Inspection Plan for Reactor Vessel Closure Head Penetrations in U.S. PWR Plants (MRP-117)

MRP / NRC

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Alloy 600 Issue Task Group (ITG)

RPV Head Working Group

Agenda

- MRP-117 Overview
- Analyses Completed
- Visual Examination
  - Coverage
  - Frequency
- Volumetric & Surface Examinations
  - Coverage
  - Frequency
- Alternative Methods/Analyses
- Future Actions

Overview of MRP-117

- Goal to Maintain Structural Integrity
  - Maintain an acceptably low probability of developing cracking that could lead to nozzle ejection or loss of ASME Code margins due to consequential wastage
    - Change in Core Damage Frequency (~ 10^{-6}/year)
    - Low probability of leakage (~10^{-2}/year)
    - Given a leak, very low probability of structurally significant wastage (<< 10^{-4})

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Overview of MRP-117 (cont'd)

- MRP-110 Safety Assessment provides technical basis
  - Submitted in April 2004 along with other detailed supporting calculations

- MRP-117 provides Inspection Requirements

- MRP-117 has been reviewed by Alloy 600 ITG and MRP IIG, not yet through the Executive Committee

- Draft Code Case intended to mimic MRP-117

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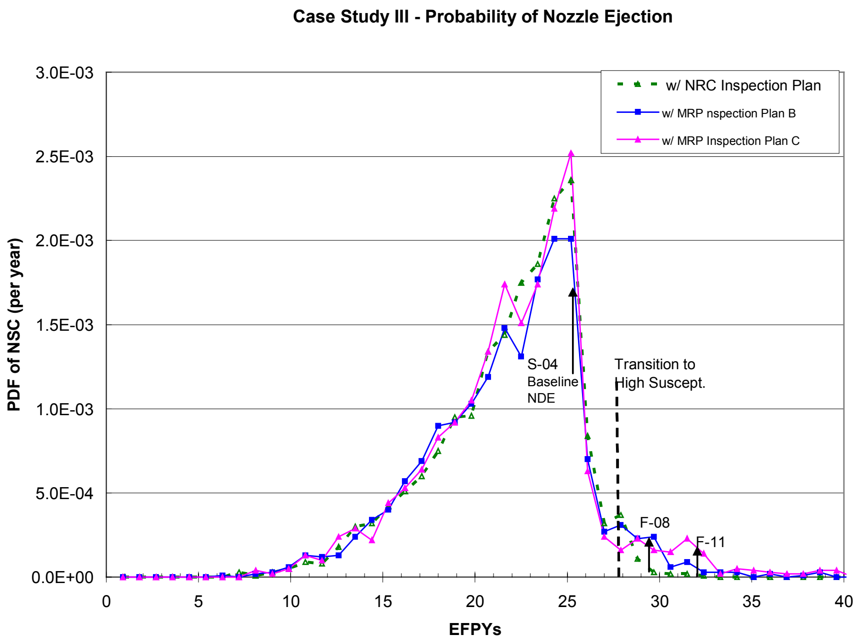
Scope of MRP-117

- Applicable to all reactor vessel closure heads (RVCHs) in domestic PWR plants
- Nozzles fabricated from Alloy 600 material and attached with Alloy 82/182 J-groove attachment welds
- Inspection requirements for replacement heads made with Alloy 690/52/152
- In the original heads, there are 30 nozzles that do not include J-groove attachment welds
  - Not addressed in MRP-117
  - To be addressed in plant-specific in-service inspection (ISI) programs.

Analyses

- Acceptable ? CDF 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



Analyses (cont'd)

- Visual inspection requirements were established by reviewing plant leakage and wastage experience (only DB had significant wastage)
  - Frequencies confirmed by deterministic and probabilistic models to be conservative

Inspection Timing Parameters

- PWSCC susceptibility grouped according to Effective Degradation Years (EDY)

  EDY = EFPY normalized to 600°F using 50 kcal/mole activation energy (characteristic of PWSCC initiation)

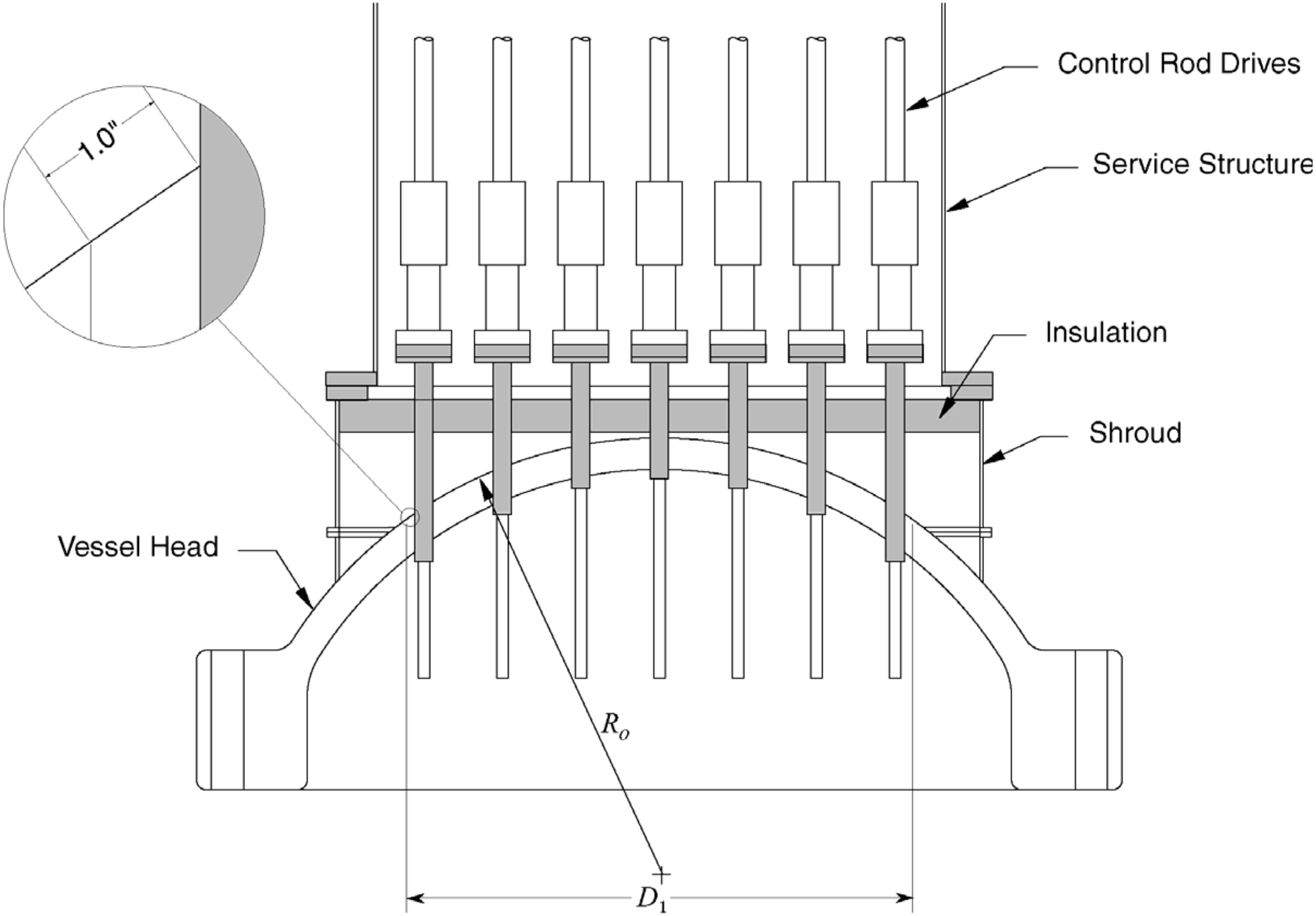
- Examination frequencies based on Re-Inspection Years (RIY)

  RIY = ? EFPY normalized to 600°F using 31 kcal/mole activation energy (characteristic of PWSCC growth)

Visual Examination Attributes

- Bare Metal Visual Examination
  - Looking for boric acid deposits and evidence of leakage or corrosion
  - Uphill and downhill of obstructions
  - Includes intersections of all nozzles to head
  - 95% of head surface in the penetration region (see figure on next slide)

Visual Examination Coverage

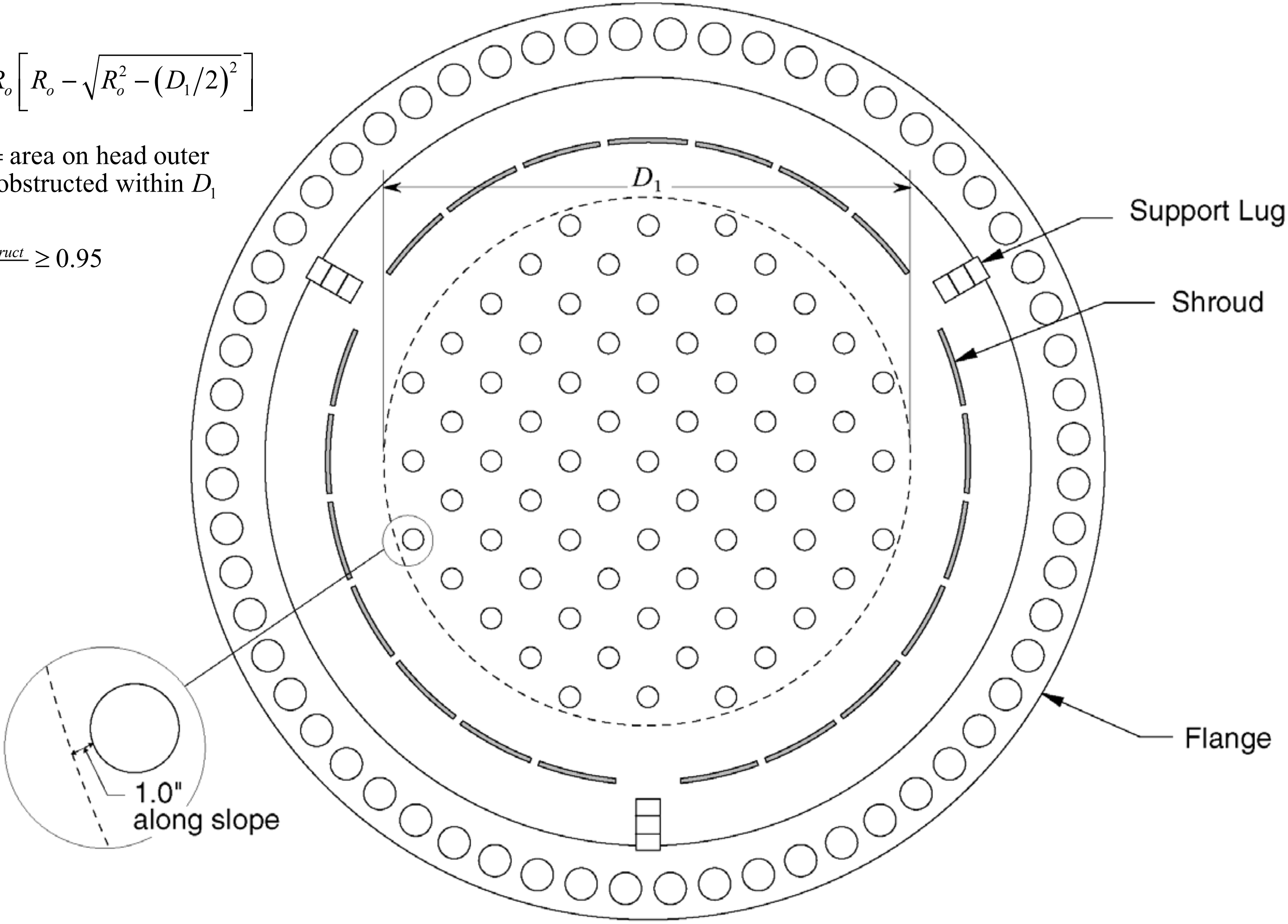


Visual Examination Coverage

$$A = 2\pi R_o \left[R_o - \sqrt{R_o^2 - (D_1/2)^2} \right]$$

$A_{obstruct}$ = area on head outer surface obstructed within D_1

$$\frac{A - A_{obstruct}}{A} \geq 0.95$$



Visual Examination Frequency

- Bare metal visual examination every outage
  - If EDY <8, extend to every 3rd outage or 5 years
    - Low probability of cracking
    - Slow crack growth for cold head plants
    - General visual required other outages
      - Multiple access points
      - Defense in depth
- Heads with Alloy 690/52/152 material
  - Bare metal visual every 3rd outage or 5 years
    - No general visual required in between

Additional Visual Examination

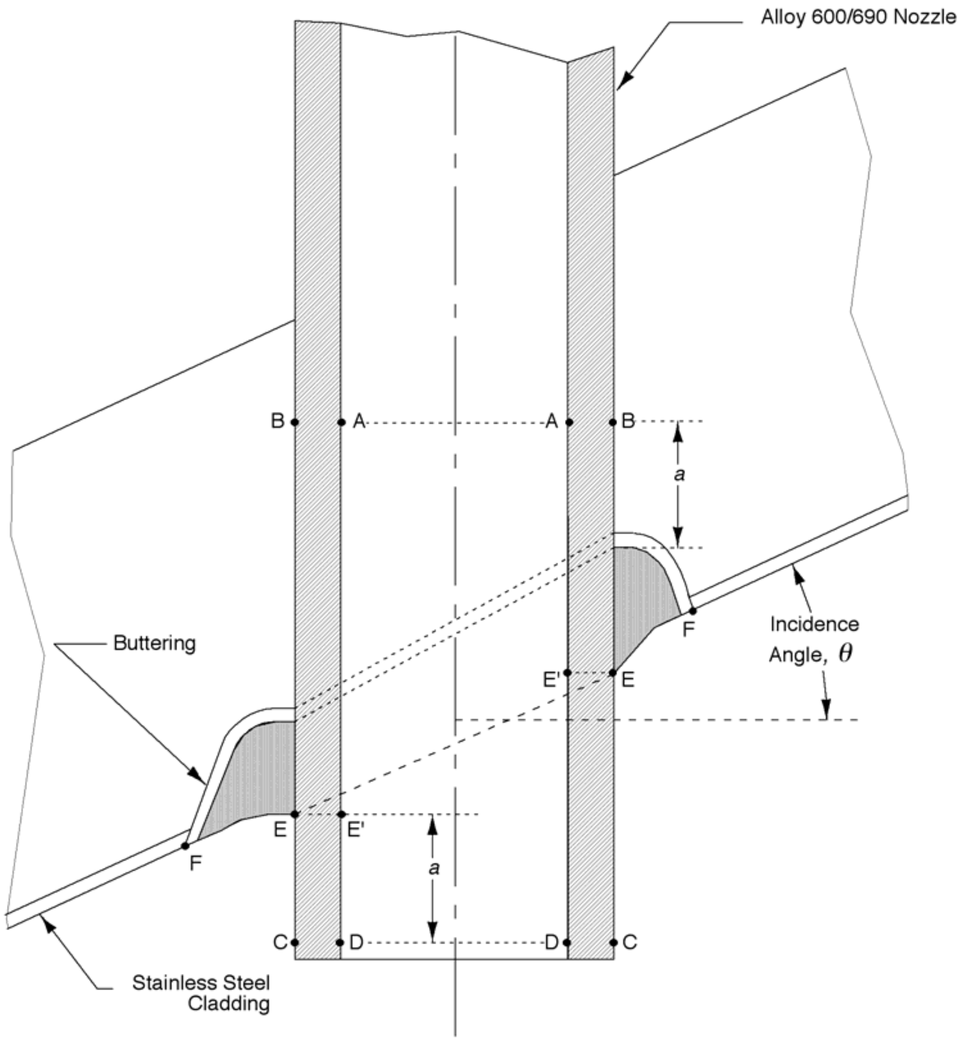
- For all plants
  - Visual inspections each refueling outage to identify potential boric acid leaks from pressure-retaining components above the RVCH

Volumetric/Surface Exam Attributes

- Three types of examination defined:
  - Type 3 – Tube volume only OR wetted surface only
  - Type 2 – Tube volume PLUS 50% of welds
  - Type 1 – Tube volume PLUS 100% of welds

- Examination volume or surface area based on generic residual stress calculations that bound the US PWR fleet for the cases examined (51 of 69 units)

Volumetric/Surface Exam Coverage



a = 1.5" for Incidence Angle, T $\leq$ 30° and ICI nozzles or 1" for Incidence Angle, T > 30°

OR

To the end of tube whichever is less

A-B-C-D = Volumetric examination zone for the tube (base metal)

A-D = Surface examination zone for the tube ID

F-E-C = Surface examination zone for the J-groove weld (filler metal and buttering) and tube OD below the weld

F-E = Surface examination zone for the J-groove weld (filler metal and buttering)

Volumetric/Surface Exam Coverage

- MRP-95 Rev 1 used to determine MRP-117 exam volume
  - 20 ksi stress limit
  - Fracture mechanics analyses of postulated flaws outside of exam volume
  - Review of prior exam data - flaw locations relative to exam volume
- MRP-117 inspection coverage limitations (studied via MRP-105 methodology):
  - 90% of each nozzle base metal exam volume*

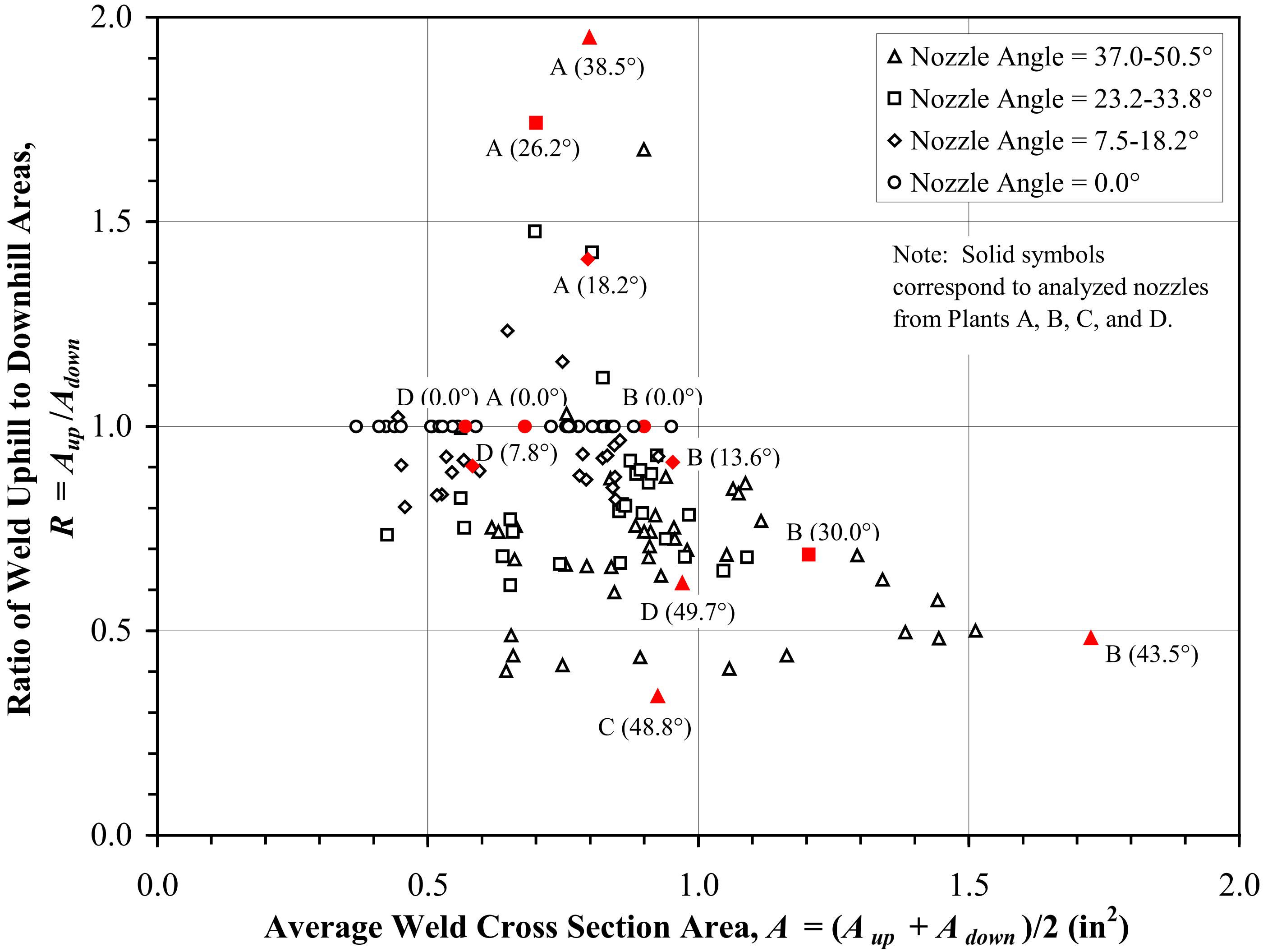
    AND
  - 95% of the total nozzle base metal exam volume* for entire head

    * or wetted surface area

Exam Volume Based on Characteristic Plants

- Plant A – B&W plant
  - nozzle angles ranging from 0° to 38°
  - nozzle yield strengths ranging from 36.8 to 50 ksi
- Plant B – Westinghouse 2-loop plant
  - nozzle angles ranging from 0° to 43.5°
  - nozzle yield strength of 58 ksi
- Plant C – Westinghouse 4-loop plant
  - nozzle angles ranging from 0° to 48.8°
  - nozzle yield strength of 63 ksi
- Plant D – large CE plant
  - CEDM nozzles
    - angles ranging from 0° to 49.7°
    - nozzle yield strengths ranging from 52.5 to 59 ksi
  - ICI nozzles
    - 55.3° nozzle angle
    - yield strength = 39.5 ksi

Weld Parameters of Characteristic Plants



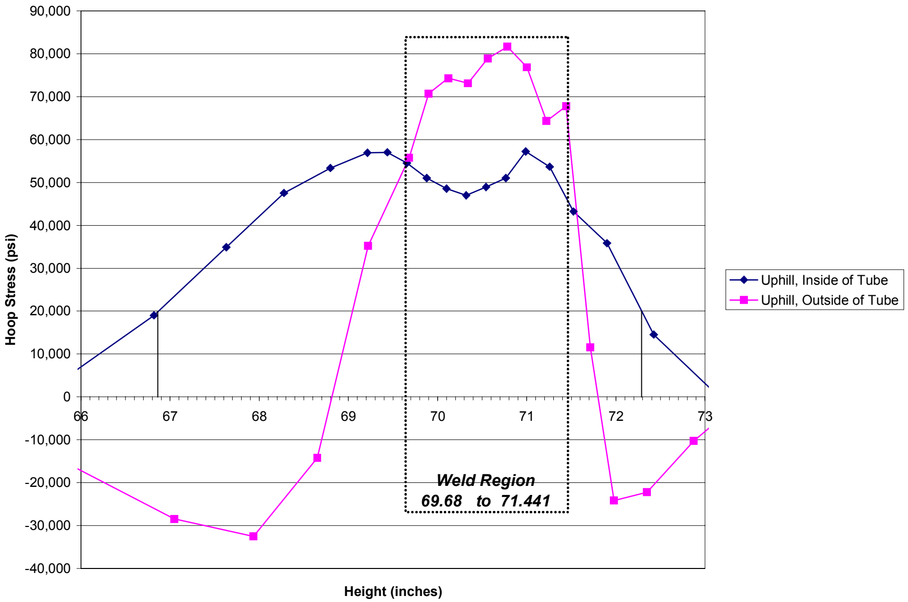
Characteristic Plants and the PWR Fleet

- Characteristic plants & nozzles selected for analysis bound nozzle angles and weld geometry factors that influence residual stresses
  - 51 of the 69 U.S. PWRs weld geometries have been evaluated
  - Analyses span expected range of nozzle yield strengths
- Therefore, examination zone definition based on these stresses is judged to be applicable to all U.S. PWRs
- MRP-117 requires that all plants
  - Verify that their specific RVCH penetration designs are bounded by the MRP-95 examination zone

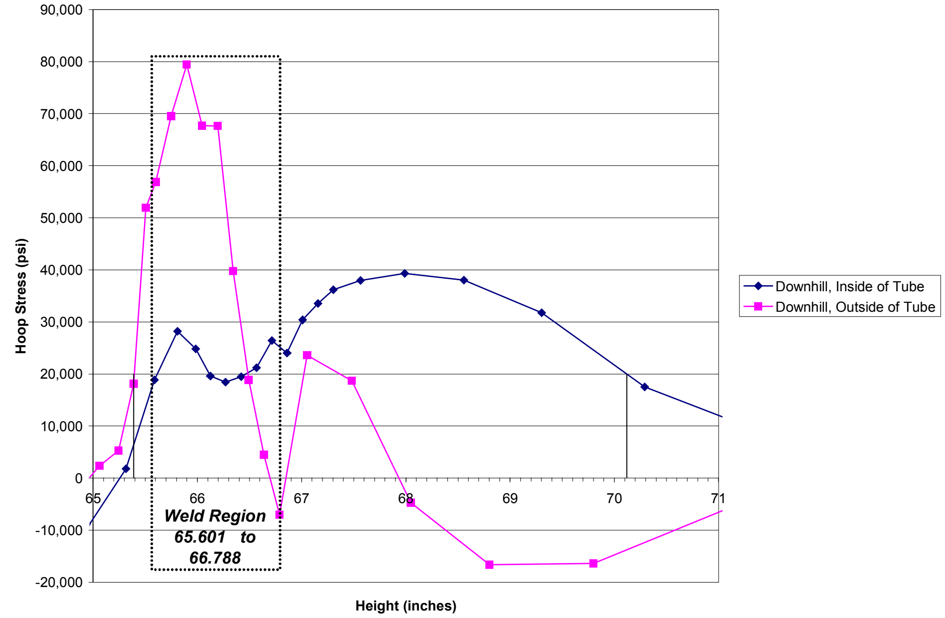
    OR
  - Develop appropriate site-specific examination zone

Typical Nozzle Stress Distributions

Uphill Side of Nozzle



Downhill Side of Nozzle



Summary of Nozzle Stresses at Edge of Exam Volume (Above Weld)

Plant	Nozzle Angle-Azimuth	Inspection Zone Dist. from Weld (inches)	Stresses at Edge of Inspection Zone Above Weld (ksi)			
			ID-Hoop	OD-Hoop	ID-Axial	OD-Axial
A	38-Downhill	5.65	8	1.4	1.8	3.1
	38-Sidehill	3.29	-3.1	-1.3	1.0	-0.1
	38-Uphill	1.00	14.2	-20.1	4.2	-7.6
A	26-Downhill	4.39	6.9	3.6	2.0	3.8
	26-Sidehill	2.93	0.0	3.1	2.3	3.7
	26-Uphill	1.50	5.4	-5.8	1.7	0.0
A	18-Downhill	3.37	4.6	0.4	4.2	1.2
	18-Sidehill	2.43	1.7	-0.2	5.5	0.1
	18-Uphill	1.50	3.9	-2.7	4.7	-2.3
A	0-All	1.50	7.0	-1.6	12.3	-7.8
B	43-Downhill	4.66	8.1	1.2	2.9	9.6
	43-Sidehill	2.80	1.1	0.6	-2.1	-4.8
	43-Uphill	1.00	15.8	-14.3	4.6	-7.0
B	30-Downhill	3.75	6.3	0.9	3.4	5.7
	30-Sidehill	2.62	2.5	2.4	-0.2	-1.3
	30-Uphill	1.50	1.3	-4.0	1.0	-3.6
B	13-Downhill	2.47	1.4	-1.4	7.7	1.6
	13-Sidehill	1.98	1.7	-1.9	7.4	-4.6
	13-Uphill	1.50	1.3	-4.4	6.3	-4.7
B	0-All	1.50	6.8	-3.9	14.4	-10.3
C	48-Downhill	5.15	13.7	-2.4	10.9	13.6
	48-Sidehill	3.04	-2.5	7.2	-1.0	0.4
	48-Uphill	1.00	11.5	-6.5	2.3	-7.4
D	49-Downhill	6.31	11.1	0.3	2.0	4.5
	49-Sidehill	3.59	-1.7	2.6	-2.1	1.3
	49-Uphill	1.00	15.5	-23.3	4.5	-12.4
D	8-Downhill	2.11	4.3	-2.0	10.6	-6.7
	8-Sidehill	1.81	4.1	-2.2	10.6	-6.3
	8-Uphill	1.50	6.0	-0.7	10.7	-7.3
D	55-Downhill(ICI)	9.88	20.2	1.7	2.2	4.6
	55-Sidehill(ICI)	5.51	5.4	13.9	-2.2	5.2
	55-Uphill(ICI)	1.50	19.1	-3.5	-1.9	-3.2

Summary of Nozzle Stresses at Edge of Exam Volume (Below Weld)

Plant	Nozzle Angle-Azimuth	Inspection Zone Dist. from Weld (inches)	Stresses at Edge of Inspection Zone Below Weld (ksi)			
			ID-Hoop	OD-Hoop	ID-Axial	OD-Axial
A	38-Downhill	1.00	-24.9	-13.2	-1.5	0.2
	38-Sidehill	3.07	9.5	-7.9	4.4	-9.5
	38-Uphill	5.08	-16.0	-0.2	-1.3	-0.9
A	26-Downhill	1.50	-31.0	-20.5	1.8	-3.5
	26-Sidehill	2.77	-4.9	-9.9	4.8	-9.5
	26-Uphill	4.02	-10.8	-5.6	0.6	-5.2
A	18-Downhill	1.50	-25.1	-19.8	5.8	-7.6
	18-Sidehill	2.34	-13.5	-14.0	8.1	-11.7
	18-Uphill	3.18	-12.3	-11.8	5.4	-9.9
A	0-All	1.50	-23.0	-28.4	6.8	-11.0
B	43-Downhill	1.00	5.5	13.1	20.0	-18.5
	43-Sidehill	2.62	8.3	-12.3	17.2	-21.2
	43-Uphill	4.19	-14.6	-2.2	1.0	-1.3
B	30-Downhill	1.50	-8.4	-10.6	15.7	-15.5
	30-Sidehill	2.42	-1.9	-11.9	13.2	-15.7
	30-Uphill	3.32	-10.4	-6.4	2.9	-7.3
B	13-Downhill	1.50	-0.1	-13.1	18.8	-20.5
	13-Sidehill	1.78	-10.3	-14.3	18.2	-19.7
	13-Uphill	2.07	-10.1	-17.2	14.2	-17.2
B	0-All	1.50	-27.8	-33.2	8.1	-12.4
C	48-Downhill	1.00	-8.9	9.0	14.9	-7.8
	48-Sidehill	3.30	12.6	-12.4	9.9	-18.9
	48-Uphill	5.52	-12.1	-0.9	2.7	1.5
D	49-Downhill	1.00	2.3	7.5	15.8	-5.4
	49-Sidehill	3.55	4.2	-9.8	9.1	-18.1
	49-Uphill	5.99	-10.8	-0.4	-0.2	3.2
D	8-Downhill	1.50	6.3	-4.4	20.3	-20.6
	8-Sidehill	1.82	2.3	-7.7	18.6	-19.8
	8-Uphill	2.13	-1.4	-10.4	16.2	-17.9
D	55-Downhill(ICI)	1.50	N/A*	N/A*	N/A*	N/A*
	55-Sidehill(ICI)	5.48	N/A*	N/A*	N/A*	N/A*
	55-Uphill(ICI)	9.58	N/A*	N/A*	N/A*	N/A*

* - Inspection zone extends beyond bottom edge of nozzle

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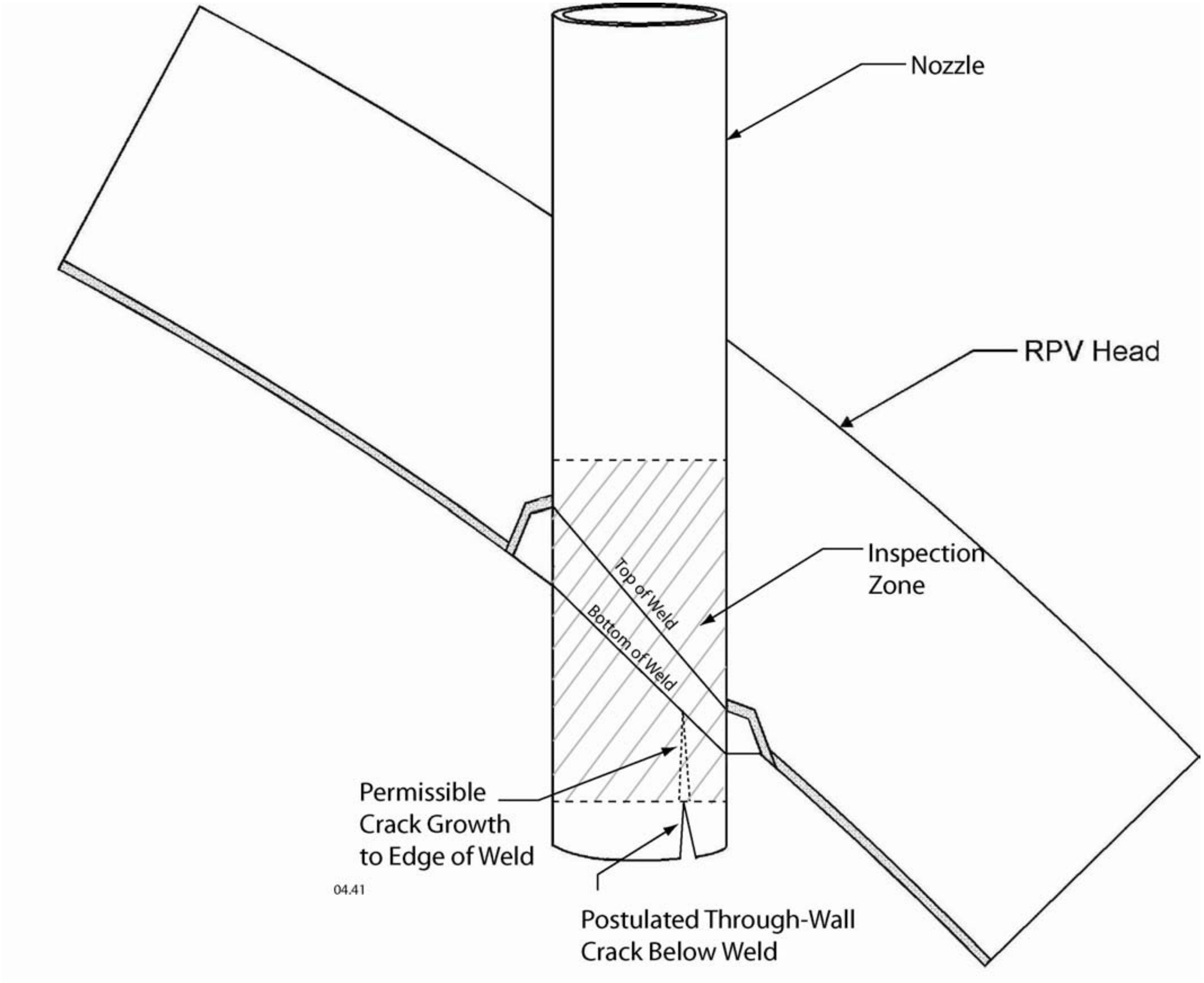
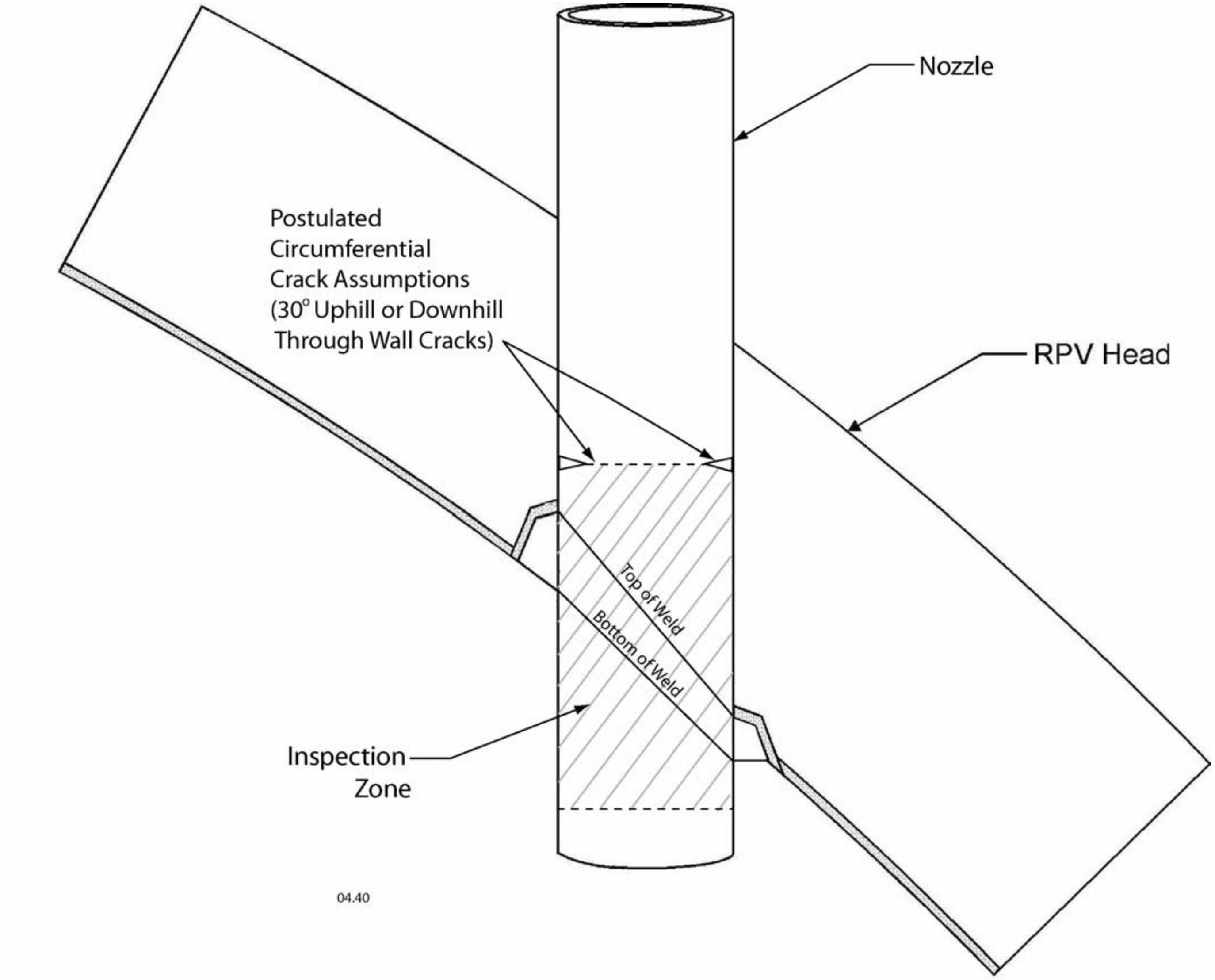
Fracture Mechanics Analysis Model – Axial Flaws below Weld



Fracture Mechanics Analysis Results – Axial Flaws below Weld

PLANT/ NOZZLE	LOCATION	K @ STARTING FLAW SIZE (KSI-vIN)	CRACK GROWTH TIME TO BOTTOM OF J-GROOVE WELD	
			EFPHs @600°F	EFPYs @600°F = RIYs
Plant A				
(B&W 38°)	DOWNHILL	< 8.19	No Growth	No Growth
	SIDEHILL	< 8.19	No Growth	No Growth
	UPHILL	< 8.19	No Growth	No Growth
(B&W 0°)	ALL	< 8.19	No Growth	No Growth
Plant B				
(W 2-LOOP 43.5°)	DOWNHILL	< 8.19	No Growth	No Growth
	SIDEHILL	21.8	135000	15.4
	UPHILL	< 8.19	No Growth	No Growth
(W 2-LOOP 30°)	DOWNHILL	< 8.19	No Growth	No Growth
	SIDEHILL	< 8.19	No Growth	No Growth
	UPHILL	< 8.19	No Growth	No Growth
(W 2-LOOP 13°)	DOWNHILL	< 8.19	No Growth	No Growth
	SIDEHILL	< 8.19	No Growth	No Growth
	UPHILL	< 8.19	No Growth	No Growth
(W 2-LOOP 0°)	ALL	< 8.19	No Growth	No Growth
Plant C				
(W 4-LOOP 48.8°)	DOWNHILL	< 8.19	No Growth	No Growth
	SIDEHILL	< 8.19	No Growth	No Growth
	UPHILL	37.7	Arrests	Arrests
Plant D				
(CE 49.7°)	DOWNHILL	< 8.19	No Growth	No Growth
	SIDEHILL	32.4	182000	20.8
	UPHILL	< 8.19	No Growth	No Growth
(CE 8°)	DOWNHILL	< 8.19	No Growth	No Growth
	SIDEHILL	< 8.19	No Growth	No Growth
	UPHILL	< 8.19	No Growth	No Growth

Fracture Mechanics Analysis Model – Circumferential Flaws above Weld



Fracture Mechanics Analysis Results – Circumferential Flaws above Weld

Growth Time from 30° to 300° Circumferential Cracks in Limiting Nozzles in Four Characteristic Plants (Assumed top head temperature = 600°F)

PLANT / NOZZLE	UPHILL (EFPH)	UPHILL EFPYs@600F =RIYs	DOWNHILL (EFPH)	DOWNHILL EFPYs@600F =RIYs
Plant A - 38° Nozzle	154874	17.68	193501	22.09
Plant B - 43.5° Nozzle	521114	61.89	94970	10.84
Plant C – 48.8° Nozzle	no growth	no growth	81572	9.31
Plant D – 49.7° Nozzle	167465	19.12	164293	18.75

Volumetric/Surface Exam Volume Technical Basis Summary

- 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 (RIY = 3)
- Review of prior inspection data, encompassing 237 detected flaws, indicates that all would have been detected if inspections had been performed over just the MRP-117 Exam Volume

Volumetric/Surface Exam Frequency

- Baseline based on EDY
  - EDY > 12; next outage
  - EDY $\geq$ 8; 2nd outage
  - EDY < 8; February 10, 2008

- Re-Inspection Before RIY = 2.25 or 8 calendar years
  - Extend to RIY = 3.0 or 10 calendar years if:
    - Last Vol/Sur was Type 2 <u>AND</u> CCDP $\leq 5 \times 10^{-3}$

      OR
    - Last Vol/Sur was Type 1
  - Maintains ?CDF ~ 10^{-6}

- Re-inspection limited to 2 cycles if flaw requiring repair found in any previous outage

Volumetric/Surface Reinspection Interval Technical Basis

- The reinspection intervals of MRP-117 are bounded by the probabilistic fracture mechanics (PFM) case studies of MRP-105
  - RIY = 2.25 equivalent or more conservative than EDY = 2.0
  - RIY = 3.0 is more conservative than EDY = 3.0
- The coverage and probability of detection assumptions of the PFM analyses bound the requirements within MRP-117
  - 90/95% coverage assumption in MRP-117
- Therefore the nozzle ejection evaluations in MRP-105 support the volumetric/surface reinspection intervals and examination coverage requirements of MRP-117

Volumetric/Surface Exam Frequency

- Heads with Alloy 690/52/152 material
  - Pre-service Inspection
  - In-service Inspections
    - Initial in-service within 6 to 10 years after head replacement
    - Re-Inspection every 10 years
  - Future revisions to inspection requirements could be demonstrated by on-going Alloy 690 studies

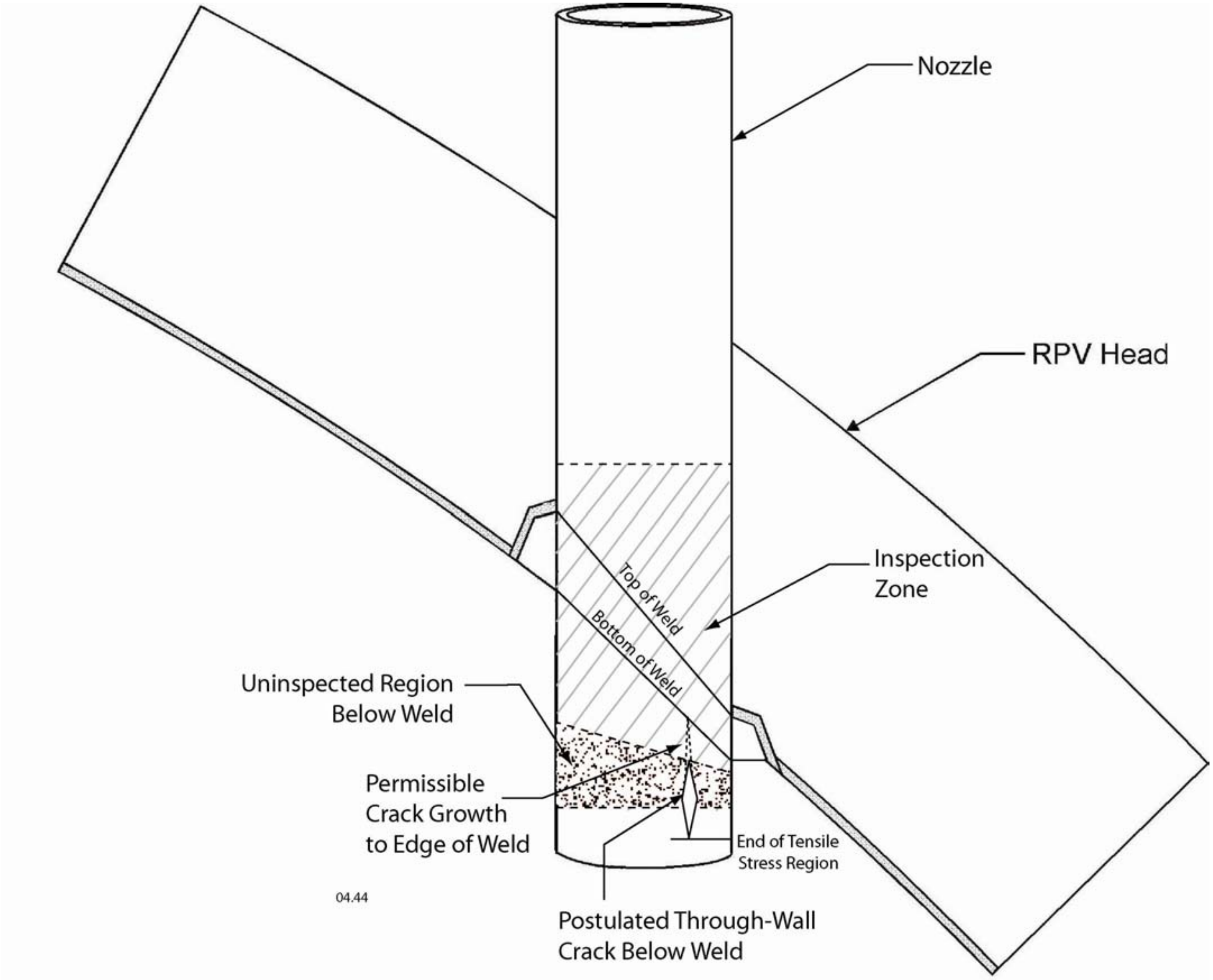
Discovery Outage

- If indication found:
  - Characterize the flaw
  - Evaluate flaw for continued service
    - IWB-3600; Code Case N-694
  - If repair required, expand to 100% Volumetric examination and BMV if not already performed
  - Repair/Replacement per Code or relief request

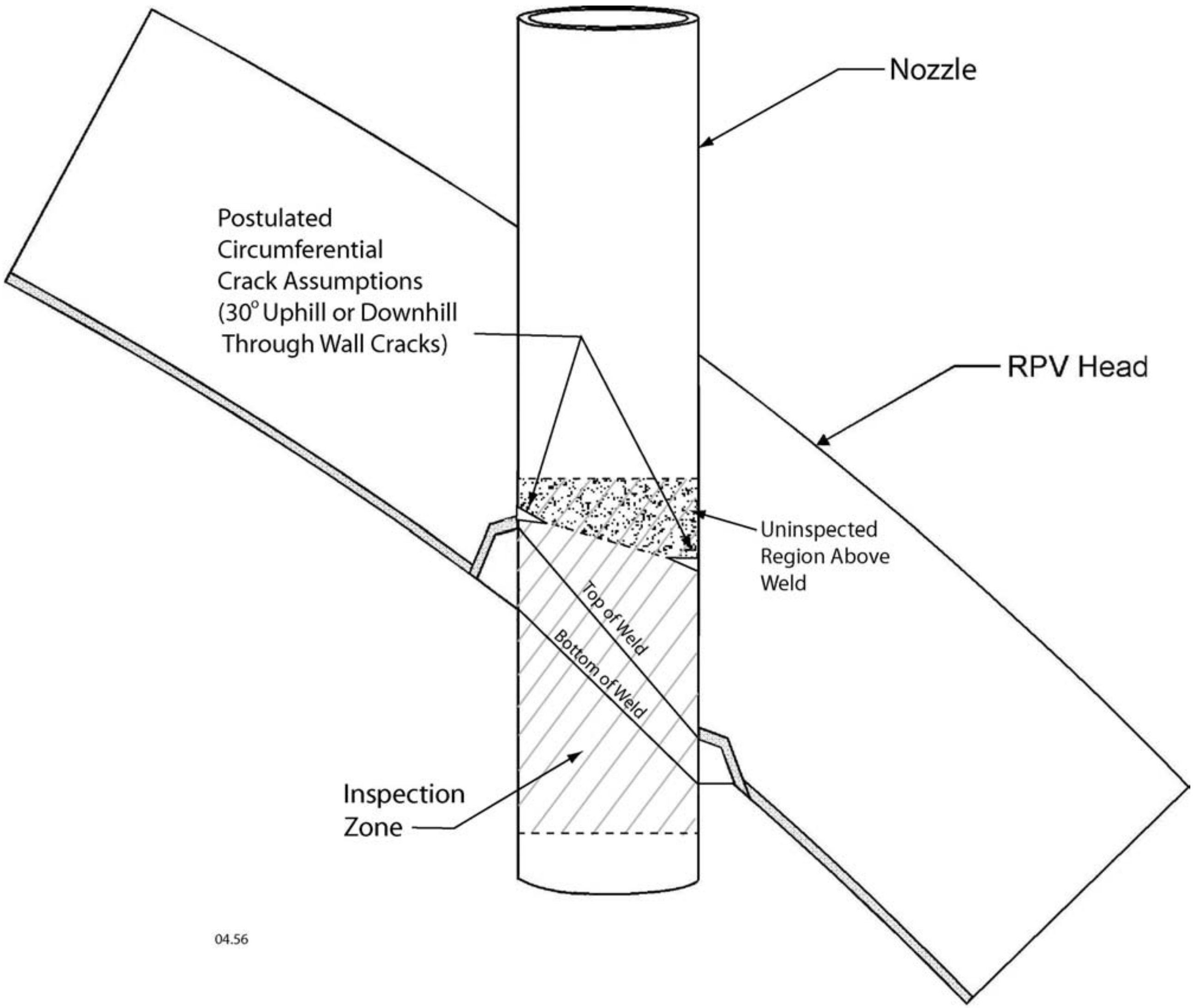
Alternate Methods/Analysis

- Appendix A to MRP-117 outlines analyses to demonstrate alternate exam volumes if MRP-117 exam volume is not achievable
- Three analysis methods (and acceptance criteria) described:
  - 20 ksi tension stress limit
  - Fracture Mechanics analysis
  - Probabilistic Fracture Mechanics
- Evaluating necessary combinations of methods for specific circumstances (lack-of-coverage location)

Appendix A – Fracture Mechanics Analysis and Criteria (below weld)



Appendix A – Fracture Mechanics Analysis and Criteria (above weld)



Appendix A – Probabilistic Fracture Mechanics Analysis and Criteria

- For plants in which no service-induced cracking that required repair has been detected:
  - compute the percentage of total required inspection volume that is not inspected for all nozzles
  - demonstrate (using methods such as those documented in MRP-105) that missed inspection zone coverage does not lead to unacceptable probabilities of leakage or nozzle ejection. This shall be demonstrated by:
    - a low probability of leakage (e.g. 5% per vessel per year or less)
    - An extremely low probability of core damage associated with the potential for nozzle ejection (i.e., on the order of 1 x 10^{-6} per vessel per year or less)

Future Actions

- MRP-117 requirements were translated into draft Code Case
- Presented draft Code Case last week to ASME Task Group on Alloy 600
    - Following incorporation of comments, expected to go out for letter ballot
- MRP will pursue approval of draft Code Case and MRP-117 in parallel

Discussion

- NRC Comments/Feedback
- Public Comment

MRP Alloy 600 RPV Head Document List

- MRP-110: Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants
  - MRP-103: Reactor Vessel Head Nozzle and Weld Safety Assessment for B&W Plants
  - MRP-104: RV Head Nozzle and Weld Safety Assessment for Westinghouse and Combustion Engineering Plants
  - MRP-105: Probabilistic Fracture Mechanics Analysis of PWR Reactor Pressure Vessel Top Head Nozzle Cracking
  - EPRI 1007842: Visual Examination for Leakage of PWR Reactor Head Penetrations
  - MRP-89: Demonstrations of Vendor Equipment and Procedures for the Inspection of CRDM Head Penetrations
- MRP-95: Generic Evaluation of Examination Coverage Requirements for Reactor Pressure Vessel Head Penetration Nozzles (Rev 1 pending)
- MRP-55: Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Material
- MRP-111: Resistance to Primary Water Stress Corrosion Cracking of Alloys 690, 52, and 152 in Pressurized Water Reactors
- MRP-117 (DRAFT): Inspection Plan for Reactor Vessel Closure Head Penetrations in US PWR Plants

Backup Slides

RPV Head Temperature Calculation

- Various methods have included:
  - thermo-hydraulic models that estimate water temperature in the upper head region
  - average of the hot leg temperatures (as measured with plant instruments)
  - plant specific models
  - measurement of the head temperature
- Where head temperature calculations were used in SA work:
  - MRP-105, Section 8 summarizes the sensitivity studies run on various parameters (stress, temperature, CGR) with the probabilistic fracture mechanics model.
    - analyzed the effect of +/- 5 deg standard deviation on the head temperature for a hot head plant - there was no significant effect on the change in core damage frequency.
  - MRP-110 Section 4 summarizes the upper head inspection results since spring 2001.
    - This section clearly demonstrates that our current temperature calculations which are used to calculate EDY are holding up well when compared to field results

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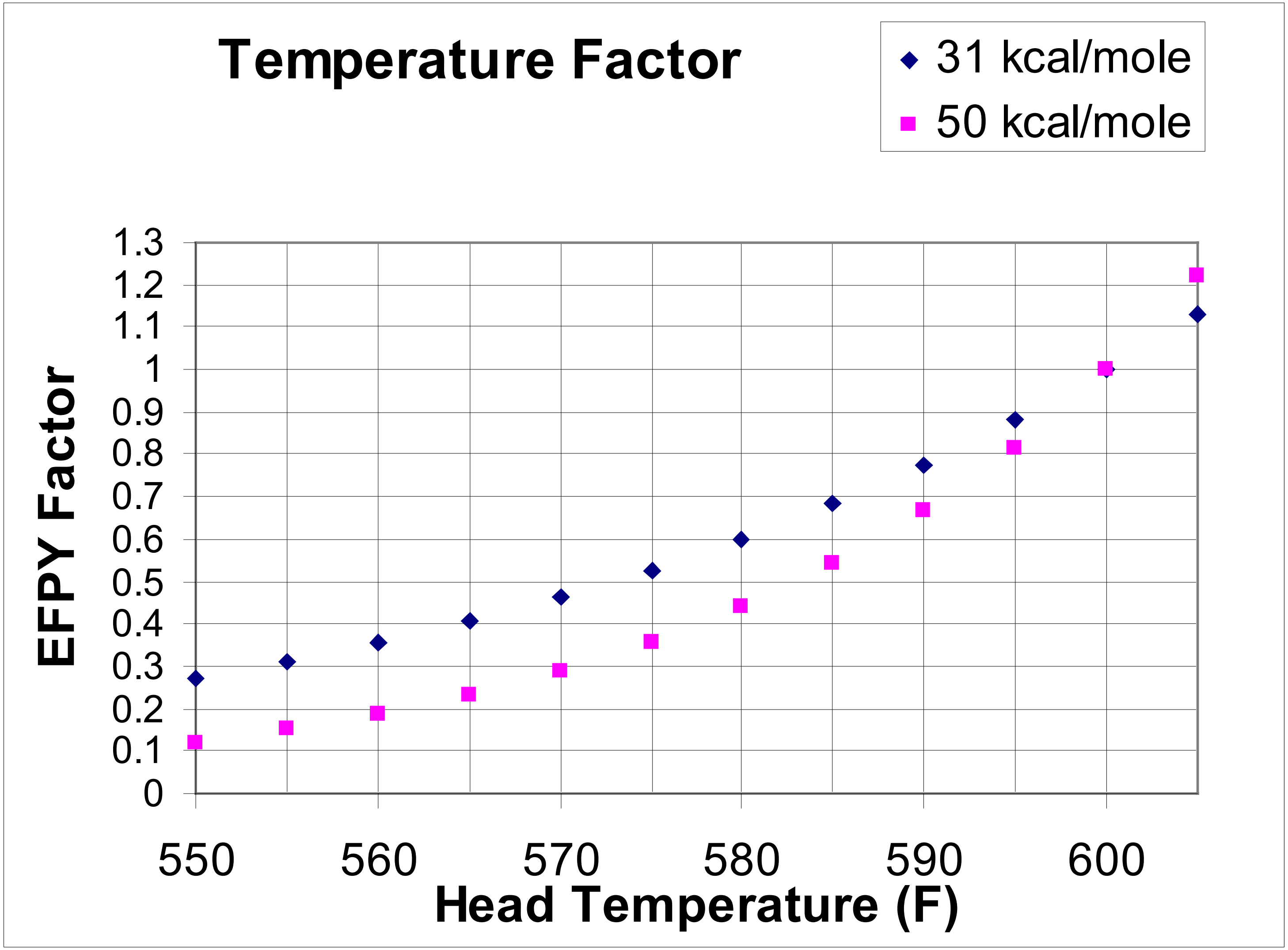
RPV Head Temperature Calculation

- Role of temperature in managing issue:
  - Currently, temperature is the primary input into the EDY calculation using an activation energy of 50 kcal/mole. Once a plant calculates EDY, this determines when the first volumetric inspection should be done (per the order and MRP-117).
  - In MRP-117, re-inspection intervals are based on RIY calc using an activation energy for crack growth of 31 kcal/mole, which means temperature won't play as large a role.
  - All plants with EDY > 12 have either volumetrically inspected or replaced. Approximately half of the plants with 8 ≤ EDY ≤ 12 have completed volumetric inspections. And just now starting to collect volumetric inspection data on plants with EDY < 8.
  - As of Dec 2003, 100% of all upper head penetrations have been inspected by BMV, UT, or ECT; or the heads have been replaced.
  - Baseline inspections for low temperature plants will 'trip' on calendar years not EDY.

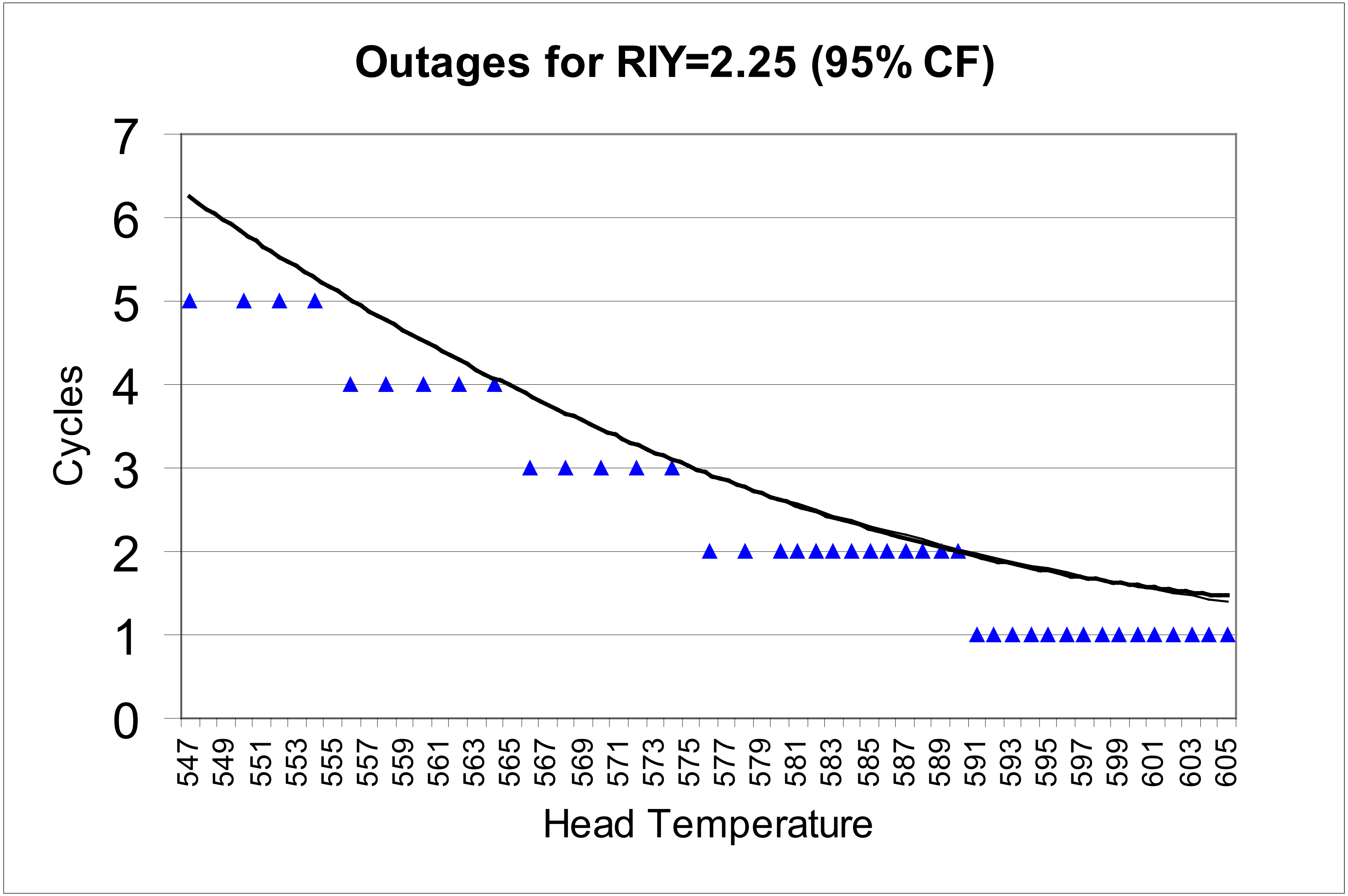
RPV Head Temperature Calculation

- Summary
  - Continue to monitor inspection data
  - Inspection results to date were used to develop model based on current head temperature estimates and have proven conservative
  - Shown by some ‘high temperature, old plants’ with no cracks identified during volumetric inspection

31 vs 50 kcal/mol



Outages for RIY=2.25 (95% CF)



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