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Application of PFM in the ASME Code Section XI

- Code Cases N-838 and N-702

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Background

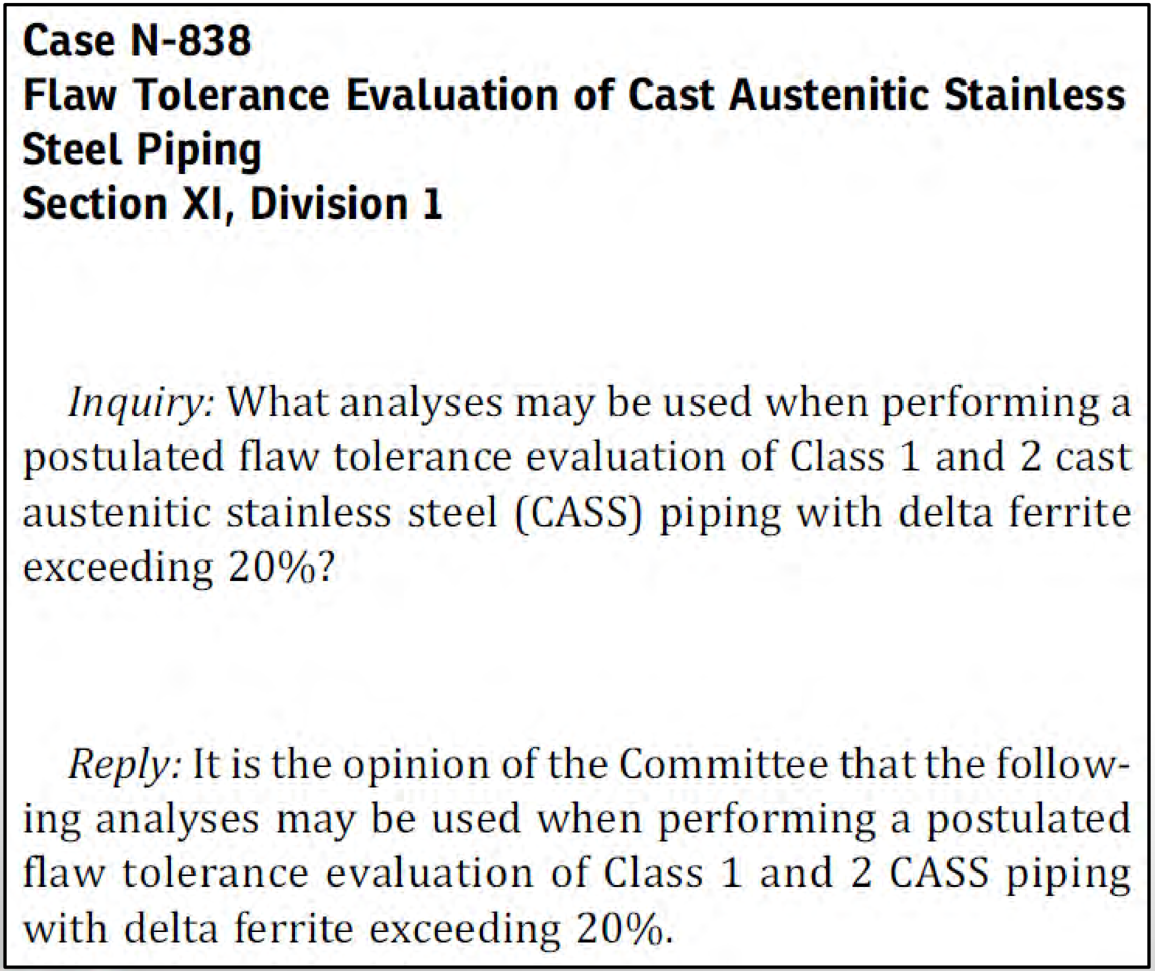
- Probabilistic Fracture Mechanics (PFM) is being widely used along with Deterministic Fracture Mechanics (DFM) to address some of the uncertainties associated with the input for the fracture mechanics assessment.

- In this context, PFM is being utilized for the ASME Code Section XI methodologies.

- This presentation covers two example applications of PFM
  - Code Case N-838 ; Flaw tolerance evaluation
  - Code Case N-702 ; Inservice inspection requirements

Code Case N-838

- Approval Date: August 3, 2015



Case N-838
Flaw Tolerance Evaluation of Cast Austenitic Stainless Steel Piping
Section XI, Division 1

Inquiry: What analyses may be used when performing a postulated flaw tolerance evaluation of Class 1 and 2 cast austenitic stainless steel (CASS) piping with delta ferrite exceeding 20%?

Reply: It is the opinion of the Committee that the following analyses may be used when performing a postulated flaw tolerance evaluation of Class 1 and 2 CASS piping with delta ferrite exceeding 20%.

Flaw Tolerance Evaluation
What's the Problem?

- CASS piping exhibits a wide range of material behavior, the worst of the aged material properties are for type CF-8M with high ferrite content (> 20%)

- The traditional method of performing a fracture mechanics evaluation may not be adequate for these components
  - Large scatter and variability in properties, in addition to the aging effects, means that material behavior is not well defined
  - There is currently no Code approved method for evaluating flaws in the CASS piping with high delta ferrite

- Assuming worst case loads, aged material properties and Code safety factors is very conservative for this application

How Can we Characterize the Flaw Tolerance of CASS Piping?

1) Deterministic Fracture Mechanics Analysis
   - Single calculation using appropriate analytical solutions (EPFM)
   - All inputs defined as bounding (i.e., conservative) values
   - Final result in terms of maximum tolerable flaw size to maintain safety factors (Code margins)

2) Probabilistic Fracture Mechanics Analysis
   - All inputs defined as probability (density) functions
   - Multiple calculations sample from the density functions
   - Final results for maximum tolerable flaw sizes in terms of conditional probability of failure

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Alternative Probabilistic Fracture Mechanics Method for CASS Piping

- Define inputs as probability functions and explicitly characterize mean values and uncertainties
- Changes in properties (e.g., toughness and strength) are determined from experimental data and predictive models
- A safety goal (e.g., conditional probability < 10^{-6}/reactor-yr) is established as a failure criteria consistent with other safety issues (e.g., Pressurized Thermal Shock)
- Results of PFM analysis can then be used to evaluate essential variables, determine sensitivity to changes and uncertainties, consider options to manage the issue, and develop flaw acceptance standards for CASS piping

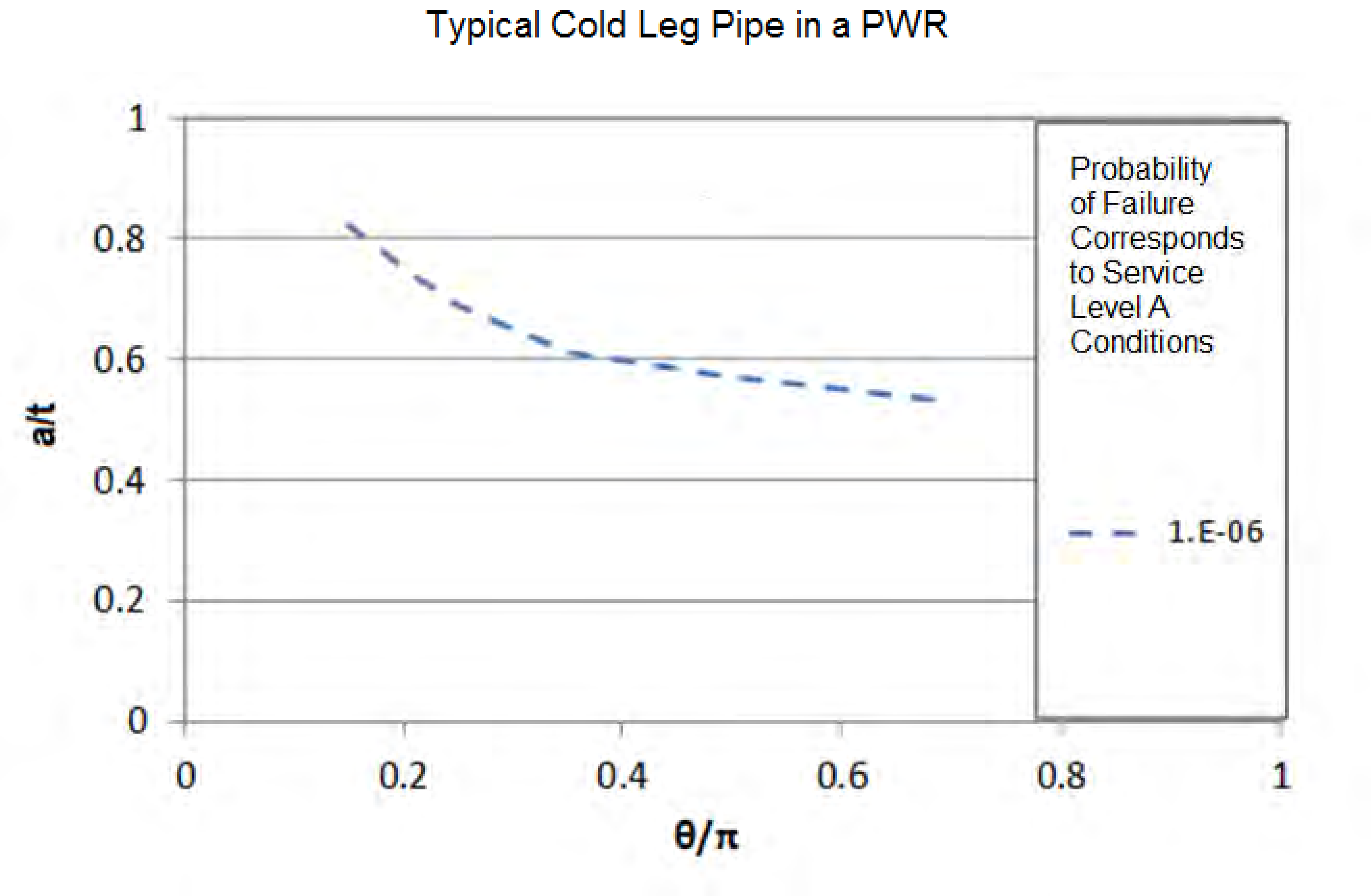
Failure Probability for Each Service Level Using PFM Method

Service Level	Prob. of Occurrence	Conditional Failure Probability
A	1.0	10^{-6}
B	~ 0.1	10^{-5}
C	$< 10^{-2}$	10^{-4}
D	$<< 10^{-2}$	10^{-4}

CASS Flaw Tolerance Method

- Perform screening to determine susceptible CASS components (with high delta ferrite content)
- Demonstrate that a one-quarter thickness reference flaw with a length six times its depth is a conservative assumption for the flaw tolerance analysis of CASS piping
- Establish appropriate fatigue crack growth law for calculating the final end-of-interval flaw size
- Determine revised flaw acceptance standards for high ferrite content CASS components (using PFM methodology and defined failure probability)

Sample Results from PFM Analysis



σm = 8 ksi, σb = 10 ksi
Fully Saturated CF-8M

Steps in Evaluating CASS Piping for Flaw Tolerance

The flaw tolerance evaluation of CASS components shall include the following steps:

1. Perform screening to determine susceptible CASS components (components with delta ferrite content exceeding 20%). Select locations for postulating flaws in susceptible (i.e., high delta ferrite) CASS components.
2. Determine the axial stresses at the location and determine the allowable flaw depths as a function of the Stress Ratio $((\sigma_m + \sigma_b)/\sigma_f)$ using the Allowable Flaw Depth vs. Length tables for circumferential flaws shown in Table 1 for Level A conditions.

Example of Flaw Acceptance Tables for Circ. Flaws (Ferrite ≥ 20%)

Table 1.

Maximum Allowable Flaw Depth-to-Thickness for Circumferential Flaws (Level A Conditions)

(Probability of Failure < 10^{-6})

Stress Ratio (1)	**Ratio of Flaw Length to Pipe Circumference, $l_f/\pi D$ [Note (3)]**							
	0.0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**≥ 0.75**
0.60	0.75	(2)	(2)	(2)	(2)	(2)	(2)	(2)
0.55	0.75	(2)	(2)	(2)	(2)	(2)	(2)	(2)
0.50	0.75	(2)	(2)	(2)	(2)	(2)	(2)	(2)
0.45	0.75	0.30	0.27	(2)	(2)	(2)	(2)	(2)
0.40	0.75	0.43	0.35	0.32	0.30	0.30	0.30	0.30
0.35	0.75	0.67	0.49	0.44	0.40	0.40	0.40	0.39
0.30	0.75	0.75	0.66	0.60	0.54	0.48	0.48	0.47
0.25	0.75	0.75	0.75	0.71	0.65	0.61	0.58	0.55
0.20	0.75	0.75	0.75	0.75	0.76	0.70	0.69	0.65
0.15	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.74
0.10	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75

Notes:

(1) Stress Ratio = $(\sigma_m + \sigma_b)/\sigma_f$

σ_m = primary membrane stress

σ_b = primary bending stress

σ_f = flow stress = 57.2 ksi (392 MPa) for CASS material

(2) Beyond the applicability of this Code Case

(3) l_f = end-of–evaluation period flaw length,

Circumference based on outside pipe diameter, D

Steps in Evaluating CASS Piping for Flaw Tolerance

3. Determine the hoop stress at the location and determine the allowable flaw depths as a function of the Stress Ratio (σ_h/S_m) using the Allowable Flaw Depth vs. Length tables for axial flaws shown in Table 4.

Example of Flaw Acceptance Table for Axial Flaws (Ferrite $\geq$ 20%)

Table 4.

Maximum Allowable Flaw Depth-to-Thickness [Note(1)] for Axial Flaws (Service Levels A, B, C and D Conditions)
(Probability of Failure < 10^{-6})

Stress Ratio [Note(2)]	**Nondimensional Flaw Length, $l_f/(R_m t)^{0.5}$ [Note (3)]**											
	0.0	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**	**1.2**	**1.4**	**1.6**	**1.8**	**2.0**	**2.2**
1.20	0.75	0.59	0.28	(4)	(4)	(4)	(4)	(4)	(4)	(4)	(4)	(4)
1.15	0.75	0.61	0.46	0.32	(4)	(4)	(4)	(4)	(4)	(4)	(4)	(4)
1.10	0.75	0.63	0.52	0.40	0.28	(4)	(4)	(4)	(4)	(40	(4)	(4)
1.05	0.75	0.66	0.56	0.47	0.37	0.29	(4)	(4)	(4)	(4)	(4)	(4)
1.00	0.75	0.68	0.60	0.53	0.45	0.38	0.33	0.29	(4)	(4)	(4)	(4)
0.90	0.75	0.71	0.67	0.63	0.54	0.45	0.38	0.37	0.34	0.33	0.33	0.33
0.85	0.75	0.71	0.66	0.62	0.58	0.53	0.50	0.46	0.46	0.45	0.45	0.45
0.80	0.75	0.71	0.68	0.64	0.61	0.57	0.53	0.53	0.53	0.49	0.49	0.49
0.75	0.75	0.72	0.70	0.67	0.65	0.61	0.58	0.58	0.54	0.53	0.53	0.53
0.70	0.75	0.74	0.72	0.71	0.70	0.65	0.61	0.61	0.61	0.58	0.57	0.57
0.65	0.75	0.74	0.74	0.73	0.73	0.70	0.65	0.65	0.65	0.61	0.61	0.61
0.60	0.75	0.75	0.75	0.75	0.74	0.73	0.70	0.69	0.69	0.65	0.65	0.65
0.55	0.75	0.75	0.75	0.75	0.75	0.74	0.74	0.70	0.70	0.70	0.70	0.69
0.50	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.74	0.74	0.73	0.73	0.73
0.45	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.74
$\leq$ 0.40	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75

Notes:

(1) Flaw Depth = a_{allow} for surface flaw
= 2 a_{allow} for a subsurface flaw
t = pipe wall thickness

(2) Stress Ratio = $\sigma_h/18.1$ (U.S. customary units: ksi)
Stress Ratio = $\sigma_h/124$ (SI units: MPa)
$\sigma_h = pR_m/t$, where R_m = mean pipe radius, and
p = internal pressure

(3) l_f = end-of-evaluation period axial flaw length

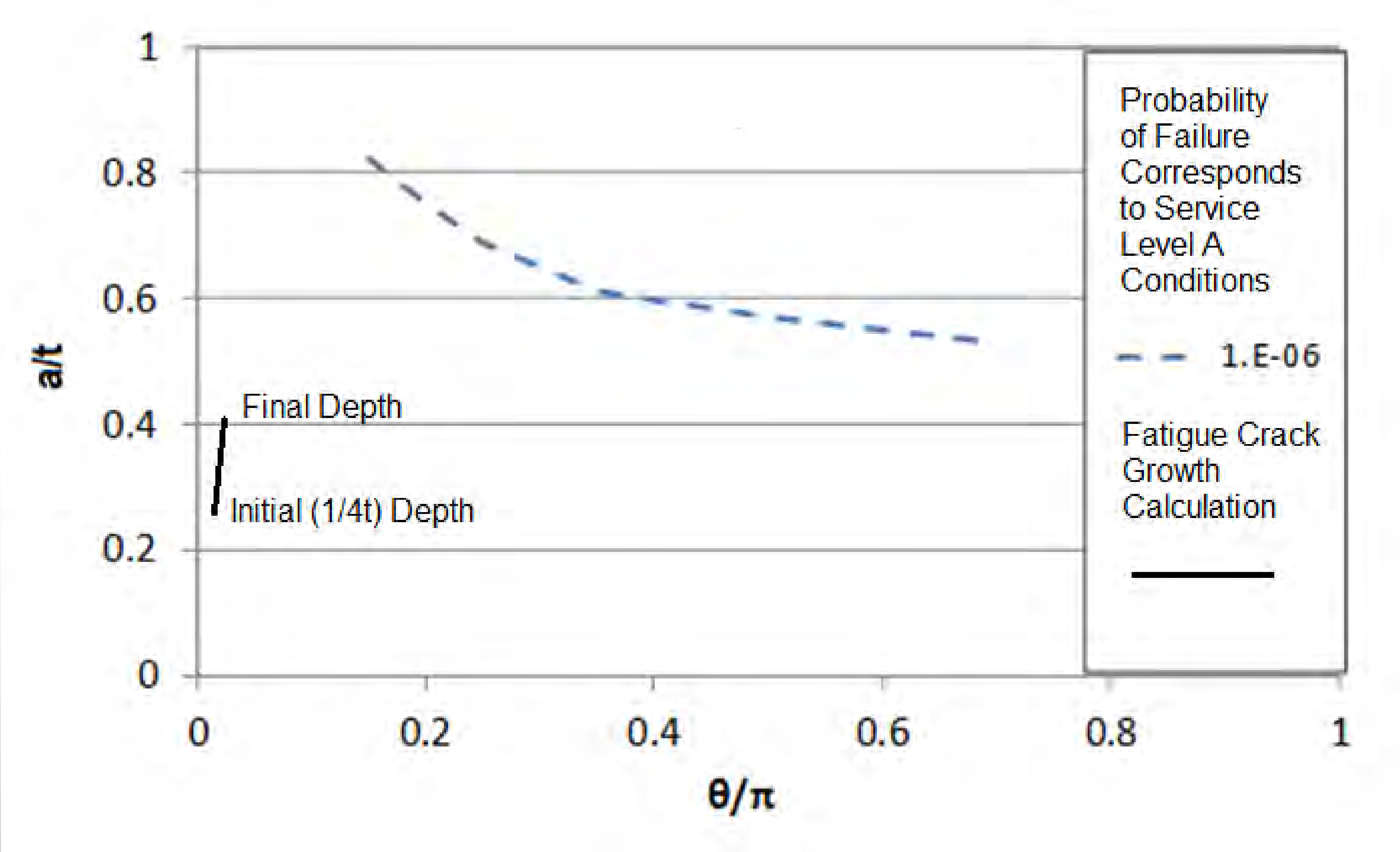
(4) Beyond the applicability of this Code Case

Steps in Evaluating CASS Piping for Flaw Tolerance (cont.)

4. Postulate a one-quarter thickness reference flaw with a length six times its depth and a perform fatigue crack growth analysis for the cyclic loading conditions during the operating interval.

5. Establish the final flaw depths at the end of the interval and confirm that the final flaw size remains below the maximum allowable flaw depth(s) from steps *(2) and (3)*.

Final Step is Fatigue Crack Growth Calculation



Example Calculations Using PFM Model

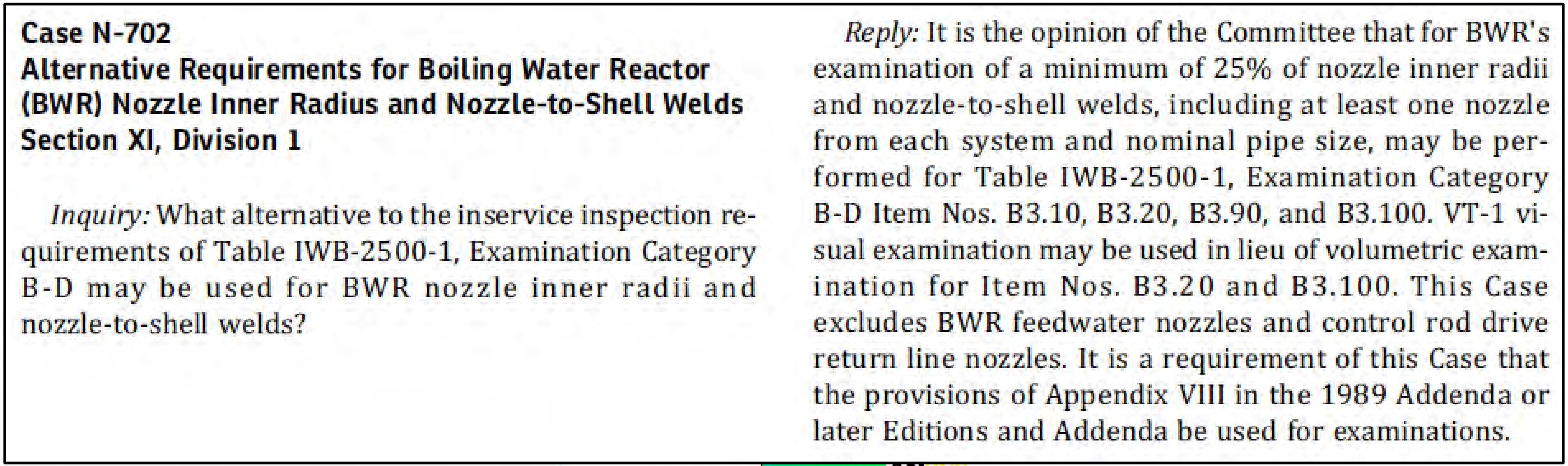
Component	Service Level	Probability of Failure	Maximum Allowable Flaw Size (Depth)		Final Flaw Depth After 60-Year Evaluation Period	
			Depth, a (in.)	a/t	Depth, a (in.)	a/t
Hot Leg	A	$10^{-6'}$	1.35	0.54	0.6444	0.2578
	B	$10^{-5'}$	1.18	0.47		
	D1	$10^{-4'}$	1.43	0.57		
	D2	$10^{-4'}$	0.95	0.38		
Cold Leg	A	$10^{-6'}$	2.61	0.86	0.7673	0.2532
	B	$10^{-5'}$	2.43	0.8		
	D1	$10^{-4'}$	2.88	0.87		
	D2	$10^{-4'}$	1.00	0.33		
Crossover Leg	A	$10^{-6'}$	1.77	0.66	0.6823	0.2538
	B	$10^{-5'}$	1.53	0.57		
	D1	$10^{-4'}$	1.69	0.63		
	D2	$10^{-4'}$	0.78	0.29		

Summary

- Aging management of susceptible CASS components involves a qualified volumetric inspection or demonstrated flaw tolerance
- A PFM method has been developed to establish maximum tolerable flaw sizes in CASS piping
- By showing large tolerable flaw sizes (i.e., depths) in CASS piping, the confirmatory volumetric examinations would be performed to show that no significant flaws could exist

Code Case N-702

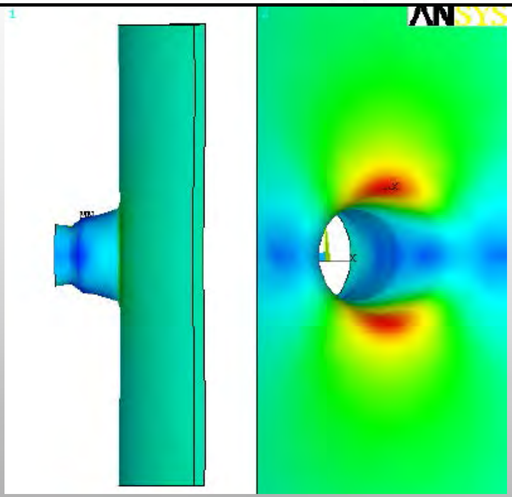
- Approval Date: February 20, 2004



Case N-702
Alternative Requirements for Boiling Water Reactor (BWR) Nozzle Inner Radius and Nozzle-to-Shell Welds
Section XI, Division 1

Inquiry: What alternative to the inservice inspection requirements of Table IWB-2500-1, Examination Category B-D may be used for BWR nozzle inner radii and nozzle-to-shell welds?

Reply: It is the opinion of the Committee that for BWR's examination of a minimum of 25% of nozzle inner radii and nozzle-to-shell welds, including at least one nozzle from each system and nominal pipe size, may be performed for Table IWB-2500-1, Examination Category B-D Item Nos. B3.10, B3.20, B3.90, and B3.100. VT-1 visual examination may be used in lieu of volumetric examination for Item Nos. B3.20 and B3.100. This Case excludes BWR feedwater nozzles and control rod drive return line nozzles. It is a requirement of this Case that the provisions of Appendix VIII in the 1989 Addenda or later Editions and Addenda be used for examinations.



Code Case N-702 (cont'd)

- Inspection requirements call for 100% inspection every 10-year interval for all BWR RPV nozzle blend radii and nozzle-to-shell welds
- A project was completed and documented in BWRVIP-108NP (EPRI Report 1016123) to provide the technical basis for the reduction of the nozzle-to-shell welds and nozzle blend radii to 25% of the nozzles every 10 years.
- BWRVIP-108NP is the technical basis document for ASME Code Case N-702.

Code Case Technical Bases (BWRVIP-108NP)

- BWR Vessel and Internals Project Technical Basis for the Reduction of Inspection Requirements for the Boiling Water Reactor Nozzle-to-Vessel Shell Welds and Nozzle Blend Radii

- Available field inspection data and performance demonstration data for BWR nozzles were evaluated. Representative nozzles for the evaluation, including core spray, main steam, and recirculation inlet and outlet nozzles were selected.

- PFM and DFM calculations were performed to assess the reliability of the nozzles after implementing the revised inspection approach.

Code Case Technical Bases (BWRVIP-108NP)

- VIPERNOZ code
  - Uses Monte Carlo methods to assess the reliability of a BWR RPV having flaw distributions, material properties, fluence distributions, and several other parameters, which are assumed to be randomly distributed.

- A DFM evaluation was also performed to demonstrate that expected flaws, based on field experience, would not jeopardize the structural integrity of the vessel.

- A flaw is selected that bounds any expected flaws based on field inspection results. Using appropriate material properties, a deterministic linear elastic fracture mechanics evaluation is performed to demonstrate that failure is not expected.

Code Case Technical Bases (BWRVIP-108NP)

- For any cracks in the nozzle blend radius region, the results show that the conditional failure probability of the nozzles (due to a low temperature overpressure (LTOP) event) are very small ($<1x10^{-6}$ for 40 years), even without any inservice inspection.

- At the nozzle-to-vessel shell weld, the conditional probability of failure—due to the LTOP event—is also very small ($<1x10^{-6}$ for 40 years), with or without any in-service inspection.

Code Case Technical Bases
(BWRVIP-241)

- The Safety Evaluation Report of BWRVIP-108 requires additional criteria to be met in order to apply the technical basis of BWRVIP-108
  - These criteria are based on the parameters defined using the RPV and nozzle dimensions.

- BWRVIP-241 : Probabilistic Fracture Mechanics Evaluation for the Boiling Water Reactor Nozzle-to-Vessel Shell Welds and Nozzle Blend Radii

Plant Specific Analysis

- Plant specific analysis is required for a relief request to extend the applicability of Code Case N-702 through 60 (or 80) years
- Monticello was the first plant to be granted relief through 60 years
- More than 10 other US BWR sites have performed plant specific analysis through SI and applied for relief through 60 years
- Plant specific analysis using the methods outlined in the technical basis documents of BWRVIP-108 and BWRVIP-241
  - **Stress analysis**
    - Either the Recirculation Inlet (N2) or Recirculation Outlet (N1) nozzle identified as bounding based on the requirements in BWRVIP-241
    - Through wall stresses from internal pressure and thermal transients determined for use in fatigue crack growth
  - **Probabilistic Fracture Mechanics (PFM) analysis**
    - Considers additional fluence, thermal fatigue cycles, and stress corrosion effects through 60 or 80 years

Ongoing Efforts

- EPRI funded research to reduce or eliminate non-RPV vessel circumferential welds, nozzle-to-vessel welds, and nozzle inner radii for both boiling and pressurized water reactors
  - Non-RPV components are not subjected to significant fluence, thus radiation embrittlement is not a concern
  - Stress intensity factor solutions and stress corrosion crack growth laws will be updated to current industry standards