Summary of MRP-479

Technical Basis for Changes to Inspection and Flaw Evaluation of CASS PWR Piping Components

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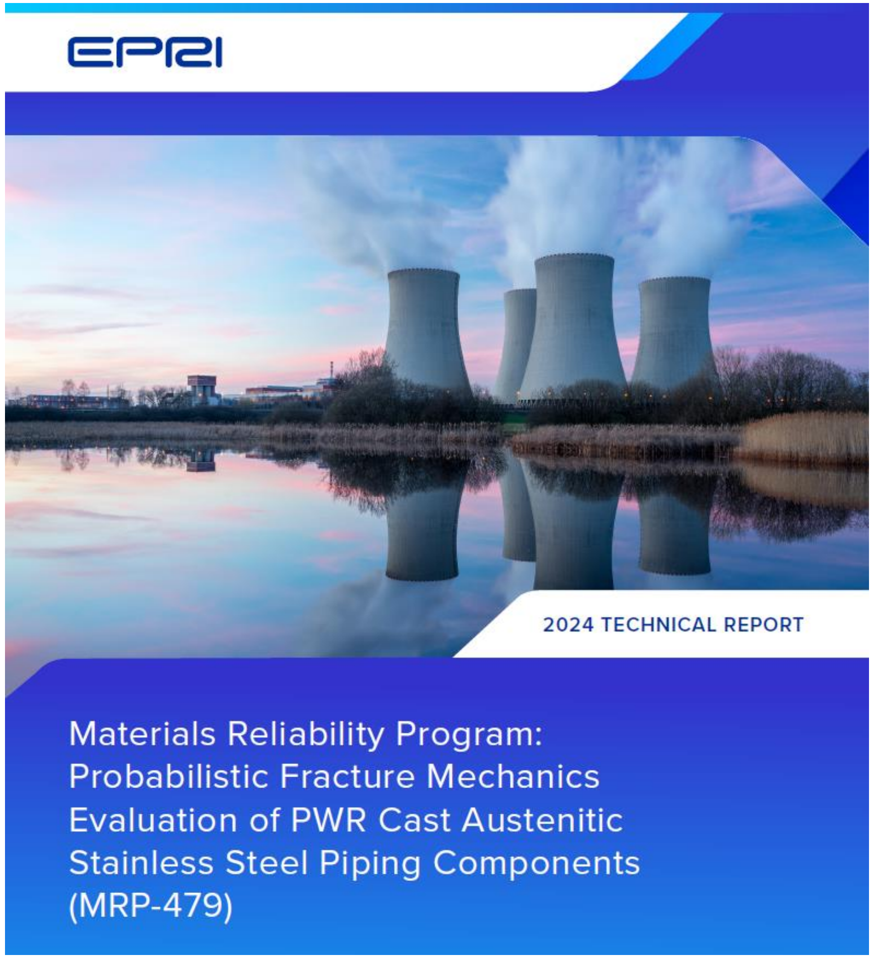
Outline

- Background
- General Discussion
- Technical Basis for Inspection of CASS without Axial Flaw Detection Capability
- Technical Basis for Evaluation of Circumferential Flaws without Crediting Depth Sizing
- Conclusions



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CASS-Specific Challenges
Background

- Because of the heterogenous cast austenitic stainless steel (CASS) material microstructure, ultrasonic testing (UT) technology applied to CASS components is not capable of meeting the PDI qualification standards that have been developed for other piping materials, particularly with regards to:
  - Detection of axial flaws
  - Depth-sizing of circumferential flaws

- In addition, thermal embrittlement of aged CASS material results in degraded material toughness, reducing acceptable flaw sizes

Class 1 CASS Piping Components in Scope

Background

- Scope consists of main loop and surge line piping in domestic PWR designs
  - Short segment of pipe fittings subject to examination is treated as straight piping, consistent with IWB-3641 approach
  - Similar metal welds and CASS at unmitigated dissimilar metal welds are in-scope
- In these piping components, CASS material is used in:
  - Westinghouse (WEC) main loop piping components
  - B&W RCP inlets and outlets
  - Combustion Engineering (CE) RCP inlets/outlets and nozzle safe ends
  - AP-1000 RCP discharge nozzle outlet
  - CE plants surge line piping (except no CASS in surge line for CE-80 design)

Axial Flaw Scope

- Main loop CASS piping components
- CASS surge line piping components

Circ. Flaw Scope

- Main loop CASS piping components

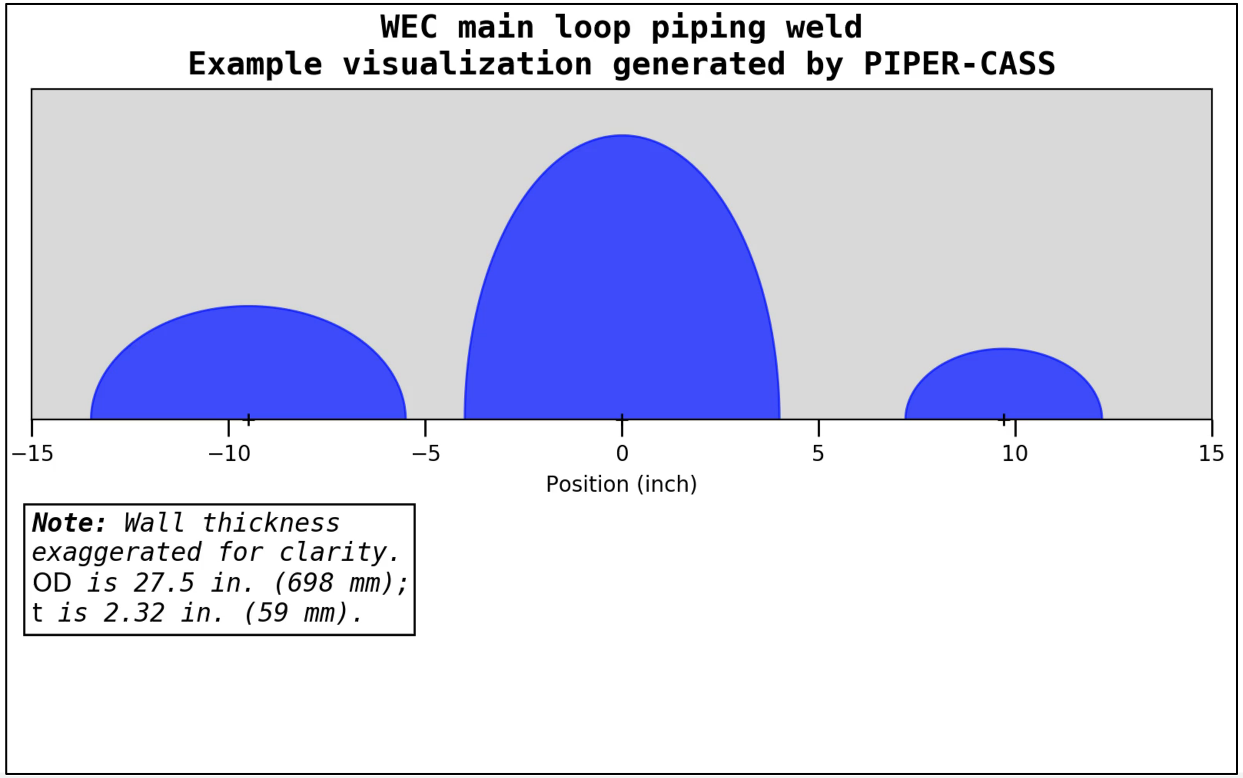
Out of Scope

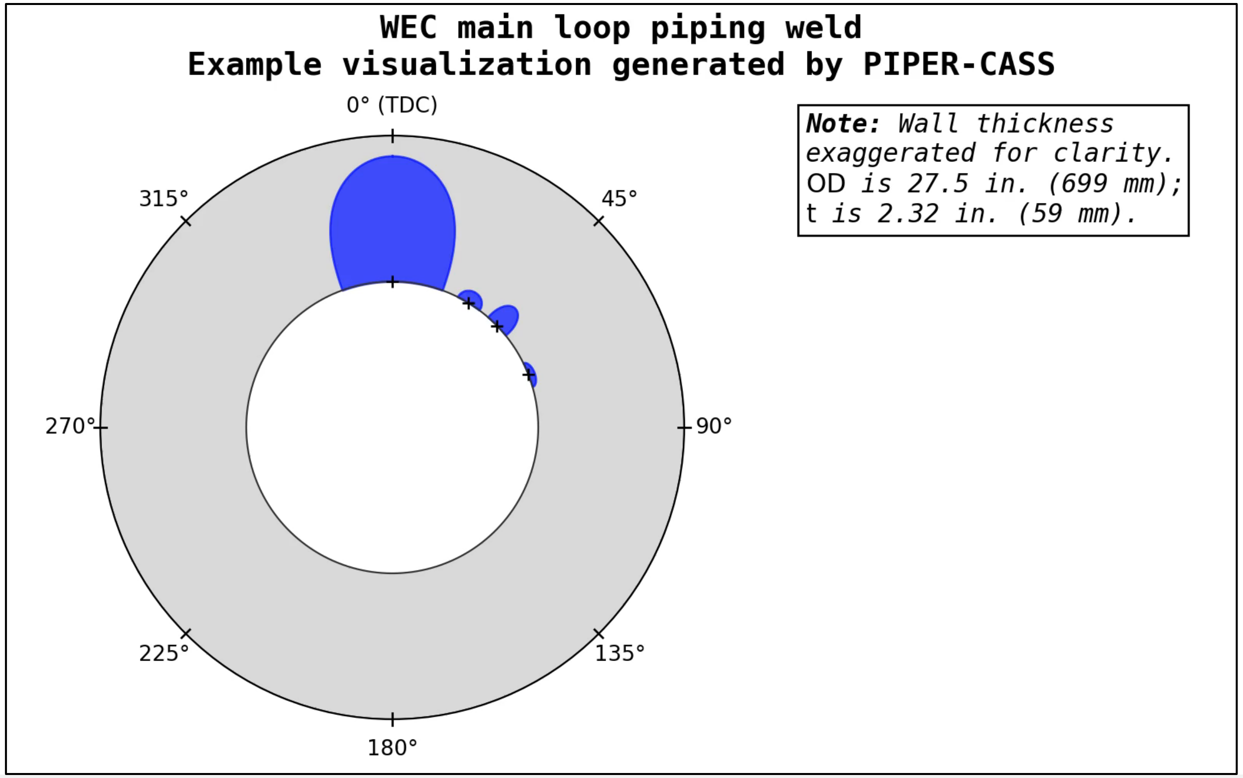
- Surge line under FPO
- Other branch connections
- SG to RCP weld (AP-1000)
- PWSCC-susceptible material

PIPER-CASS Software

Background

- PIPER-CASS (Piping Integrity Probabilistic Evaluation for Reactors – CASS) is custom PFM software developed by EPRI (under commercial quality assurance program) that is tailored for evaluation of CASS
  - Enhanced EPFM stability solver for degraded toughness materials like thermally aged CASS, and extended EPFM stability checks to part-through-wall flaws (in addition to net section collapse stability models)
  - Greater flexibility when defining operating transients, with integrated thermal stress solver
  - Relationships and correlations included to reflect nature of variability in CASS material properties
- Successfully benchmarked versus xLPR

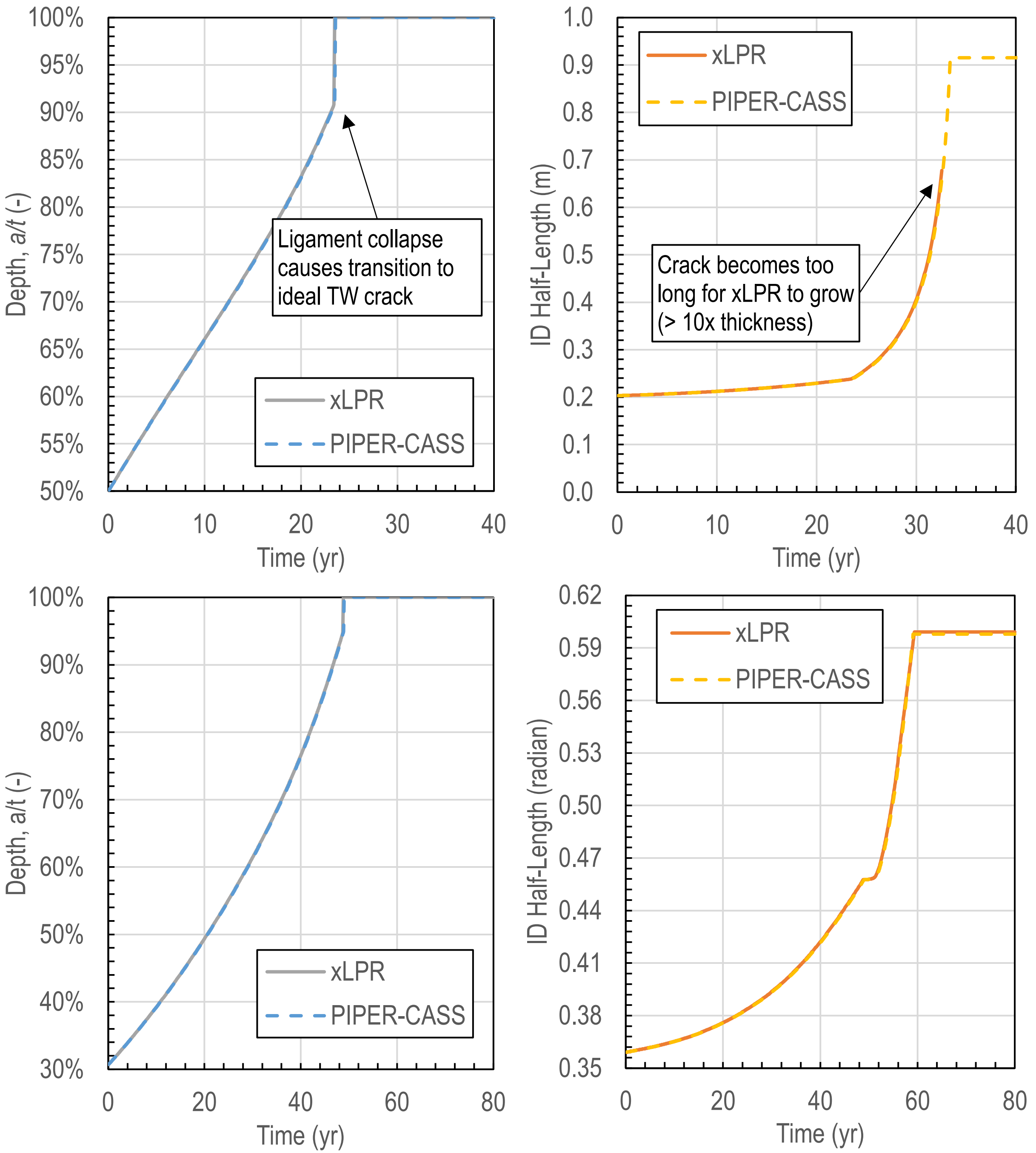




Benchmarking versus xLPR

Background

- PIPER-CASS automated test suite implements compatible test cases from xLPR modules
- Developed input sets compatible with both xLPR and PIPER-CASS for benchmarking integrated codes
- A separate PIPER-CASS version (git branch) is maintained to reconcile modeling differences and account for known xLPR bugs
- Achieved matching benchmark results
  - Differences in submodule test cases dispositioned using debugging mode of IDE, comparing xLPR FORTRAN modules versus PIPER-CASS Python
  - Differences in benchmarking dispositioned by halting xLPR at key timesteps to inspect variable values within GoldSim framework; compared to PIPER-CASS values via IDE debugging mode
  - Submitted bugs identified in xLPR to the xLPR program



Acceptance Criteria

General Discussion

- Consider cumulative conditional probability of rupture for a single weld location
  - Conditional on transient occurrence for a given Service Level loading
- PIPER-CASS applies the same acceptance criteria as MRP-362, Rev. 1
  - MRP-362, Rev. 1 provides the technical basis for Code Case N-838, which is conditionally approved by the US NRC (with conditions unrelated to the PFM acceptance criteria)
  - MRP-362, Rev. 1 assesses the failure probabilities implied by the deterministic flaw evaluation procedure of ASME Section XI for allowable circumferential flaw sizes and assuming limit load failure given probabilistically distributed material flow strength
  - Resultant marginal probability of rupture is 10^{-6} for each Service Level and represents the acceptable risk of a LOCA when leaving a piping flaw in service

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

General Inputs for PFM Analyses

General Discussion

- WEC reactor coolant system (RCS) main loop piping geometry cases
  - WEC 1: 27.5 in. (699 mm) outside diameter, 2.32 in. (58.9 mm) wall thickness
  - WEC 2: 37.59 in. (955 mm) outside diameter, 3.09 in. (78.5 mm) wall thickness

- Combustion Engineering (CE) surge line piping geometry cases **(axial flaw cases only)**
  - CE 1: 12.75 in. (324 mm) outside diameter, 1.01 in. (25.7 mm) wall thickness
  - CE 2: 12.75 in. (324 mm) outside diameter, 1.31 in. (33.3 mm) wall thickness

Applicability to RCP Nozzles in B&W, CE, and AP-1000 Plants

General Discussion

- A comparison of geometry and load differences shows that the conclusions of the PFM analyses for Westinghouse CASS main loop piping extends to reactor coolant pump (RCP) nozzle CASS locations in B&W, CE, and AP-1000 plants
  - Predicted fatigue crack growth during a single fuel cycle is very small
  - Wall thickness affects both distance for crack to grow through wall as well as the magnitude of thermal gradient stresses
    - The WEC case thicknesses bracket the other plant locations
  - Heatup and cooldown transients are major contributors to fatigue crack growth
    - Reviews of the differences in transients among the designs supports the conclusion regarding the applicability of the PFM results to main loop components in the other plant designs
- This conclusion applies to the conclusions for the PFM analyses of both the axial and circumferential flaw cases

Case / Component	ID (inch)	OD (inch)	t (inch)	R_i/t	Norm. Op. P (psig)	Avg Hoop Pressure Stress (ksi)
WEC 1	22.9	27.5	2.32	4.9	2250	11.1
WEC 2	31.4	37.6	3.09	5.1	2250	11.4
B&W RCP Suction	28.0	33.0	2.5	5.6	2155	12.1
B&W RCP Discharge	28.0	33.0	2.5	5.6	2155	12.1
CE RCP Suction	29.9	36.1	3.1	4.8	2250	10.9
CE RCP Discharge	29.9	36.1	3.1	4.8	2250	10.9
AP-1000 RCP Discharge	22.0	27.1	2.56	4.3	2235	9.6

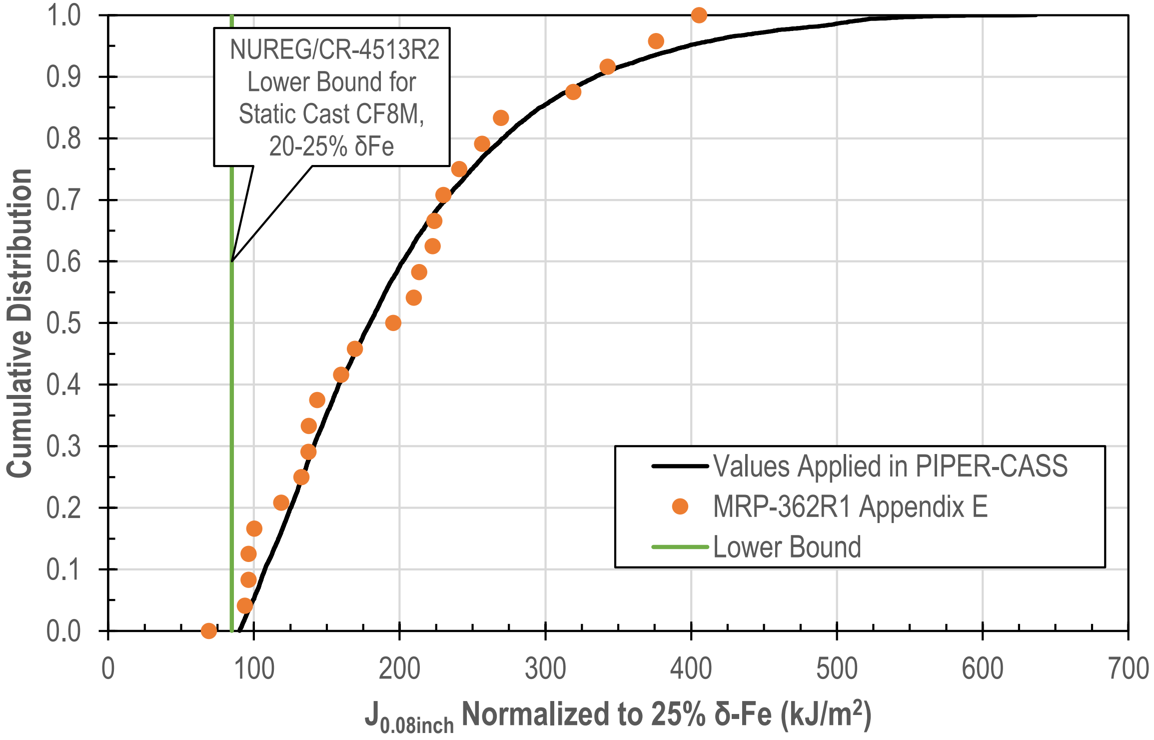
General Inputs for PFM Analyses

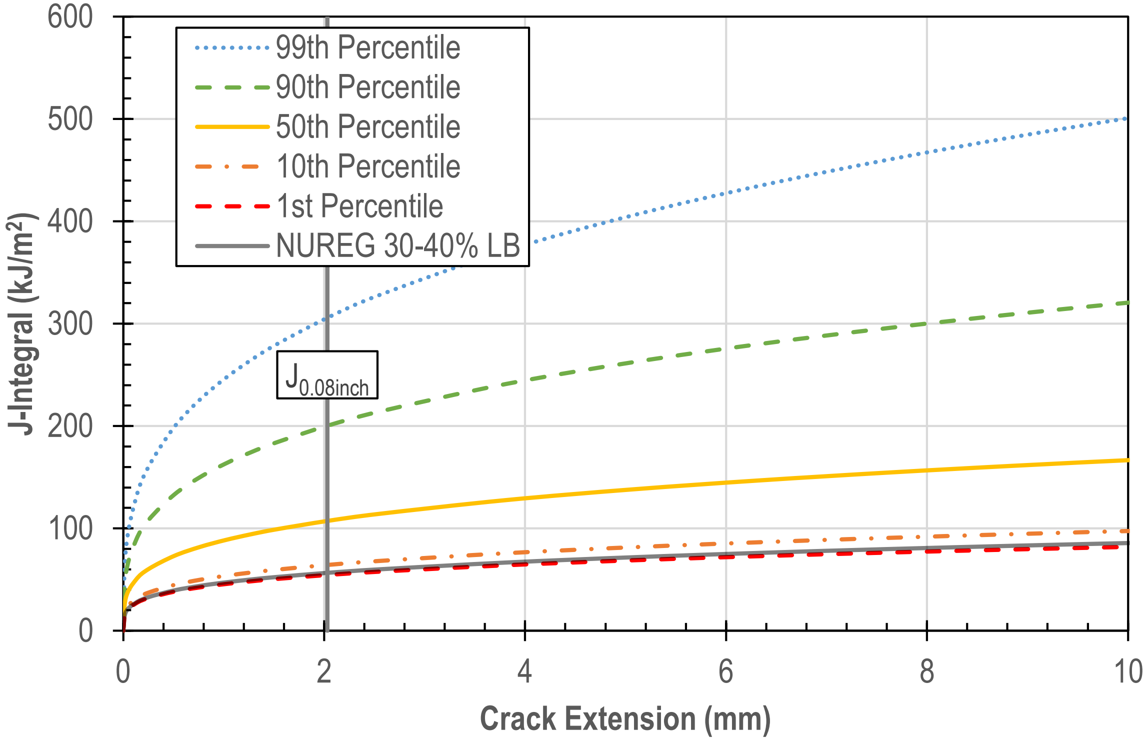
General Discussion

- Stresses caused by normal operation and transients
  - Fatigue growth of axial flaws occurs by radial thermal gradient stresses (RTGS) and pressure transients
  - Fatigue growth of circumferential flaws occurs by piping load transients (e.g., OBE) and pressure transients; part-through-wall flaws also grow by RTGS
- Flaw stability assessed under loads for each of the four Service Levels: A, B, C, and D
- Material modeled as CF8M, at the fully-aged condition
  - CF8M is the CASS alloy subject to the lowest fracture toughness at saturation of thermal aging effects
  - Fracture toughness calibrated considering the data in MRP-362 R1 Appendix E for fully aged toughness at operating temperature
  - Conservatively assumed nominal 40% δ-ferrite

General Inputs: Fracture Toughness

General Discussion





- The J-R material toughness in PIPER-CASS is based on sampling of Charpy Impact C_V data
  - Applied relations from NUREG/CR-4513 R2 for fully-aged Type CF8M to get J-R curve parameters
- Variability in the value for the J-R curve at extension of 0.08 inch was calibrated considering the data in MRP-362 R1 Appendix E for fully aged toughness at operating temperature
  - Distribution extends beyond the lower bound value recommended by NUREG/CR-4513 R2

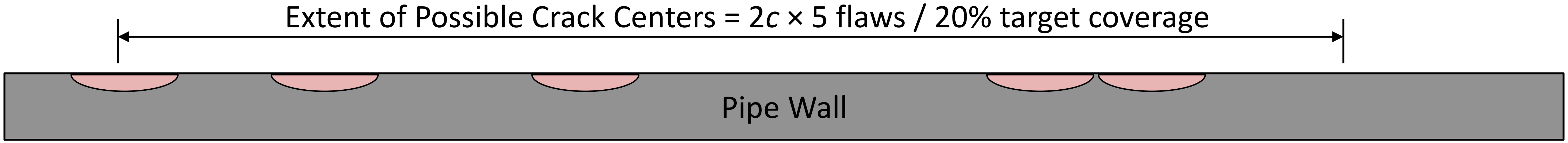
Inspection without Crediting Axial Flaw Detection (ASME Record 23-2033)

Approach

- **Objective:** Investigate axial fatigue cracking assuming no benefit of periodic NDE nor online leak detection
  - Assess whether inspections to detect axial cracking are necessary to maintain structural and leak tight integrity
- Fatigue crack growth for 80 years is modeled using probabilistic fracture mechanics (PFM) to bound the concerns for both fatigue crack initiation and manufacturing flaws
  - Custom PFM code (PIPER-CASS) shares many of the same models as xLPR, but is tailored for evaluation of CASS (e.g., added part-depth flaw EPFM stability solvers)

Key Inputs for PFM

- Base cases include transients for base load operation
  - MRP-393 provides best-estimate transient definitions for RCS piping based on plant experience
  - CE surge line transients defined using a design specification, with frequency set to best-estimate values based on plant experience
- Initial flaw assumption at time zero selected to reasonably bound any manufacturing flaws actually present in the piping, as well as the effect of fatigue crack initiation over operating life, with base cases having:
  - Five (5) coplanar part-through-wall flaws
  - Depth of 25% of the thickness
    - EPRI TR-100034 states that 1% of flaws missed by pre-service examinations have a depth of ≥ 15% through-wall
  - Conservatively assuming flaws to be wetted and located on the inside surface
  - Initial length of each individual flaw based on 6:1 aspect ratio ($2c/a = 6$)
  - Coplanar cracking present over ~20% of the modeled length to aggressively consider the effect of multiple flaw initiation



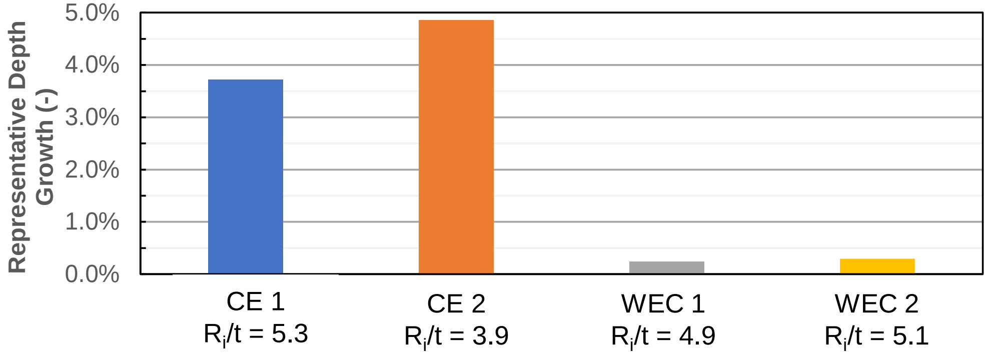
Sensitivity Cases Considered

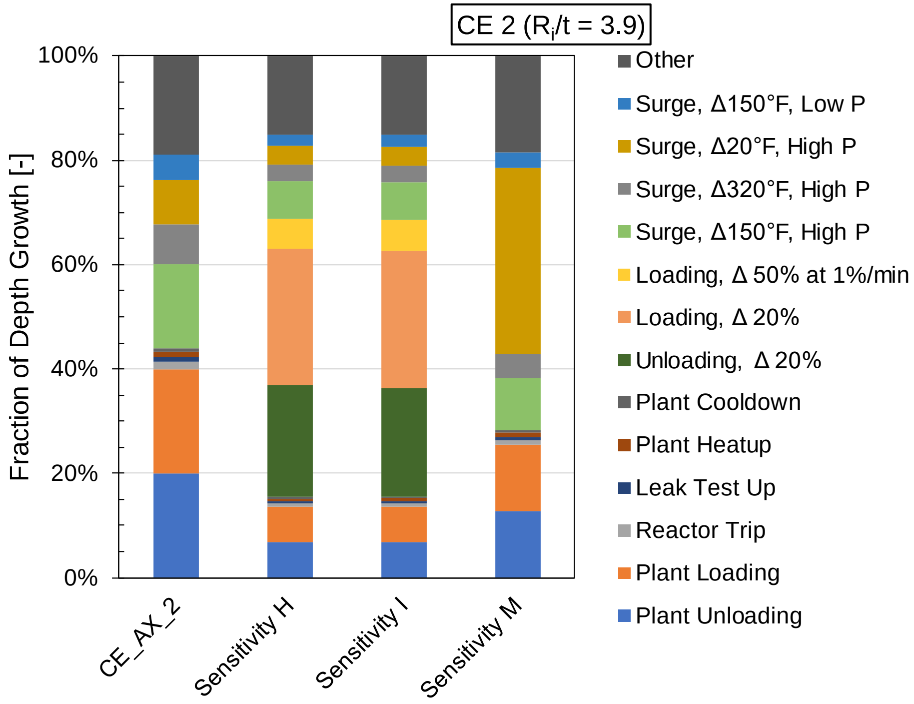
Sensitivity Case	Description	Applicability
A	Remove factor of 0.8 on growth	WEC, CE
B	Only include upper 50th percentile of C_{ss} distribution	WEC, CE
C	Elevated WRS: Apply weld repair (WEC) or 50% higher WRS magnitude (CE)	WEC, CE
D	Remove WRS	WEC, CE
E	Increase rate of Heatup and Cooldown transient to 100°F/hr and disable rise time limit	WEC
F	Apply transients at design basis frequency	WEC
G	100% flawed length at 50% depth	WEC
	Distribution of detected manufacturing flaws in large-bore CASS elbows	CE 1 geometry
H	Use of flexible power operations (FPO), with 0.5%/minute power ramp rate for 80%-100% and 100%-80% loading/unloading (begins part-way through operation for CE)	WEC, CE
I	Same as H, except 1%/minute power ramp rate	WEC, CE
J	Apply normal variations in pressure and temperature with a reasonable magnitude	CE
K	100% flawed length at 33% depth	WEC
	8 initial flaws (32% flawed length)	CE
L	Unaged material	WEC, CE
M	Increase minimum flow rate from 0.3 m/s to 0.5 m/s	CE
N	Single through-wall flaw with same length as base case initial flaw (*base case 3 in PVP paper)*	WEC 1 geometry
O	Targeted final through-wall crack size (*base case 4 in PVP paper)*	WEC 1 geometry
t1, t2, t3	Temporal convergence sensitivity, 5 day, 25 day, or 50 day timestep (respectively)	CE

FPO modeled as increased frequency of loading and unloading, with different ramp rates (0.5-2.0% power per minute) and power changes (Δ 20-70% power change) resulting in total of 330 loading and unloading events per year

PFM Results

- **PFM modeling under normal base loading conditions yields a rupture probability that meets the acceptance criteria across all Service Levels to cover 80 years of operation (< 10^{-6} probability of rupture after 80 years)**
  - **Probability of leakage is similarly low (< 10^{-6})**
- Modest flaw growth in CE surge lines under base load operation
  - On average, 25% deep flaws in the surge line grew to less than 30% deep
  - Axial flaw growth in CE surge line driven by surges (including within loading and unloading)
- Slight growth of postulated flaws in WEC main loop piping
  - On average, 25% deep flaws in the main loop piping grew to less than 26% deep in 80 years
  - Axial flaw growth in WEC main loop piping driven by transients with large rise times and large pressure changes (heatup/cooldown) as well as by abrupt power changes (trips)
- WEC main loop cases with 80 years of FPO did not result in ruptures
  - Amount of growth under FPO is sensitive to power ramp rate (slower is better)
- CE surge line piping cases show 20 years of FPO after 60 years of base load operation yields an unacceptable rupture probability
  - FPO cases conservatively assumed insurge and outsurge events to occur with each change in power level, consistent with loading/unloading transients





"Representative depth growth" is the average of the total flaw growth divided by the initial quantity of cracks

Axial Cracking Sensitivity Study Results

Table 6-2
Sensitivity Case Cumulative Probabilities of Occurrence over 80 Years for Sensitivity Cases Applied to WEC_AX_1

Case Name	Service Levels with Ruptures	Cumulative Probability of Rupture			Leakage
		Service Level A	Service Level B	Service Level C/D	
A	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
B	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
C	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
D	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
E	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
F	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
G	A B C/D	3.53E-4	3.57E-4	2.75E-3	3.57E-4
H	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
I	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
K	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
L	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
N	None	< 1E-6	< 1E-6	< 1E-6	N/A

Table 6-3
Sensitivity Case Cumulative Probabilities of Occurrence over 80 Years for Sensitivity Cases Applied to WEC_AX_2

Case Name	Service Levels with Ruptures	Cumulative Probability of Rupture			Leakage
		Service Level A	Service Level B	Service Level C/D	
A	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
B	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
C	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
D	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
E	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
F	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
G	A B C/D	9.43E-3	9.55E-3	6.90E-2	9.55E-3
H	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
I	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
K	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
L	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6

For WEC main loop piping cases, the only realizations with ruptures occurred in Sensitivity Case G, which has an unrealistically large initial flaw size ($^a/_t = 50\%$ and $c > 16t$).

Table 6-4
Sensitivity Case Cumulative Probabilities of Occurrence over 80 Years for Sensitivity Cases Applied to CE_AX_1

Case Name	Service Levels with Ruptures	Cumulative Probability of Rupture			Leakage
		Service Level A	Service Level B	Service Level C/D	
A	None	< 1E-6	< 1E-6	< 1E-6	5E-7
B	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
C	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
D	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
G	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
H	A B C/D	2.03E-5	3.33E-5	6.30E-5	6.04E-05
I	A B C/D	2.34E-5	3.33E-5	7.03E-5	6.56E-05
J	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
K	A B C/D	5E-7	5E-7	1.6E-6	1.0E-06
L	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
M	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6

Table 6-5
Sensitivity Case Cumulative Probabilities of Occurrence over 80 Years for Sensitivity Cases Applied to CE_AX_2

Case Name	Service Levels with Ruptures	Cumulative Probability of Rupture			Leakage
		Service Level A	Service Level B	Service Level C/D	
A	A B C/D	5E-7	5E-7	1.0E-6	2.1E-6
B	A B C/D	5E-7	5E-7	5E-7	5E-7
C	B C/D	< 1E-6	5E-7	5E-7	5E-7
D	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
H	A B C/D	7.97E-5	1.11E-4	1.80E-4	2.17E-04
I	A B C/D	8.80E-5	1.14E-4	1.67E-4	2.04E-04
J	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
K	A B C/D	5E-7	1.0E-6	2.1E-6	1.0E-06
L	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
M	A B C/D	3.1E-6	4.2E-6	6.3E-6	6.8E-06

For CE surge line piping cases, Sensitivity Cases H and I do not meet the acceptance criteria, so piping under FPO is excluded from scope. The limiting service level result is modestly above the acceptance criteria on a log-basis for Sensitivity Case M (minimum flow rate), which is judged to be aggressive as it magnifies the influence of the assumed 836 yearly hot standby surges.

Conclusions for Axial Cracking

- **PFM modeling results show that periodic examination to detect axially oriented flaws is unnecessary to ensure pipe structural and leak tight integrity for the following cases:**
  - WEC main loop piping in both base load PWRs and PWRs operating under flexible power operation (FPO)
  - CE surge lines in base load PWRs
- For WEC main loop piping:
  - The analyses show a benefit for significantly reduced fatigue crack growth when the power ramp rate is limited to less than 0.5% per minute for routine loading and unloading operation
- For CE surge lines:
  - The analyses show a benefit for significantly reduced fatigue crack growth when insurge and outsurge events are reduced in frequency
  - Under FPO, there is an increased concern for fatigue crack growth due to the potential for a large number of insurge/outsurge transients to be triggered by FPO power shifts

Periodic examination to detect axially oriented flaws is unnecessary

Evaluation of Circumferential Flaws without Crediting Depth Sizing (ASME Record 24-1062)

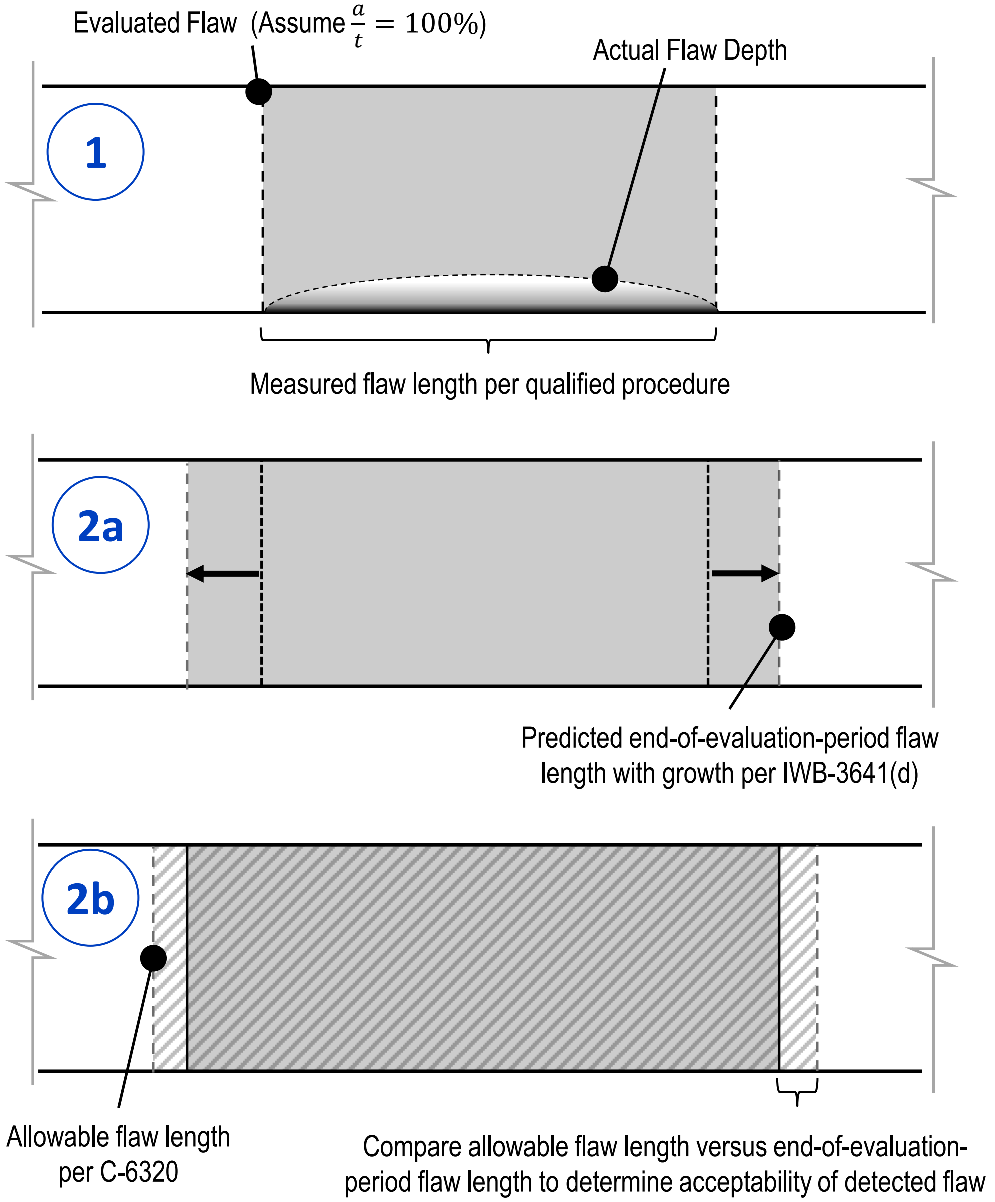
Approach

- **Objective:** Investigate circumferential fatigue cracking assuming periodic NDE without a qualified flaw depth-sizing capability
  - Assess whether an alternative flaw evaluation methodology that assumes the detected flaw is an idealized through-wall flaw results in acceptably low rupture probabilities for lengths up to the limit of applicability
- Custom PIPER-CASS code models fatigue crack growth of a through-wall flaw in main loop piping at a plant under FPO for one fuel cycle (up to 2 years) to assess rupture probability of a flaw accepted for continued service using the proposed methodology
  - Length of initial flaw corresponds to limit of applicability of methodology, with piping loads set to the maximum at which that flaw would remain allowable
  - PIPER-CASS shares many of the same models as xLPR, but is tailored for evaluation of CASS (e.g., enhanced convergence of EPFM stability solver)

Approach: Alternative Flaw Evaluation Methodology

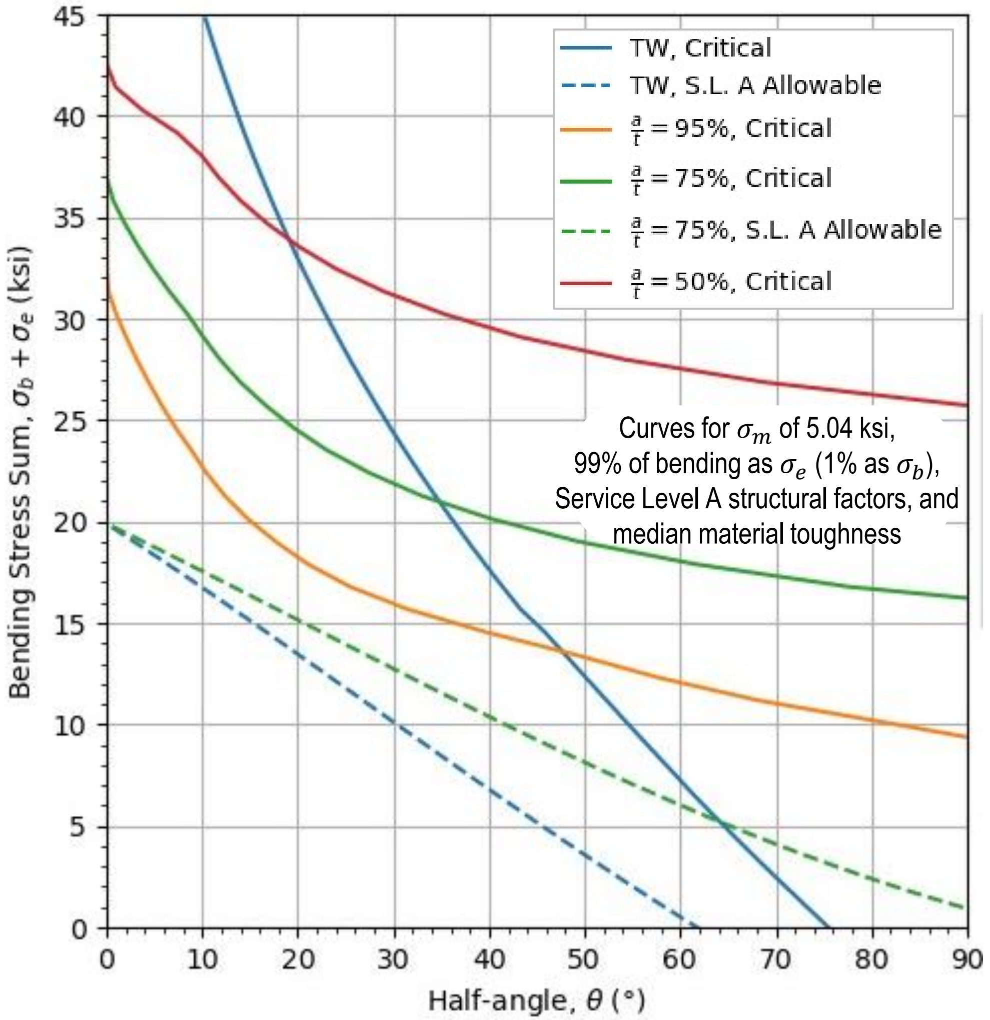
1. Determine length of detected flaw through qualified NDE
   a. Methodology only applies if measured length is less than the limit of applicability, total length (2θ) ≤ 32°
2. Perform a Nonmandatory Appendix C flaw evaluation, except modify the procedure to conservatively assume a through-wall flaw (a/t = 100%)
   a. Consider subcritical fatigue crack growth of detected flaw to predict the end-of-evaluation-period flaw length in accordance with IWB-3641(d), conservatively assuming a through-wall flaw
   b. Perform flaw stability check for the assumed though-wall flaw having the end-of-evaluation-period length using the equations specified by C-6320, with:
      - the appropriate Z-factor for the cast alloy and ferrite content of the flawed component, and
      - a/t = 1.0 in C-5320 equations

For simplicity, the curvature of the pipe is not shown in these figures



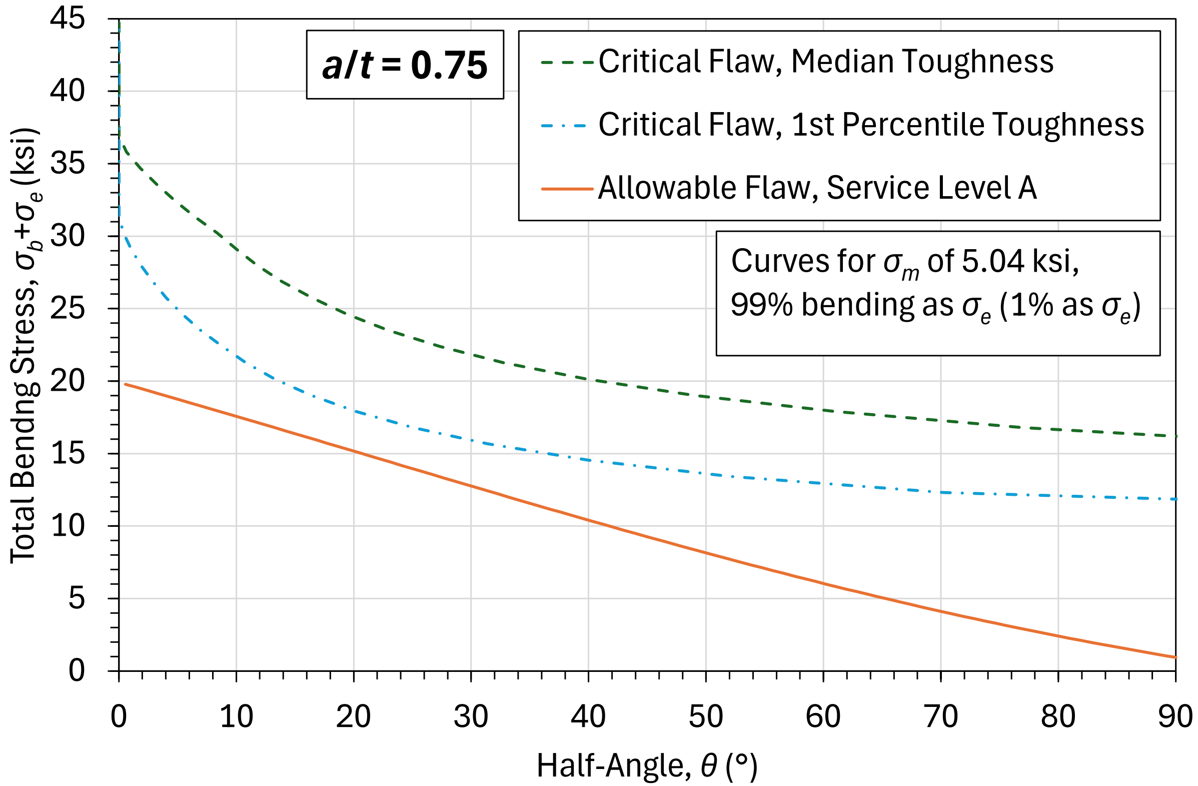
Approach: Comparison of NMA C and EPFM Solutions

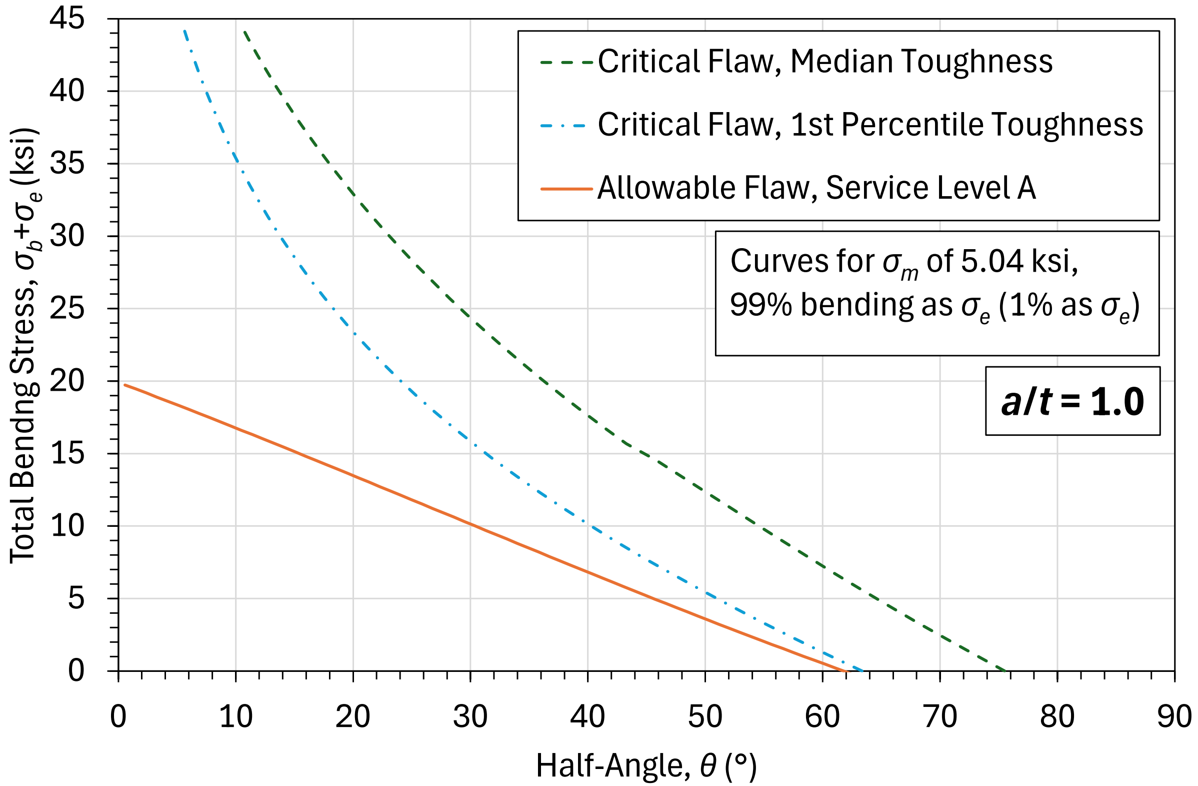
- Margin is illustrated by comparing the maximum allowable (dashed lines) and critical (solid lines) loads
  - Allowable loads calculated using Section XI, Nonmandatory Appendix C-6000 (Z-factor approach)
    - C-6000 Z-factors developed based on idealized through-wall cracks under pure bending loads
  - Critical loads calculated using the PIPER-CASS EPFM crack stability model deterministically
- The Z-factor approach provides greater margin for shorter flaws at the depth of *a*/*t*=1.0 assumed in the proposed methodology



Approach: Comparison of NMA C and EPFM Solutions

- Material toughness influences the structural margin by changing the critical flaw size
  - Plots below show curves from prior figure plus the critical flaw size at lower toughness
- Treating secondary stresses as primary in PIPER-CASS has a conservative effect



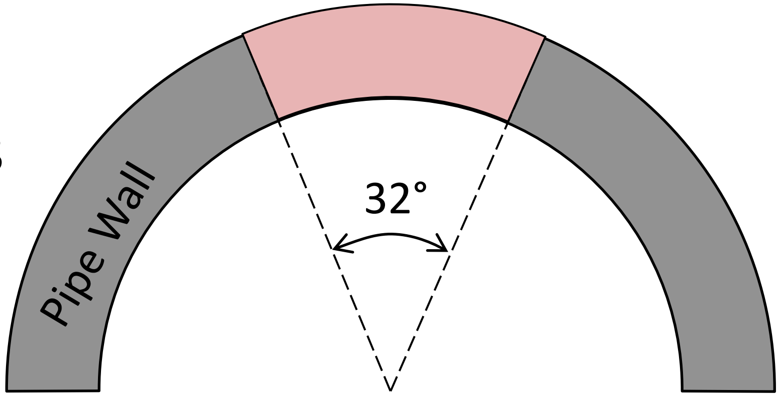


For assumed *a/t* = 1.0, there is greater margin for shorter flaws

EPRI

Key Inputs for PFM

- Base cases include transients for base load operation as described in MRP-393 as well as the FPO transients with a 1% power/minute ramp rate or greater (equivalent to axial flaw Sensitivity Case I)
  - MRP-393 provides best-estimate transient definitions for WEC RCS main loop piping based on plant experience
- Initial flaw is a 32° idealized through-wall flaw, which is the most limiting case
  - Length sizing uncertainty of RMSE = 0.75 inch is explicitly modeled
- Piping loads for each Service Level A to D are the maximum allowable loads for a crack with the initial flaw length (32°) and a/t = 100%
  - PFM approach conservatively treats secondary stresses as primary stresses



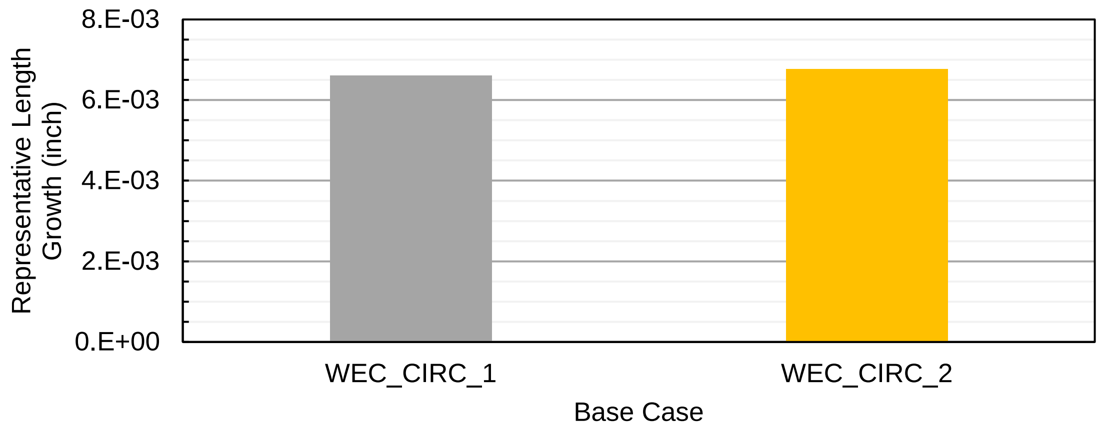
Sensitivity Cases Considered

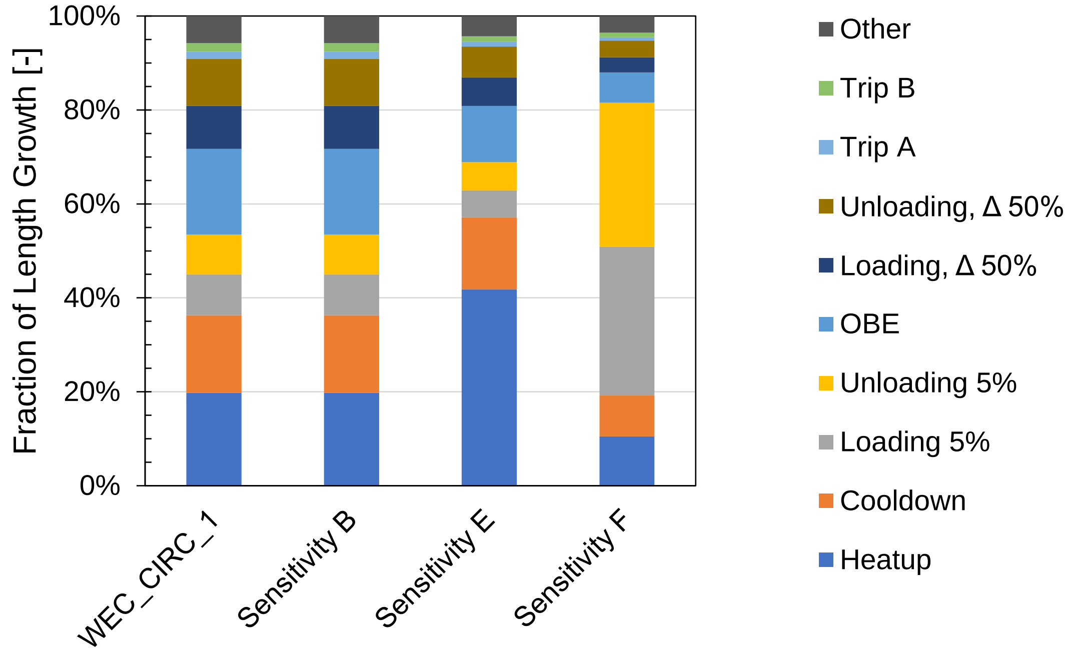
Sensitivity Case	Description
A	Remove factor of 0.8 on growth
B	Only include upper 50th percentile of C_{ss} distribution
C	Elevated WRS: Apply weld repair WRS profile with a part-depth flaw (a/t=50%)
E	Increase rate of Heatup and Cooldown transient to 100°F/hr and disable rise time limit
F	Apply transients at design basis frequency
G	Initial part-depth flaw (a/t=50%)
H	Use of flexible power operations, with 0.5%/minute power ramp rate for 80%-100% and 100%-80% loading/unloading
L	Unaged material
P	Increase length sizing uncertainty from RMSE=0.75 to 1.0 inch
Q	CF8 material (increased toughness and FCGR coefficient but decreased strength and Z-factor for allowable loads)
R	25% δ-ferrite (increased toughness but decreased Z-factor, leading to higher allowable piping loads)
S	Increased membrane stress in piping loads
t1, t2, t3	Temporal convergence sensitivity, 5 day, 25 day, or 50 day timestep (respectively)

Blue indicates a difference from axial flaw cases;
Transients for axial flaw Sensitivity Case I were included in the base case for circumferential flaws

PFM Results

- Flaw stability results for main loop piping limited by material toughness and initial size rather than by growth
  - The average fatigue crack growth over 2 years is very small
  - Critical crack size is strongly dependent on the material toughness (EPFM stability criterion is limiting versus net section collapse (NSC))
  - The initial flaw size is sampled to model length sizing uncertainty
    - Longer initial sizes more likely to challenge crack stability for given loads





Circumferential Cracking Sensitivity Study Results

Table 7-2
Sensitivity Case Results for WEC_CIRC_1

Case Name	Service Levels with Ruptures	Cumulative Probability of Rupture			
		Service Level A	Service Level B	Service Level C	Service Level D
A	D	< 1E-6	< 1E-6	< 1E-6	5E-7
B	D	< 1E-6	< 1E-6	< 1E-6	5E-7
C	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
E	D	< 1E-6	< 1E-6	< 1E-6	1.0E-6
F	D	< 1E-6	< 1E-6	< 1E-6	2.1E-6
G	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
H	D	< 1E-6	< 1E-6	< 1E-6	5E-7
L	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
P	C D	< 1E-6	< 1E-6	4.7E-6	3.80E-5
Q	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
R	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
S	D	< 1E-6	< 1E-6	< 1E-6	3.44E-5

Table 7-3
Sensitivity Case Results for WEC_CIRC_2

Case Name	Service Levels with Ruptures	Cumulative Probability of Rupture			
		Service Level A	Service Level B	Service Level C	Service Level D
A	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
B	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
C	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
E	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
F	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
G	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
H	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
L	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
P	D	< 1E-6	< 1E-6	< 1E-6	2.1E-6
Q	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
R	None	< 1E-6	< 1E-6	< 1E-6	< 1E-6
S	D	< 1E-6	< 1E-6	< 1E-6	3.6E-6

All base and sensitivity cases meet the acceptance criteria

Conclusions for Circumferential Cracking (1 of 2)

- PFM modeling results show that the alternative flaw evaluation methodology that does not rely on depth sizing information ensures pipe structural integrity for one fuel cycle (up to 2 years) of continued operation when applied to circumferential cracking in WEC main loop CASS piping components
  - This methodology does not generically apply to flaws with a full-length (2θ) longer than 32° or to flaws in surge line locations, but a component- or plant-specific analysis may justify its use at these locations
  - Limit of applicability recognizes that the Z-factor approach provides greater margin for shorter flaws

Alternative flaw evaluation methodology applies to flaws in main loop piping with total length ≤ 32°

Conclusions for Circumferential Cracking (2 of 2)

- The assumption of an idealized through-wall crack for both the PFM and modified flaw evaluation methodology addresses the lack of a qualified depth sizing process
  - Assuming an idealized through-wall crack is a conservative approach from the standpoints of subcritical crack growth and crack stability (verified with sensitivity case modeling a part-through-wall crack)
- A qualified length-sizing process with an uncertainty of RMSE = 0.75 inch or smaller on the full crack length (2θ) was assumed in the modeling

Overall Conclusions

Conclusions

- PFM results show that structural integrity is maintained without crediting periodic examination to detect axially oriented flaws
  - Applies to main loop piping components under base load and flexible power operations
  - Applies to surge line piping components under base load operation
- PFM results show structural integrity is maintained by applying the alternative flaw evaluation methodology for circumferential cracks without relying on depth sizing information
  - Applies to main loop piping components under base load and flexible power operations
  - Only applies to flaws with total length ≤ 32° (a plant-specific analysis may justify application for longer flaws); PFM analyzed one fuel cycle (up to 2 years) of continued operation
- Final, comprehensive EPRI report 3002023893 (MRP-479) is now publicly available on EPRI website
  - Freely downloadable at: https://www.epri.com/research/products/000000003002023893
  - Provides technical basis for development of new ASME Code Cases (see ASME Records 23-2033 and 24-1062)

Questions?

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Backup Slides

Publications

- EPRI Technical Report 3002023893 (MRP-479)
  - Publicly available on EPRI website (https://www.epri.com/research/products/000000003002023893)
  - Provides final comprehensive results and conclusions for the overall effort, including for both axial and circumferential cracking
  - Report to serve as technical basis for both axial flaw effort (ASME Record 23-2033) and circumferential flaw effort (ASME Record 24-1062)
  - Relative to earlier publications below, MRP-479 includes updated treatment of insurge and outsurge events during plant heatup and cooldown for CE surge lines

- Earlier publications, superseded by MRP-479
  - EPRI Technical Updates (EPRI member access only)
    - Probabilistic Fracture Mechanics Evaluation of PWR Cast Austenitic Stainless Steel Piping Components (3002020449) – Aug. 2021
    - Probabilistic Fracture Mechanics Evaluation of PWR Cast Austenitic Stainless Steel Piping Components – Axial Cracking Methods and Results (3002025221) – Nov. 2022
  - ASME PVP paper (PVP2023-107363)
    - Summary of 2022 EPRI Technical Update providing results of axial cracking work

Additional Details on PFM Inputs

Transient Inputs - WEC

- Transients for base load operation are input as described in MRP-393
  - Provides “best-estimate” *P*,*T* time history and number of occurrences
- Flow velocity for all transients is assumed to be 25.1 m/s
  - For smaller R_i, corresponds to 100k gpm, which is highest normal operating flow rate of U.S. PWRs
  - Higher flow rate is conservative, causes more severe thermal stress gradients

Base Load Transient Name	Frequency [per year]
Heatup	3.33
Cooldown	3.33
Loading 5	16.67
Unloading 5	16.67
Large Step Decrease	0.33
Loading 15	3.33*
Unloading 15	3.33*
OBE	0.67
Trip A	3.83
Trip B	2.67
Trip C	0.17
Primary Side Leak Test	0.166
Secondary Side Leak Test	0.166

* For circumferential flaws, these transients are replaced by the FPO transients in the base case.

Transient Inputs - CE

- Transient pressure and temperature history for base load operation are input as described in the design specification for the pressurizer of a CE PWR
- Frequency of plant transients adjusted, to "best-estimate" frequency of about 19% design basis*
  - Design basis "Normal Variations" transient is excluded
    - Modeled unrealistic +/- 100 psig pressure variation at about 2 occurrences *per hour*
- Includes surge events during loading/unloading and heatup/cooldown
  - Each of these transients includes multiple surge events (near-instantaneous temperature changes between hot leg and pressurizer temperatures)
- Flow rate varies by transient
  - Transients P,T histories that include substantial surges have flow rate set to average surge flow rate (surges for heatup/ cooldown are modeled separately, consistent with design basis)
  - Minimum flow velocity of 0.03 m/s is enforced for all transients to obtain reasonable heat transfer rates

Transient Name	Frequency [per year]
Heatup	2.38
Cooldown	2.38
Loading	15.0
Unloading	15.0
Step Load Increase	6.5
Step Load Decrease	6.5
Reactor Trip	1.92
Leak Test Up	1.93
Leak Test Down	1.93
Loss of Flow	0.017
Loss of T-G Load	0.13
Loss of Secondary Pressure	0.08

* CE surge line flaw tolerance evaluation [ML15314A161] applies transients at 19% of the design basis frequency

Transient Inputs - FPO

- Flexible power operations (FPO) transients are modeled by scaling and shifting the pressure and temperature history of plant loading and unloading transients to model the desired power change and ramp rate
  - Apply different ramp rates (0.5%-2.0% power per minute) and power changes (change of 20%-70% power), resulting in total of 330 loading and unloading events per year
- For circumferential flaw cases, FPO is part of the base case
- For axial flaw cases, FPO is a sensitivity case

FPO Transient Name	Frequency * [per year]
Loading 30→100%, 2% per min	4
Unloading 100→30%, 2% per min	4
Loading 50→100%, 1% per min	50
Unloading 100→50%, 1% per min	50
Loading 80→100%, 1% per min	276
Unloading 100→80%, 1% per min	276

Stability Loads

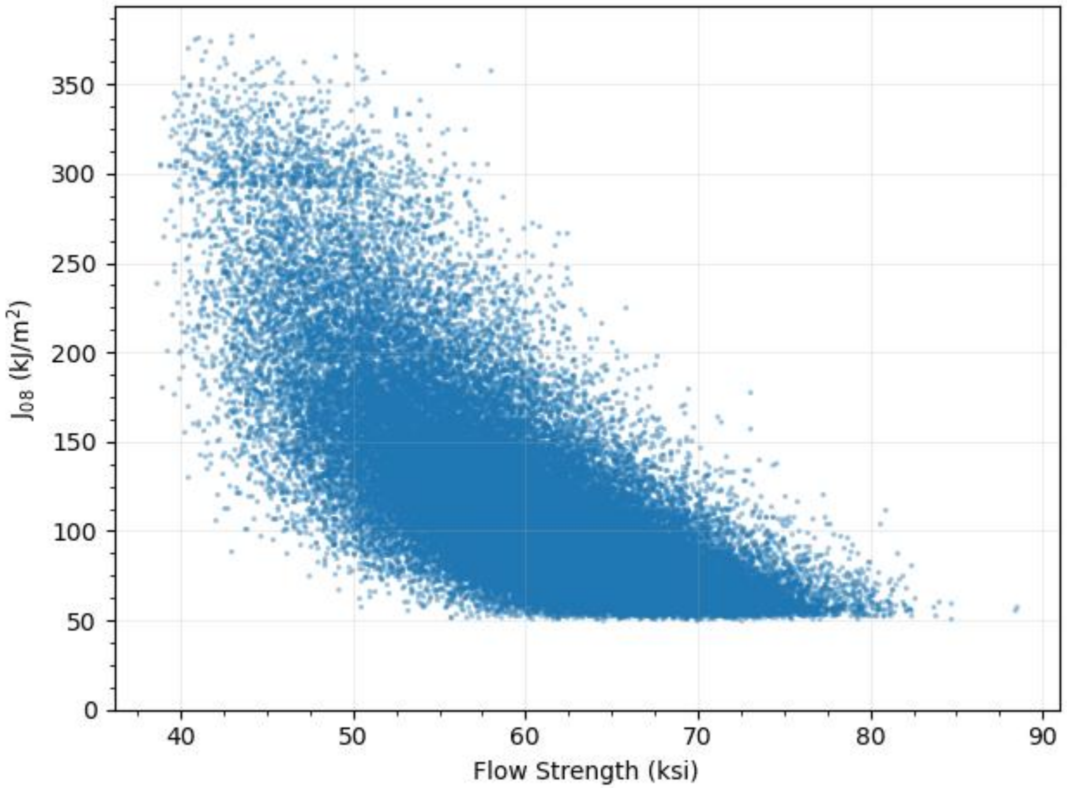
- Flaw stability evaluated at each of the four Service Levels: A, B, C, and D
  - Stability is evaluated every timestep
- Pressures were chosen to bound the pressures in design basis documents for the components being evaluated, with Service Level C/D being higher than the design pressure
- Piping loads are the maximum allowable loads for a crack with the initial flaw length and *a*/*t* = 100% for each service level
  - Secondary piping stresses conservatively treated as primary
  - Piping loads only applicable to circumferential flaw cases

Service Level	Pressure (psig)	
	WEC Cases	CE Cases
A	2,250	2,250
B	2,315	2,400
C/D	2,550	2,576

Material Inputs

- Inputs applicable to CF8M, at the fully-aged condition, are applied for base cases
  - CF8M is the CASS alloy subject to the lowest fracture toughness at saturation of thermal aging effects
  - Strength and toughness discussed on following slides
- Probabilistic fatigue crack growth inputs of xLPR
  - The ASME Code Case N-809 and N-809-1/-2 equations correspond to the 70th and 90th percentile, respectively, of the xLPR distribution
- Ramberg-Osgood relationship for stress-strain curve using the same correlation as MRP-362 R1 Appendix A
  - Reference stress adjusted per NUREG/CR-6142 for consistency with xLPR
- Other required material inputs (e.g., density, conductivity) from ASME Code, Section II-D

Material Inputs – Strength

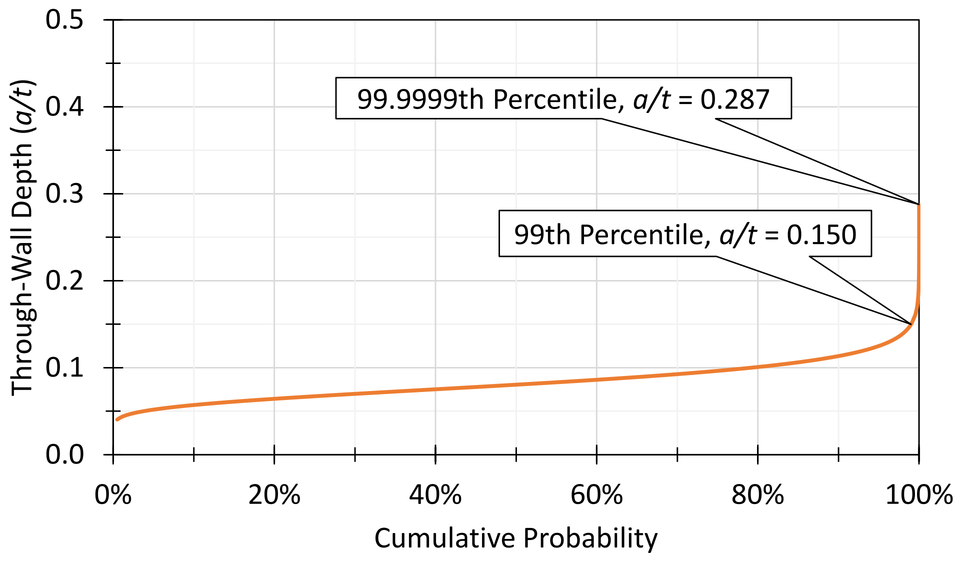


Plot shows data from an example base case PFM run (with 50,000 realizations) for fully aged flow strength and toughness at operating temperature with 40% δ-ferrite

- Material strength inputs (YS and UTS) based on MRP-362 R1 Appendix E data for fully aged material at ~600°F (~316°C)
- PIPER-CASS includes correlations between C_V and YS and C_V and UTS to obtain the observed correlation between $J_{0.08}$ and strength for the fully aged data at ~600°F (316°C) in MRP-362 R1 Appendix E
- In addition, PIPER-CASS cases apply lower bound limits for YS and UTS at 90% of the respective Code minimum values at operating temperature

Initial Axial Flaw Selection Bases – NDE at Casting

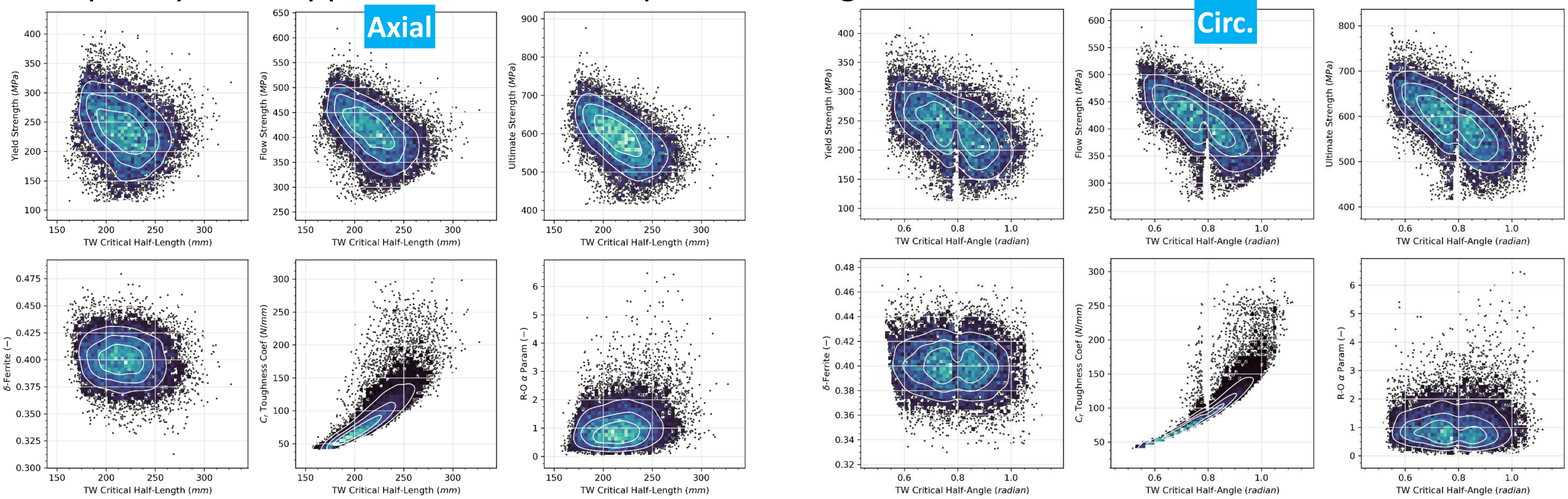
- All in-scope CASS products and adjoining welds were subject to pre-service examination requiring 100% radiography coverage, supplemented by mag-particle or liquid-penetrant exam
  - Per ASME B31.7 or Section III
  - EPRI TR-100034 recommends that 1% of flaws missed by pre-service examinations have a depth of 15% through-wall (figure at right)



- **PIPER-CASS initial flaw selection does not credit these examinations for the number or density of initial flaws**
  - Surface examination is not credited for the initial size of flaws
- Acceptance criteria for mag-particle and liquid-penetrant examination of CASS base metal per B31.7-1969 per 1-724.5.3 and 1-724.5.4 disallows:
  - Any cracks or linear indications
  - Rounded indications with dimensions > 3/16"
  - Four or more indication in a line separated by 1/16" or less edge to edge
  - Ten or more rounded indications in any 6 in2 of surface

Input Effects on Critical TW Half-Length

- Material toughness (see C_r coefficient at right) is strongly correlated with critical crack size
  - EPFM stability criterion is limiting versus net section collapse (NSC)
  - Point loci also reflect correlation applied to reflect aged CASS having increased strength and degraded toughness
- Convergence studies on time step for flaw growth and on number of realizations for rupture frequency were applied to ensure adequate convergence of PFM results



δ-Ferrite variability is the assumed aleatory uncertainty in actual δ-ferrite when the nominal is at the limiting 40%

Gap in circumferential point loci due to piecewise-linear equation for `psi` at π/4 and π/3 in J-integral calculation (and for `dpsi_dtheta` in dJ/dθ) [identical to xLPR equations]