ELECTRIC POWER RESEARCH INSTITUTE

Steam Generator Task Force / NRC Technical Meeting

Technical Bases for Extended Inspection Intervals

February 24, 2020

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Topics

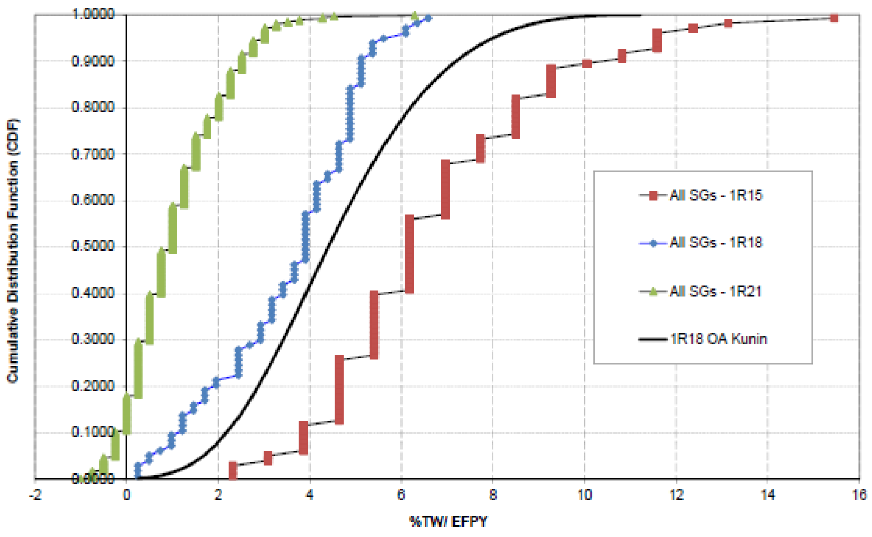
- 690TT Operating Experience
- 600TT Operating Experience
- Feasibility Study for Alloy 600TT Operational Assessments
- Summary
- Proposed Changes to Steam Generator Technical Specifications
- Discussion

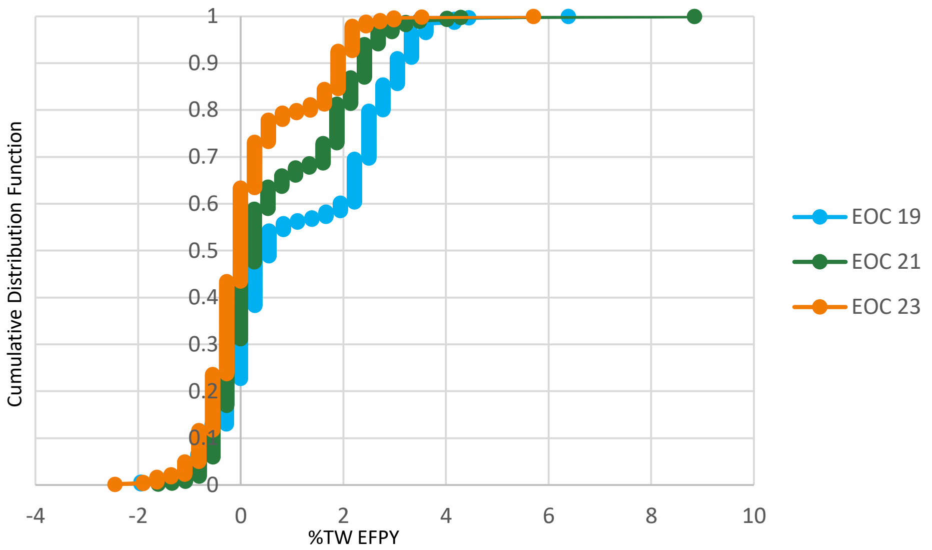
690TT Operating Experience
Jeremy Mayo

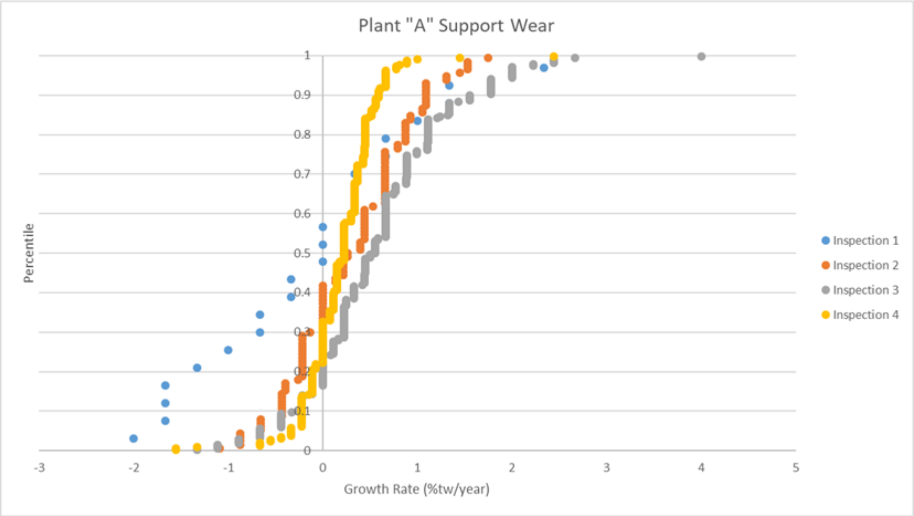
Alloy 690TT Operating Experience

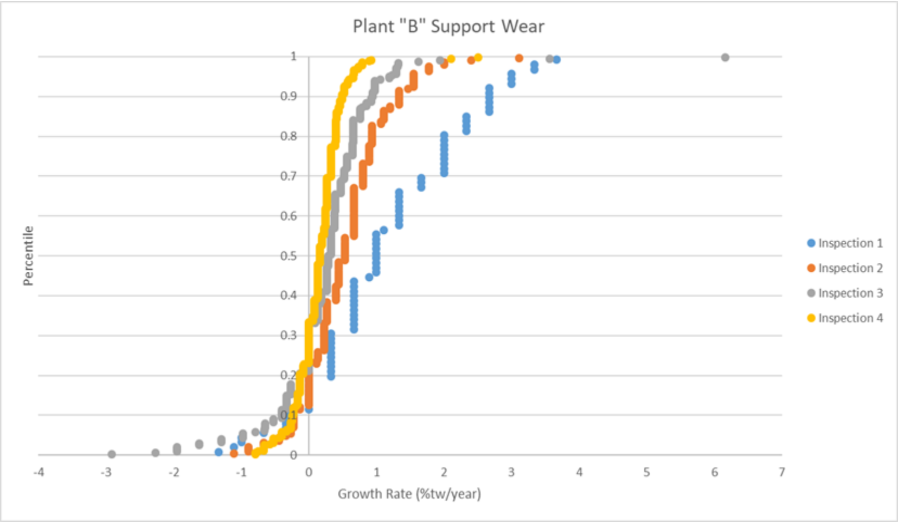
- Significant experience gained over the course of 15 years since TSTF-449 and TSTF-510
- The US fleet can be separated into three categories
  - Category 1: Few or no wear indications (less than 100)
    - 21 units
    - 15 of these units have plugged no tubes for structure wear
      - Among these are units that have been in service since the 1990's
    - The other 6 have plugged less than 10 for structure wear
    - Can justify 96 EFPM
  - Category 2: Moderate number of wear indications (between 100 and 2,000) and low growth rates
    - 12 units
    - We will demonstrate that 96 EFPM is feasible
  - Category 3: High number of wear indications or high growth rates (greater than 2,000)
    - 11 units
    - Must operate less than 96 EFPM according to their operational assessment unless the aggressive wear is neutralized

Example Growth Data from Typical Category 2 SGs

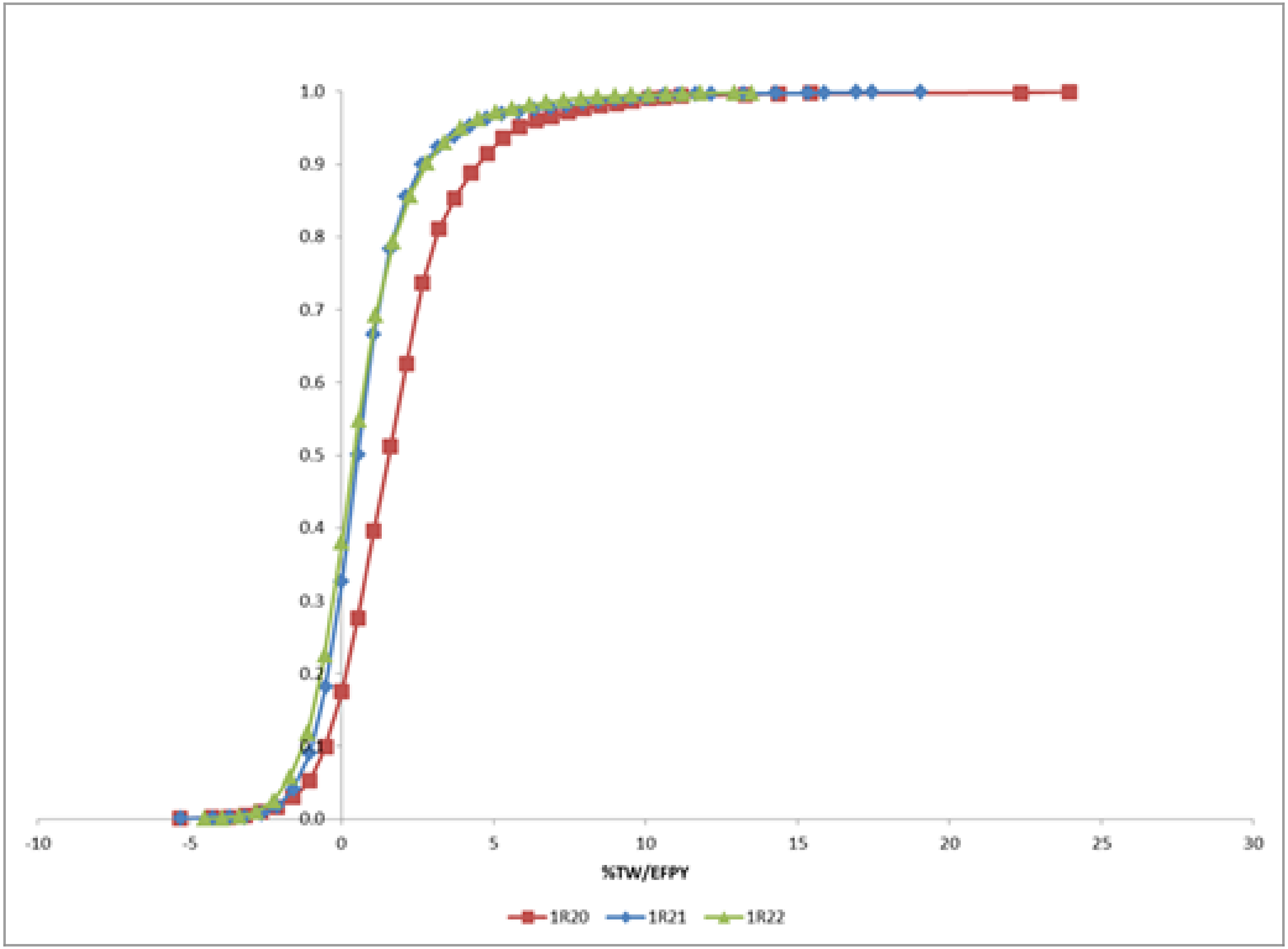








Example Growth Data from a Category 3 SG



OA Methodology Overview

- Single flaw degraded tube analyses model the worst flaw.
  - Arithmetic
  - Simplified Statistical
  - Mixed Arithmetic/Simplified Statistical
  - Monte Carlo
- Fully probabilistic analyses model the entire tube bundle
  - Fully probabilistic means that uncertainties, flaw character distributions, growth distributions, probabilities of detection and other inputs are randomly sampled for each simulation and each simulation is repeated many times over.
- All OA methods are conservative, fully probabilistic analyses are the most accurate and realistic projection of the SG condition.

Summary

- Like TSTF-449 and TSTF-510, the maximum interval between inspections is a not-to-exceed limit
  - The operational assessment validates the inspection interval
- The majority of the Alloy 690TT fleet have well understood wear rates that attenuate over time with indications that have been in service for more than 96 EFPM
- The operational assessments have conservatively predicted wear in terms of severity
- No Alloy 690TT plant has failed performance criteria for structure wear

600TT Operating Experience
Lee Friant

History and Trending of Alloy 600TT SCC

- A600TT cracking was reported in 2002 in high residual stress tubes
  - Identified as axial ODSCC at TSP intersections on tubes with high residual stress (42 indications on 15 tubes both hot and cold leg)
  - The tubes with high residual stress make up a small population in the tube bundle
    - This population has been identified for each Alloy 600TT SG and is evaluated separately
  - No new tube support indications in high residual stress tubes have been identified since 2015
  - Cracking in high residual stress tubes is not considered in this evaluation
- Tube end cracking is not considered due to uniqueness of residual stress distribution, limited inspection history, and application of H*

History and Trending of Alloy 600TT Tubes with SCC

Mechanism	Location	Plant G1	Plant G2	Plant S	Plant D	Plant C	Plant Y1	Plant Y2	Plant P	Plant N2	Total
Ax ODSCC	TTS	5		2							7
Ax PWSCC	TTS	1		3							4
Circ ODSCC	TTS	60	1			1	1				63
Circ PWSCC	TTS	1							1		2
Circ PWSCC	BLG	7			1	3		3	2		16
Ax ODSCC	Dent/Ding			2							2
Ax PWSCC	U-bend	2									2
Ax ODSCC	TSP (non HS)				2						2
Ax ODSCC	TSP (HS)			18 (1)	4 (2)					5 (3)	27
Total		76	1	25	7	4	1	3	3	5	125

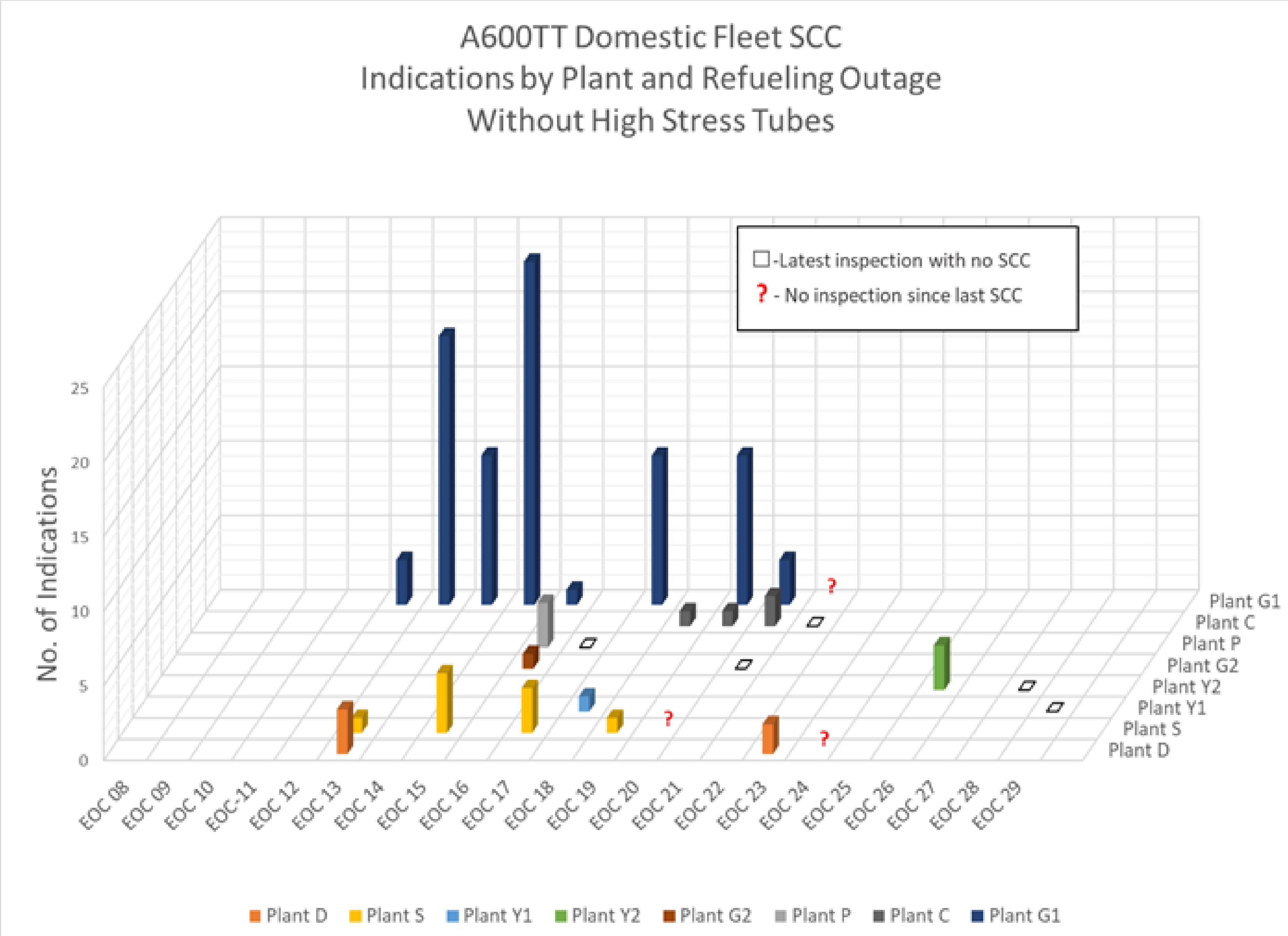
(1): None reported since 2003 (2): None reported since 2015 (3): None reported since 2012

- First observation of cracking in tubes considered in this evaluation was in 2004, Plant D, circ PWSCC at bulge several inches below TTS
- There are 17 plants in the A600TT fleet; one to shutdown in 2021, thus 16 plants going forward
- 9 of these 16 have reported SCC at various tube bundle locations
- 1 of these 9 has only reported SCC on tubes with high residual stress
- Plant G1 is the lead plant in terms of number of indications

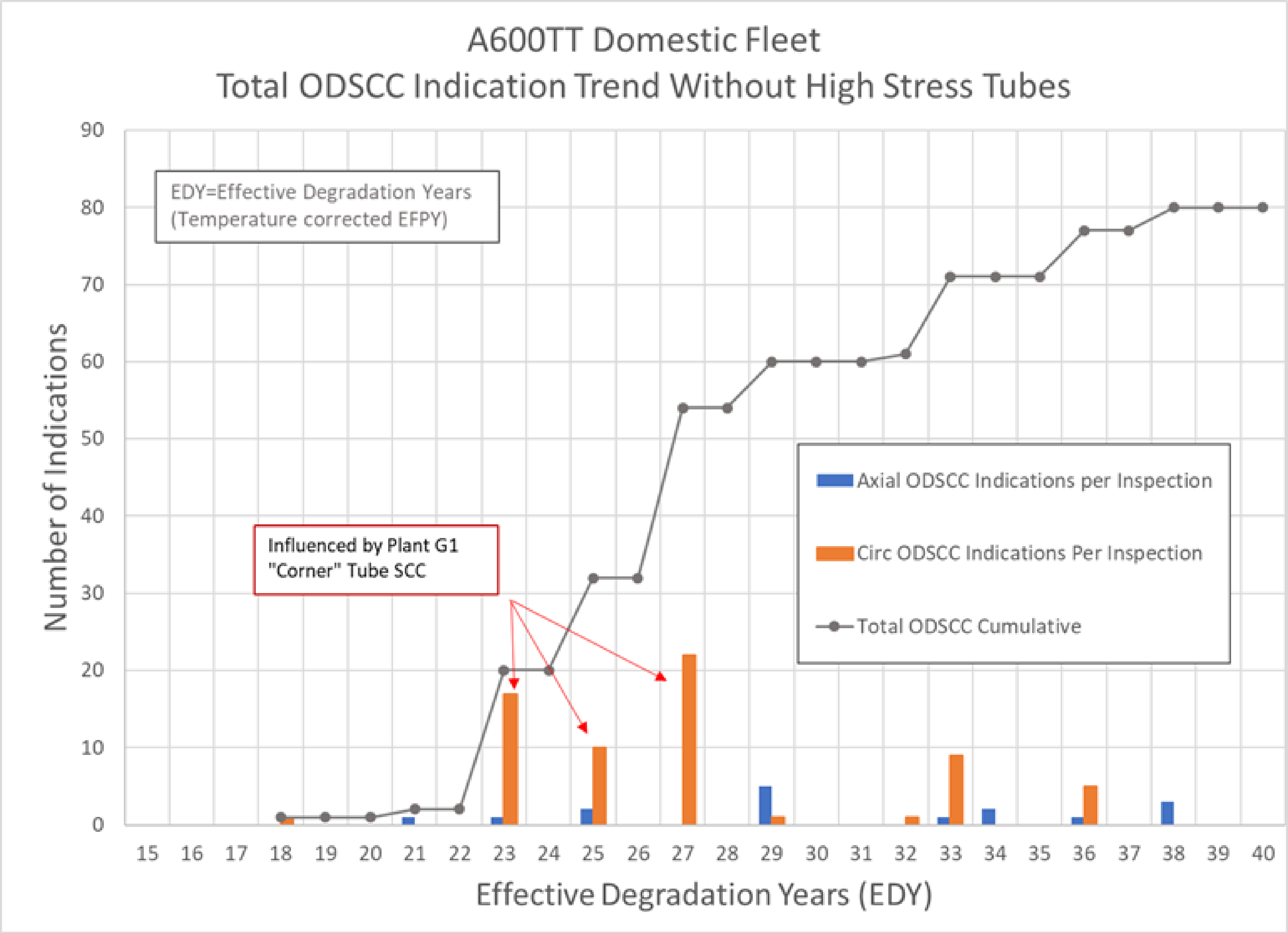
History and Trending of Alloy 600TT SCC

- 4 of the 9 plants with SCC have only reported SCC in one outage; i.e., one occurrence
- Plant S has repeat observations :
  - Axial ODSCC at TTS: 4 cycles between observations
  - Axial PWSCC at TTS: 2 cycles between observations
- Plant G1 has repeat observations:
  - Circ ODSCC at TTS: 2 to 3 cycles between groups of observations
  - Axial ODSCC at TTS: 4 cycles between observations
- Plant C reported short arc length circ PWSCC at bulges well below TTS for three successive inspections
  - History review shows these indications were present for many inspections

Available data does not suggest a rapidly increasing initiation rate nor a large susceptible population size in the Alloy 600TT fleet



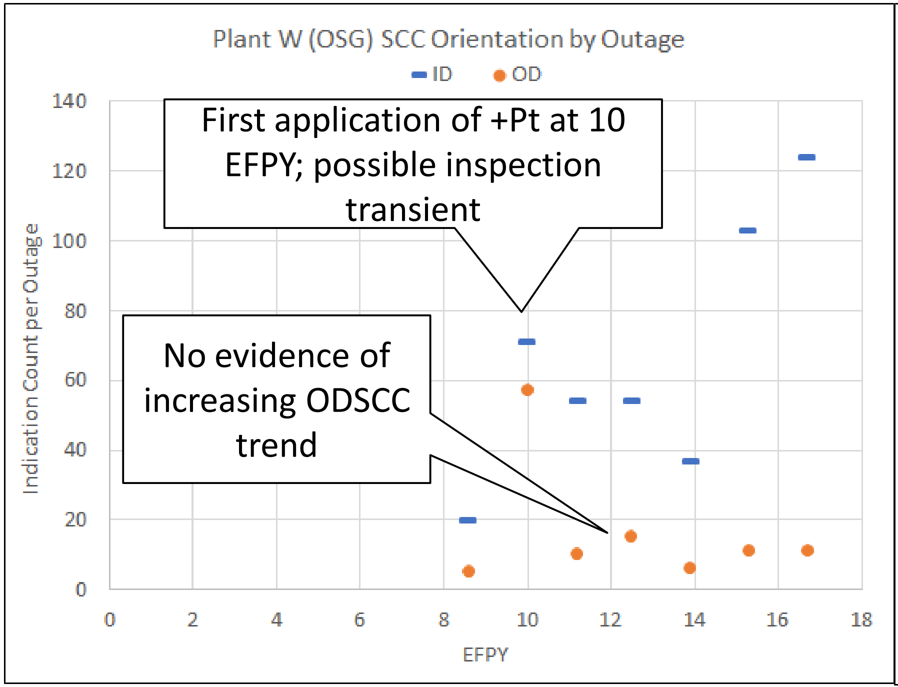
A600TT Domestic Fleet SCC
Indications by Plant and Refueling Outage
Without High Stress Tubes
No. of Indications
0
5
10
15
20
25
□-Latest inspection with no SCC
? - No inspection since last SCC
EOC 08
EOC 09
EOC 10
EOC 11
EOC 12
EOC 13
EOC 14
EOC 15
EOC 16
EOC 17
EOC 18
EOC 19
EOC 20
EOC 21
EOC 22
EOC 23
EOC 24
EOC 25
EOC 26
EOC 27
EOC 28
EOC 29
Plant G1
Plant C
Plant P
Plant G2
Plant Y2
Plant Y1
Plant S
Plant D
Plant D
Plant S
Plant Y1
Plant Y2
Plant G2
Plant P
Plant C
Plant G1

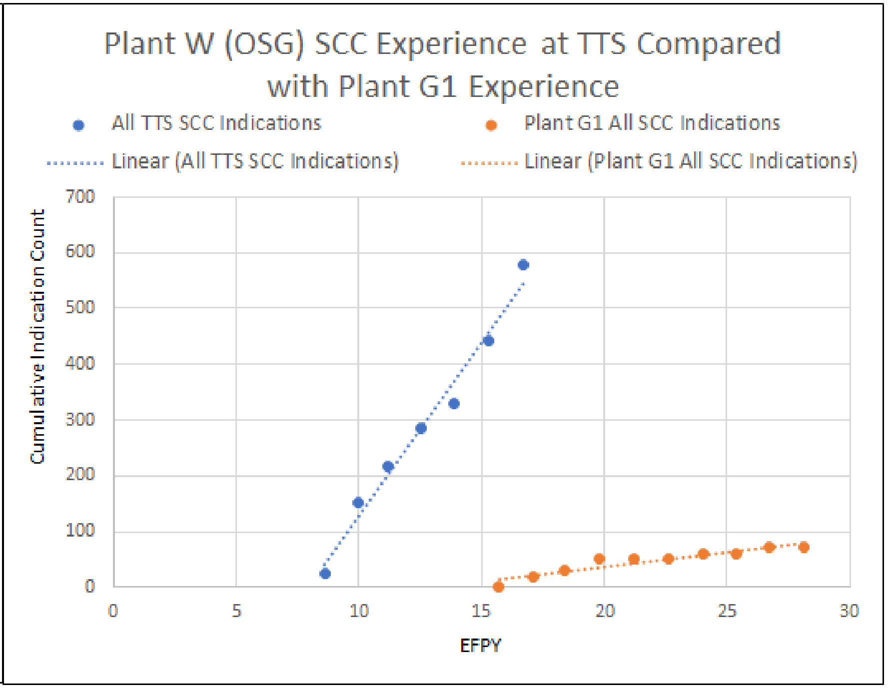

A600TT Domestic Fleet
Total ODSCC Indication Trend Without High Stress Tubes
EDY=Effective Degradation Years
(Temperature corrected EFPY)
Influenced by Plant G1
"Corner" Tube SCC
Axial ODSCC Indications per Inspection
Circ ODSCC Indications Per Inspection
Total ODSCC Cumulative
Number of Indications
0
10
20
30
40
50
60
70
80
90
15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
Effective Degradation Years (EDY)

Comparison of Material Performance in a Replaced Model F SG with Both Alloy 600MA and Alloy 600TT

- A600TT material in Rows 1 – 10 (1208 tubes/SG)
- A600MA in Rows 11 and higher (4418 tubes/SG)
- First A600MA observation: 8.6 EFPY, 25 tubes affected at TTS (pancake)
- Four A600TT tubes affected at 10 EFPY (+Point)
  - 1 ID circ
  - 2 OD circ (potential false calls)
  - 1 ID axial
- One A600TT tube affected at 13.6 EFPY: ID axial
- Cumulative indication count through last inspection (16.7 EFPY): 578 (545 tubes at TTS and below)
  - 463 ID, 115 OD (axial vs circ counts approximately equal)
  - A600TT: 0.062% tubes affected
  - A600MA: 3.07% tubes affected
- Current tech spec philosophy was driven by Alloy 600MA cracking experience. Alloy 600TT is much less susceptible, cracking is much less aggressive, number of affected tubes is and will continue to be much lower.

Original A600MA, Model F SG Experience vs Plant G1 Model F SG (Lead A600TT Plant) Experience

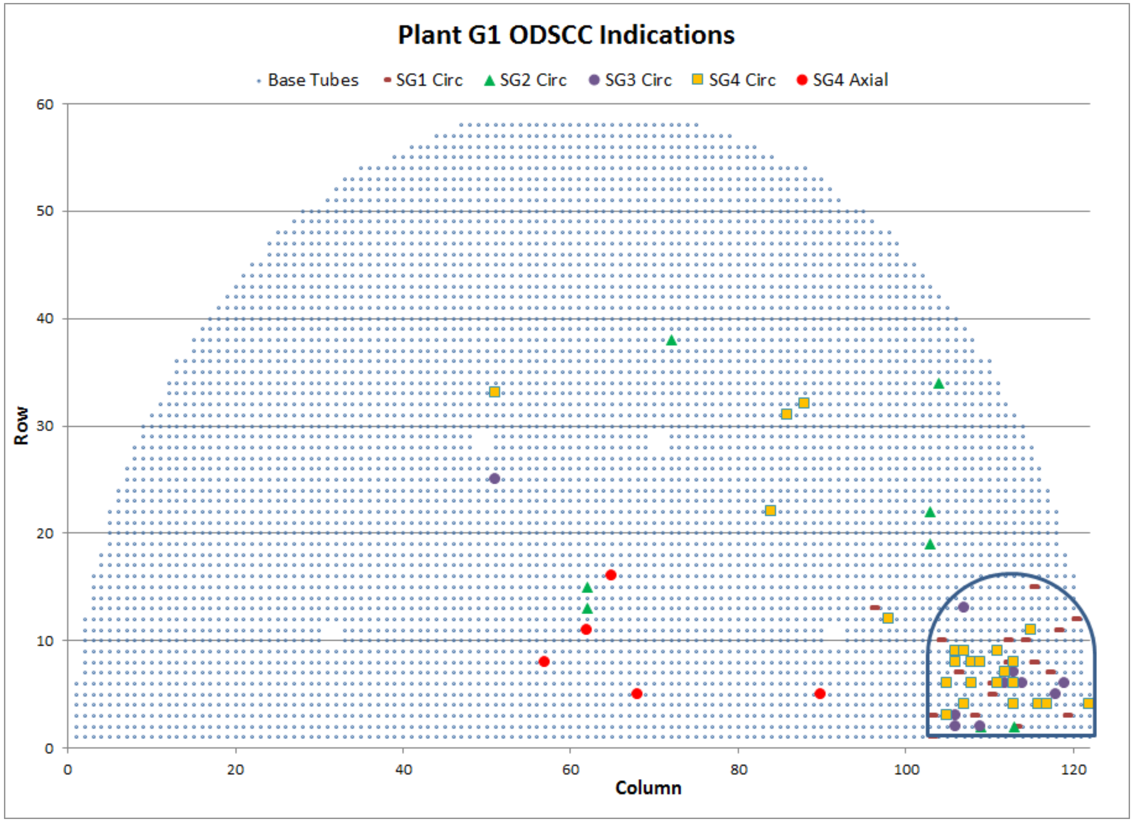




- Thermally treated material testing during the development stage showed dramatic improvement in PWSCC resistance compared to 600MA whereas the improvement in ODSCC resistance while much improved, was not as dramatic as for PWSCC.
- The observed A600TT performance to date is consistent with Alloy 600TT development data

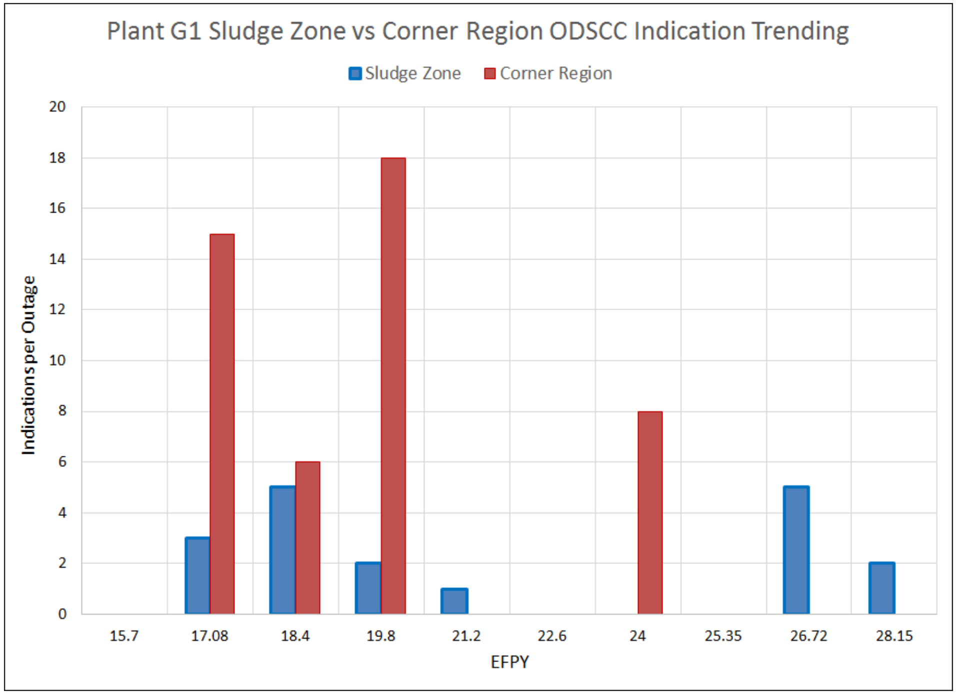
Plant G1: Lead A600TT SCC Plant ODSCC

- 65 tubes affected by ODSCC at TTS; 60 circumferential, 5 axial
- Large number of affected tubes in a small region not traditionally associated with ODSCC (“corner region”)
- Axial ODSCC indications in SG4 only

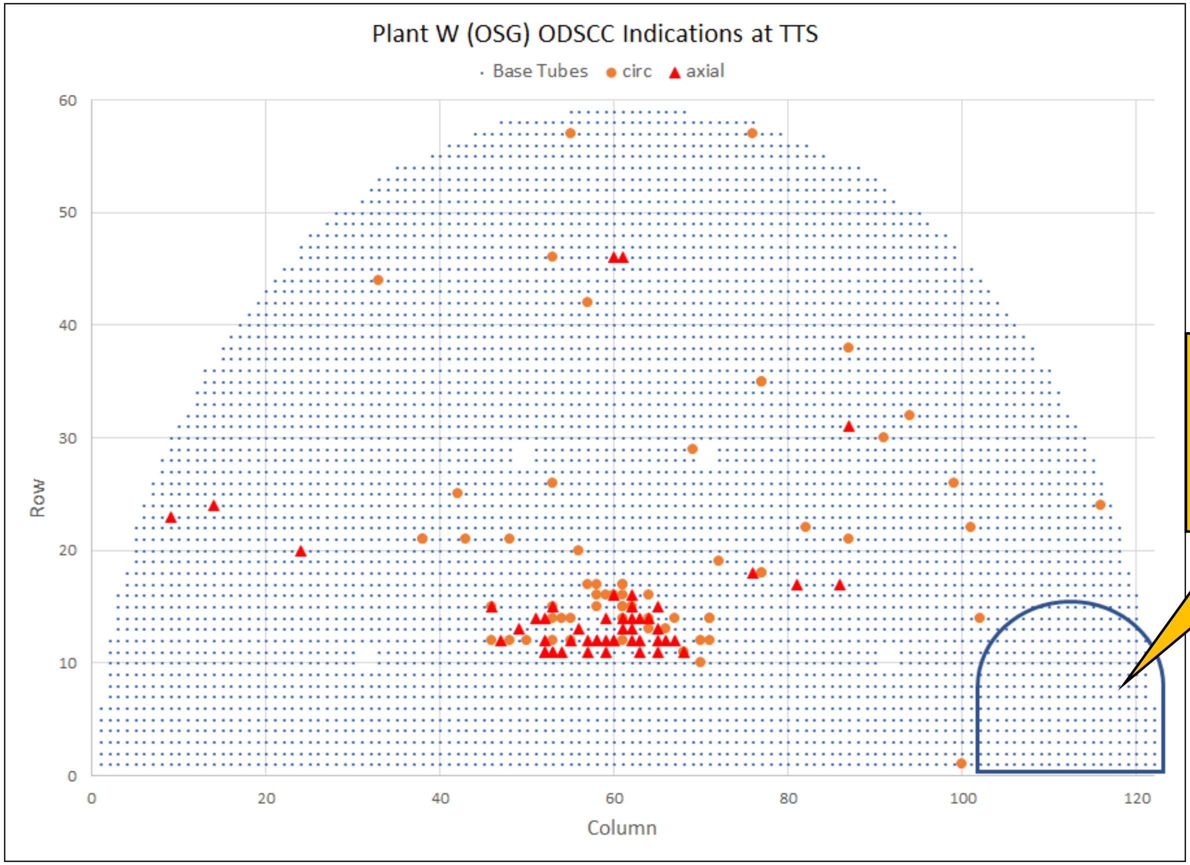


Plant G1: A600TT Lead Plant

- Corner region tubes show strong decreasing frequency trend
- Described by a Weibull function with high slope and low characteristic life (CL)
- Likely that susceptible population is exhausted
- The rest of the tube bundle suggests an initiation function described by a Weibull function with low slope and large CL
  - This function would not predict a large increase in initiations



Corner Region Experience is Unique to Plant G1 (Not seen in Alloy 600MA or other Alloy 600TT units)



No SCC flaws located in Corner Region

Summary

- Plant G1 corner region experience is unique to Plant G1
  - Axial ODSCC only reported in SG4
- A600TT PWSCC experience is exemplary
  - 24 affected tubes across 16 plants (0.008% affected)
  - Replaced Model F SG: 463 A600MA tubes affected (2.62%), 3 A600TT tubes affected (0.062%)
- A600TT ODSCC experience is exemplary
  - 27 affected tubes (excludes corner tubes at Plant G1 and all TSP ODSCC in high residual stress tubes) across 16 plants (0.01% affected)
  - Replaced Model F SG: 113 A600MA tubes affected (0.64%), 2 A600TT tubes affected (0.041%)
- Despite the A600MA material deficiency in the replaced Model F SG, ODSCC trending does not show an increasing trend, therefore no basis to conclude A600TT would experience an increasing trend
- Current tech spec philosophy was driven by Alloy 600MA cracking experience. Alloy 600TT is much less susceptible, cracking is much less aggressive, number of affected tubes is and will continue to be much lower.

Feasibility Study for Alloy 600TT Operational Assessments

Helen Cothron

Operational Assessments for Alloy 600TT

- A feasibility study was performed using two independent vendors for Alloy 600TT fleet
  - Considering plants with reported cracking and plants with no reported cracking
- The two approaches differed but both were within the constraints of the Integrity Assessment Guidelines

Example from One Vendor
Jay Smith

Fully Probabilistic OA Method

- Fully probabilistic multi-cycle OA projections were performed using methods and processes in accordance with the EPRI SG Integrity Assessment Guidelines
  - Objective: Assess the condition of a typical plant with A600TT tubing for inspection intervals up to 72 EFPM with regard to the SG structural and leakage performance criteria
  - Degradation Mechanisms selected for evaluation
    - Axial PWSCC at expansion transitions
    - Circumferential ODSCC at expansion transitions
- In support of the OA evaluations, raw eddy current data was obtained and re-analyzed for all reported SCC indications in A600TT tubing, including the data from the two prior inspections
  - SCC indications were sized by a single analyst
    - Line-by-line depth profiling
  - SCC flaw size distributions compiled
  - SCC flaw growth rates were determined

Fully Probabilistic OA Method and Inputs

- In a fully probabilistic analysis, distributions defining the flaw size, growth rate, POD, material property, uncertainties and other relevant inputs are sampled for a simulation to determine burst and leakage performance parameters
  - 100,000 simulations performed for OA projection

- Inputs important to the fully probabilistic OA include,
  - Probability of Detection (POD)
  - Beginning-of-Cycle (BOC) flaw population size distributions (depth, length, PDA)
  - Number of BOC flaws
  - Weibull failure projection for flaws that initiate during the inspection interval
  - Growth rate distributions (depth, length, PDA)
  - Flaw Shape Factor distributions (depth and length)
  - Tube material property strength parameters (yield and ultimate) and associated uncertainties
  - Burst relation uncertainties
  - Plant specific parameters, $3 \cdot \Delta P_{NOP}$, P_{SLB}, maximum allowable accident leak rate, current EFPY, future cycle durations, tube dimensions and number of tubes.

Fully Probabilistic OA Method and Inputs

- BOC flaw size distributions
  - Obtained from POD curves and evaluation of data from reanalysis of historical A600TT SCC data
  - EPRI MAPOD software used to generate noise-based POD curves
    - Flaw size to voltage amplitude correlation (Ahat) functions developed from re-analysis of applicable ETSS datasets
    - Noise voltage amplitude distributions from a Model F plant
    - Industry signal-to-noise thresholds of 1.5 and 2.2
  - BOC length size distribution determined from evaluation of A600TT SCC look-back data with consideration to NDE sizing uncertainties
  - BOC percent degraded area (PDA) size distribution determined from depth POD and shape factor monte carlo simulations benchmarked to A600TT SCC look-back data
- The number of BOC flaws and number of flaws that initiate during the inspection interval were determined using Weibull failure projections with the SCC experience of A600TT plants

Fully Probabilistic OA Method and Inputs

- Determined flaw growth rate distributions for depth, length, and PDA from A600TT SCC reanalysis
  - Results showed that the A600TT flaw growth rates are better than the typical default growth rates (based on 600MA) from the EPRI SG Integrity Assessment Guidelines
- Plant specific parameters used were typical of A600TT fleet
  - Model F designed SG that operates with a tube differential pressure of 1400 psi and primary hot leg temperature of 615^{o} F with a current operating life of 30 EFPY
- A best estimate case was determined for each of the two degradation mechanisms (Base Case)
  - Sensitivity evaluations were performed to assess effects of changes to key inputs

Fully Probabilistic OA Method and Inputs

- OA Sensitivity Evaluation performed for comparison to the best estimate Base Case. Input sensitivities performed for
  - Number of BOC indications
  - Flaw growth rates
  - Inputs affecting POD
    - Tube noise
    - Signal-to-noise threshold values
  - Maximum depth to average depth shape factors

Fully Probabilistic OA Results

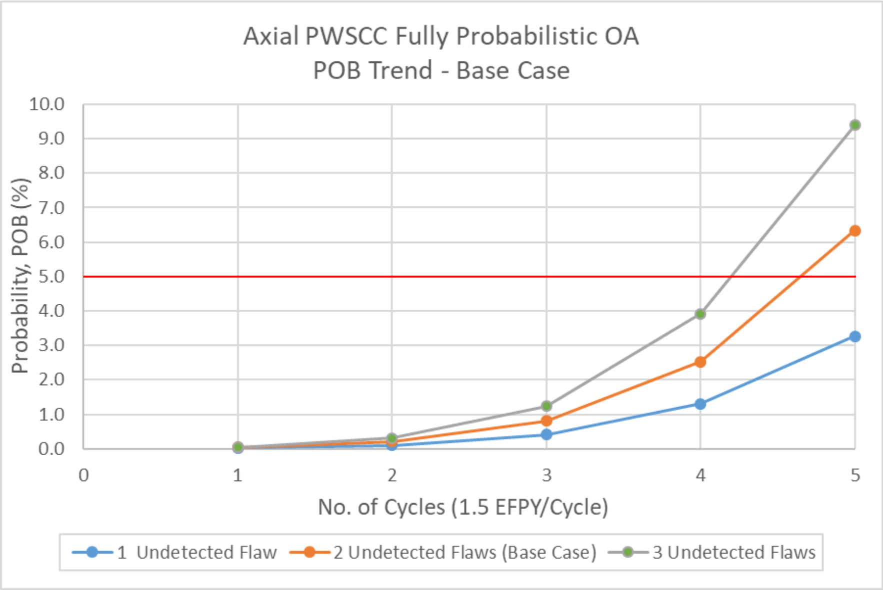
- Results for the OA projections for the best estimate Base Case for axial PWSCC at expansion transitions
  - All SG performance criteria were satisfied for up to 72 EFPM
    - Probability of Burst: 2.53%
    - Probability of Leakage: 0.44%
    - Performance Criterion: ≤5%

- Results for the OA projections for the best estimate Base Case for circumferential ODSCC at expansion transitions
  - All SG performance criteria were satisfied for up to 72 EFPM
    - Probability of Burst: 0.01%
    - Probability of Leakage: 1.7%
    - Performance Criterion: ≤5%

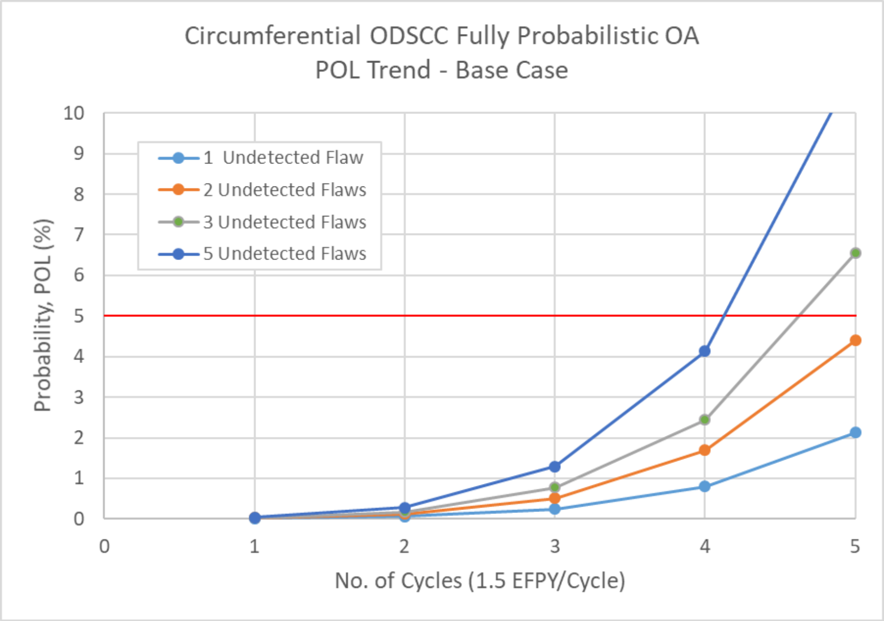
Fully Probabilistic OA Results

- Based on the results of the sensitivity studies, the following observations were made
  - The number of BOC flaws and flaw growth rate have a large influence on the acceptable inspection interval duration
    - The inspection interval was limited to <72 EFPM for some of the sensitivity cases evaluated
      - Higher growth rates and/or larger number of BOC flaws could limit the inspection interval
- The fully probabilistic OA model was benchmarked to existing plant degradation experiences and shown to be conservative

Example Base Case OA Results for Limiting Criterion



- Sensitivity cases were performed with up to 5 undetected flaws



Fully Probabilistic OA Study Conclusions

- A 72 EFPM inspection interval was successfully demonstrated using existing Industry OA methods for SCC for a typical A600TT plant

- Higher plant specific growth rates and/or higher incidence of SCC initiation could limit inspection intervals to less than 72 EFPM

- This assessment demonstrates that Alloy 600TT plants could go more than one cycle after finding cracks

Example from Second Vendor
Bill Cullen

Approach to Feasibility Study Performance

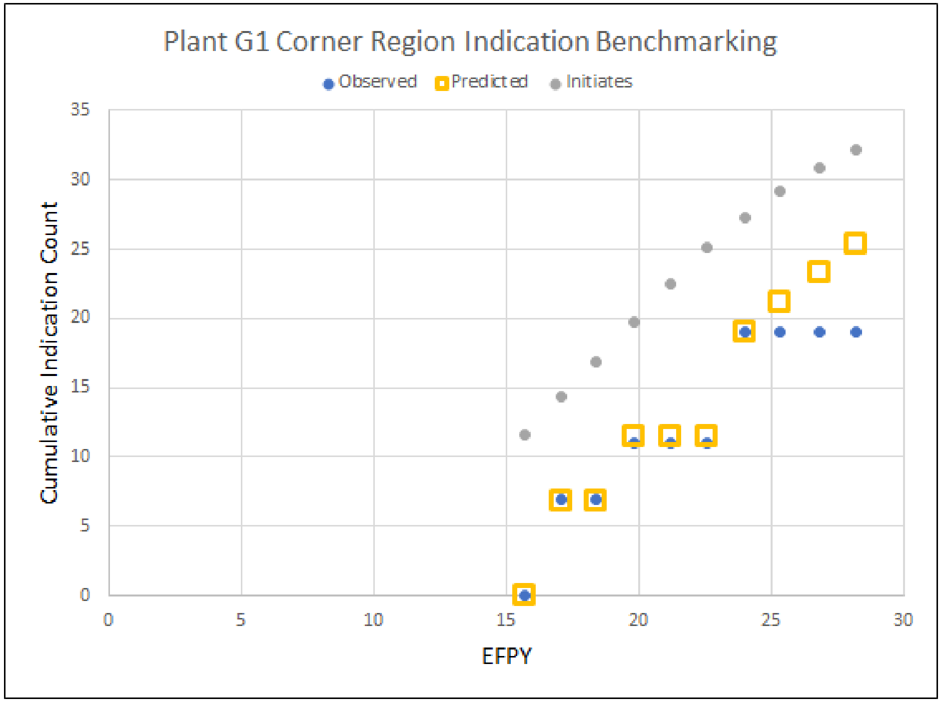
- Utilized conservative assumptions for growth rate, POD, and initiation function
- Multi-cycle modeling software with capability to simulate detection performance over a 10 cycle period used to benchmark the initiation function model against actual plant SCC performance
- ODSCC mechanisms (bound PWSCC experience) benchmarked with excellent convergence establishes confidence in the model and the analysis
- Since ODSCC mechanisms bound PWSCC experience, ODSCC OA results can conservatively be applied to PWSCC

Approach to Feasibility Study Performance – POD and Growth Rates

- Industry POD curves conservatively adjusted to provide a bounding, conservative assessment
  - Models additional non-detected indications at shallow depths
  - Adjustments primarily performed for depths <40%TW while maintaining depth associated with POD of 0.95
- Investigated methods regarding X-Probe POD simulation which suggest improved detection performance
- Growth rate study performed using flaw parameters at time of detection and results of history review
  - Concluded that IAGL typical default values remain bounding
  - Used IAGL default values in the feasibility study to avoid growth rate effects associated with hard chemical cleaning (Plant G1)
  - Monte Carlo simulation of assumed initiation point with growth produces excellent benchmarking of Plant G1 circumferential ODSCC depths
  - Growth rates were averaged over total incubation period

Approach to Feasibility Study Performance – Initiation Function Development

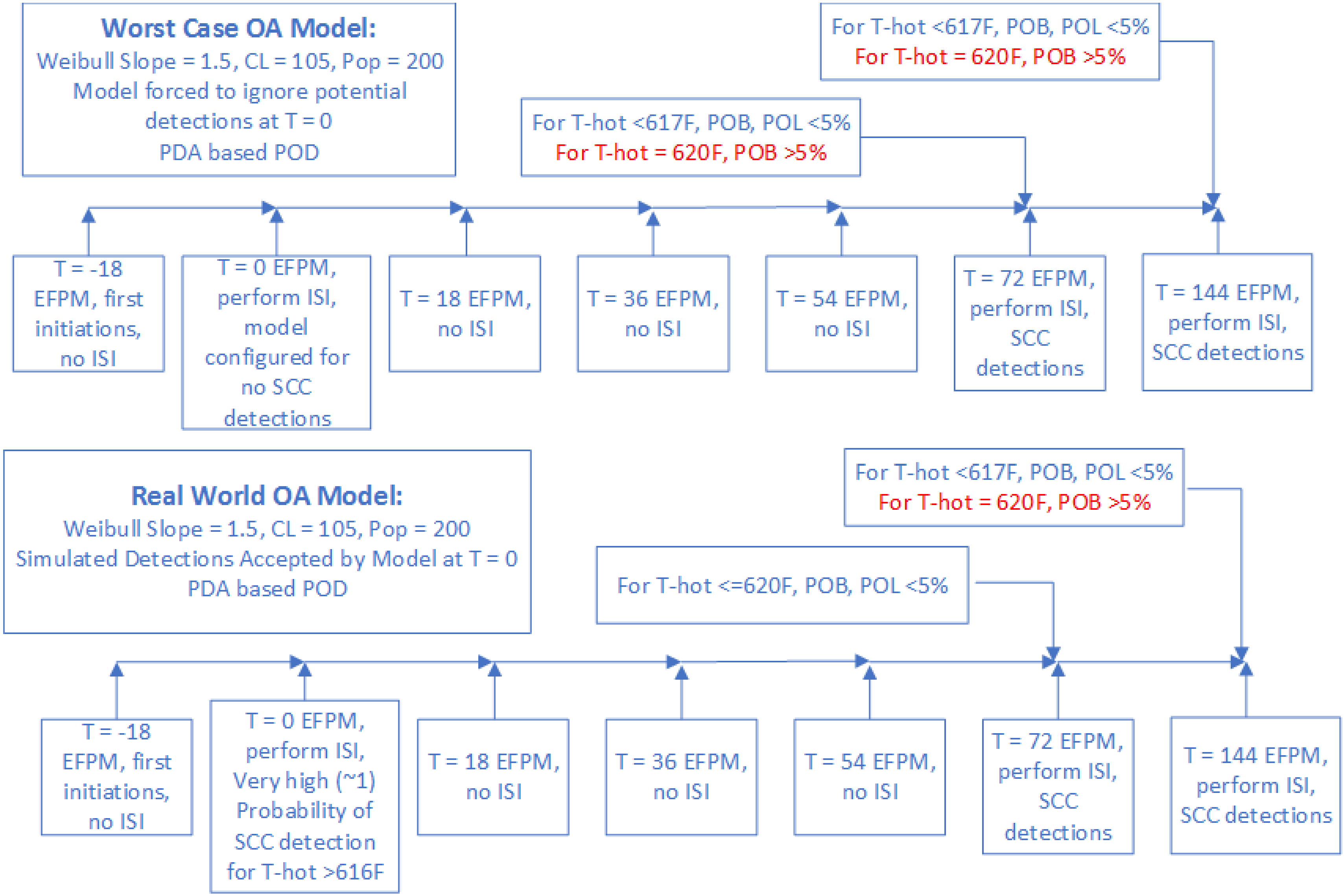
- Initiation function is the most important element of benchmarking past SCC performance
- Iterative process which converges predicted indication counts over time as well as depth of detected indications
- Initiation function includes both detected and non-detected indications
- When predictions match observations there is a high confidence in the optimized initiation function
- Similar plots developed for all evaluated mechanisms



OA Example Cases:

- All axial ODSCC (TTS + dents/dings) and PWSCC lengths combined to produce a bounding EOC length distribution that can be applied to all axial SCC OAs
- Bounding circumferential EOC length distribution developed from all observed indications plus additional 45 degree arc allowance
- Lead plant analyses (SCC detection) performed to establish safe multi-cycle operation continuing forward from last inspection
- Generic multi-cycle cases use two different Weibull slopes to evaluate both uniform initiation and increasing initiation trends
- Generic cases model SCC initiation one cycle prior to the next inspection – worst case model
- Flaw generation and detection is driven by the POD curve, initiation function, and growth rate
- Generic cases address plants with no SCC history as well as future SCC detection following multi cycle operation

Circumferential ODSCC OA Cases: Multi-Cycle Timeline



Conclusions

Lead Plant (G1) Axial SCC at TTS

- Feasibility study examined 54 EFPM operation beyond the last reporting; POB, POL <<5% limit
  - Analyses based on Plant G1 optimized growth rate
  - Expectation that 72 EFPM operation could be supported
- Sensitivity case using excessive growth rate supports 54 EFPM operation
- Analyses based on Plant G1 optimized growth rate
- Plant S: 72 EFPM beyond the last reporting; POB, POL <<5%

Lead Plant (G1) Circumferential SCC at TTS

- Feasibility study examined 72 EFPM operation beyond the last reporting with Plant G1 optimized growth rate; POB,POL <<5% limit
- Sensitivity case using 620F default growth rate supports >54 EFPM but <72 EFPM
- For the other three plants with only one reported circumferential ODSCC, Plant G1 results are an extremely conservative bound

Conclusions: Plants without SCC History

Axial SCC at TTS, Dings, Dents

- Operation up to 72 EFPM is supported for T-hot <=620F

Circumferential SCC at TTS

- For T-hot <617F, 72 EFPM operation is supported
- For T-hot = 620F, operation limited to 54 EFPM but only for the Worst Case Model, which may be an unrealistic model
- For T-hot <=620F, if 1 indication in any SG is reported at the next inspection, 72 EFPM operation is supported for the 1st 72 EFPM operating period (applies also to plants with SCC history)
- If 2 or 3 indications are reported in any SG at the next inspection or after the 1st 72 EFPM period, operation is limited to 54 EFPM for the next period

Bounding Results for Generic Axial Cracking OAs - Probability of Burst and Leakage with no Axial Cracking Reported

Thot (degF)	600	611	620
POB after 36 EFPM POL	0.1% 0.1%	0.2% 0.3%	0.6% 1%
POB after 54 EFPM POL	0.1% 0.1%	0.5% 0.5%	1.2% 1.8%
POB after 72 EFPM POL	0.2% 0.1%	0.8% 0.9%	1.8% 3.2%

For all scenarios, POB, POL are REDUCED following the next operating period of equal length. Thus, operation for up to 72 EFPM is supported following SCC detection (provided number of flaws and structural equivalent depths are bounded by the model results)

Bounding Results from Generic Circ OAs - Probability of Burst and Leakage with no Circ Cracking Reported

Thot (degF)	600	611	620
POB after 36 EFPM POL	0.01%	0.14%	0.13% [1] <1%
POB after 54 EFPM POL	0.02%	0.5%	0.35% [1] <1%
POB after 72 EFPM POL	0.11%	1.6%	1.94% [1]

[1] Real World Model

Summary
Steve Brown

Summary

- Alloy 690TT data shows the proposed 96 EFPM extension is acceptable
- Alloy 600TT data shows no propensity for rapidly increasing crack initiation rate
- Both vendors showed that Alloy 600MA default growth rates in the Integrity Assessment Guidelines are conservative for Alloy 600TT
- Both vendors show that given the behavior of Alloy 600TT, inspection during the outage following detection of cracking is not necessary to ensure safe operation
- Based on examples provided, 72 EFPM operation between inspections can be justified

Proposed Changes to SG Technical Specifications
Brian Mann

SGMP Proposal

Item	A600MA	A600TT	A690TT
Inspection Period Not To Exceed	24 EFPM	~~48 EFPM~~ 72 EFPM	~~72 EFPM~~ 96 EFPM
Inspect 100% Tubes Within	~~60 EFPM~~ 24 EFPM	~~120 / 96 / 72 EFPM~~ 72 EFPM	~~144 / 120 / 96 / 72 EFPM~~ 96 EFPM
Cracking	If crack indications are found in any SG tube, then the next inspection for each affected and potentially affected SG for the degradation mechanism that caused the crack indication shall be at the next ~~not exceed 24 effective full power months or one~~ refueling outage ~~(whichever results in more frequent inspections).~~		

- Plants with OAs that support the maximum operating period, and intend to operate for that duration between inspections must perform 100% inspection of potential and existing mechanisms each time they inspect
- Plants with OAs that do not support the maximum operating period or do not wish to operate that long between inspections may sample to achieve 100% within the applicable maximum period duration
- Would like to discuss eliminating the highlighted paragraph or rewording

Changes to the Section 5.5.9 Steam Generator (SG) Program

- Paragraph d – Added plant-specific (e.g., bracketed) option for plants approved for H*
- Paragraphs d.2
  - Provides fixed inspection periods (24, 72, or 96 EFPM)
  - Requires inspecting 100% of the tubes every inspection period
- Corresponding Changes to Paragraphs d.2
  - Fixed inspection periods eliminates the need for paragraphs d.2.a), b), c), and d).
- Paragraph d.3
  - This draft reworded the inspection after crack indications are identified to simply state they will be inspected at the next refueling outage.
  - The industry would like to discuss eliminating this paragraph or rewording

Changes to the Section 5.6.7 Steam Generator Tube Inspection Report

- Reordered existing requirements to provide information for each degradation mechanism found:
  - Existing (TSTF-510) Items c, e, g, h
- Expanded item g (now b.3) to include “the margin to the tube integrity performance criteria and comparisons to the predicted margin.”
- Added new item b.6, “Predicted margin to the tube integrity performance criteria at the next inspection, including the assumed growth rate.”
- New items b.2, b.3 and b.6 replace existing item d, “Location, orientation (if linear), and measured sizes (if available) of service induced indications.”
- Added a bracketed item for H* reporting

Discussion

Acronyms

- +Pt – Plus point probe
- BLG - Bulge
- BOC – Beginning of cycle
- EOC – End of cycle
- CL - Characteristic life
- EFPM – Effective full power month
- EFPY – Effective full power year
- ETSS – Eddy current technique specification sheet
- H* - Alternate repair criteria for steam generators with hydraulic expansions
- HS – High residual stress tubes
- IAGL – Integrity Assessment Guidelines
- ISI – Inservice inspection
- MA – Mill annealed
- NOP – Normal operating pressure
- OA – Operational assessment

Acronyms

- ODSCC – Outside diameter stress corrosion cracking
- OSG – Original steam generators
- PDA – Percent degraded area
- POB – Probability of burst
- POD – Probability of detection
- POL – Probability of leak
- PWSCC – Primary water stress corrosion cracking
- SCC – Stress corrosion cracking
- SG – Steam generator
- SL – Structural limit
- SLB – Steam line break
- TSP – Tube support plate
- TSTF – Tech Spec Task Force
- TT – Thermally treated
- TTS – Top of tubesheet
- TW – Through wall

Together…Shaping the Future of Electricity