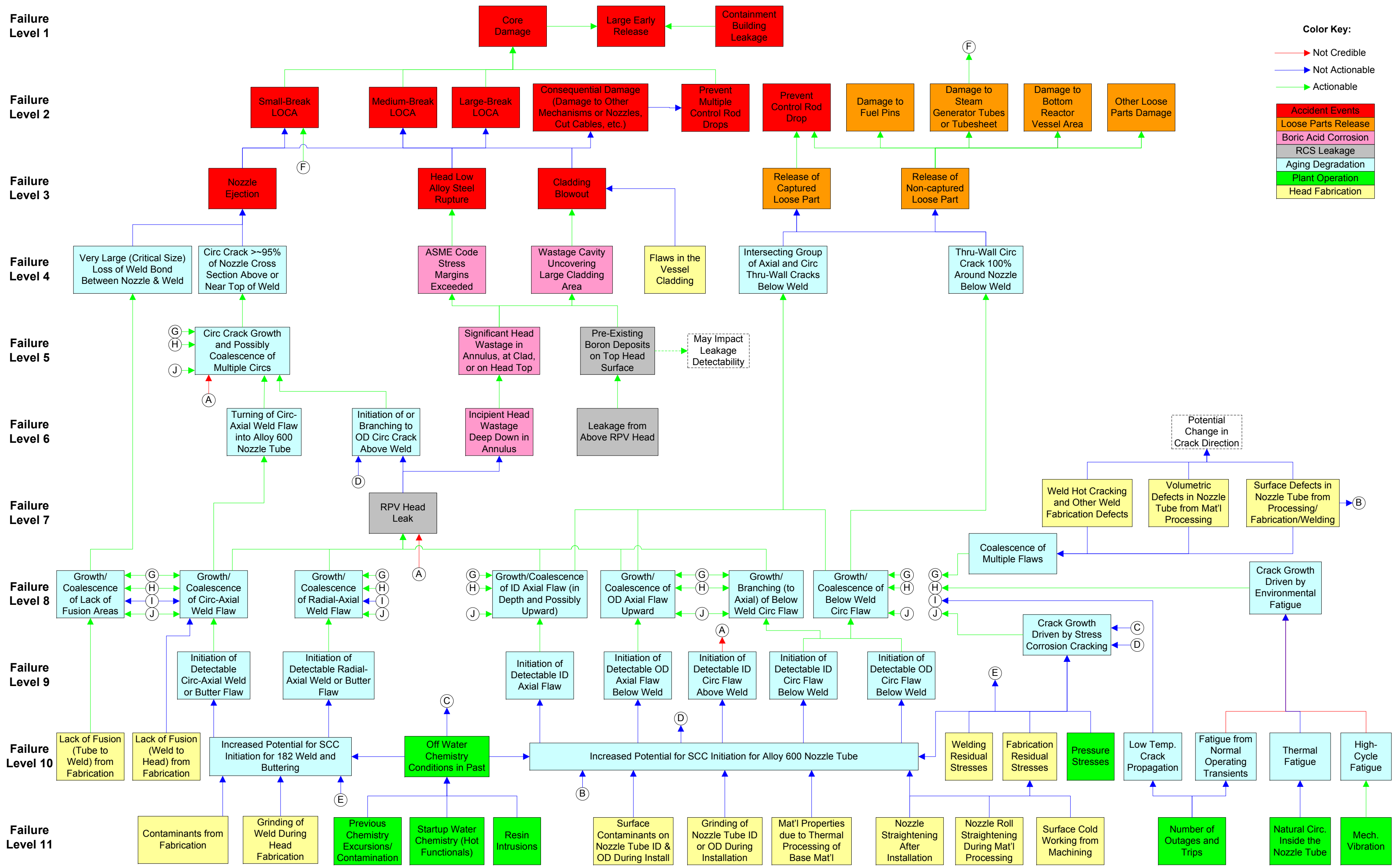
Technical Basis for N-729-1

MRP-110 FMEA Failure Path Flow Chart



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Technical Basis for N-729-1

FMEA Conclusions

- The FMEA results:
  - confirm that nozzle ejection and head wastage are the two major potential safety concerns
  - help define the inspection capabilities that are needed to detect degradation in a timely fashion
- The generation of loose parts is a potential third concern that helps to set the required inspection area for periodic non-visual inspections
- The FMEA results were used in combination with the overall safety assessment results to set appropriate inspection requirements to maintain substantial margin against safety-significant failures

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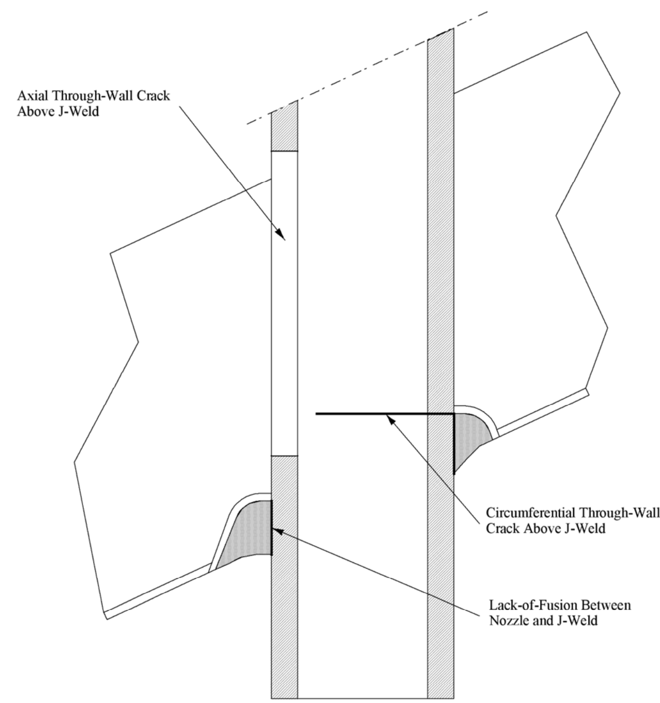
Technical Basis for N-729-1

Flaw Tolerance

- Top heads and their nozzles are highly flaw tolerant
  - Critical axial crack length is much greater than the height of the nozzle region subject to welding residual stresses
  - Critical length of through-wall circ flaw in tube is a large fraction of the circumference
  - FEA calculations show that ASME Code primary membrane and membrane plus bending stress requirements are still met assuming a substantial volume of low-alloy steel head material is lost



Typical Results for CRDM Nozzle

	2500 psi	6750 psi
Axial through-wall flaw in nozzle above J-weld	14.3 inches	5.3 inches
Circ. through-wall flaw above J-weld	330°	284°
Lack of fusion between nozzle and weld	327°	271°

Table 3-1 of MRP-110:
Critical Flaw Angles for Through-Wall Circ Nozzle Flaws

Nozzle Type	Nozzle Geometry	*OD* (in)	Flaw Angle θ for P_{flow} = 2500 psi (deg)	Flaw Angle θ for P_{flow} = 6750 psi (deg)	Limiting Nozzle of Type
CRDM	Westinghouse CRDM	4.000	330	285	
			329	281	
	B&W CRDM	4.002	328	281	✓
CEDM	CE CEDM Type 1a	4.050	331	288	
	CE CEDM Type 1b	4.050	331	288	
	CE CEDM Type 2	3.850	323	268	
	CE CEDM Type 3/4	3.495	318	254	✓
	CE CEDM Type 5	4.275	334	293	
ICI	CE ICI Type 1	5.563	293	195	✓
	CE ICI Type 2	4.500	309	232	
	CE ICI Type 3	6.625	313	244	

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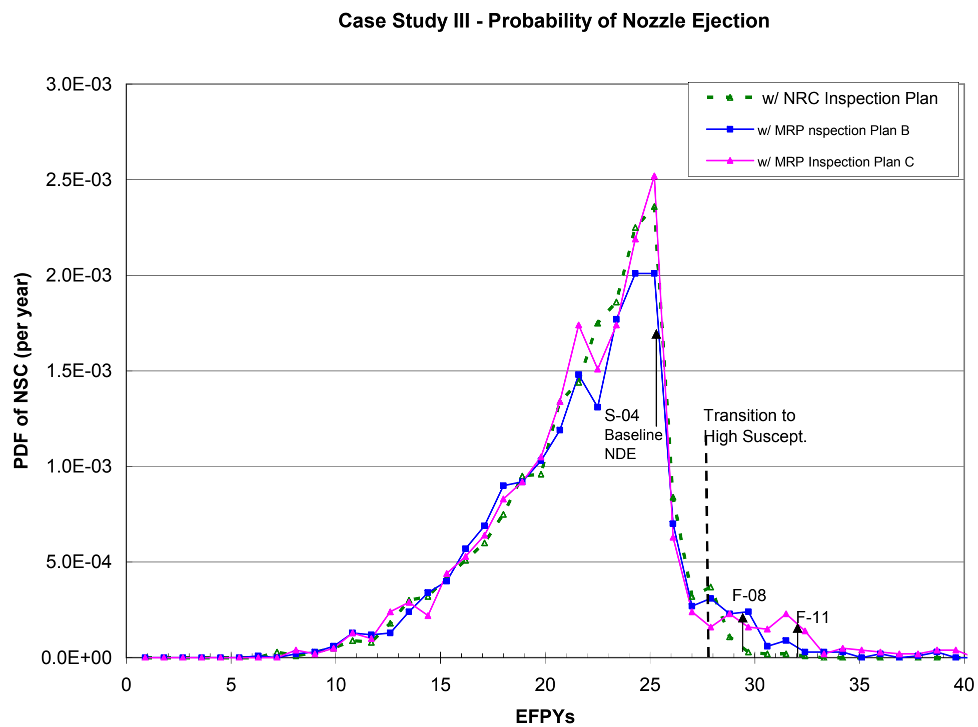
Technical Basis for N-729-1

MRP-105 Probabilistic Analyses

- Acceptable change in core damage frequency (ΔCDF) demonstrated via Probabilistic Fracture Mechanics (PFM) model of penetration cracking
  - Benchmarked to known cracks and leaks
  - Conservative assumptions
  - Includes probability of leak and nozzle ejection versus time
  - Effect of volumetric and surface inspections included in model
  - Deterministic analyses confirm frequencies are conservative



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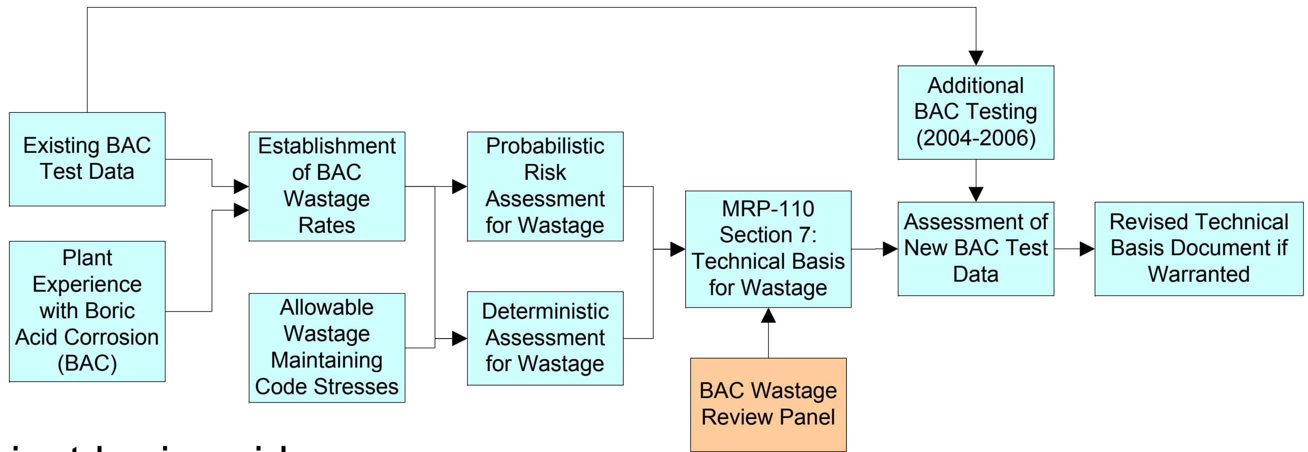
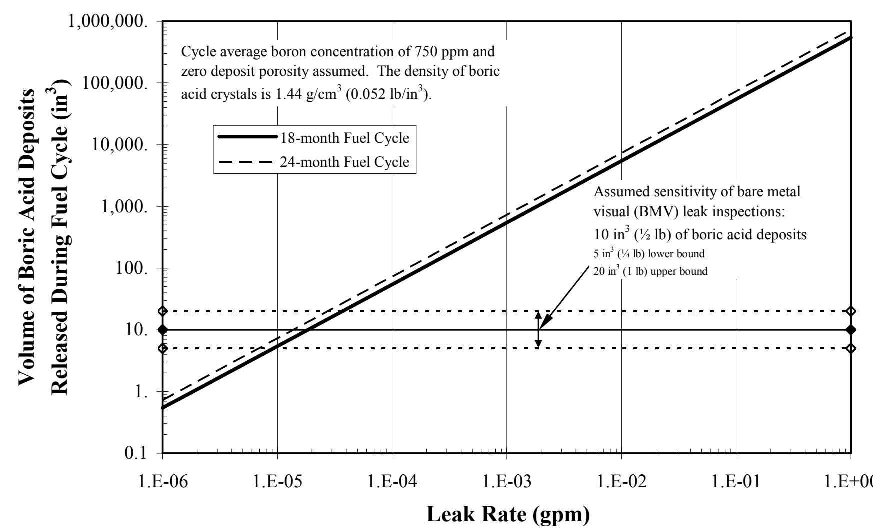
Technical Basis for N-729-1

Boric Acid Corrosion Assessments

2002-04 Process to Develop Wastage Technical Basis, including additional BAC testing planned at that time



- Adequate protection against boric acid corrosion/wastage is provided by visual exams performed at appropriate intervals for evidence of leakage
- Evaluation was supported by:
  - Experience with over 50 leaking CRDM nozzles, including that associated with the large corrosion cavity detected in 2002 at one PWR
  - BAC lab testing and analyses showing key role of leak rate and large volumes of boron deposits that are produced for the substantial leak rates necessary for extensive local cooling



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Technical Basis for N-729-1

MRP-95R1 Basis for Volumetric or Surface Exam Coverage

- Exam Volume selected based on 20 ksi tension stress limit
- Fracture Mechanics analyses demonstrate that postulated flaws outside of and just impinging on Exam Volume will not grow unacceptably in time period until next inspection
- Review of prior inspection data, encompassing 237 detected flaws, indicates that all would have been detected if inspections had been performed over just the Exam Volume

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Technical Basis for N-729-1

MRP-117 – Inspection Methodology Bases

- The inspection regime provides protection against:
  - Pressure boundary leakage
  - Circumferential nozzle cracking and nozzle ejection
  - Generation of loose parts
  - Significant boric acid wastage of the low alloy steel head

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Technical Basis for N-729-1

MRP-110 Top Level Safety Assessment – Conclusions

- Axial nozzle cracking is not a credible mechanism leading to nozzle rupture
- Significant margin against nozzle ejection due to circumferential cracking in nozzle tube
- Periodic bare metal visual examinations provide assurance against significant wastage of the low-alloy steel head material
- Set of safety assessment documents demonstrates that:
  - program of periodic non-visual NDE inspections at appropriate intervals supplemented by periodic bare metal visual examinations provides adequate protection against potential safety-significant failures resulting from aging degradation mechanisms
- PFM Analysis (MRP-105) shows a low probability of pressure boundary leakage resulting from the appropriate program of periodic inspections
- MRP-117 and N-729-1 define the appropriate inspection intervals, coverage, and characteristics

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Technical Basis for N-729-1

Follow-up Activities After 2004

- Examination of CRDM penetrations from retired North Anna 2 head
- Boric acid corrosion testing program
- Evaluate mitigation options
  - Zinc addition
  - Peening
- Ongoing assessment of inspection results

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Technical Basis for N-729-1

NRC Conditions on N-729-1

- N-729-1 is incorporated by reference in 50.55a(g)(6)(ii)(D)(*1*)
- N-729-1 is conditioned by 50.55a(g)(6)(ii)(D)(*2*) through (*6*), summarized as follows:
  - (*2*) Note 9 (extension to RIY = 3 if surface exams are performed) shall not be implemented
  - (*3*) The licensee shall perform volumetric and/or surface examination of essentially 100 percent of the required volume or equivalent surfaces of the nozzle tube, as identified by Figure 2
  - (*4*) The ultrasonic examinations shall be performed using personnel, procedures and equipment that have been qualified by blind demonstration on representative mockups
  - (*5*) If flaws attributed to PWSCC have been identified, the volumetric or surface re-inspection interval must be each refueling outage
  - (*6*) Appendix I of ASME Code Case N-729-1 shall not be implemented without prior NRC approval

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Updated Technical Basis (MRP-395)

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Introduction

Scope of MRP-395

- All Alloy 600 top head J-groove nozzles in U.S. PWRs
  - Same scope as for ASME Code Case N-729-1

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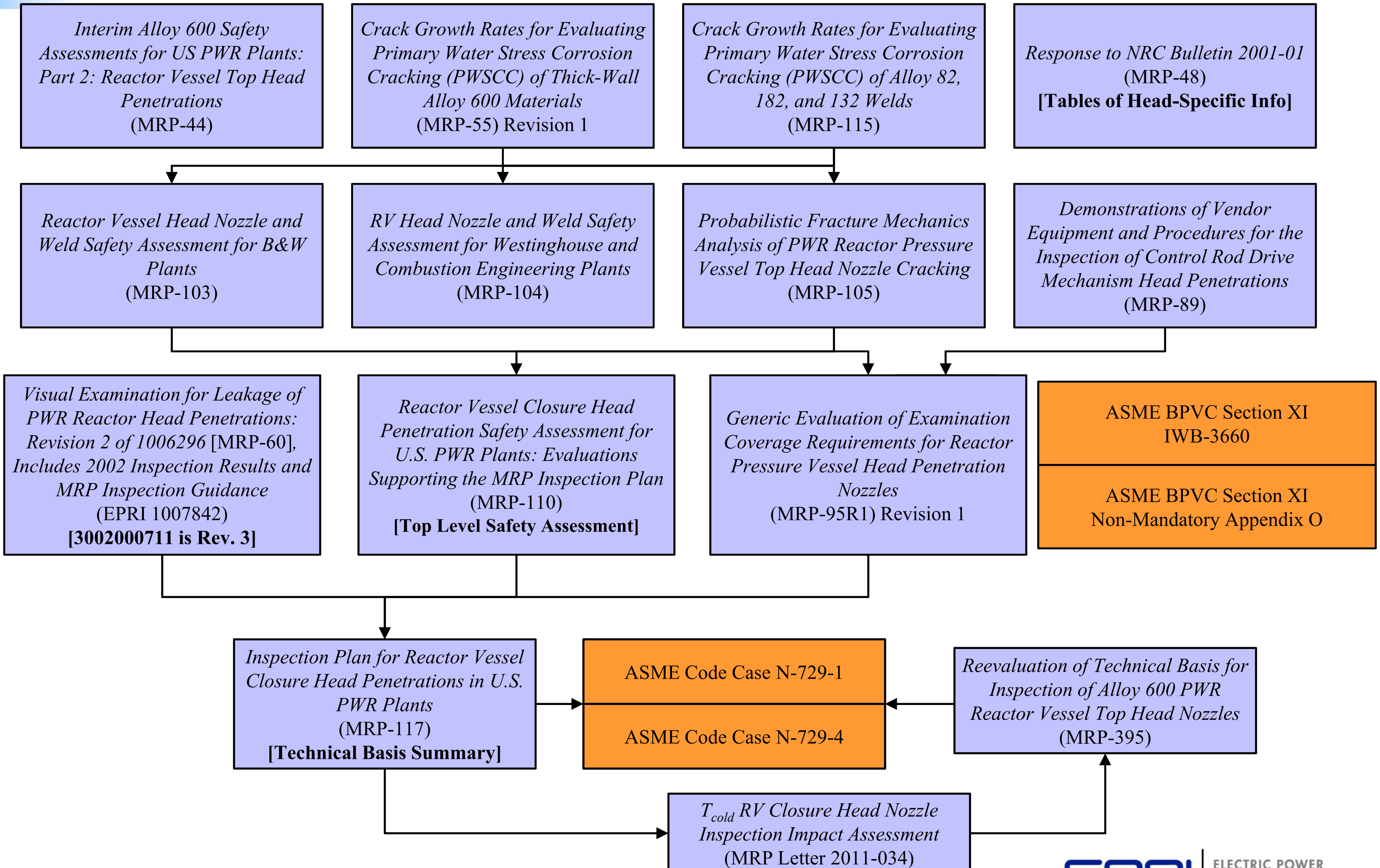
Introduction

Relevant Documents



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Updated Technical Basis (MRP-395): Assessment of Plant Experience

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Inspection Results Summary

Timeline of PWSCC in Alloy 600 Head Nozzles at T_{cold}

- PWSCC indications have been detected in five U.S. cold heads:
  - 2007 in one CRDM nozzle and 2014 in one CRDM nozzle
    - 2007 indication associated with lack-of-fusion defects
  - 2011 in four CRDM nozzles
    - Included some base metal flaws not connected to the weld
  - 2012 in four CRDM nozzles and 2014 in three CRDM nozzles (two others repaired in 2014 for indications that did not appear to be growing)
  - 2012 in one CRDM nozzle
  - 2012 in five CRDM nozzles and 2013 in one CRDM nozzle
- This apparent PWSCC degradation was detected in its relatively early stages
  - with modest numbers of nozzles affected by part-depth cracking
  - often located below the weld, where the nozzle tube is inside (not directly a part of) the pressure boundary
- All PWSCC indications in cold heads have been in heads with nozzles fabricated from Alloy 600 material produced by one supplier
- No indications of PWSCC detected in the 14 inspected cold heads with other categories of nozzle material
  - 12 of 14 have now had at least two volumetric or surface exams (+1 other replaced)

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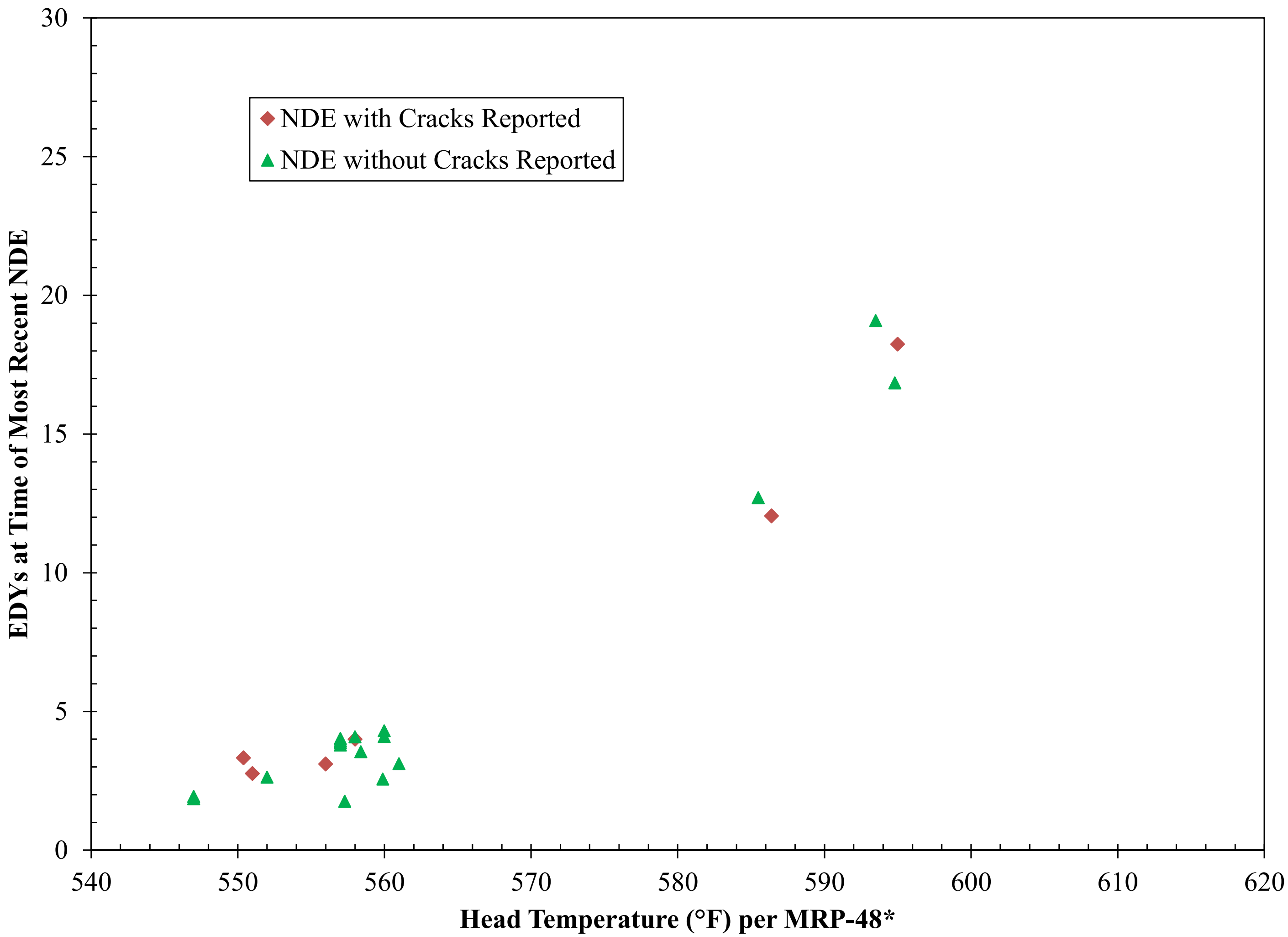
Updated Assessment of Plant Experience

Effect of Time at Temperature – NDE Results for 24 Heads with Alloy 600 Nozzles Still in Service



* Head temperatures for B&W designed plants assumed to be 8°F higher than T_{hot}

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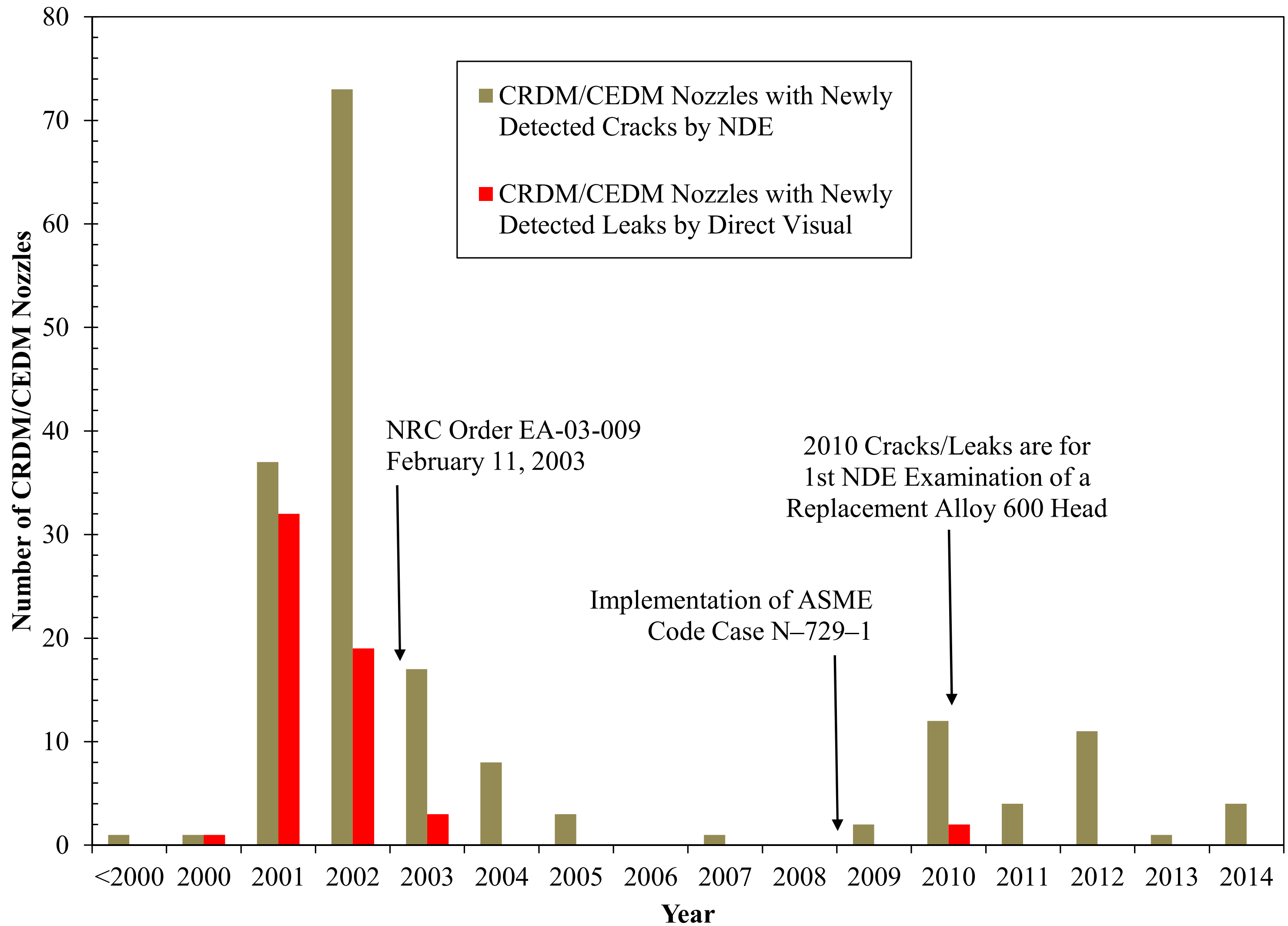
Updated Assessment of Plant Experience

U.S. Fleet Status – PWSCC Detections in Top Head Nozzles



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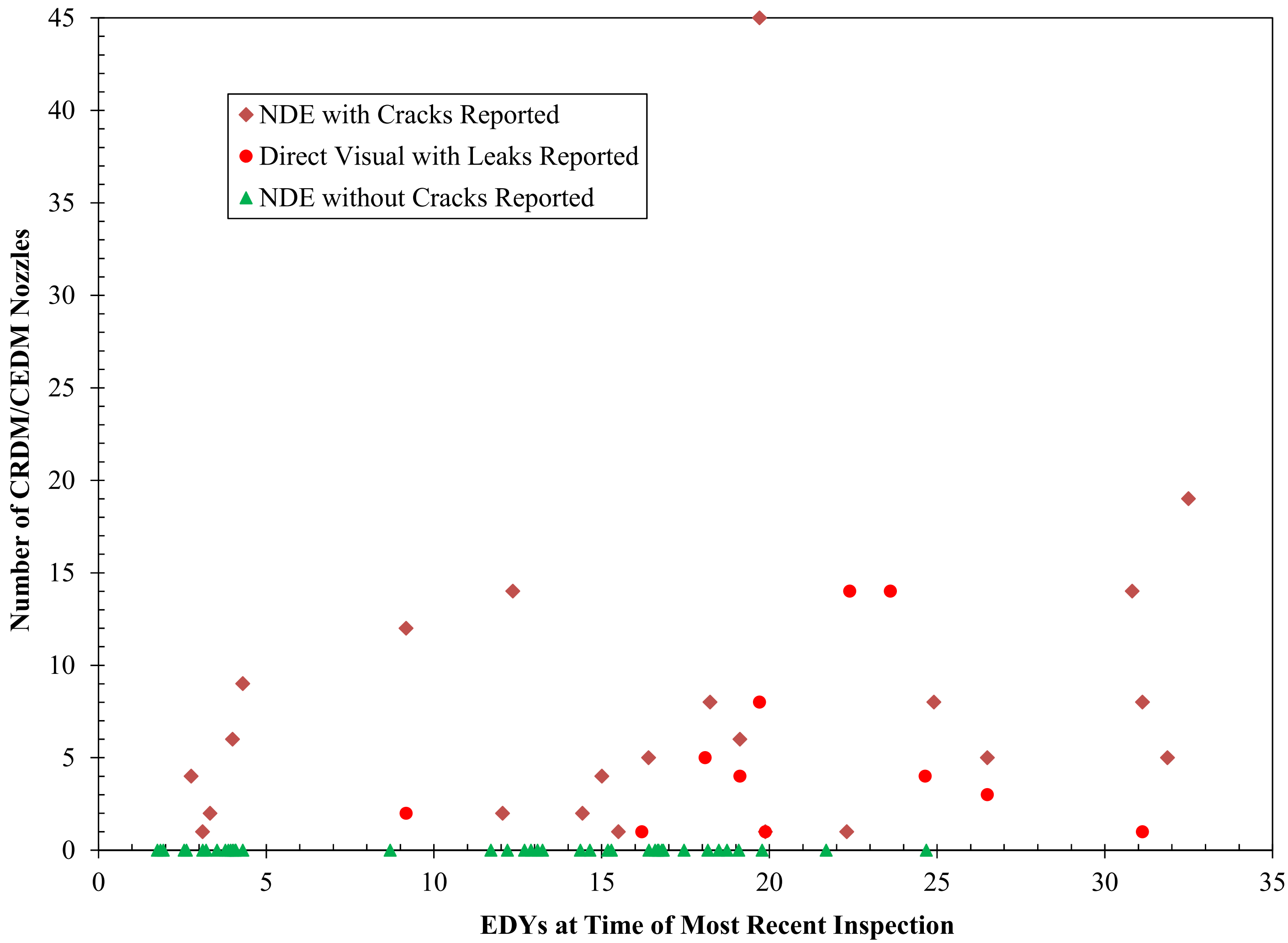
Updated Assessment of Plant Experience

Effect of Time at Temperature – NDE Results for 63 Heads with Alloy 600 Nozzles



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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 visuals 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
  - 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

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Sufficiency of Current Requirements for Visual Exams of Cold Heads (1/3)

- Experience has shown that PWSCC flaws located in the weld metal often extend into the base metal, and are thus detectable via UT from the nozzle ID
- Most of the industry experience with PWSCC flaws has been those that initiated on the OD of the tube material, primarily at the interface with the J-groove-weld
  - These areas can be effectively examined ultrasonically
- There have been no cases of weld flaws growing to the annulus and causing leakage after a UT examination has been performed of 100% of the CRDM/CEDM nozzles in a head
  - Most susceptible heads operating at the highest temperatures have been replaced
  - Nonetheless there have been no cases of detected leakage after UT has been first applied to all CRDM/CEDM nozzles in a head

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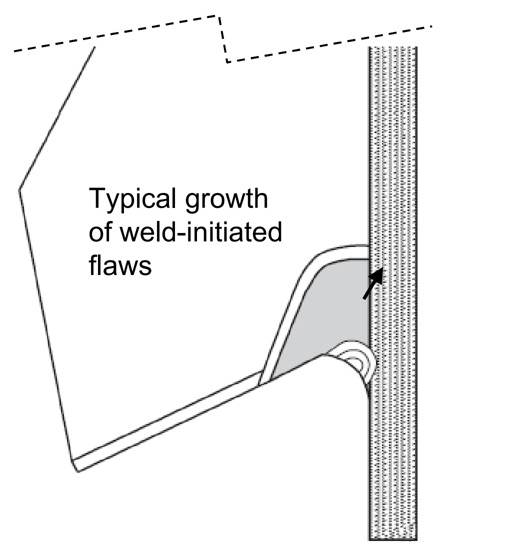
Sufficiency of Current Requirements for Visual Exams of Cold Heads (2/3)

- There is no direct safety significance of flaws located exclusively in the weld metal:
  - J-groove welds are large welds with significant structural margin. Nozzle ejection due to a flaw located exclusively in the J-groove-weld is not credible
  - The leak rate produced by a flaw exclusively located in the weld metal is likely to be much smaller than that which could result in significant boric acid corrosion of the low-alloy steel material
- For a weld flaw to lead to the possibility of a safety-significant circumferential flaw in the nozzle tube (i.e., a large circumferential flaw located in the nozzle tube that could lead to nozzle ejection if it were to grow to encompass a large fraction of the wall cross section) would very likely require that leakage be produced that is detectable during visual examinations of the upper head surface



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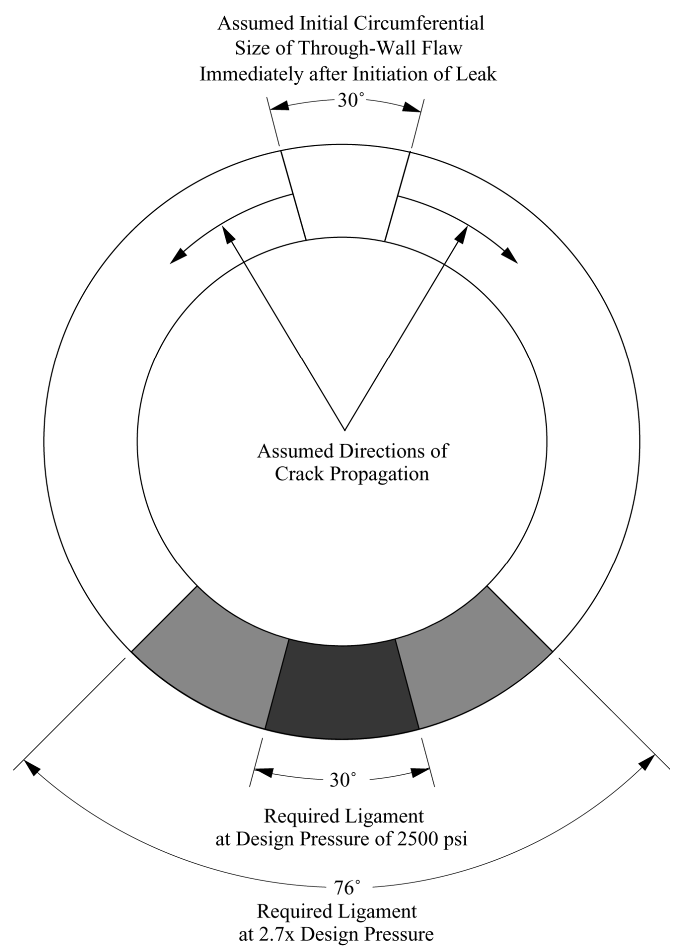
Sufficiency of Current Requirements for Visual Exams of Cold Heads (3/3)

- Evidence of leakage detectable by visual examination was present in all 7 cases of circumferential cracking in the CRDM nozzle tube above the top of the weld (all predating N-729; see Section 4 of MRP-110)
- The detailed probabilistic calculations of MRP-395 explicitly model the possibility of a pre-existing weld flaw ultimately leading to nozzle ejection
- The modeling work demonstrates an acceptably small effect on nuclear safety
  – The probabilistic modeling maintains the key conservatism of the original MRP-105 probabilistic technical basis that a weld flaw reaching the nozzle annulus is assumed to immediately produce a 30° through-wall circumferential flaw in the nozzle tube



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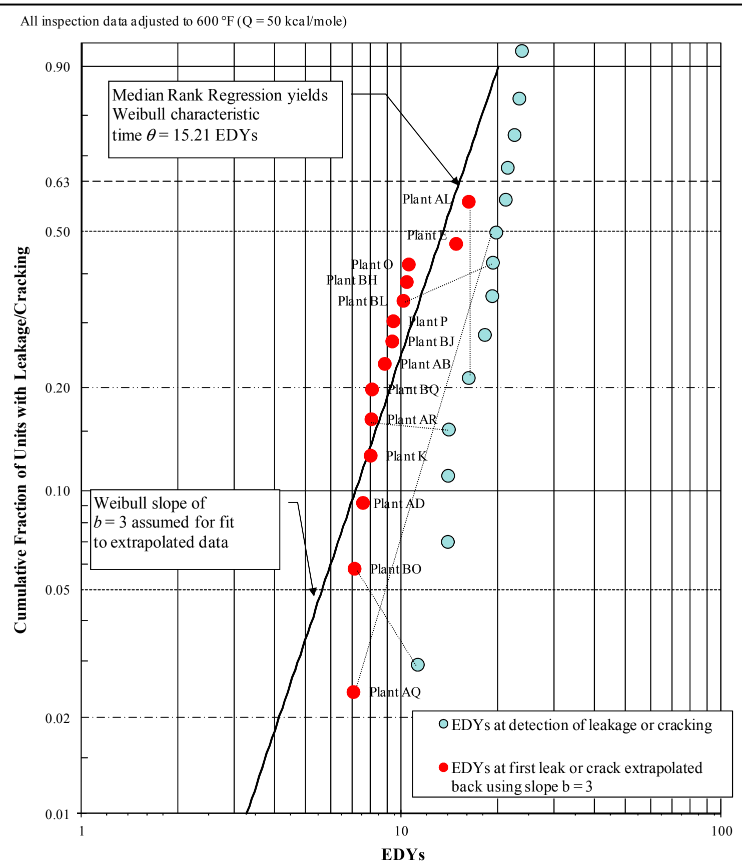
Industry Weibull Fit

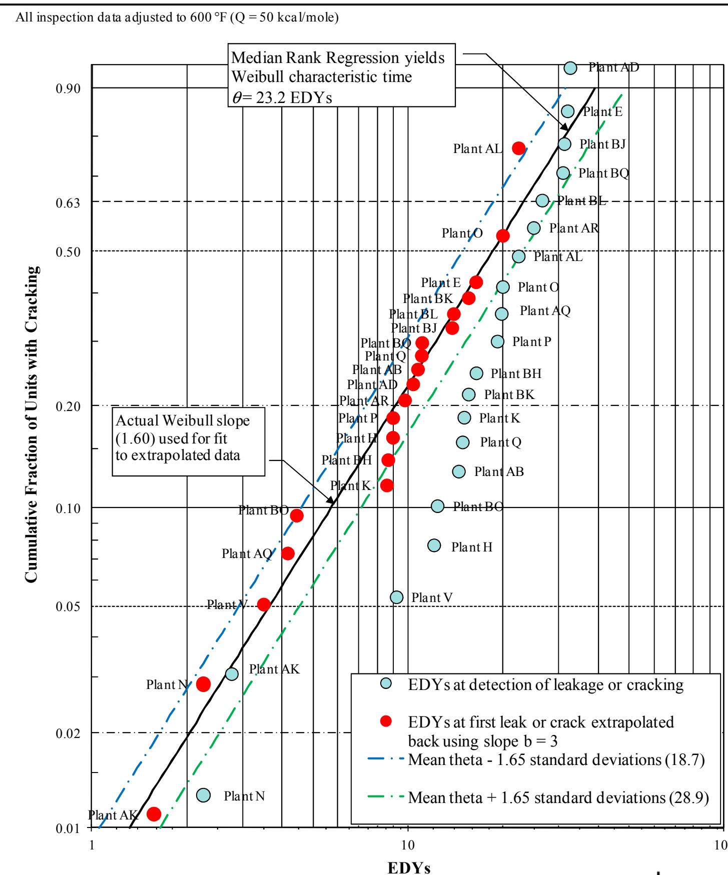
Time to First PWSCC Initiation on Alloy 600 Top Heads

- Based on two-parameter Weibull model fit to plant detection data
  - Multiple indications on a top head are resolved by back-extrapolating time of first initiation assuming a Weibull slope of 3

Weibull model fit to U.S. plant data in **2003** for top head detections



Weibull model fit to U.S. plant data in **2011** for top head detections



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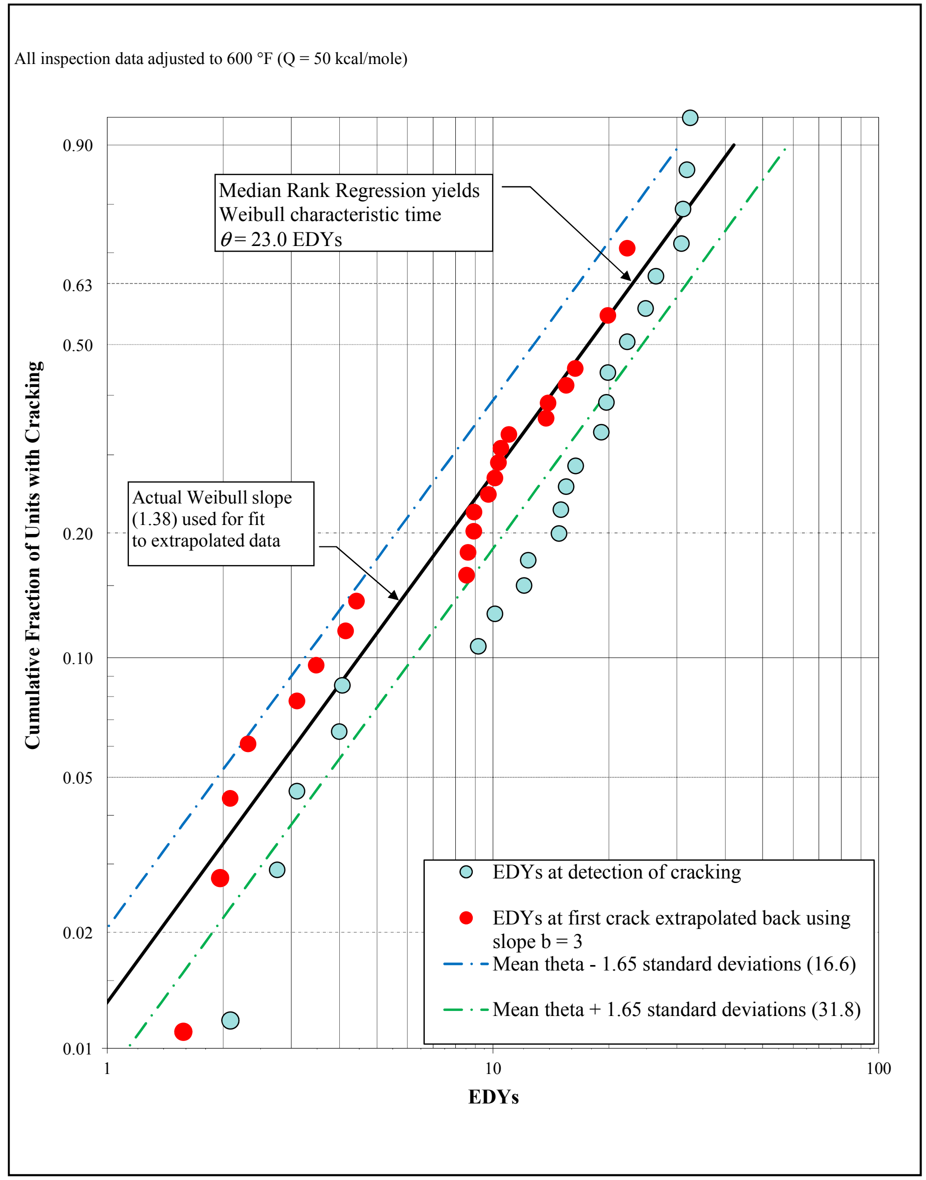
Industry Weibull Fit

Updated to Latest Alloy 600 Top Head PWSCC Experience

- Considers additional PWSCC reported at three cold heads up to 2013:
  - 6 nozzles at one cold head (5 in 2012, 1 in 2013)
  - 4 nozzles at one cold head (2012)
  - 1 nozzle at one cold head (2012)
  - 2014 experience subsequent to MRP-395 calcs was for additional nozzles in already affected heads
- Similar to fit in 2011
  - Slightly reduced Weibull slope (1.38 vs. 1.60)
  - Slight increase in probability of cracking for small EDY values (applicable to cold heads)



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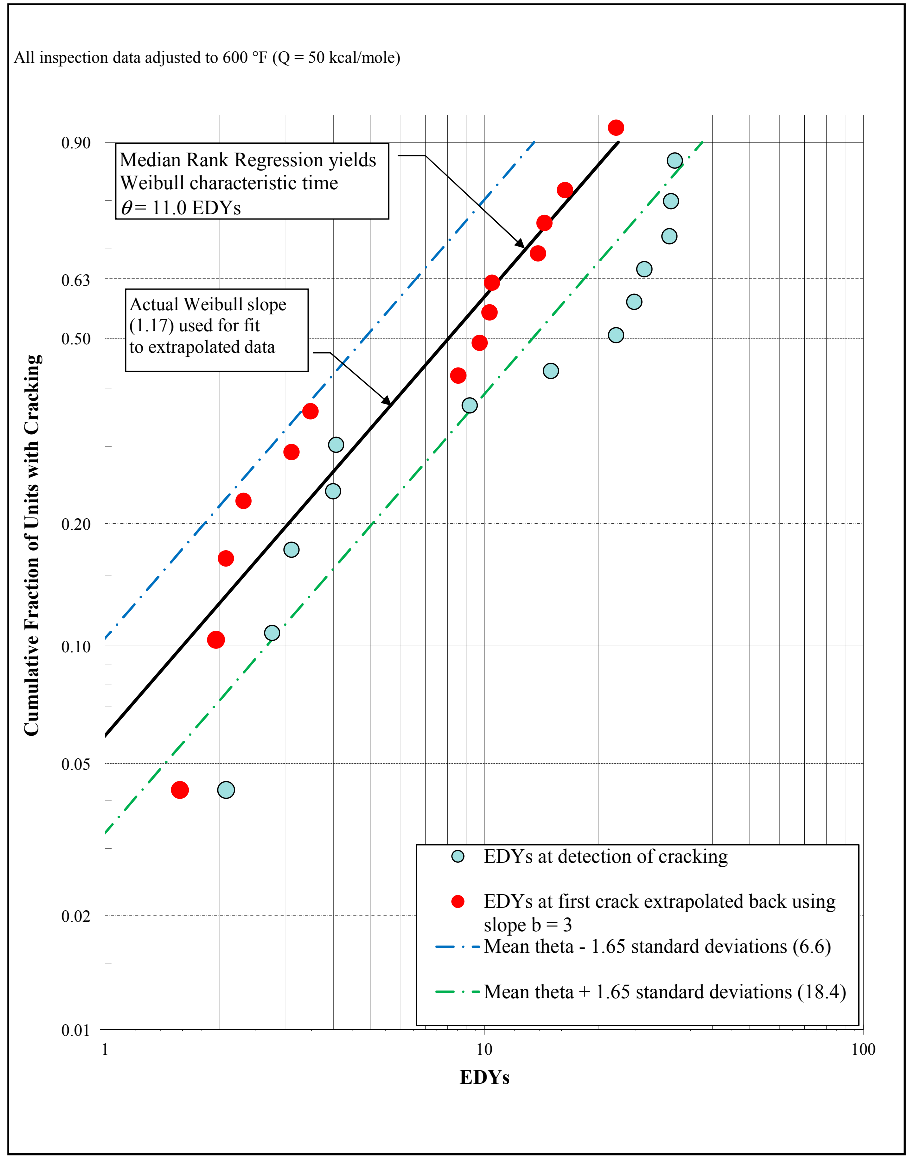
Industry Weibull Fit

Top Head Alloy 600 PWSCC Experience for B&WTP Material

- Considers cracking experience at 16 top heads with B&WTP material, reported up to 2013
  - 6 of these top heads still operating (all at Tcold)
- More aggressive than fit to all material suppliers
  - Reduced time it takes to have half of heads affected (from 18 to 8 EDY)
  - Reflects an increase in probability of cracking, particularly at small EDY values (applicable to cold heads)



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Updated Assessment of Plant Experience

Implied Crack Growth Rates – Cold Heads

- Flaw indication data from the following experience were assessed for their consistency with the crack growth rate assumptions of the probabilistic analyses:
  - 2011 Cold Head Experience
  - 1st 2012 Cold Head Experience
  - 2nd 2012 Cold Head Experience
  - 2013 Cold Head Experience
  - 2014 Cold Head Experience
  - 1994-96 Non-Cold Head Experience
  - 2005 Non-Cold Head Experience
  - 2009 Non-Cold Head Experience
  - 2010 Non-Cold Head Experience
- The results are consistent with the crack growth rate assumptions of the probabilistic analyses, with crack growth rate material variability percentiles less than 95%

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Updated Assessment of Plant 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}
- Fitting a Weibull model specific to experience with B&W Tubular Products material results in a more aggressive initiation model
- Plant experience including the recent experience with part-depth PWSCC in a limited number of CRDM nozzles operating at T_{cold} validates the conclusions of the original N-729-1 technical basis

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Updated Assessment of Plant Experience

Conclusions (cont'd)

- 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
  - One nozzle with a PWSCC indication in 2014 was detected at a T_{cold} plant volumetrically inspecting every other outage
    - Indication was about 35% through-wall at time of repair
    - Indication was axial, at the weld toe, and almost an inch below the nozzle annulus
    - Demonstrates the effectiveness of such an inspection frequency

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Updated Technical Basis (MRP-395): Deterministic Analyses

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Deterministic Modeling

Approach

- Crack growth calculations modeled using 75th percentile growth models from MRP-55R1 and MRP-115
- Part-depth flaws modeled to start at 10% thickness (assumed detectable flaw size) and growth through-wall
- Through-wall circumferential flaws at the J-groove weld modeled to start at 30° and grow to 300°
- Results of various existing growth calculations were adjusted to 555°F, 563°F, and 605°F
  - MRP-105
  - Examination frequency relief request
  - Technical basis for CRDM nozzle inspection interval
  - Calculations performed for this report

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Deterministic Modeling

Results

- Time between assumed detectable flaw size (10% TW) and leakage (100% TW) for cases considered:
  - Between RIY = 2.6 and RIY = 5.3
  - Equivalent to between 8.4 and 17 EFPY at 555°F, between 6.7 and 14 EFPY at 563°F, and 2.3 and 4.7 EFPY at 605°F
- Time between evident leakage (assumed through-wall 30° circumferential flaw) and risk of net section collapse (assumed to result at 300°) for cases considered:
  - Between RIY = 8.3 and 22
  - Equivalent to between 27 and 72 EFPY at 555°F, 22 and 58 EFPY at 563°F, and 7.4 and 20 EFPY at 605°F

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Deterministic Modeling

Conclusions

- Results for part-depth flaws provide confidence that inspection intervals are sufficient to prevent leakage
- Results for circumferential flaws demonstrate large margins to preclude possibility of nozzle ejection

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Updated Technical Basis (MRP-395): Probabilistic Analyses

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Probabilistic Modeling

Approach

- Probabilistic model is essentially the same as that presented in the appendices of MRP-375 (EPRI 3002002441) and Appendix B of MRP-335 Rev. 1 (EPRI 3002000073)
  - Additional flexibility added to scheduling of first simulated inspection
- Initiation model parameter inputs are based on updated Weibull fits
  - Weibull fit to all material suppliers
  - Weibull fit to nozzle material supplied by B&WTP
  - Bounding Weibull case calibrated to “Alloy 600 replacement head” experience
- Models “cold” heads as well as “hot” heads operating near the hot-leg temperature (605°F was assumed)
- Investigate dependence of probabilistic results to various sensitivity cases
  - Inspection sensitivity cases
  - Model sensitivity cases

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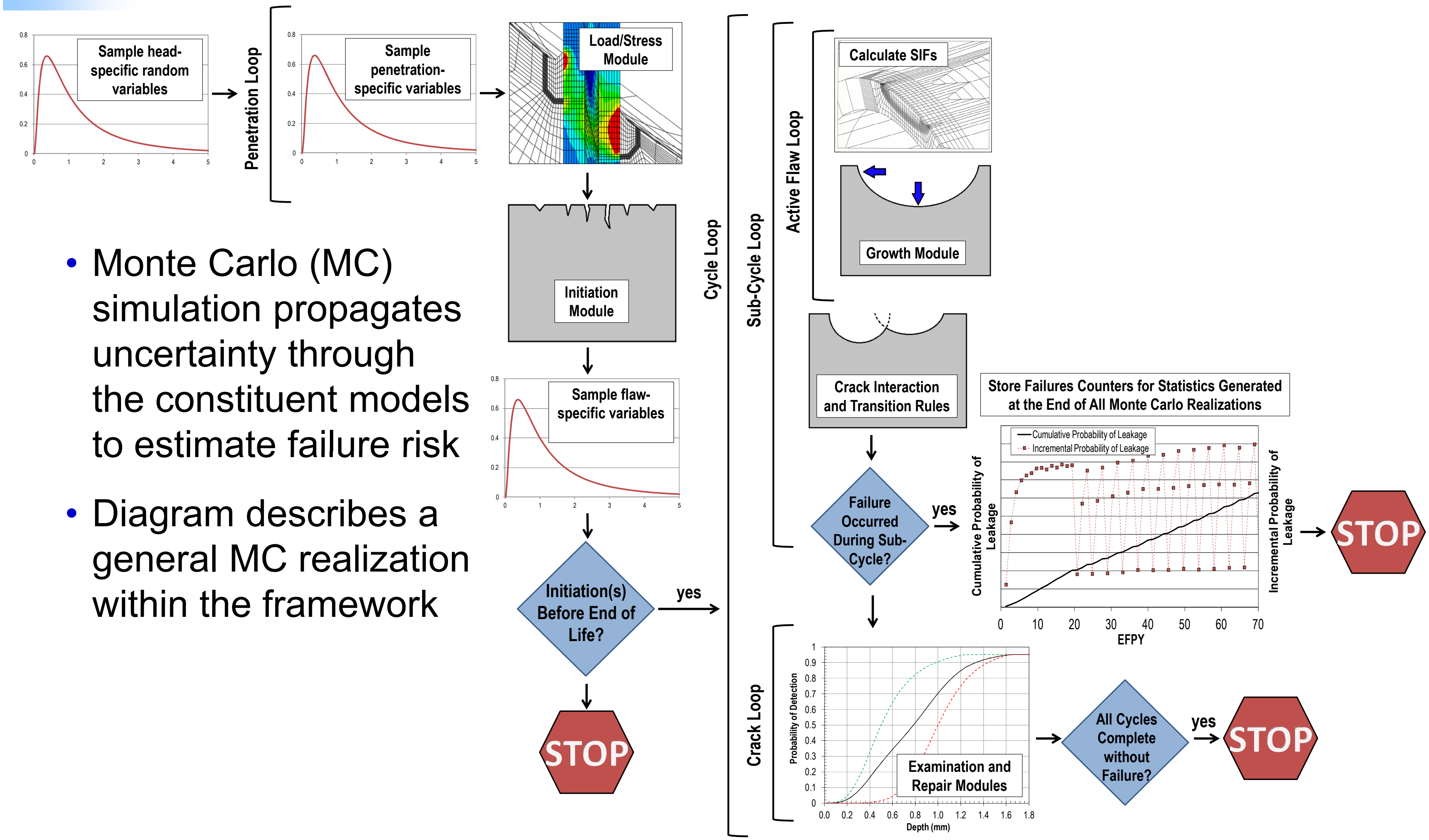
Probabilistic Approach

Description of RPVHPN Probabilistic Model

- Monte Carlo (MC) simulation propagates uncertainty through the constituent models to estimate failure risk
- Diagram describes a general MC realization within the framework



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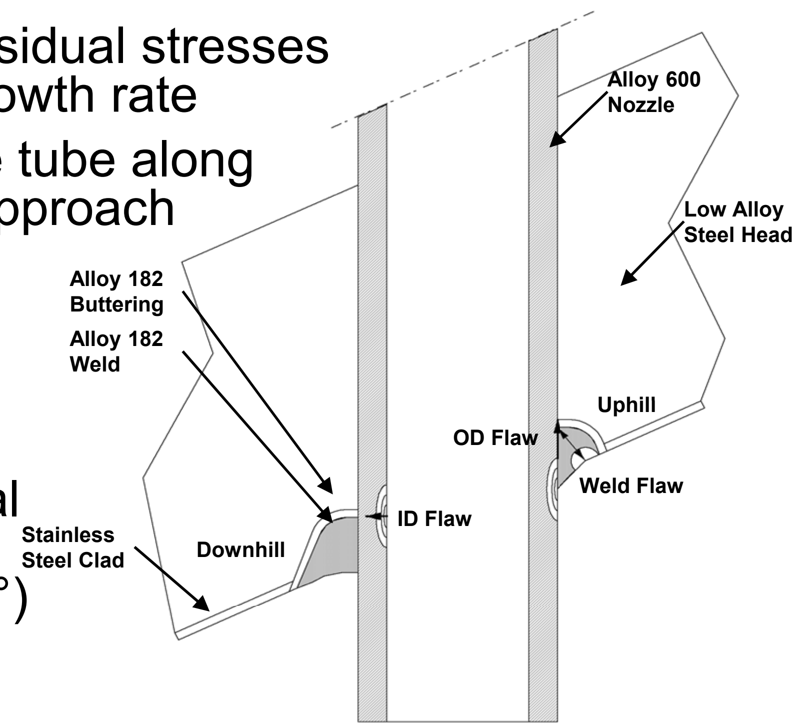
Probabilistic Approach

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 breeches the OD nozzle annulus
  - Assumed to immediately initiate a 30° 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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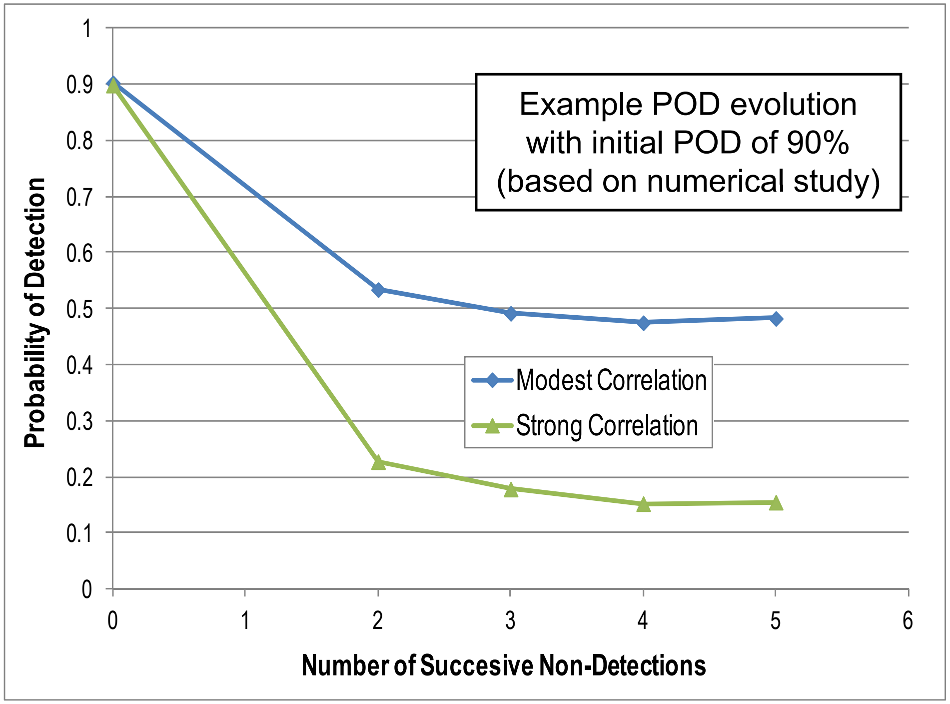
Probabilistic Approach

Non-Destructive Examination (NDE)—Correlation of Successive Exams

- Probability of flaw detection (POD) models were developed using qualification data, vendor data, standards, and plant experience
- NDE methods included in simulations:
  - Ultrasonic testing (UT) for flaws in base metal
  - Eddy current testing (ET) for flaws on wetted surfaces
  - Visual examination (VE) exam for evidence of leakage
- Correlated sampling for successive examinations simulates effect of flaw characteristics on POD



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Probabilistic Approach

Cases Evaluated

- Three temperatures studied with inspection intervals of RIY = 2.25:
  - 1 (24-month) cycle at 605°F
  - 4 (18-month) cycles at 563°F
  - 5 (18-month) cycles at 555°F
- Three inspection intervals studied:
  - One refueling cycle
  - Two refueling cycles
  - 2.25 RIY
- Three initiation Weibull models studied:
  - All material supplier Weibull
  - B&W Tubular Products Weibull
  - Weibull calibrated to the results of the "Alloy 600 replacement head" inspection
- Various sensitivity cases performed to verify robustness of conclusions to modeling and input assumptions
- Model benchmarked versus MRP-105 as a software validation and verification activity; resulted in reasonable agreement considering detailed differences in modeling methodology

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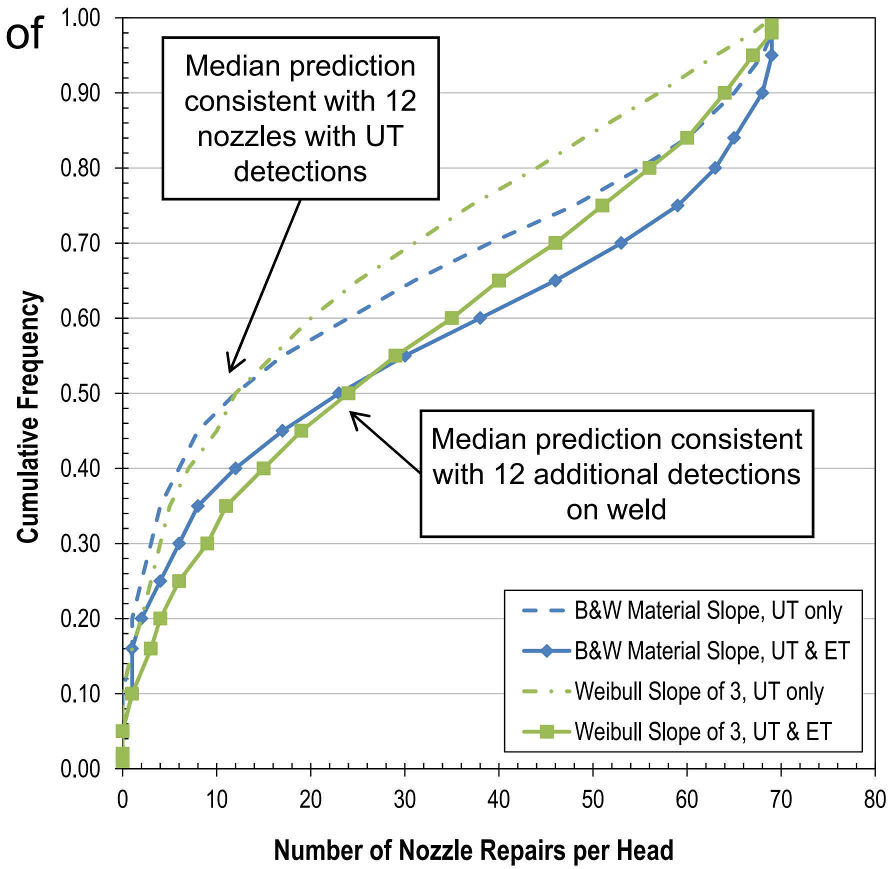
Weibull Initiation Model

Calibration to Replacement Alloy 600 Head

- Compile detection data from first inspection of an Alloy 600 replacement head, operating from 2004 to 2010
  - 12 nozzle with UT detections, 9 nozzles with ET detections on weld, and an additional 3 nozzle detections by PT on weld
- Simulate conditions of the Alloy 600 replacement head and calibrate initiation Weibull model parameters to obtain median of 12 UT detections in base metal
  - Apply best-estimate temperature and actual number of nozzles
  - Simulate UT and ET examination after 6 years of simulated operation
  - Apply uncertainty in Weibull initiation model derived from data for B&WTP material
- Use calibrated initiation parameters in main probabilistic assessment cases to ensure that results cover all operating heads



Initiation model calibrated for two Weibull slopes

- Standard slope assumption (b = 3)
- Best-fit Weibull slope to B&WTP data (b = 1.17)

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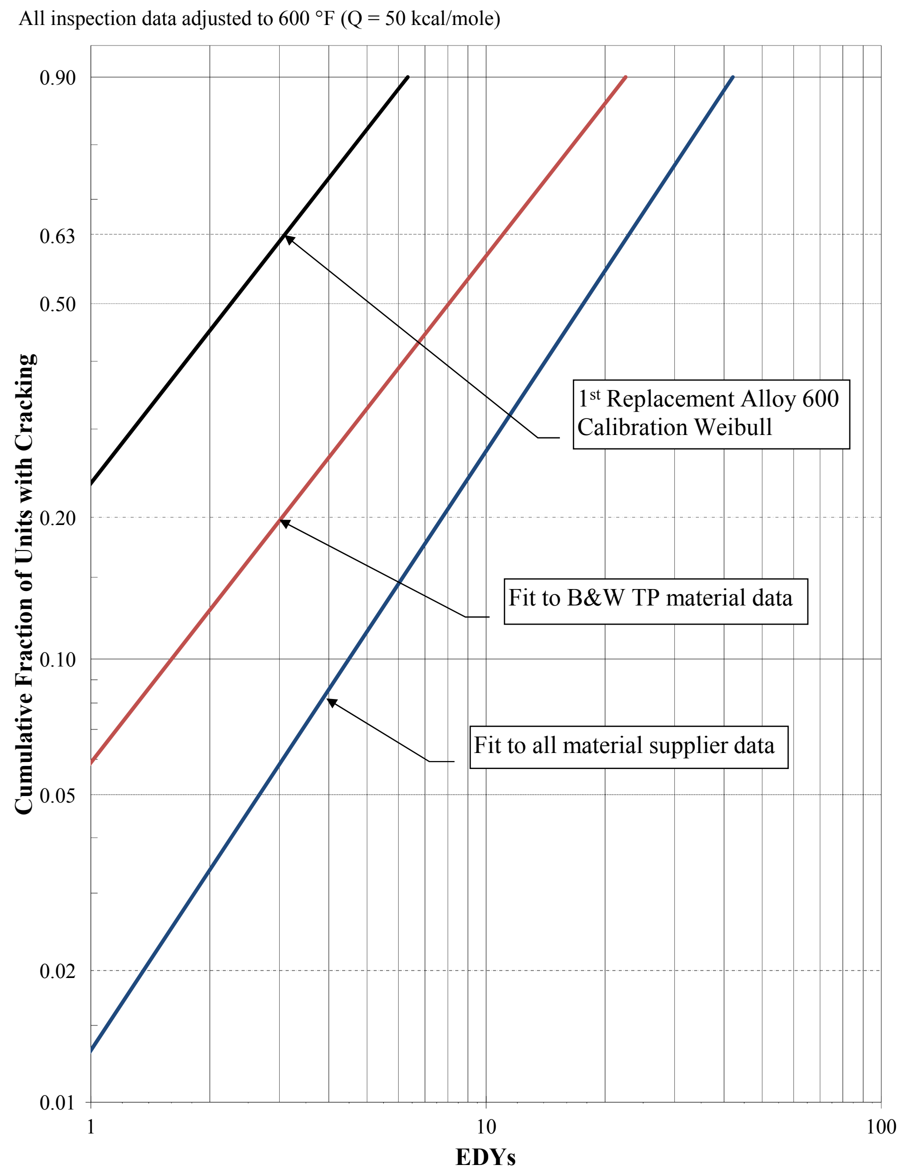
Weibull Initiation Model

Models Used in MRP-395

- Comparison of three crack initiation Weibull models used in study



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Probabilistic Results Format

Reported Statistics and Target Criteria

- Average Ejection Frequency (AEF) – average rate (per year) of ejections per head
- Average Leakage Frequency (ALF) – average rate (per year) of new leaking penetrations per head
- Nozzle Ejection Frequency Criterion (per Head Basis)
  - Maximum acceptable time-averaged core damage frequency = 1E-6 / yr
  - Upper bound conditional core damage probability for medium-break LOCA = 2E-2
  - Acceptance criterion for the nozzle ejection frequency is 1E-6 / 2E-2 = 5E-5 / yr

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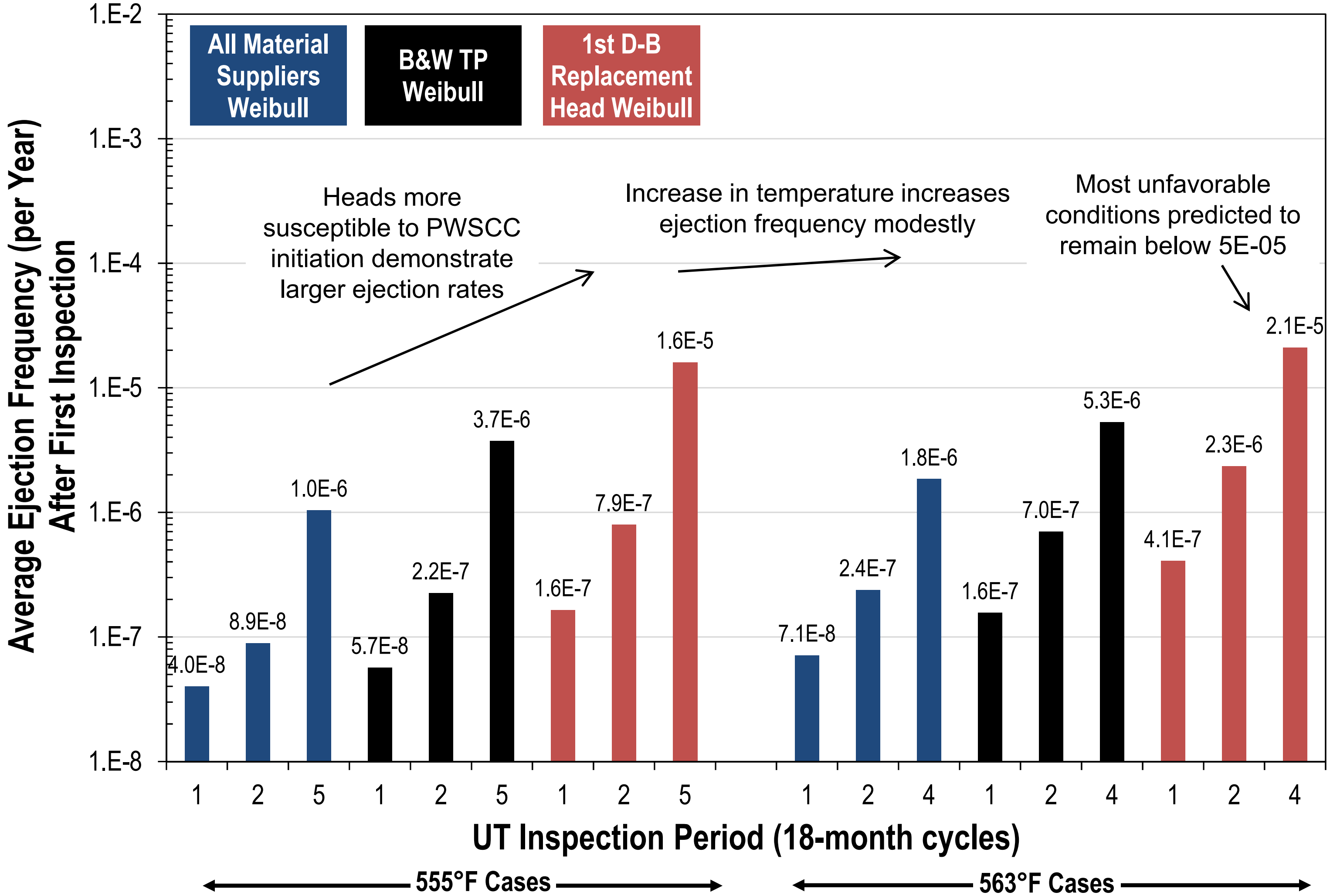
Main Results

Average Ejection Frequency Versus Temperature, UT Inspection Period, and Assumed Initiation Model



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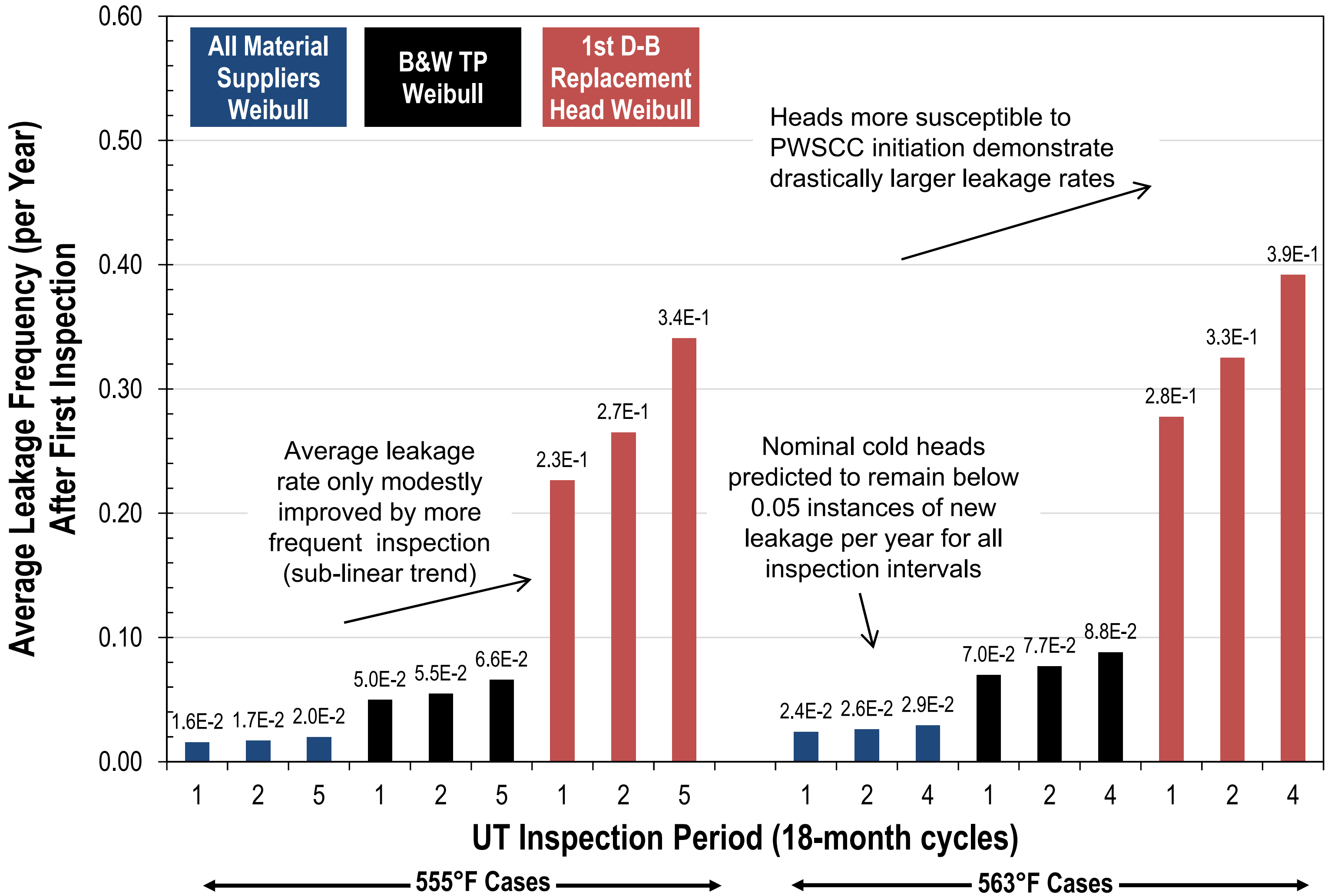
Main Results

Average Leakage Frequency Versus Temperature, UT Inspection Period, and Assumed Initiation Model



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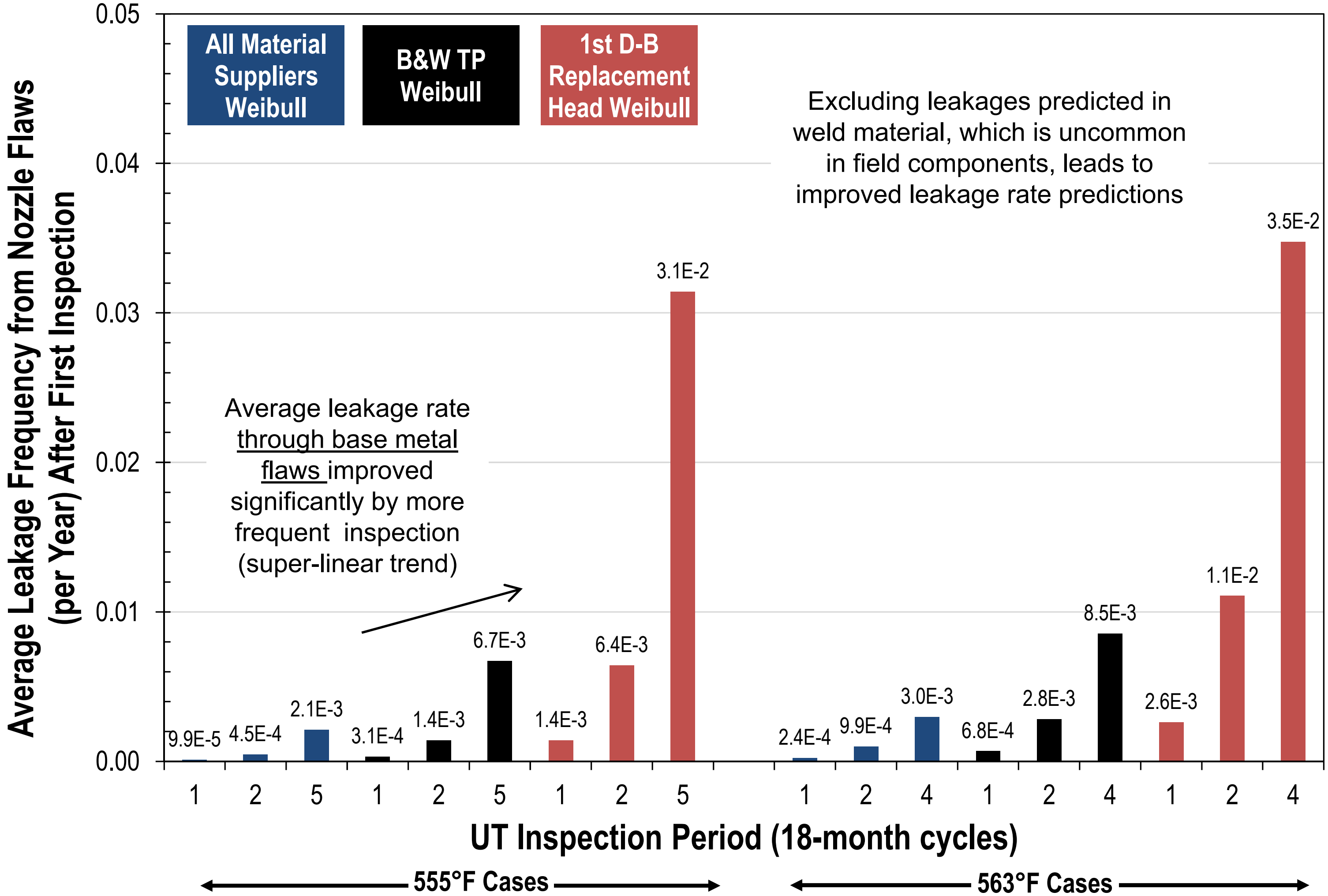
Main Results

Average Leakage Frequency (Excluding Leaks due to Flaws Initiating in Weld Material)



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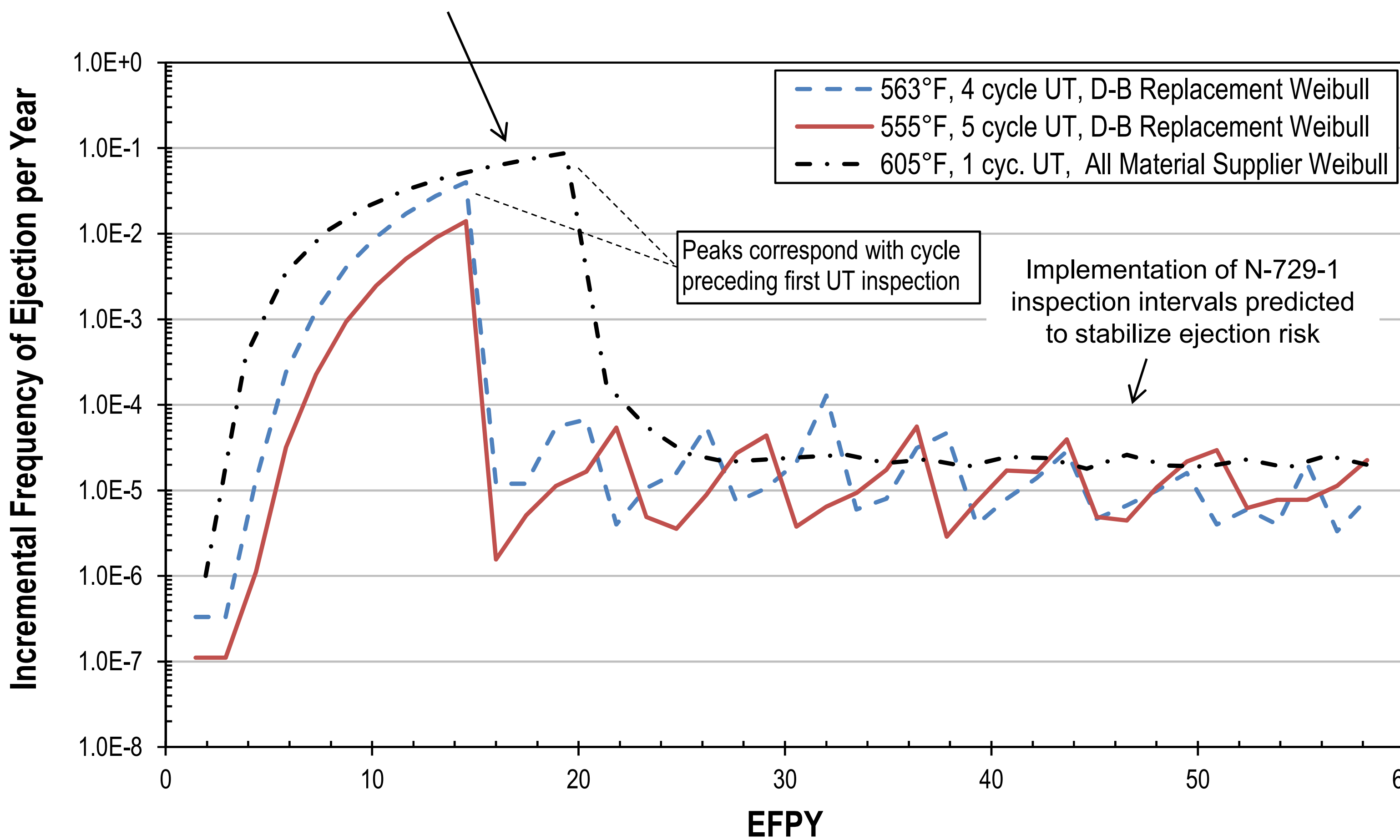
Main Results

Incremental Ejection Frequency Versus Time for Different Temperature Heads Under N-729-1 Inspection Requirements

Hot head uninspected for over 20 EFPYs predicted to have 10% likelihood of ejection per year. This demonstrates model conservatism. Predictions after first inspection are relevant to the benefit of periodic exams.



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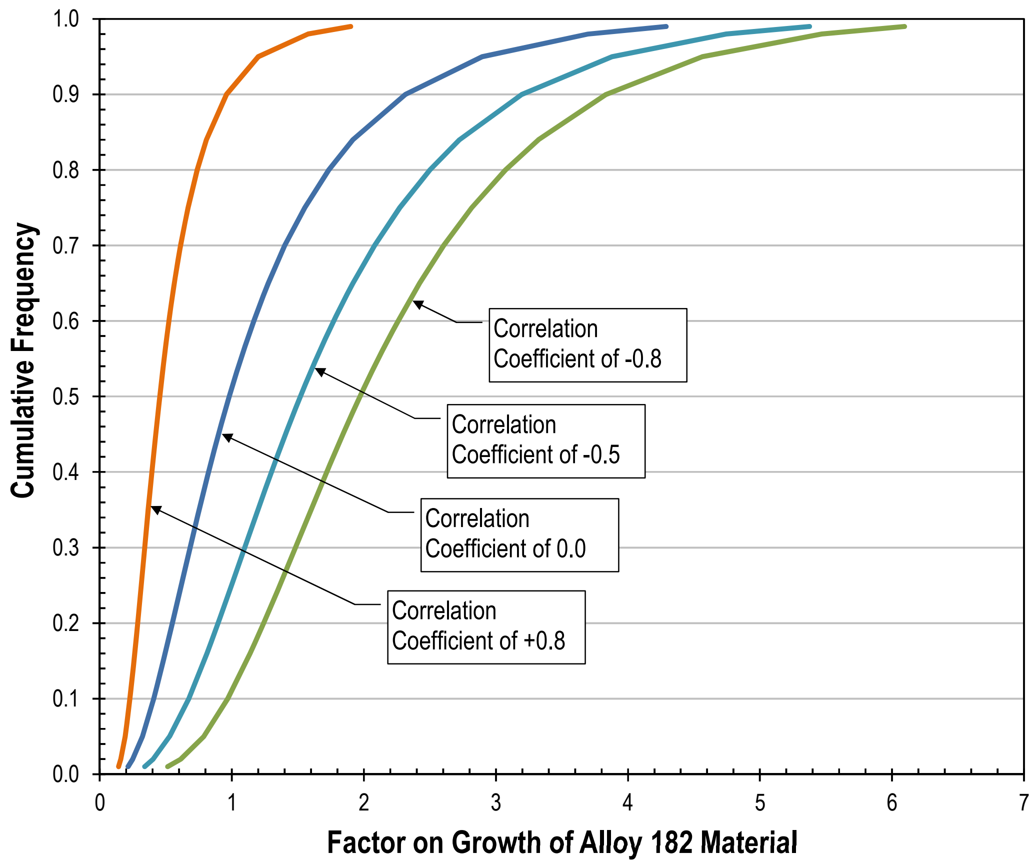
Sensitivity Cases

Effect of Initiation-Growth Correlation on Growth Rate of Active Flaws

- Negative correlation coefficient between initiation and growth simulates that a material more susceptible to PWSCC initiation is more susceptible to PWSCC growth
- Evaluated effect of correlation on growth rate by recording growth factor for initiated flaws during Monte Carlo experiment



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Discussion of Results

- Even for cold head modeled to have material as susceptible as the "Alloy 600 replacement" head, risk of ejection is acceptably low for inspections scheduled per RIY = 2.25
- Leakage probabilities are influenced by the rate of initiated flaws
- Inspections are effective in maintaining a low probability of leakage due to base metal cracking
  - The leakage results excluding flaws initiated in the base metal are most realistic as plant experience shows a low probability of leakage due to flaws located exclusively in the weld metal
- The "Alloy 600 replacement head" Weibull model is conservative since it bounds plant experience

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Probabilistic Modeling Conservatisms

- Significant modeling conservatisms are maintained in the current probabilistic approach supporting the aforementioned conclusions:
  - PWSCC initiation is assumed uniform at ID, OD and weld locations and weld flaws are modeled as being undetectable prior to leakage
  - A through-wall 30° circumferential flaw located at the top of the weld is assumed to be produced immediately upon nozzle leakage
  - Conservatively low POD values for UT and VE were assumed
  - An environmental factor was assumed to increase the growth rate of circumferential cracks in contact with the OD annulus of RPVHPNs
  - Axial ID flaws on RPVHPN tubes are assumed to always initiate at the elevation having the highest hoop stresses
  - Bounding high K solutions are used in some cases for flaw growth

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Updated Technical Basis (MRP-395): Assessment of Concern for Boric Acid Corrosion (BAC)

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BAC Wastage Evaluations

Introduction

- The periodic visual examinations for evidence of pressure boundary leakage of ASME Code Case N-729-1 conservatively addresses the concern for boric acid corrosion
  - Original technical basis was summarized in Section 3.4 of MRP-117
- Bare metal visual examination (VE) interval of lesser of every third refueling outage or 5 years for heads with < 8 EDY (effectively those at T_{cold}) and no previously detected PWSCC
  - Very low probability of leakage calculated for such heads in MRP-105
  - Slower crack growth means longer time for the leak rate to in increase to a point that may support boric acid wastage (Section 7 of MRP-110)
  - Visual assessment including under the insulation from multiple access points (VT-2) is required during the other refueling outages to check for gross evidence of the buildup of boron and/or corrosion product deposits

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BAC Wastage Evaluations

Plant Experience

- No through-wall cracking has been observed in the U.S. after the first in-service volumetric or surface examination was performed of all CRDM or CEDM nozzles in a given head
- Periodic visual examinations performed under the insulation at appropriate intervals are highly effective in detecting any leakage caused by PWSCC before any discernible material loss
  - 2010 case of multiple leaking CRDM nozzles resulted in no discernable corrosion of the low-alloy steel head
  - Periodic BMV detected 2013 case of reactor vessel bottom-mounted nozzle leakage at a U.S. PWR before wastage occurred

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BAC Wastage Evaluations

Experience with Leaking CRDM Nozzles

- Most leaking CRDM nozzles were repaired in a manner such that if significant wastage had occurred, it should have been detected
- Only two nozzles in one head showed significant wastage in the surrounding head material
  - The wastage at these nozzles was accompanied by evidence of leakage that was readily detectable several years prior to the large cavity being discovered
- The remaining nozzles generally showed no discernible material loss beyond the small gaps between the Alloy 600 nozzle material and the low-alloy steel head material evident through ultrasonic “leak path technology” inspections
  - In two cases, visible but small wastage volumes were observed (each estimated to be less than 1 in^3)

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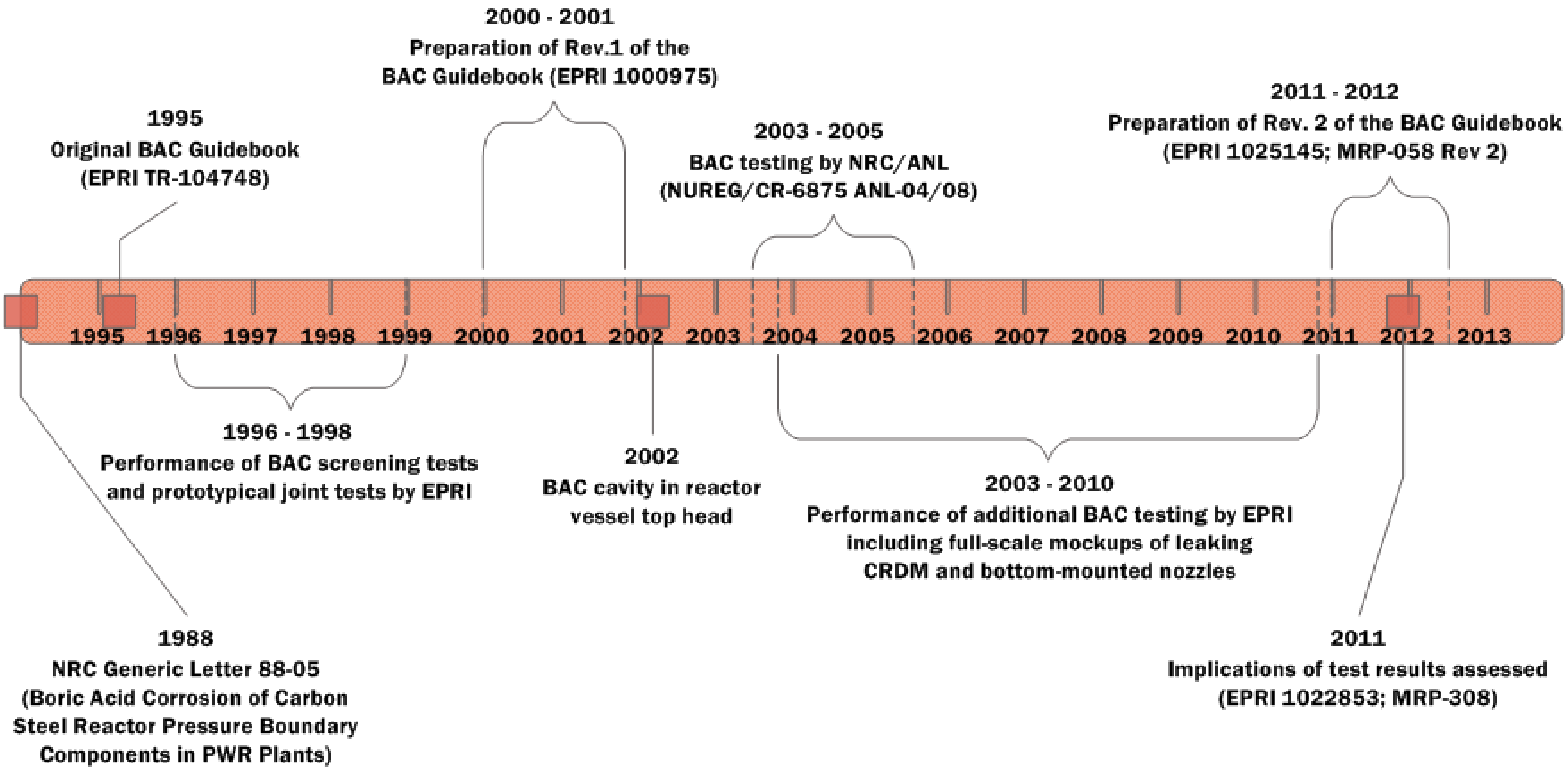
EPRI BAC Guidebook Rev. 2

Phases of Guidebook Development



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EPRI BAC Guidebook Rev. 2

Industry Experience — Key Experience Since Revision 1

- Focus in Guidebook Rev. 1 was on leaks at sealed joints such as gasketed joints. In Rev. 2 focus also includes leaks caused by PWSCC
- Corrosion of carbon & low-alloy steel (C&LAS) due to leaks caused by PWSCC
  - 2002 reactor pressure vessel head cavity event was the major event of this type
  - No structurally significant cases of corrosion of C&LAS pressure boundary parts since this 2002 event
- Corrosion of C&LAS due to leaks at sealed joints
  - No structurally significant cases of corrosion of C&LAS pressure boundary parts such as bolting since about 2000

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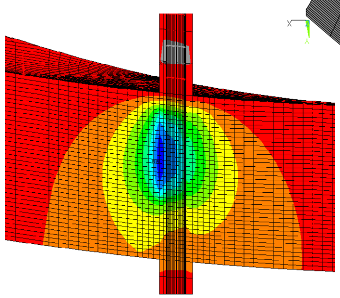
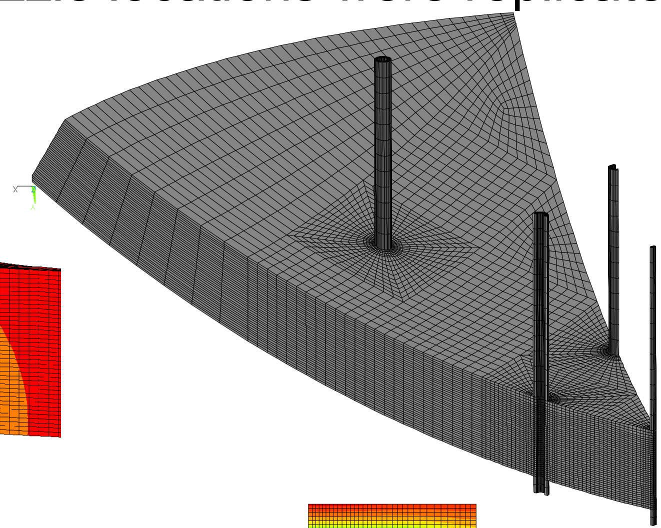
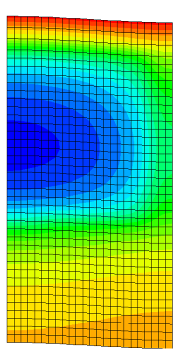
BAC Testing with Full-Scale Mockups

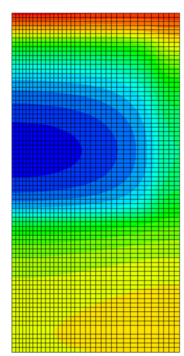
- Design of full-scale mockups ensured the thermal-hydraulic conditions at the nozzle locations were replicated in the full-scale mockups



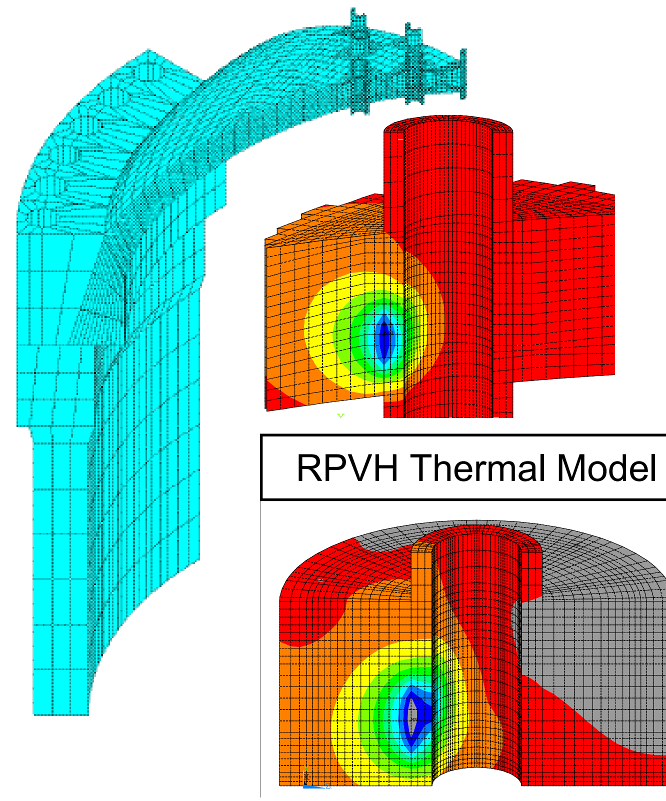




Annular Region of RPVH Thermal Model



Annular Region of Mockup Thermal Model



RPVH Thermal Model

Mockup Thermal Model

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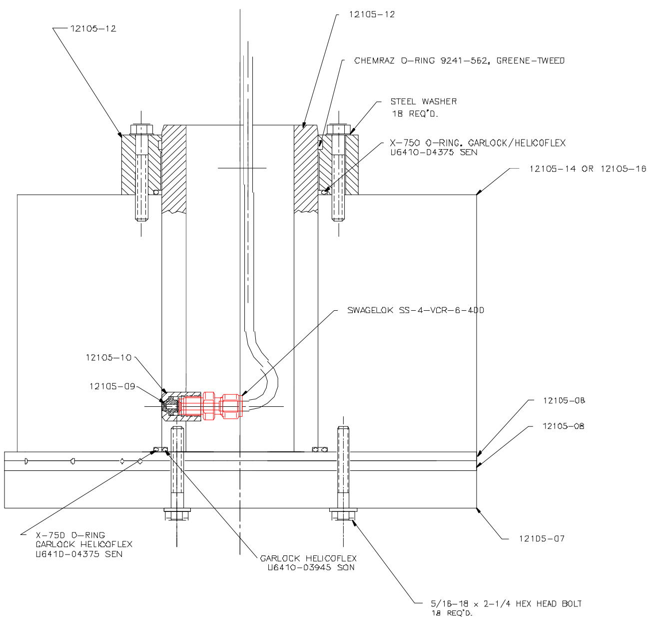
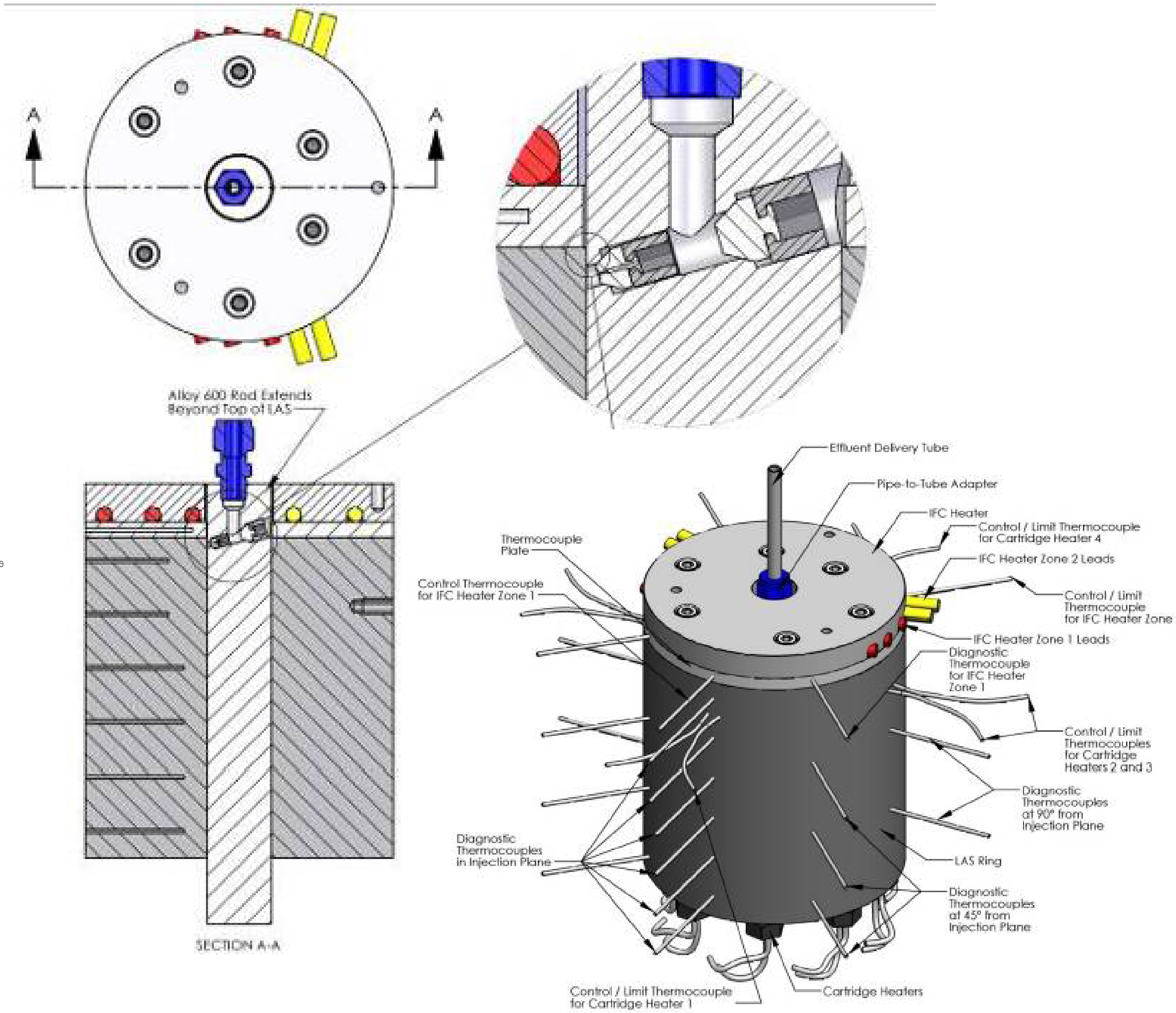
BAC Testing with Full-Scale Mockups

- Design of Full-Scale Mockups



CRDM Nozzle Mock-Up Design



BMN Mock-Up Design

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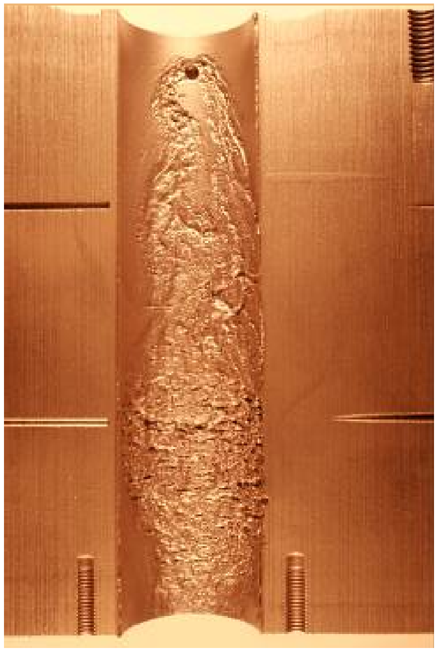
BAC Testing with Full-Scale Mockups

- Low-alloy steel wastage was quantified using molds of sectioned mockups

Example of Sectioned CRDM Nozzle Mockup
Volumetric Leak Rate = 0.1 gpm
Volumetric Wastage Rate = 4.1 in^3/yr



Example of Sectioned BMN Mockup
Volumetric Leak Rate 0.01 gpm
Volumetric Wastage Rate– 2.3 in^3/yr

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Implications Assessment of BAC Testing (MRP-308)

- The objective is to investigate the validity of the assumptions and technical bases that were used to develop the current inspection requirements for the RPV top and bottom heads
- The full-scale mockup results provide the best experimental simulations of conditions expected to exist in an actual leaking nozzle
  - Confirm that the wastage rates observed in the full-scale mockup tests support the assumptions used in the safety assessments
  - Confirm the effectiveness of visual inspection to detect the existence of a leak

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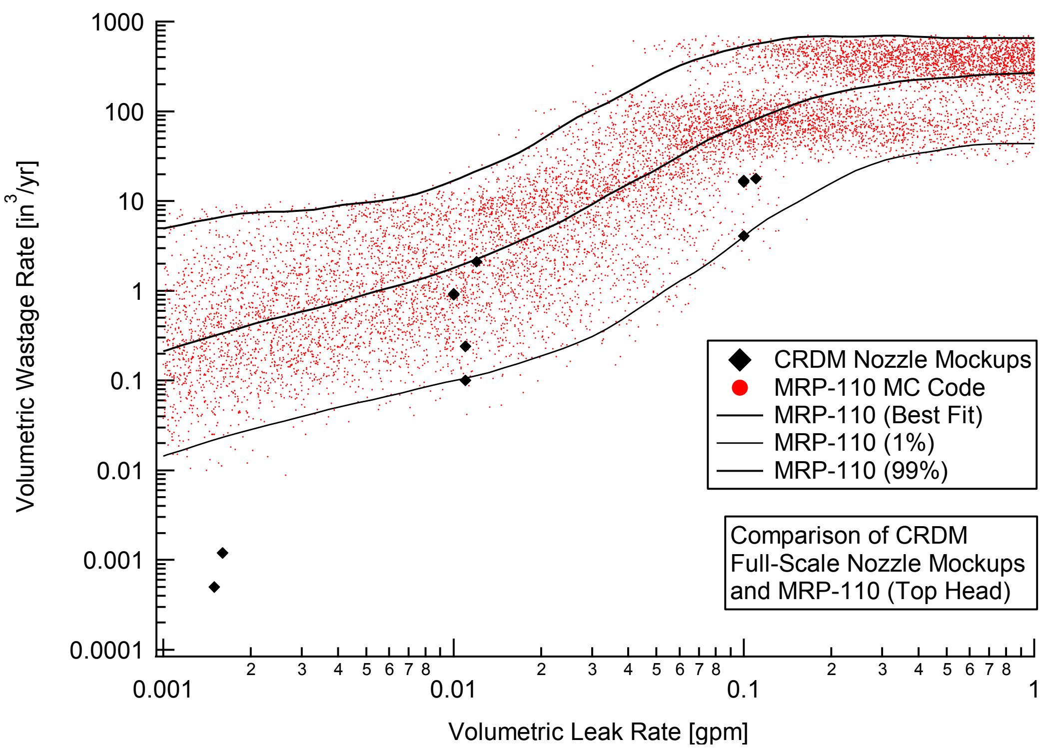
Implications Assessment of BAC Testing

MRP-308 Comparison of Wastage Rates – MRP-110

- The MRP-110 model was used to generate instantaneous volumetric wastage rates covering the range of flow rates tested with the full-scale mockups.
- The instantaneous wastage rate vs. leak rate data was then evaluated to determine the mean and bounding percentile (1st and 99th) curves (non-parametric fit).
- The full-scale mockup results are bounded by the statistical variations of the model used in the MRP-110 safety analysis for top heads.



Volumetric Wastage Rate per MRP-110 Probabilistic Model Compared to Full-Scale Mockup Results (Top Head)

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Implications Assessment of BAC Testing

Effectiveness of Visual Exams for Leakage – CRDM Nozzle Mockups

0.01gpm

0.1gpm

0.1gpm

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Implications Assessment of BAC Testing

Conclusions Regarding Current Inspection Requirements

- Based on the results of the full-scale mockup test results, the wastage rates used in the safety assessments are shown to be representative of conditions expected in the field
- All full-scale mockup tests had visual evidence local to the exit of the annulus for all conditions tested, confirming the effectiveness of visual inspections
- Based on the full-scale mockup tests, both the volumetric wastage rate and effectiveness of visual examination to detect a leak have been shown to support the modeling elements used in the technical analyses of the safety assessments

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Updated Technical Basis (MRP-395): Conclusions

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Conclusions

Adequacy of Current ASME Code Case N-729-1 Inspection Interval for Volumetric Examinations (RIY = 2.25)

- Clearly successful in managing the PWSCC concern for top heads
  - No through-wall cracking has been observed in the U.S. after the outage that the first in-service volumetric or surface examination was performed of all CRDM or CEDM nozzles in a given head
  - Since 2004, no circumferential PWSCC indications in the nozzle tube and located near or above the top of the weld have been detected
  - Has been effective in detecting the PWSCC degradation reported in its early stages, with modest numbers of nozzles affected by part-depth cracking, often located below the weld, where the nozzle tube is inside (not directly a part of) the pressure boundary
- Maintains nuclear safety with substantial margins, even for probabilistic cases assuming frequencies of PWSCC crack initiation at the most susceptible end of the range of plant experience
- Low probability of pressure boundary leakage

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Conclusions

Acceptability of Performing Volumetric Examination Every Other Refueling Outage for Heads Operating at T_{cold} with Prior PWSCC

- 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 probabilistic calculations support applying the RIY = 2.25 interval to heads with previously detected PWSCC (4 or 5 cycles 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
  - 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
- As discussed in Section 6.2 of MRP-395, 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

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Conclusions

Adequacy of Current Code Case N-729-1 Requirements for Periodic Visual Examinations for Evidence of Pressure Boundary Leakage

- The boric acid corrosion concern continues to be adequately addressed by the visual exam requirements of N-729-1, including the current periodic visual exams for evidence of leakage for cold heads (EDY < 8):
  - Reduced risk of substantial boric acid corrosion rates affecting a head operating at T_{cold} in comparison to one operating at higher temperature
    - Demonstrated low probability of leakage for cold heads
    - Substantial benefit of operation at T_{cold} in increasing the time required for a part-depth flaw to grow through-wall and cause leakage
    - Substantially reduced crack growth rates for cold heads, increasing time for leak rate to increase in the unlikely case of through-wall cracking
  - Supplemental requirement for VT-2 visual exam under the insulation through multiple access points in outages that the VE is not completed
    - Given the large amount of boron deposits that necessarily accompanies substantial rates of boric acid corrosion, the VT-2 requirement is an effective supplement to the periodic VE exams

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Conclusions

Adequacy of Current Code Case N-729-1 Requirements for Periodic Visual Examinations for Evidence of Pressure Boundary Leakage (cont'd)

- The boric acid corrosion concern continues to be adequately addressed by the visual exam requirements of N-729-1, including the current periodic visual exams for evidence of leakage for cold heads (EDY < 8):
  - Switch to VE every outage if flaws unacceptable for continued service are detected
  - Results of 2003-10 MRP Boric Acid Corrosion Test Program
    - Corrosion rates and resulting conditions observed were found to be consistent with key assumptions made in the original analytical work
  - Any leaks that might occur due to through-weld PWSCC that is not detectable via the periodic volumetric or surface exams of the nozzle tube are expected to be relatively small
  - Periodic "leak path assessment" exam required by 10 CFR 50.55a(g)(6)(ii)(D)(*3*) is a method for detecting through-wall PWSCC and leakage that is independent of the visual exams, resulting in increased overall confidence in detecting any leakage in a timely fashion
- This conclusion is not dependent on the volumetric or surface reexamination interval for cold heads with previously detected PWSCC being one rather than two 18-month fuel cycles

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Conclusions

Effect of Emergent CRDM Nozzle PWSCC Detected in 2014

- During a spring 2014 refueling outage, a cold head repaired 5 additional CRDM nozzles
  - Previously repaired 4 CRDM nozzles due to PWSCC in fall 2012
  - A comparison of this experience versus the 2010 experience for the "replacement Alloy 600 head" shows similar material susceptibility
  - Head replacement has been announced for 2017
- During a fall 2014 refueling outage, a cold head repaired 1 additional CRDM nozzle due to PWSCC (previously had repaired 1 CRDM nozzle in 2007)
- The "replacement Alloy 600 head" calibration case remains the bounding probabilistic analysis case and is insensitive to additional reports of cold head PWSCC
- The crack growth rates implied by this new experience were assessed using the same approach described in Section 2.2 of MRP-395 and are consistent with the crack growth rate assumptions in the probabilistic analyses

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Recommendations

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Recommendations

Volumetric or Surface Inspection Interval for Heads without Previously Detected PWSCC

- Conclusion:
  - The existing RIY = 2.25 interval for volumetric or surface inspection is still supported by updated plant experience and PWSCC analyses
    - Extremely low probability of nozzle ejection
    - Low probability of leakage
- Recommendations:
  - Maintain the RIY = 2.25 interval for heads without previously detected PWSCC
  - Also maintain coverage requirements for the volumetric or surface exams

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Recommendations

Volumetric or Surface Inspection Interval for Heads with Previously Detected PWSCC

- Conclusion:
  - Updated plant experience and analyses show that volumetric or surface examination of a head operating at T_{cold} (i.e., cold head) every other refueling outage, rather than every refueling outage as currently required by 10 CFR 50.55a(g)(6)(ii)(D)(*5*), is sufficiently conservative
- Recommendations:
  - ASME to reinstate the two-cycle periodicity of Code Case N-729-1
  - NRC approve revised version of N-729 reinstating the two-cycle periodicity
  - In the interim, NRC approve any plant relief requests allowing cold heads with nominal 18-month fuel cycle and with previously detected PWSCC to be volumetrically or surface examined every other refueling outage

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Recommendations

Visual Examinations for Leakage

- Conclusion:
  - The current periodic visual exams for evidence of leakage remain valid for cold heads (EDY < 8) without previous detection of any flaws unacceptable for continued service
- Recommendation:
  - Maintain current requirement for heads with EDY < 8 per Note (4) of Table 1 of N-729-1 and of N-729-4:

    "*If EDY < 8 and no flaws unacceptable for continued service under -3130 or -3140 have been detected, the reexamination frequency may be extended to every third refueling outage or 5 calendar years, whichever is less, provided 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. This IWA-2212 VT-2 visual examination may be performed with the reactor vessel depressurized.*"

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