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Corey Thomas, SNC (MSC Chair) – Auxiliary Piping Stress Corrosion Cracking Operating Experience Focus Group and Industry Coordination – Presentation #XX

June 2026 NRC/Industry Materials Technical Exchange Meeting

Agenda

- EDF Stainless Steel SCC and Thermal Fatigue OE Update
- Auxiliary Piping SCC OE Focus Group Update

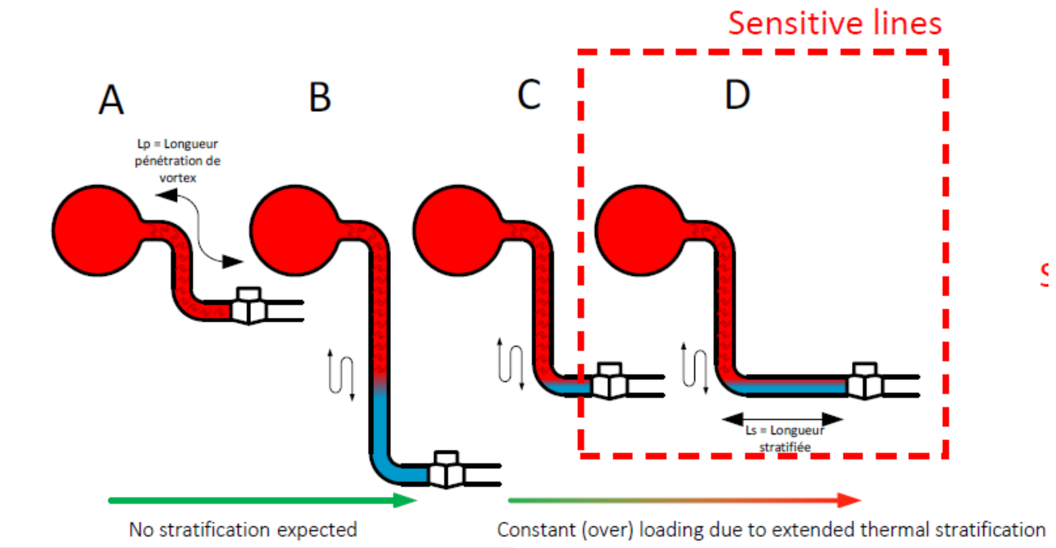
EDF Stainless Steel SCC and Thermal Fatigue OE Update

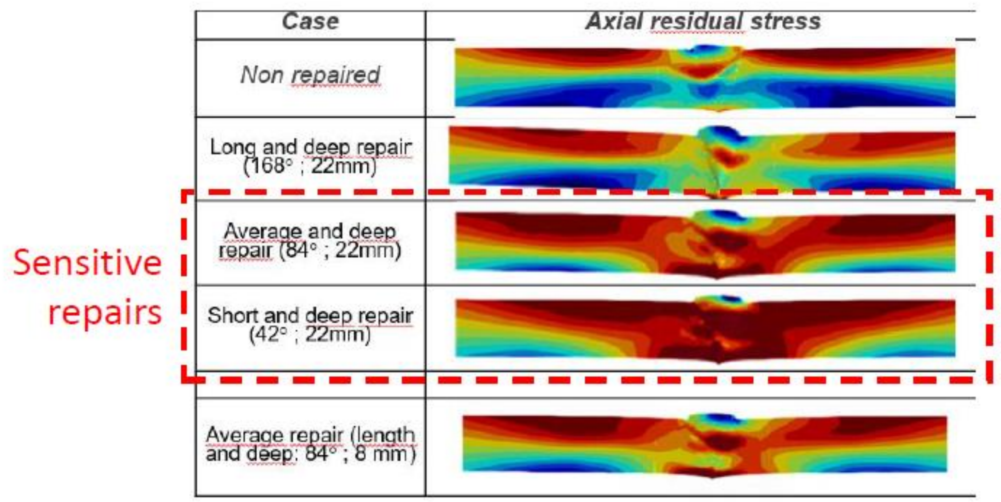
EDF Feedback on Operating Experience (1/12)

- Overall summary
  - End of 2021, intergranular SCC (IGSCC) flaws were discovered in the ID welds and HAZs of austenitic stainless steel Safety Injection (SI) and Residual Heat Removal (RHR) lines connected to non-isolable primary system branch lines (“dead legs”)
  - Initially unexpected degradation, but was then suspected to affect other reactors
  - An extensive NDE program was launched on 8” to 14’’ diameter auxiliary lines
  - Preventive replacement of all potentially sensitive portions of lines was undertaken
  - These operations led to detection of further instances of cracking
    - Thermal fatigue flaws (17 new cases between 2022 and 2025)
    - IGSCC flaws affecting certain welds with repairs from plant construction (10 cases)
      - Two flaws in repaired welds were uncharacteristically deep relative to the ‘atypical’ IGSCC flaws
  - Evidence of variable local thermo-hydraulic behavior on lines of similar design
  - Investigations have been extended to other austenitic SS primary circuit components
    - Main coolant lines, surge lines and <8” OD lines

EDF Feedback on Operating Experience (2/12)

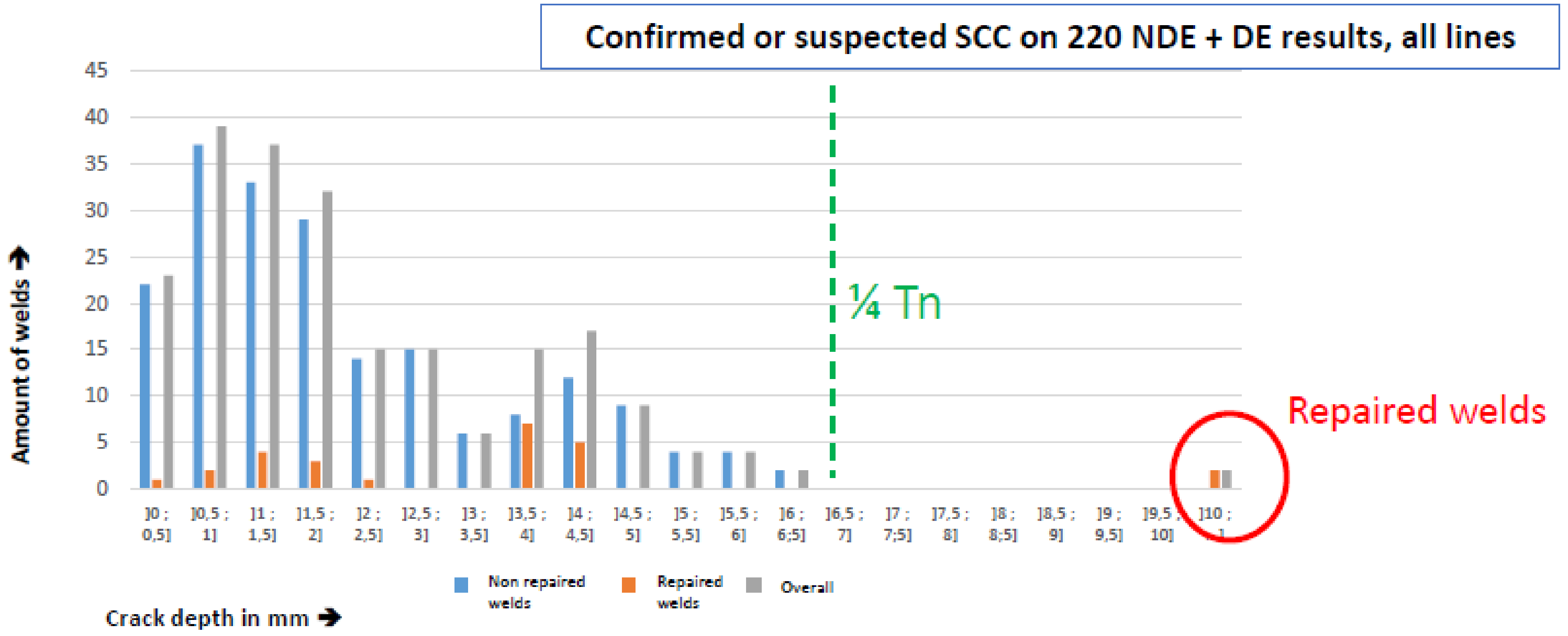
- Overall summary
  - End of 2025, over 1600 welds subjected to NDE and/or Destructive Examination (DE)
    - More than 1500 welds on 8'' to 14'' SI and RHR auxiliary lines
    - Over 230 IGSCC flaws (60% < 2mm depth) identified from DE
    - 18 IGSCC flaws on less sensitive lines, 10 of which were on welds that had been repaired at fabrication (incl. the deepest ones)
  - Root Cause Analysis (RCA) : "1st order" parameters identified (main hypotheses – thermal stratification and severe weld repairs)





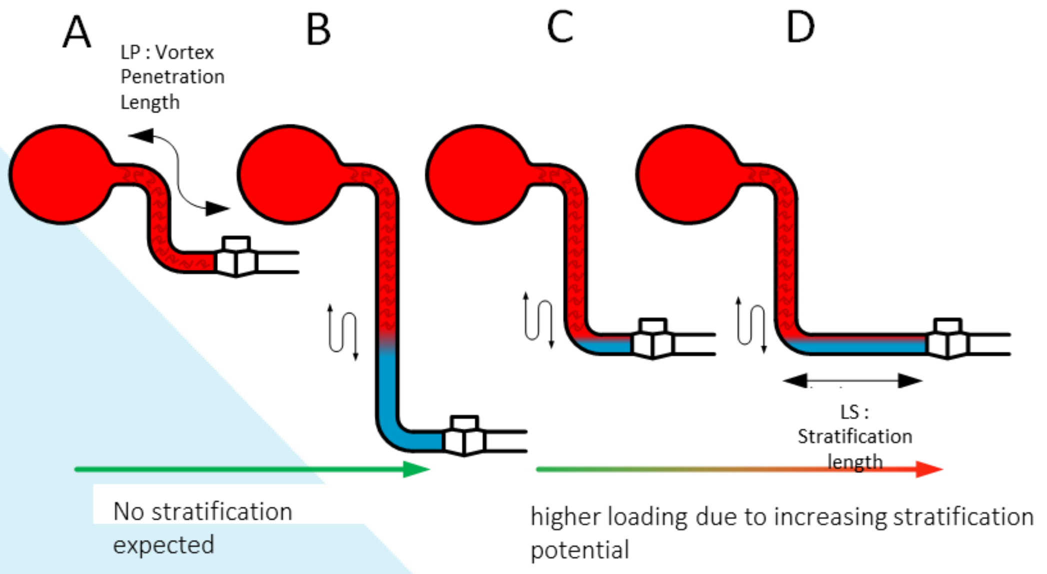
EDF Feedback on Operating Experience (3/12)

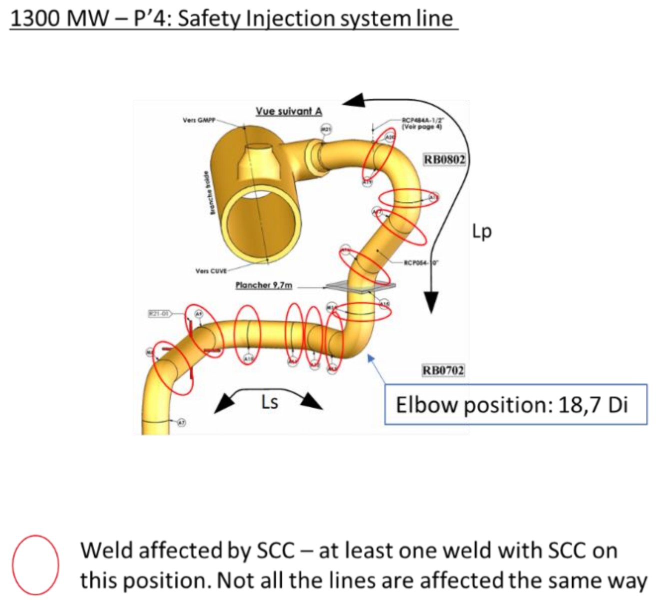
- Past operating experience
  - SCC Susceptible lines - Multiple flaws present
    - Angular extensions of the flaws can be substantial - up to 360° (total circumference)
    - Depth can reach ¼ Tn but mostly (≈60% of time) below 1/10 Tn (< 2mm)
  - Other lines - Isolated flaws only, with a depth rarely >2mm
    - On some repaired welds, depth greater than 1/10 Tn and even greater than ¼ Tn on 2 welds



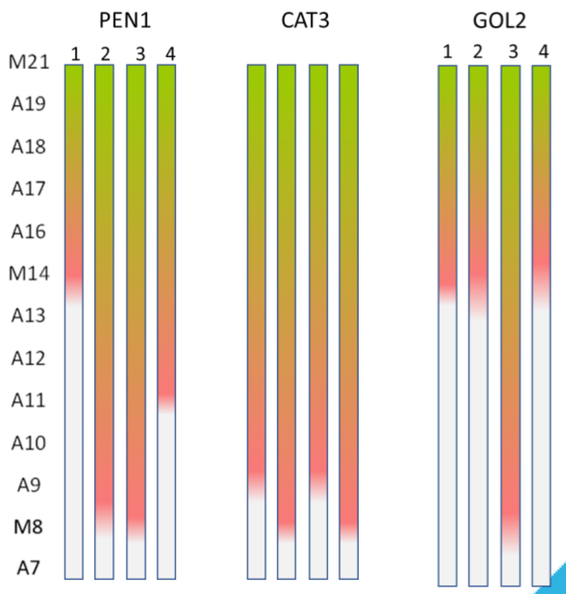
EDF Feedback on Operating Experience (4/12)

- Past operating experience





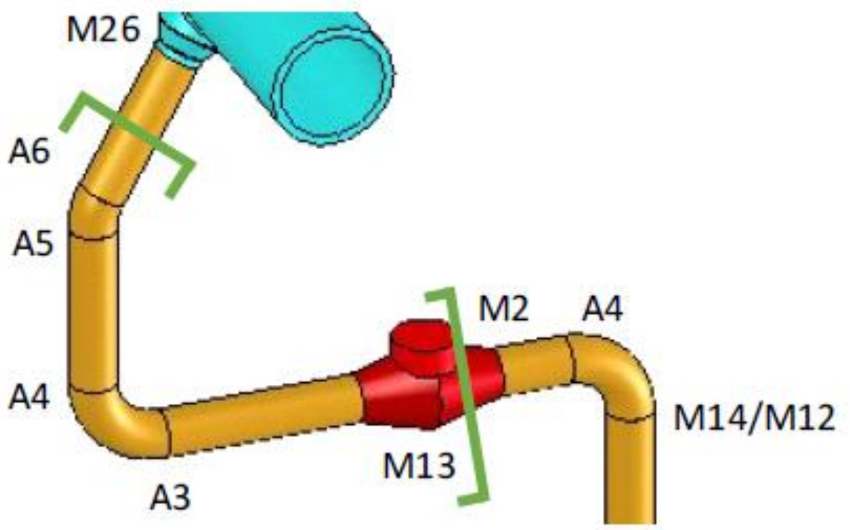
- External oxidation of pipes (over 200°C) reveals a greater than expected variability of the vortex thermal influence for an identical line design on different loops of a given reactor, and between similar reactors
- Example from 10'' SIS on cold leg, 1300MWe P'4 type 4 loop reactors



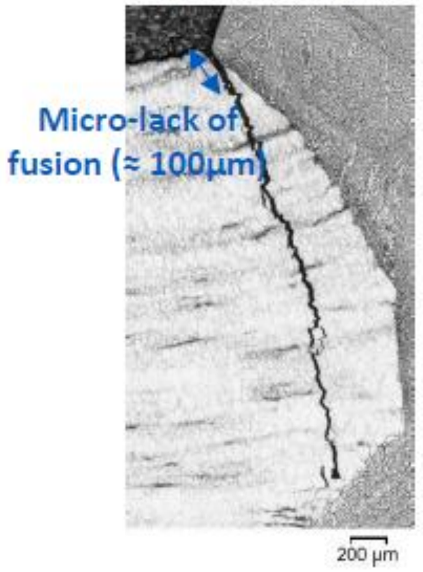
- D shape found to be especially sensitive to IGSCC
- IGSCC is seldom identified on A & C shape lines
- One line in which IGSCC was identified was a B shape line, however actual thermal stratification conditions were typical of a D shape line

EDF Feedback on Operating Experience (5/12)

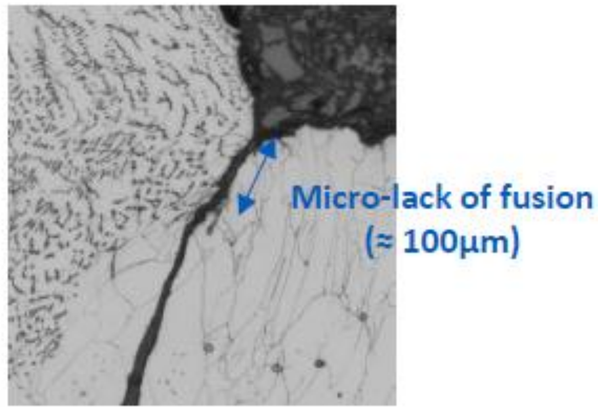
- Recent operating experience (Civaux 2)
  - 2025, during a scheduled maintenance/refueling outage
    - ISI NDT (UT) was performed on all new welds (replaced in 2022)
      - ❑ On one RHR hot leg line, a thermal fatigue flaw (2,6 mm depth max) was found on an A3 weld, initiated on a sub millimetric acceptable imperfection – micro lack of fusion
      - ❑ On the other RHR hot leg line, an IGSCC flaw (2,6 mm depth max) was found on an A6 weld, initiated on a sub millimetric acceptable Imperfection – micro lack of fusion
      - ❑ No UT indications on other welds of those two lines



2025 IGSCC (A6 weld)



2025 thermal fatigue (A3 weld)



EDF Feedback on Operating Experience (6/12)

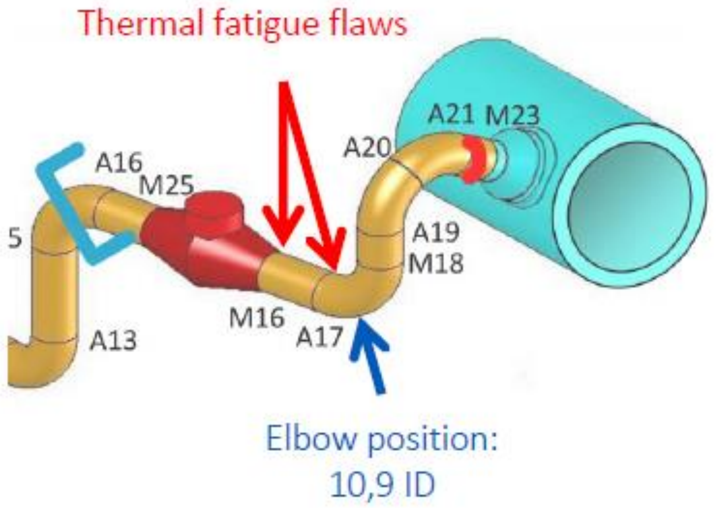
- Recent operating experience
  - 2025 Conclusions from Civaux 2
    - N4 reactors RHR on hot leg lines were historically inspected as potentially sensitive to thermal fatigue
    - Since 2022 investigations, both IGSCC and thermal fatigue flaws were expected on the RHR lines
    - Lessons learned on recent OE
      - When all conditions are met with respect to temperature, susceptible lines (thermal stratification), incubation time can be very short (< 2 years) – crack propagation estimated at ~1 mm/year
      - Initiation time for the thermal fatigue flaws was surprising although associated with the effect of a small imperfection located at the most stressed area of the weld
      - SCC drivers are consistent with the available knowledge
      - Hot legs operated at 320°C is an aggravating factor for both IGSCC & Thermal Fatigue

EDF Feedback on Operating Experience (7/12)

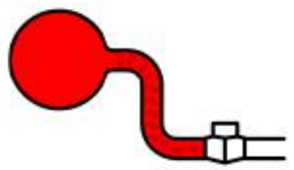
- Recent operating experience
  - Surge Line Investigations
    - Surge lines are 14” or 16’’ lines but are not subject to thermal stratification
      - 41 welds inspected by UT or DE (DE of 8 welds at Fessenheim 1) thus far, including mostly repaired welds
      - A single UT suspected indication detected on a 16” surge line weld of a 1300MWe reactor (P’4 type) during a 10 year inspection outage – weld repaired at construction
        - Weld removed to characterize the flaw
        - DE confirmed that there was no degradation at this UT indication
  - Smaller diameter auxiliary lines (<8” OD) – 126 welds, mostly repaired
    - With little thermal stratification risk and lower weld plastic strain levels along welds, are believed to be less susceptible to IGSCC
    - Over 60 welds (2” – incl. Sockets Welds, 3”, 4” & 6” lines) have been removed in two years on the EDF fleet and subject to DE
      - No IGSCC nor thermal fatigue have been detected to date

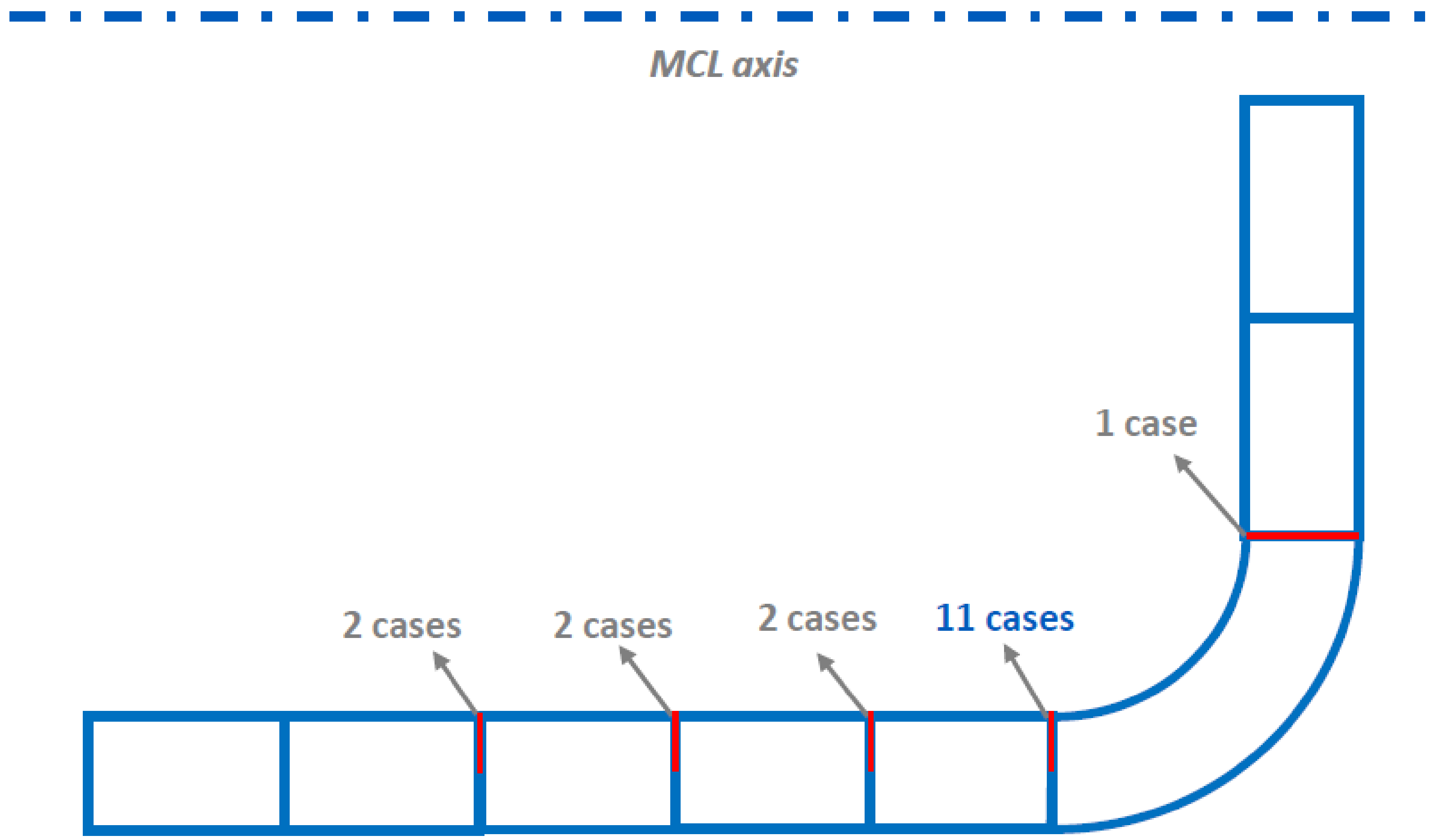
EDF Feedback on Operating Experience (8/12)

- Thermal Fatigue overview
  - Total of 18 cases identified on 8" to 14'' lines since 2013
  - All affecting "Down Horizontal" or "Horizontal" line configurations



Thermal stratification wasn't expected on this type of short horizontal lines !





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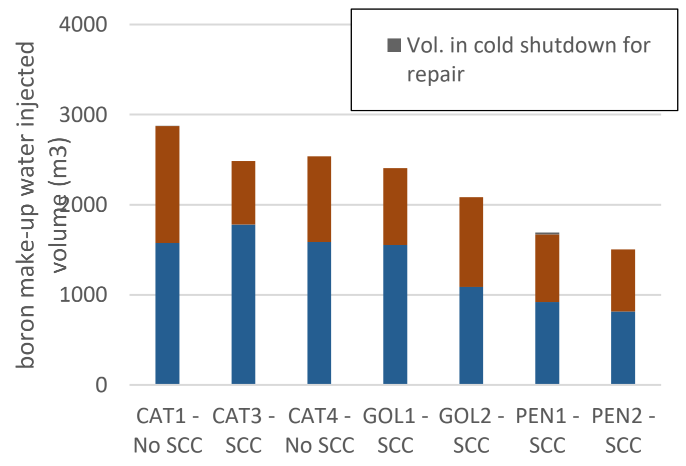
EDF Feedback on Operating Experience (9/12)

- Fundamental Understanding
  - Sensitivity of a given weld to IGSCC seems to be driven by accumulation of aggravating factors
    - ❑ Line design enhancing thermal stratification risk, presence of thermal stratification and extent
    - ❑ Severe weld repairs
    - ❑ Cyclical loads
  - 2nd order effects that can assist initiation such as component misalignment, small manufacturing defects
    - Not all small manufacturing defects (e.g. micro lack of fusion) on susceptible or non-susceptible lines propagate into IGSCC flaws or thermal fatigue flaws

EDF Feedback on Operating Experience (10/12)

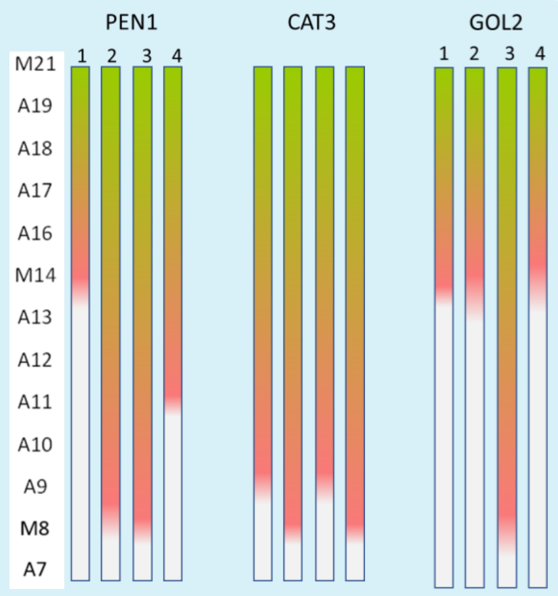
- Fundamental Understanding
  - Material/manufacturing and environment factors
    - ❑ No pollutants observed during operation or in the cracks analyzed by destructive examination (DE)
    - ❑ Stainless steel pipes with higher sulfur content could be a bit less susceptible to IGSCC propagation, but %S is considered to be a secondary factor; No significant trend seen in the percentage nitrogen content
    - ❑ O_2 ingress
      - ❖ Water injection (aerated) occurs on one primary cold leg loop, but all four cold leg loops similarly affected by IGSCC, which implies O_2 not a relevant variable
      - ❖ Numerous IGSCC cases observed in hot legs where no dissolved oxygen been measured (thousands of DO measurements on 11 different reactors, always <10 ppb)



  - Temperature
    - ❑ No IGSCC or thermal fatigue identified in ‘cold’ portions (T<200°C) of longest dead legs

EDF Feedback on Operating Experience (11/12)

- Fundamental Understanding
  - Weld Residual Stress
    - Weld residual stress and increased hardness make some areas (HAZ, near the weld) more likely to be susceptible to IGSCC and have a positive effect crack propagation
    - Some welds repairs, judged as "severe" regarding the depth and length of the excavation for the weld repair, can enhance IGSCC susceptibility
  - Mechanical and thermohydraulic behavior
    - Variability of IGSCC development between lines and reactors with a strictly similar design is believed to be mostly induced by different local thermo-hydraulic behaviors, linked to vortex penetration
      - Different thermal loadings can be induced on each loop, given the vortex position is different from one line to another
      - Variation of the vortex's position in a given line during operation can lead to cyclical loads that would cause cracking
        - Could explain why some reactors (CAT1-4) with susceptible lines did not show any defect when their twins (CAT2-3) were affected by IGSCC



EDF Feedback on Operating Experience (12/12)

- Maintenance strategy
  - EDF has replaced all SCC "Susceptible lines"
  - Surveillance
    - Multi element encoded UT techniques
    - Detect both SCC and thermal fatigue flaws
  - Scope and frequency adjusted for each line as a function of:
    - Intrinsic sensitivity to SCC and thermal fatigue
    - Severity of welds repairs
  - Thermal instrumentation of dead legs
  - Mitigation solutions
    - Recent implementation of MSIP for small flaws allowing weld replacement at a later outage – significant implementation of MSIP ongoing
    - ID grinding (flushing) of welds to remove small manufacturing defects and reduce stress concentration factors and introduce beneficial compressive stress on inner surface (200MPa (29ksi))
      - Using qualified vendors with remote tooling
      - Benefit of weld root flushing regarding IGSCC has been highlighted by EDF SCC OE (almost no IGSCC on more than 100 flushed welds on sensitive lines)

Auxiliary Piping SCC OE Focus Group Update

Purpose of the Auxiliary Piping SCC OE Focus Group

- Coordinates efforts between the PWR Owners Group and EPRI-MRP in evaluating this OE
- Focus
  - Understanding causal factors associated with recent auxiliary piping SCC operating experience and the potential relevance to the rest of the industry
  - Development of industry positions and/or guidance as needed
  - Regulatory interactions

Auxiliary Piping SCC OE Focus Group Roadmap

	2021	2022	2023	2024	2025	2026
Utilities	Provide Research Guidance					
			ASME Code Guidance for CGR			
EPRI		SCC White Paper	Complete (MRP 2022-018)			
	PWR SS SCC CGR (MRP-458)		Complete			
		WRTC Type 316LN Strain-Hardening Research			Initial Scope Complete	
		MRP-236-R2 Pressure Boundary SS SCC OE - In progress				
PWROG		Industry Inspection Survey		Complete		
		Safety Assessment, PWROG-23007-NP		Complete		
			Applicability Assessment, PWROG-24002 Complete			
ASME			CGR Curves, RI-ISI Review - In progress			
NRC				Endorse CGR Curves		
		Safety Assessment (ML23236A079)				

Interim guidance for inspections transmitted via PWROG Letter OG-23-82
Revision 1 of letter issued July 2024

Status of PWROG Program Tasks (1/3)

- Task 1: Focus Group
  - Meetings
    - Multiple in-person and virtual Focus Group Meetings have been held since April 2022
      - ❑ A meeting was held with EDF of 3/13/2026 and a follow up meeting held on 5/27/2026
    - Presentation at Industry/NRC Tech Exchange 5/25/22, 6/14/23, 6/25/24, 6/17/25
    - Presentation at ACRS Meeting 11/16/22
    - Virtual presentation for Japan Virtual Workshop 2/13/23
    - Presentation at NRC Public Meeting 2/21/2024
    - European PWROG Materials Workshop 11/5/2024
    - Expert Panel meeting regarding weld/WRS held 7/12/23

Status of PWROG Program Tasks (2/3)

- Task 2 Part : Safety Assessment (PWROG-23007-NP)
  - Complete April 2023
  - Transmitted to NRC For Information May 2023 (‘read only’ access)
  - PWROG letter OG-23-82 issued; defines the NEI 03-08 Needed Guidance regarding IGSCC specific examination methods
  - PWROG letter OG-23-82 Rev 1 issued to include FAQs
- Task 2 Part 2: Applicability Assessment
  - Tasks 4 (PWROG-23036-P; Task 4 Core Flood Line Sample Flaw Evaluation) and 5 (PWROG-23040-P; Westinghouse Flaw Stability Assessment of Stress Corrosion Cracking Operating Experience in Non-Isolable Stainless Steel Branch Piping) (completed – inputs to Applicability Assessment)
  - PWROG 24002 Rev 0; An Assessment of the Potential Applicability of the EDF Safety Injection Line Cracking Experience to the PWR Fleet – submitted to NRC for information (OG-25-141)

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Status of PWROG Program Tasks (3/3)

- Task 3: Data Collection
  - Data incorporated into Safety Assessment (Task 2 Part 1), Complete
- Task 4: B&W Core Flood Line Sample Case
  - Final report published and transmitted (PWROG-23036-P)
- Task 5: WEC SI Line Sample Case
  - Final report published and transmitted (PWROG-23040-P)

Tasks 4 and 5 supported the Applicability Assessment (Task 2 Part 2)

- PWROG-24011-P, “Applicability of Stress Corrosion Cracking of Stainless Steel Observed in EDF Plants to other Designs,” issued
  - Reviewed vintage US plant material hardness and sulfur content to compare to EDF OE
    - Estimated 30x to >200x slower SCCGR for vintage US SS pipe (due to effects of lower hardness and higher sulfur content)
    - Assumes same stress level (material difference only)

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IGSCC Survey Results up until June 2, 2026

Line type	2023 # Welds	2023 Plant	Spring 2024 # Welds	Spring 2024 Plant	Fall 2024 # Welds	Fall 2024 Plant	Spring 2025 # Welds	Spring 2025 Plant	Fall 2025 # Welds	Fall 2025 Plant	Spring 2026 # Welds	Spring 2026 Plant	Total by Line
Safety Injection Accumulator (10/12/14")	4 3	McGuire 1 Sizewell B	8 1	Krško Surry 1	4 2 3	Comanche Peak 2 McGuire 2 Vogtle 1	3 3 6	Comanche Peak 1 McGuire 1 Waterford 3	3 2 2	Farley 1 Palo Verde 3 Wolf Creek	*3* *1*	*Comanche Peak 2* *Watts Bar 1*	44
Core Flood (14")			2 1	Davis-Besse Oconee 3									3
Safety Injection (6" or smaller)	3	Sizewell B (HPCIS)	2 2	North Anna 1 DC Cook 2			1 1	DC Cook 1 Vogtle 2	3 1	Palo Verde 3 (3") Wolf Creek	2	McGuire 2	15
RHR/ Decay Heat Removal (10", 12", 14")	2 2 6	DC Cook 1 Oconee 2 Sizewell B	1 1 2 6 1 2 2	Almaraz 2 (H) Braidwood 1 Davis-Besse Krško North Anna 1 Oconee 3 Vandellos 2	1 7 1 2 1 4	Almaraz 1 (H) Asco 1 Braidwood 2 Comanche Peak 2 Point Beach 2 (DH) Salem 2	2 1 4	Comanche Peak 1 Farley 2 Watts Bar 2	4	Farley 1	4 1	McGuire 2 (one 6") VC Summer	57
Pressurizer (PZR) Spray	2	McGuire 1	1 4 1 2 2 2	Almaraz 2 (UH) Braidwood 1 Davis-Besse Krško Surry 1 Vandellos 2	1 5 2	Almaraz 1 (UH) Surry 2 Vogtle 1	3 8 6 2	Comanche Peak 1 DC Cook 1 Vogtle 2 Waterford 3	1 2 3 2 1	North Anna 1 Palo Verde 3 Sequoyah 1 Surry 1 Wolf Creek	*4* 1 8 2	*Comanche Peak 2* Vogtle 1 McGuire 2 Surry 2	61
PZR PORV Supply Lines			8	DC Cook 2							*6*	*Sizewell B*	8
Various Welds	12	Sizewell B (EBS)	6 38 *3*	Krško (*Charging*) Ringhals 3 *STP 2 (RHR Mixing Tee)*	*TBD* 33 2 *3*	*ANO 2* Ringhals 4 Sizewell B (PZR Surge) *STP 1 (RHR Mixing Tee)*	*3* 1	*Callaway* Waterford 3 (CH)			1	McGuire 2 (Charging)	93
TOTAL EXAMS COMPLETED	34	10 U.S.	95	29 U.S.	68	24 U.S.	41	All U.S. so far	24	All U.S. so far	19	All U.S. so far	281

Fall 2026 # Welds	Fall 2026 Plant
11	*Farley 2*
3	*Vogtle 2*
3	*Sequoyah 2*
3	*McGuire 1 (6" SI)*

Spring 2027 # Welds	Spring 2027 Plant
2	*Farley 1*

147 U.S.

<u>Legend:</u>

Confirmed complete

Confirmed scheduled but not confirmed complete

Need to confirm line type and final # of welds examined

Need to confirm line type only

Still looking for confirmation of prior exam completions and future exam plans

Please email <u>Anees Udyawar, Craig Wicker, and Heather Malikowski</u> with any exam scheduling/completion updates

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IGSCC Survey Results up until June 2, 2026

Line type	2023		Spring 2024		Fall 2024		Spring 2025		Fall 2025		Spring 2026		Total by Line
	# Welds	Plant	# Welds	Plant	# Welds	Plant	# Welds	Plant	# Welds	Plant	# Welds	Plant	
Safety Injection Accumulator (10/12/14")	4 3	W4 W4-Int'l	8 1	W2-Int'l W3	4 2 3	W4 W4 W4	3 3 6	W4 W4 CE	3 2 2	W3 CE W4	*3* *1*	*W4* *W4*	44
Core Flood (14")			2 1	B&W B&W									3
Safety Injection (6" or smaller)	3	W4-Int'l (HPCIS)	2 2	W3 W4			1 1	W4 W4	3 1	CE (3") W4	2	W4	15
RHR/ Decay Heat Removal (10", 12", 14")	2 2 6	W4 B&W W4-Int'l	1 1 2 6 1 2 2	W3-Int'l (H) W4 B&W W2-Int'l W3 B&W W3-Int'l	1 7 1 2 1 4	W3-Int'l (H) W3-Int'l W4 W4 W2 (DH) W4	2 1 4	W4 W3 W4	4	W3	4 1	W4 (one 6") W3	57
Pressurizer (PZR) Spray	2	W4	1 4 1 2 2 2	W3-Int'l (UH) W4 B&W W2-Int'l W3 W3-Int'l	1 5 2	W3-Int'l (UH) W3 W4	3 8 6 2	W4 W4 W4 CE	1 2 3 2 1	W3 CE W4 W3 W4	*4* 1 8 2	*W4* W4 W4 W3	61
PZR PORV Supply Lines			8	W4							*6*	*W4-Int'l*	8
Various Welds	12	W4-Int'l (EBS)	6 38	W2-Int'l *(Charging)* W3-Int'l	33 2	W3-Int'l W4-Int'l (PZR Surge)	1	CE (CH)			1	W4 (Charging)	93
TOTAL EXAMS COMPLETED	34	10 U.S.	95	29 U.S.	68	24 U.S.	41	All U.S. so far	24	All U.S. so far	19	All U.S. so far	281

147 U.S.

Fall 2026	
# Welds	Plant
11	*W3*
3	*W4*
3	*W4*
3	*W4 (6" SI)*

Spring 2027	
# Welds	Plant
2	*W3*

Legend:

Confirmed complete

Confirmed scheduled but not confirmed complete

Still looking for confirmation of prior exam completions and future exam plans

Please email Anees Udyawar, Craig Wicker, and Heather Malikowski with any exam scheduling/completion updates

PWROG-24002 - Applicability Assessment

- Purpose: Identify the potential root cause(s) of the atypical SCC events reported in France and Japan and evaluate whether the conditions associated with those potential root cause(s) exist within the PWROG fleet.
- Conclusions
  - Literature review shows Type 316LN is not considered to be a root cause of atypical SCC in EDF plants, and no PWROG plants use Type 316LN in the relevant piping.
  - Analytical modeling confirms that high weld residual stresses (WRS) can produce shallow (~20% through wall) but long (circumferential) cracks that remain stable over plant life.
  - Hypothesis was that exceptionally high WRS was responsible for the occurrence of the atypical SCC, however, atypical SCC OE reflects WRS profiles that are both typical and atypical where the WRS is often of the order of 30 ksi (206 MPa) at the ID, for unrepaired welds, dependent upon the weld process employed.

PWROG-24002 - Applicability Assessment

- Conclusions (cont.)
  - High hardness (>240 HV) in EDF cracked welds indicates significant welding-induced plastic strain; limited U.S. samples show lower hardness, implying potentially lower susceptibility.
  - Sulfur content differences: U.S. piping typically has higher sulfur (0.01–0.03 wt%), which corresponds to 10–70× lower SCC growth rates than low-sulfur EDF piping—but sulfur's effect on initiation is still uncertain.
  - Thermal stratification contributes to EDF SCC, but 25 PWROG units with similar layouts show no confirmed SCC, despite matching susceptible configurations.
  - Dissolved oxygen is not considered to be a decisive factor—EDF found SCC regardless of proximity to makeup water injection points.
  - Weld repairs can cause deeper but typical SCC (not atypical), and such flaws remain stable; Ohi-3 had no weld repairs

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PWROG-24002 - Applicability Assessment

- Conclusions (cont.)
  - Extensive inspections: EDF: >1000 welds checked; >200 SCC found.
  - PWROG: no confirmed atypical SCC in 1027 welds (2010–2022), plus no findings in 69 U.S. and 133 European welds inspected with IGSCC-specific techniques (2023–2025).
  - Ohi-3 event appears isolated, with no additional findings after >800 Japanese fleet inspections.
  - Overall conclusion: No clear evidence that EDF/Ohi-3 atypical SCC conditions exist in the PWROG fleet.
    - Differences in materials, welding practices, sulfur content, and operating conditions likely reduce PWROG susceptibility.
  - As additional inspection results become available using IGSCC-qualified procedures and personnel, the industry will gain a clearer understanding of whether atypical SCC could apply to the PWROG fleet.

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MRP-236 Rev 2

- Purpose: MRP-236 contains information concerning SCC of primary circuit pressure boundary stainless steel, including an OE database
  - Last revision was completed in 2017, which found no cases of SCC in the non-isolable portions of branch piping
  - New revision (in progress) is reviewing OE since 2017
    - Only confirmed cases of SCC in non-isolable portions of branch piping have occurred in the EDF fleet and one case in Japan
    - Revision will also include a review of the thermal fatigue OE database (MRP-85R2/MRP-468) for cases that have the potential to be EDF-like SCC
- Status:
  - Draft developed and reviewed by EPRI
  - Working with EDF to provide additional OE information to support report completion

Next Actions

- Issue draft MRP-236 Revision 2 for member review 3rd quarter 2026
- Follow-up meeting with EDF to discuss recent OE and assess as appropriate
- Current plans are to sunset the Focus Group by end of 2026 but maintain the OG-23-82 NEI 03-08 requirement for utilities to continue performing examinations using IGSCC methods