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# NRC/Industry Meeting Regarding Tube-to-Tubesheet Weld and Divider Plate Cracking Report

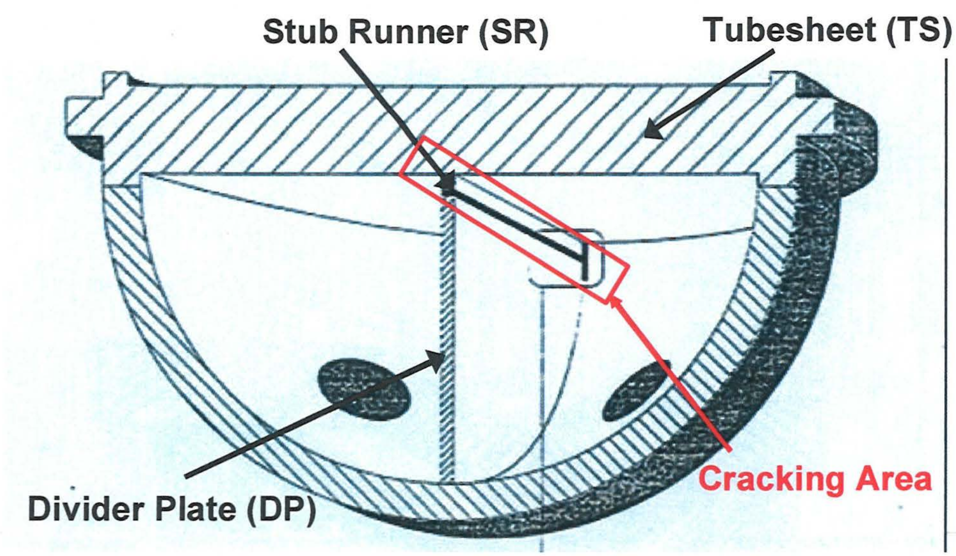
Helen Cothron, Manager
EPRI Steam Generator Management Program

Richard Smith, Sr. Associate
Structural Integrity Associates

Greg Kammerdeiner
First Energy

# Background

- Primary Water Stress Corrosion Cracking has been reported in the weld between the divider plate and the stub runner in French and Swedish steam generators with Alloy 600 divider plate and Alloy 82 and 182 weld material
- SGMP completed a multi-phase project in 2010 that concluded that these cracks were not safety significant



# Phase I Determined the Limiting Steam Generator

- Phase I evaluated operating experience and determined limiting model steam generator
  - Cracks observed in divider plate and stub runner weld heat affected zones in foreign fleet.
  - Westinghouse Model 51 steam generators determined to be the limiting case for US plants.
  - Model 51 is limiting case due to thinnest divider plate and greatest vertical displacements of the centerline of the tubesheet under normal and accident conditions.
  - Compared well with foreign operating experience

## Phase II Assessed Transients, Stress Reports, and Repairs

- Analysis of transients (LOCA and Non-LOCA)
- Analysis of multiple crack geometries
  - Multiple and combined origin sites
- Review of ASME Code stress reports to determine if they are affected by degraded divider plate condition
- Review of steam generator tube repairs

# Background / Overview

- The design analyses for the following components did not take credit for the divider plate:
  - Tubesheet
  - Channel head
  - The lower shell
  - Tubesheet to channel head junctions
  - Tubesheet to lower shell junctions
  - Tube-to-tubesheet welds

# Analyses Not Affected by a Degraded Divider Plate

- Supporting analysis and boundary conditions for lower steam generator complex
- The performance or safety function of the steam generator and the affected loop during a postulated accident condition
- The supporting analysis basis for tube plugs installed prior to 1989
- C* Alternate Repair Criteria
- H* Alternate Repair Criteria
- Alloy 800 sleeves



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## Analyses Sensitive to a Degraded Divider Plate but Conservative

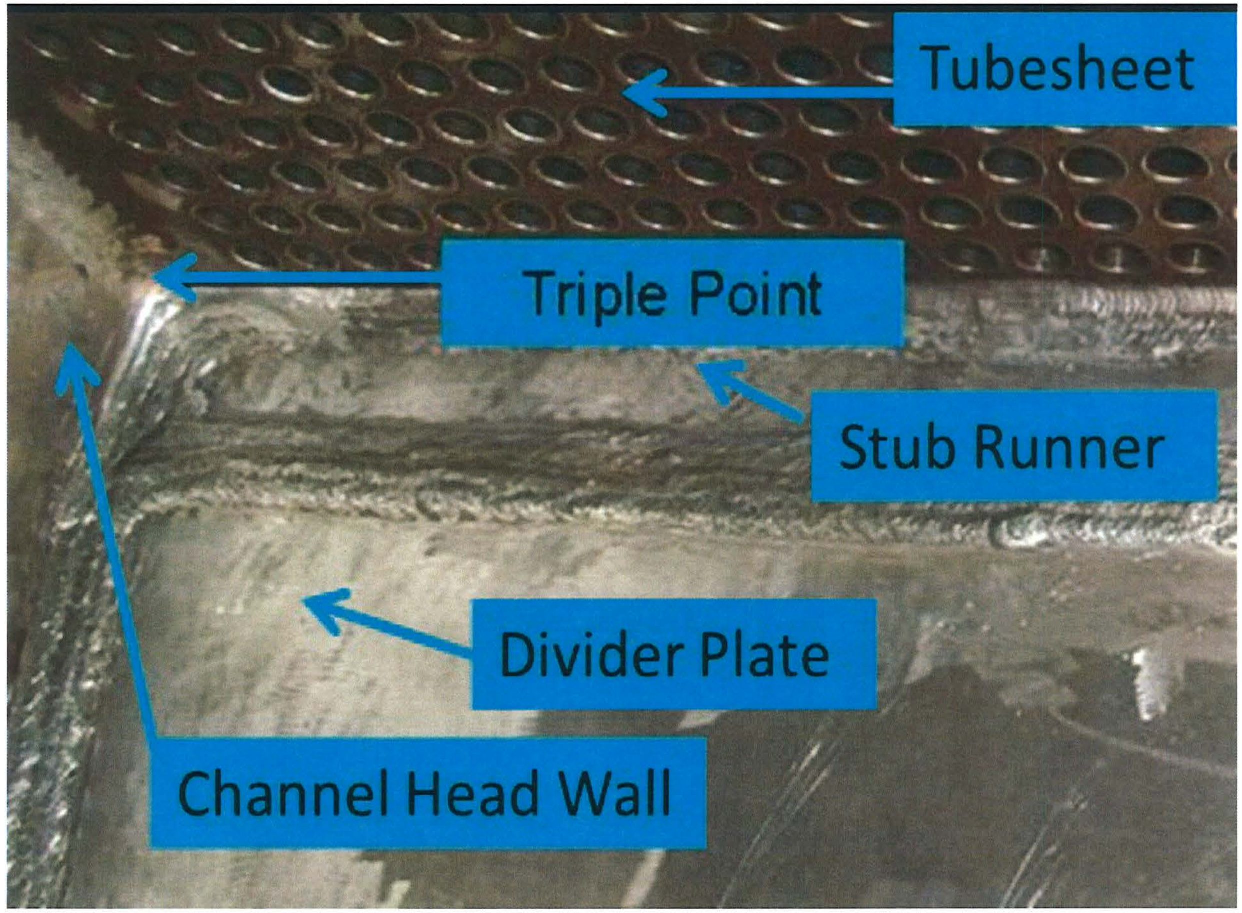
- Divider plate factor of 76% of the vertical displacement was used in analyses for
  - Steam generator mechanical tube plugs used after 1989
  - Laser welded and TIG welded sleeves
  - F* Alternate Repair Criteria
  - W* Alternate Repair Criteria
- Conservative because 76% is **greater than the vertical displacement associated with a fully degraded divider plate (64%)**

## Phase II Conclusions

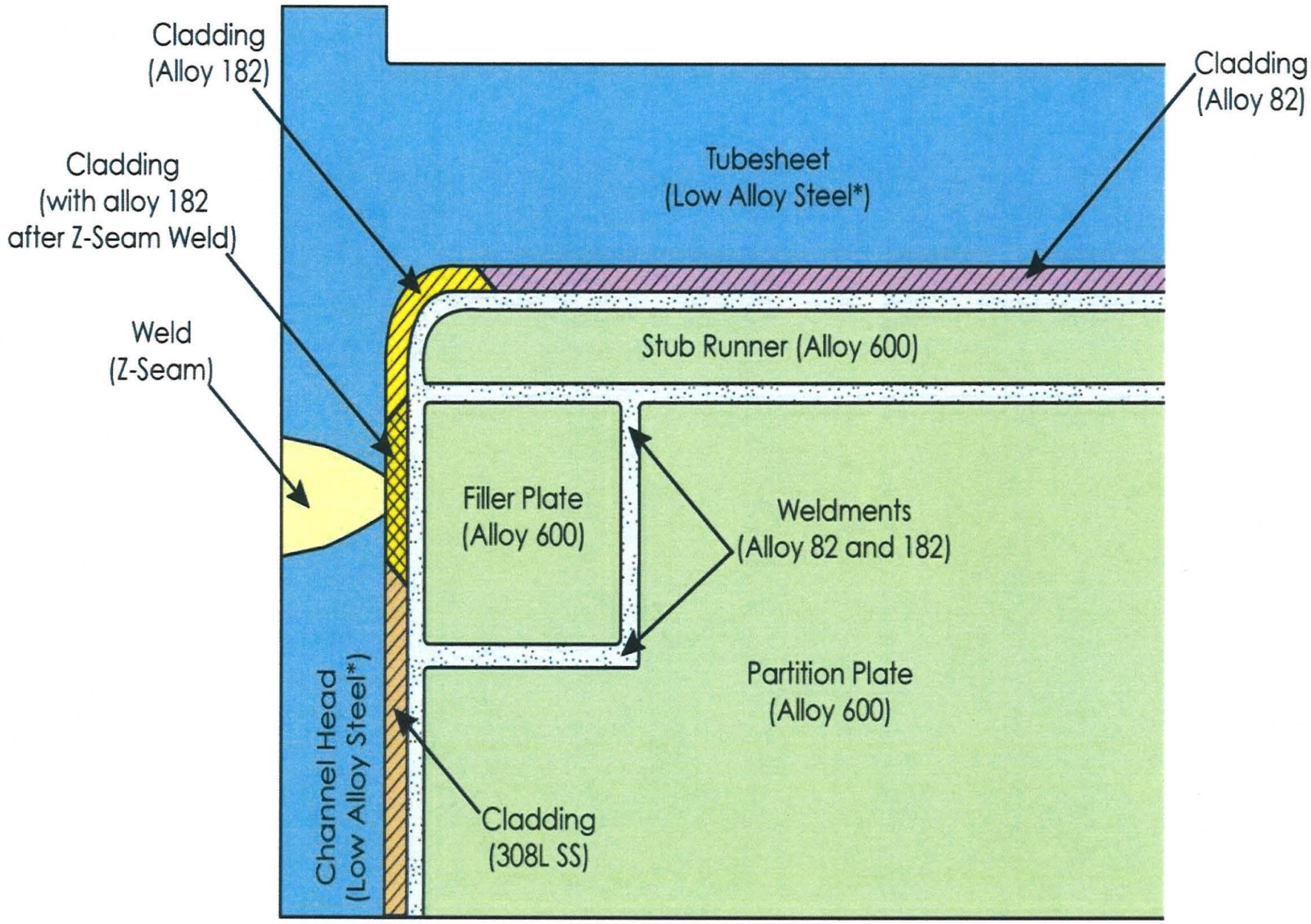
- No identified need for US plants to inspect for PWSCC based on program results
  - Degraded divider plate is not a safety concern during operations
  - Degraded divider plate is not a structural concern during operations
  - Degraded divider plate does not affect existing repair criteria or repair tools
  - Divider plate inspection not mandated by ASME Code

# Divider Plate Crack Propagation

- When US plants began submitting license renewal applications to the NRC, the potential crack propagation over extended period of operation became a concern
- SGMP began a project in 2011 to address the concerns of cracks propagating over time to pressure boundary components such as the channel head or the tube-to-tubesheet weld



# Divider Plate to Channel Head/Tubesheet Weld Configurations





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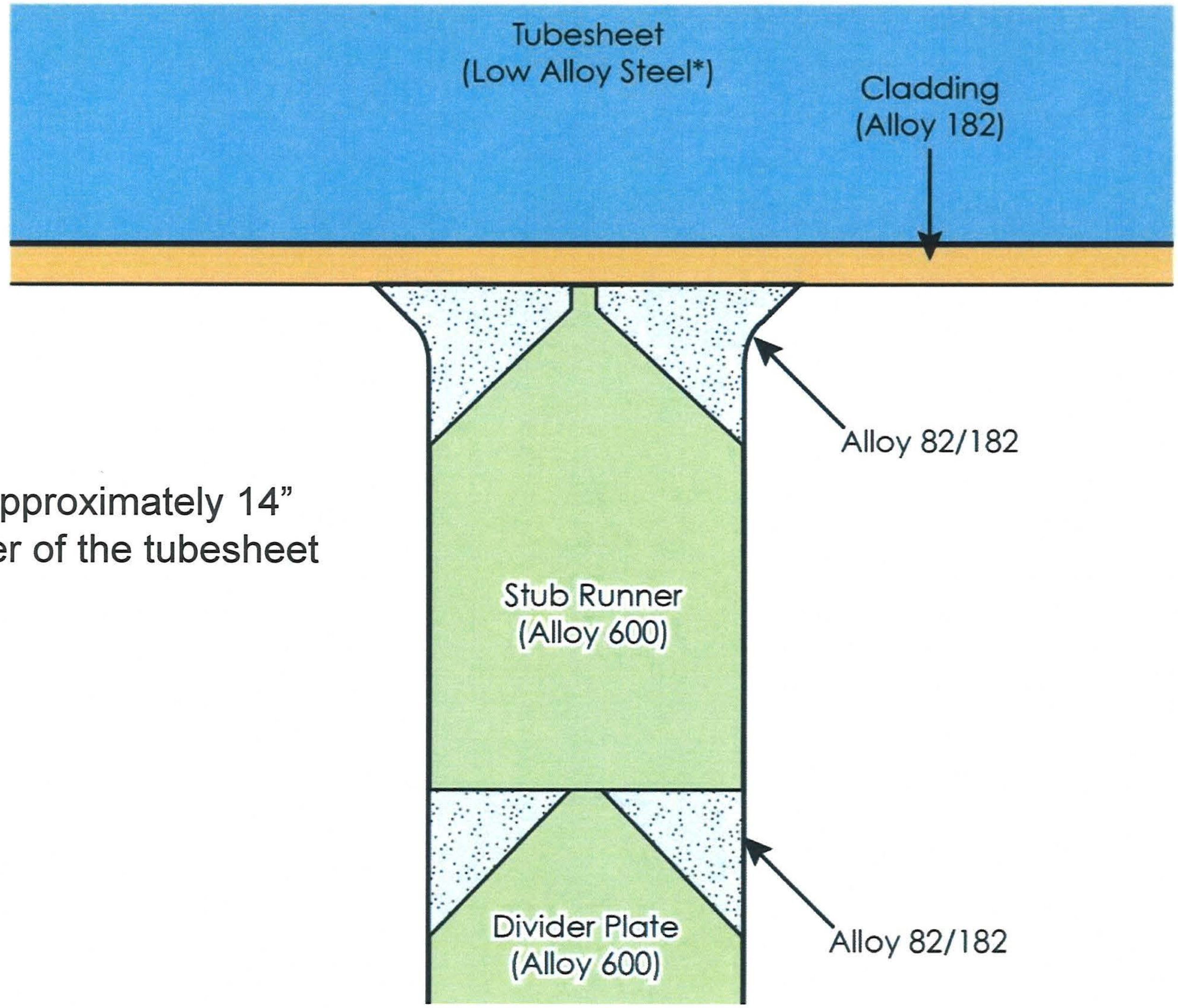
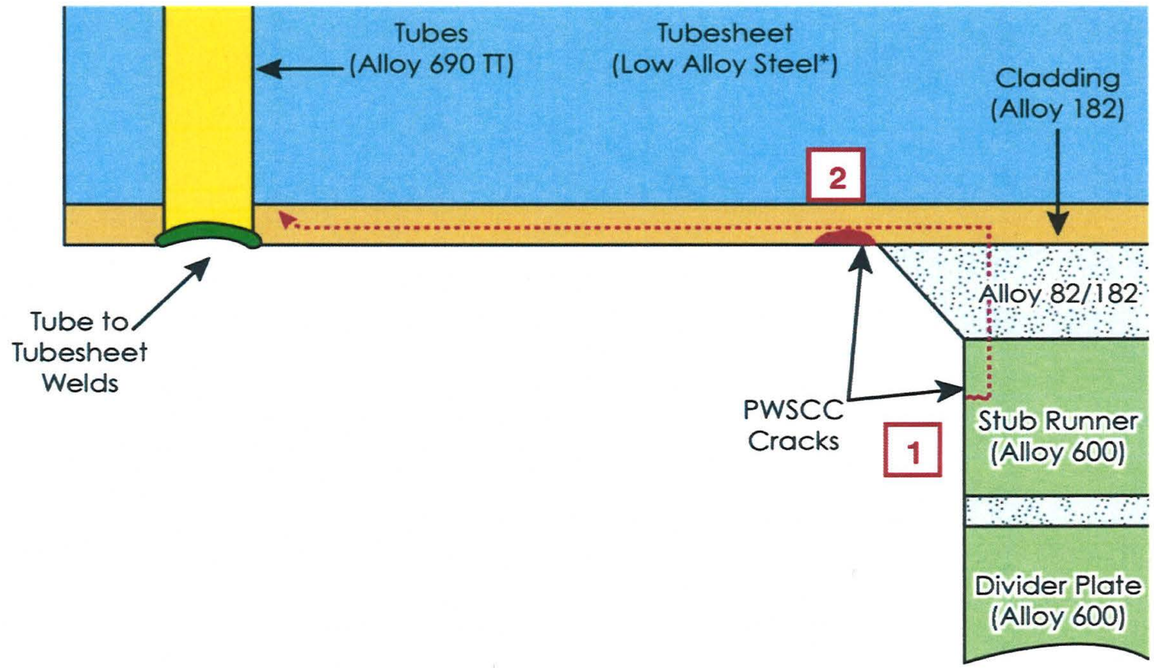
# Divider Plate – Tubesheet Center Configuration




- 182 used approximately 14” in the center of the tubesheet

# Divider Plate Crack Propagation Scenarios

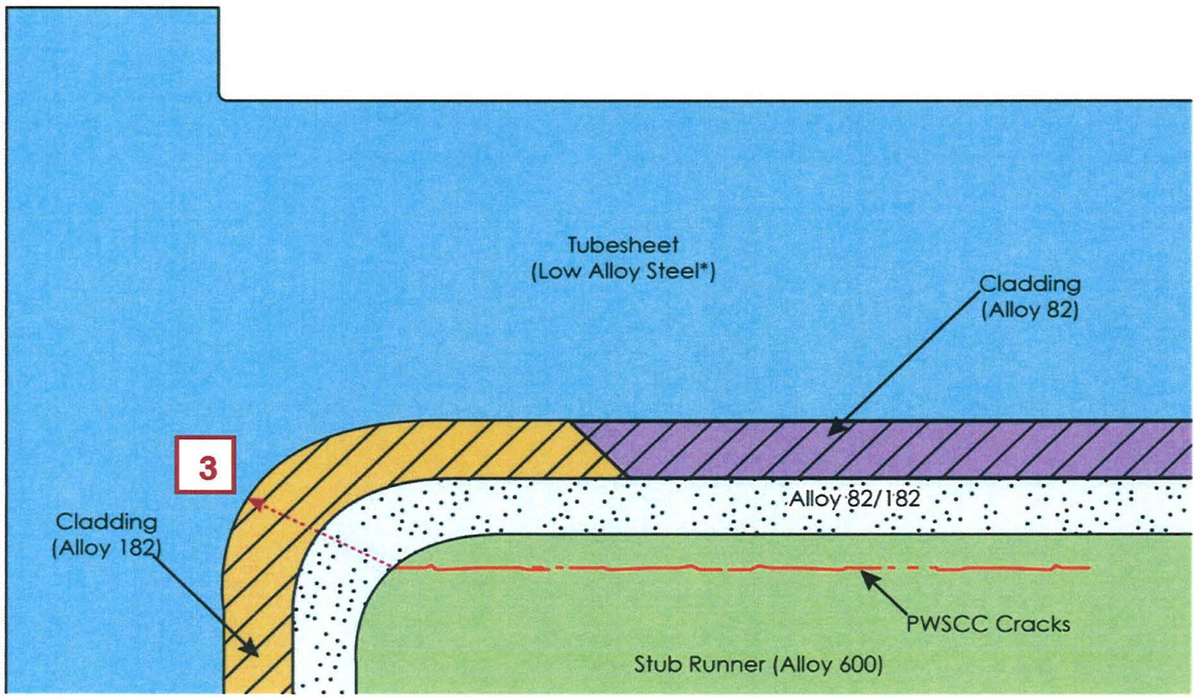



Scenario 1 assumes cracks initiate in the divider plate assembly and propagate to the tube-to-tubesheet weld

Scenario 2 assumes cracks initiate in the tube-to-tubesheet weld or the cladding

# Divider Plate Crack Propagation Scenarios

Scenario 3 assumes cracks initiate in the divider plate assembly and propagate through the stub runner, the 182 weld at the triple point and through the low allow steel

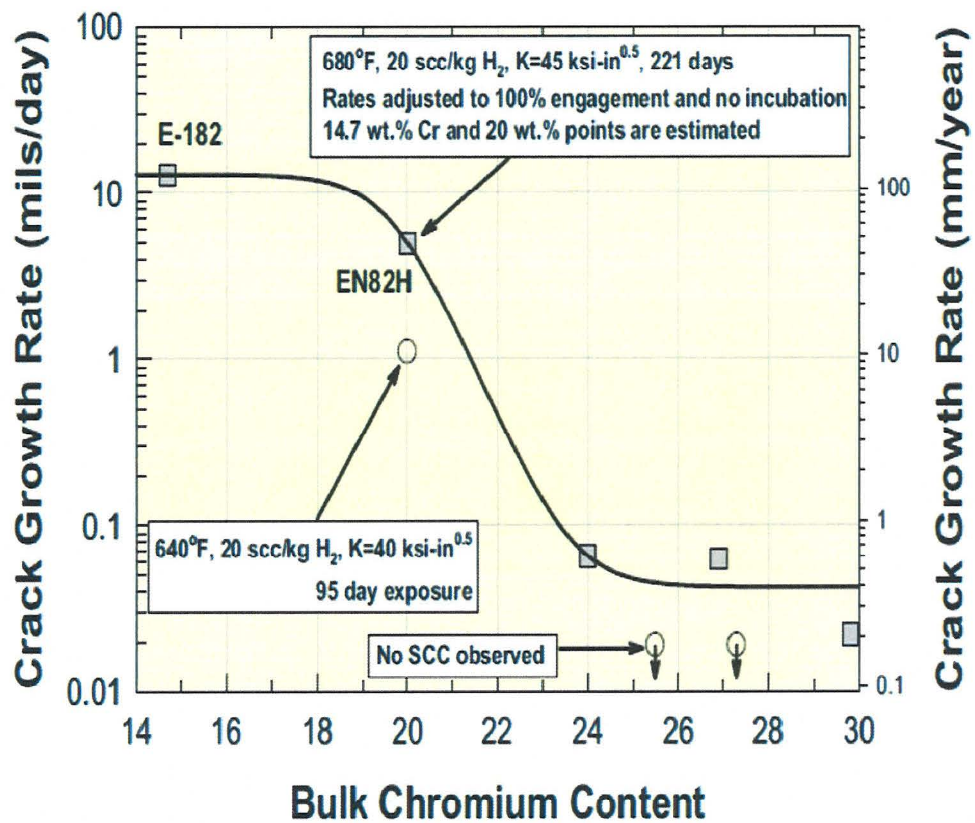


# Scenarios 1 and 2

Concerning the Tube-to-Tubesheet Weld

# Tube-to-Tubesheet Weld Cracking

- Industry has accepted a 24% chromium content as a conservative threshold for PWSCC initiation
  - Chromium levels down to 20% have excellent resistance to initiation based on testing and operational experience
- Objective of this project was to determine the chromium content in an autogenous weld between Alloy 690 tubing and 82 or 182 weld material
  - Construct a tube-to-tubesheet mockup to investigate





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# Field Material Review

| Statistic | Alloy 690 (product analysis) | FM 82 | FM 182 |
|---|---|---|---|
| Mean | 29.3 | 20.7 | 14.4 |
| Maximum | 29.7 | 21.5 | 16.5 |
| Minimum | 29.0 | 19.6 | 13.6 |

- Review of chromium content in tube and tubesheet cladding material
  - SGMP Alloy 690TT steam generator tubing specification recommends a minimum chromium concentration of 28.5 weight percent
  - 191 heats of Alloy 690 tubing material were reviewed and the minimum concentration is 29 weight percent
    - All three tubing suppliers were represented
  - 17 heats of Alloy 82 were reviewed and the minimum chromium is 19.6
  - 27 heats of Alloy 182 were reviewed and the minimum chromium is 13.6

# Fabrication of the Mockup

Material used for tube-to-tubesheet mockup

| C | Si | Mn | P | S | Cu | Ni | Cr | Mo | Co | Ti | Nb + Ta | Al | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alloy 182 (.187-in x 14) | | | | | | | | | | | | | |
| .022 | .47 | 5.1 | .001 | .002 | .01 | 67.99 | 16.52 | -- | -- | .54 | 1.83 | -- | 7.4 |
| .022 | .34 | 6.67 | .003 | .001 | .01 | 68.81 | 14.92 | -- | -- | .49 | 1.39 | -- | 7.27 |
| Alloy 82 (30-mm Strip) | | | | | | | | | | | | | |
| .029 | .18 | 2.96 | .004 | .002 | .02 | 71.61 | 21.47 | -- | .03 | .29 | 2.44 | -- | .85 |

| C | Si | Mn | P | S | Cu | Ni | Cr | Mo | Co | Ti | Nb + Ta | Al | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| .019 | .19 | .30 | .009 | .001 | .04 | 60.4 | 29.3 | .02 | .011 | .25 | .004 | .17 | 9.3 |

%Cr is on the upper end for cladding but we are measuring dilution not absolute composition





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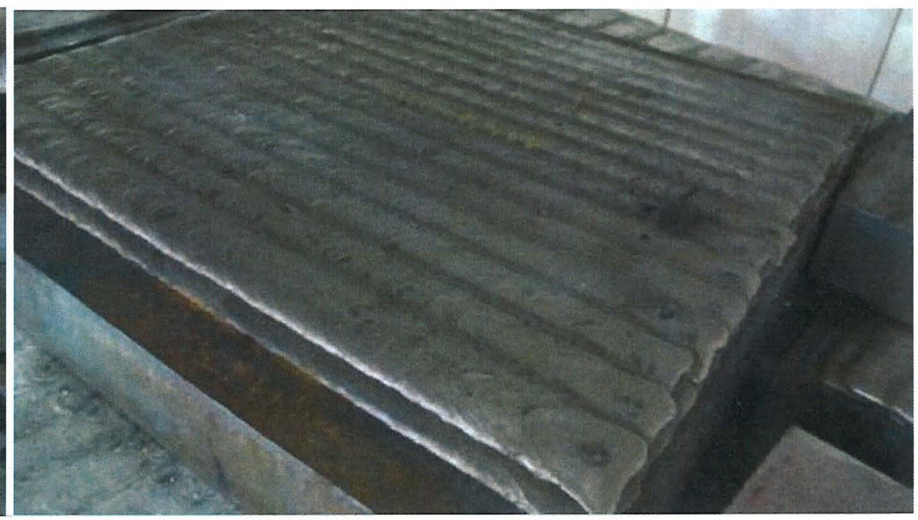
# Fabrication of the Mockup

182 Shielded Metal Arc Welding (SMAW) process

SGMP developed prototypical tube-to-tubesheet mockups to analyze chromium levels in the tube-to-tubesheet welds

82 - Electroslag Welding (ESW) Strip cladding







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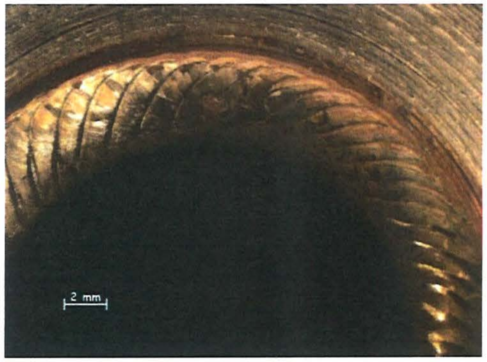
# Analysis of the Chromium Content

- The mockup was designed as a 3 X 4 tube-to-tubesheet matrix having 82 cladding on one side and 182 cladding on the other side
- An Alloy 690 tube was inserted into each drilled cylinder, positioned flush with each end, and welded autogenously using the Liburdi Dimetric P-Head autogenous GTAW welder (see next slide).

# Analysis of the Chromium Content

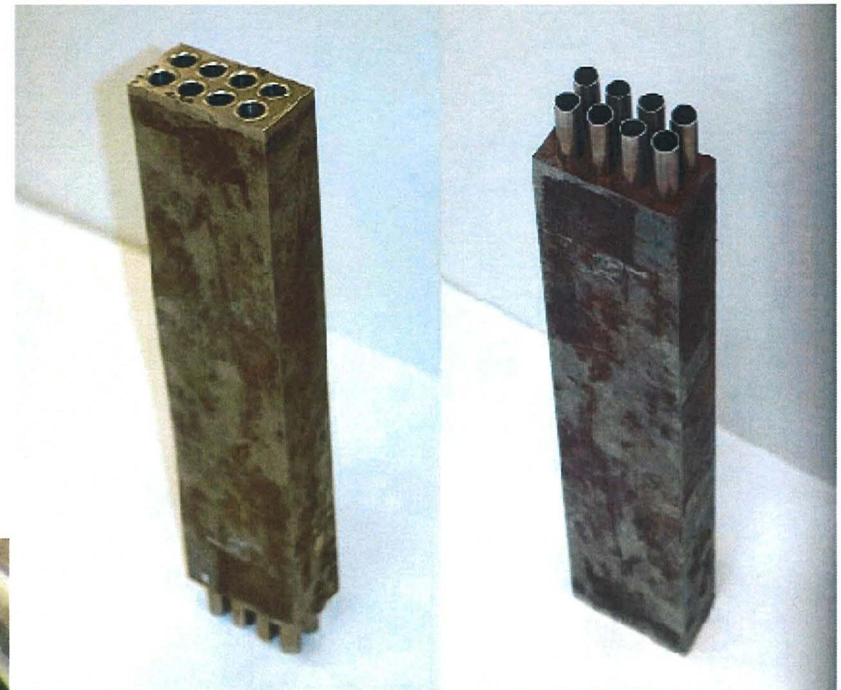
- Plugs were removed from the tubesheet, cross sectioned, and weld dilution was evaluated
- It had been estimated that the weld dilution would be 50% from the tube material and 50% from the cladding material since the weld is autogenous GTAW

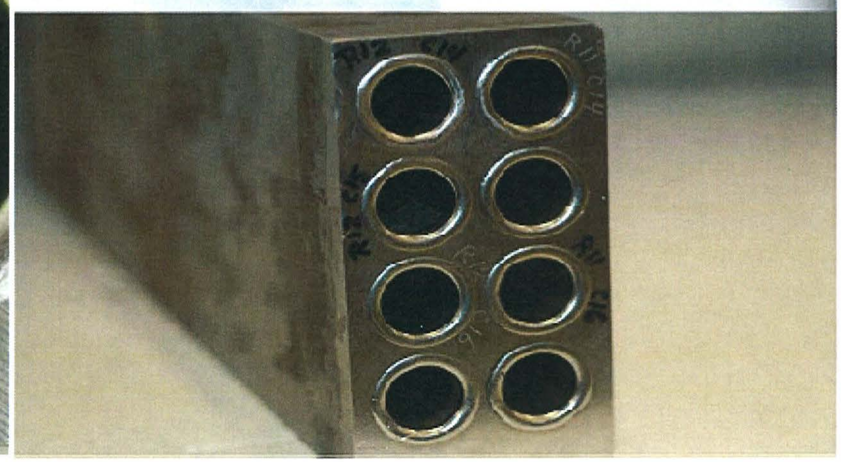

40 cross-sections were available for 82 welds and 34 for 182 welds to include in the tube-to-tubesheet weld dilution distributions

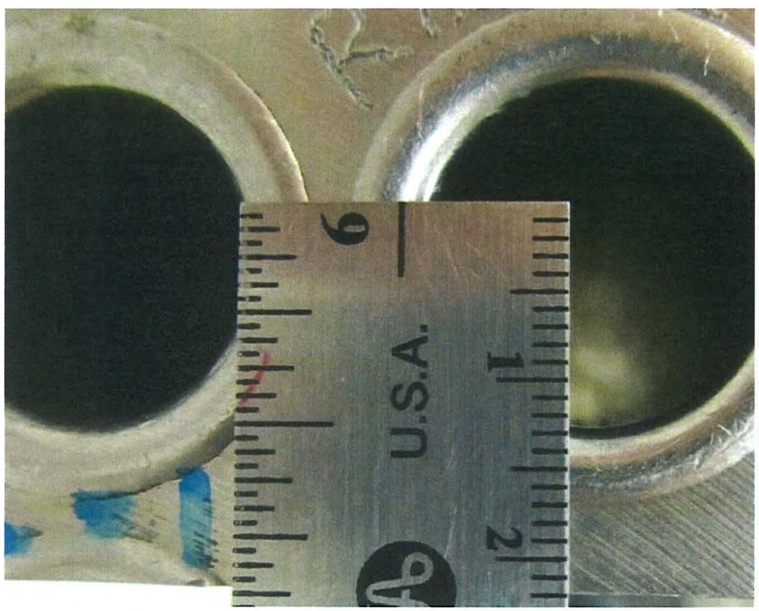


# Comparison of Mockups

- SGMP has a mockup from a replacement steam generator fabricator with Alloy 82 clad and 690 tube material
  - Used to compare geometry of the fabricated mockup welds and to compare dilution









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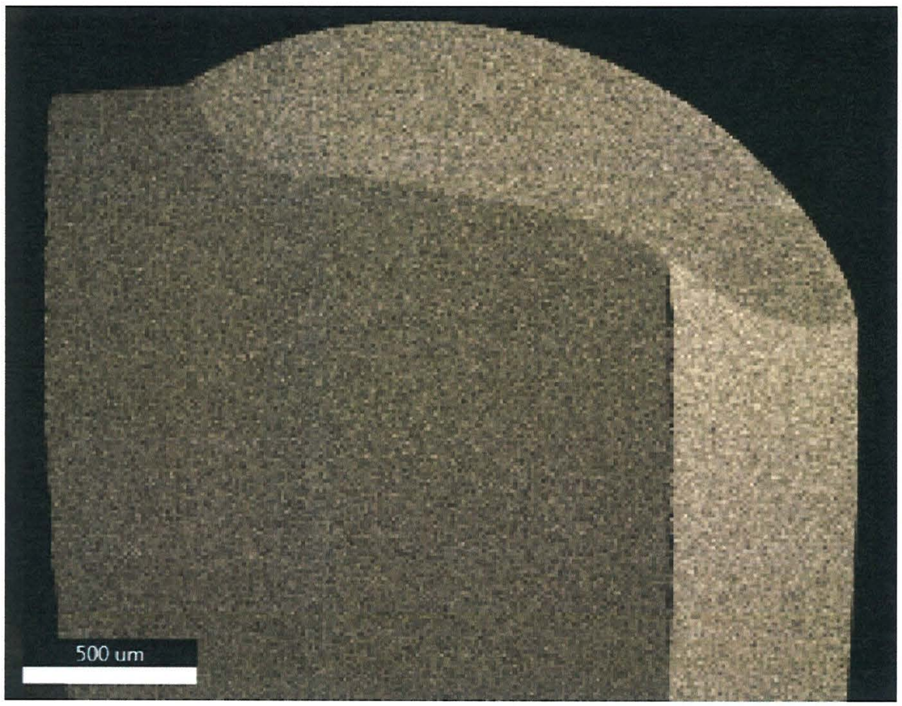
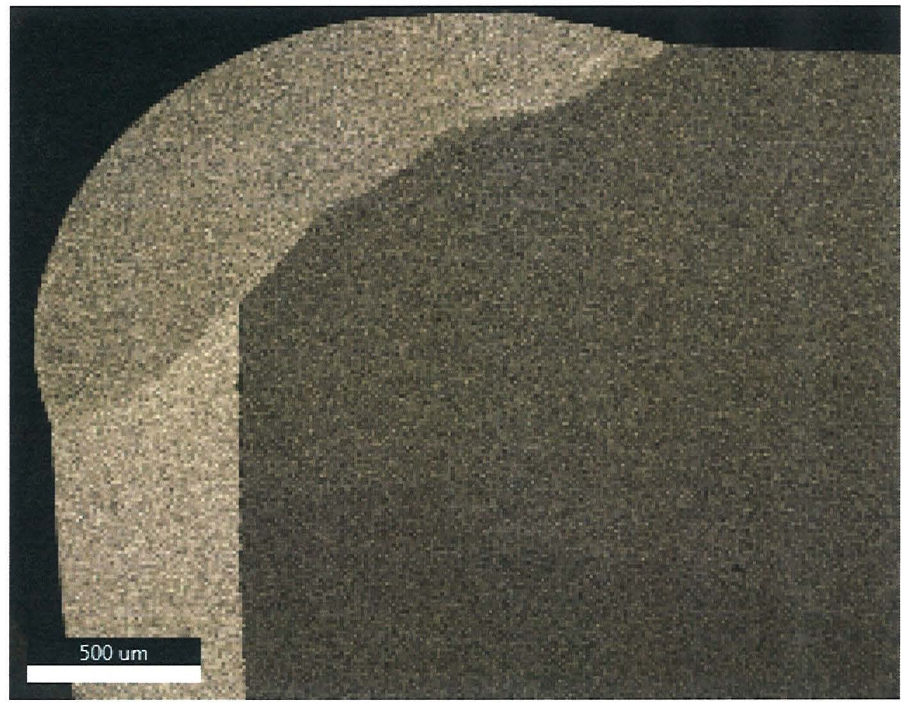
# Comparison of Mockups

Mockup from RSG Fabricator




SGMP Mockup




Similarity between the etched weld cross-section in the SGMP mockup to the one fabricated for this project





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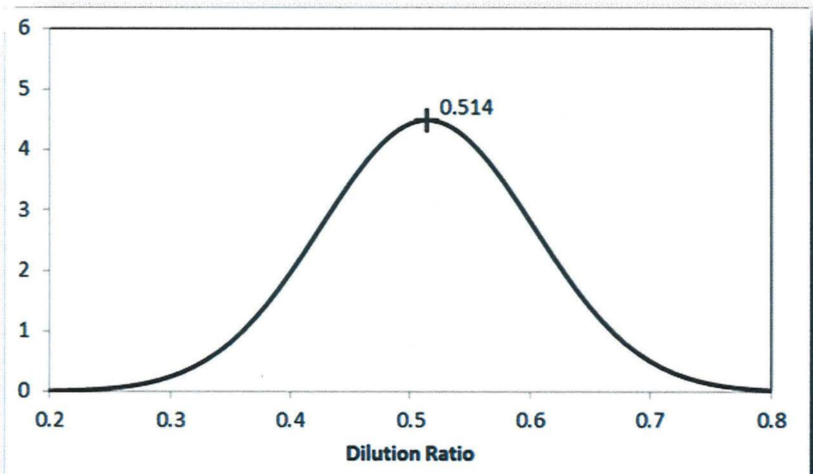
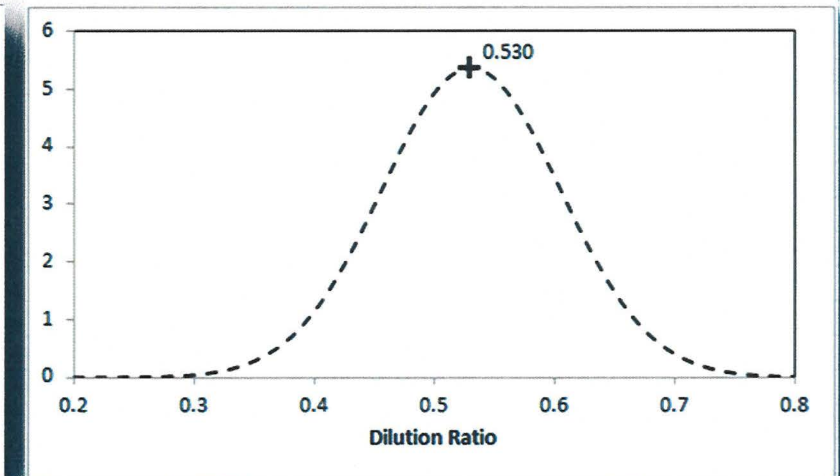
# Analysis of Chromium Content

- The EPRI SEM system was used to mark and measure areas of features on sample cross-section macrostructures
  - Measurements were used to compute the weld dilution
  - Dilution measurements were analyzed to a “normal distribution”



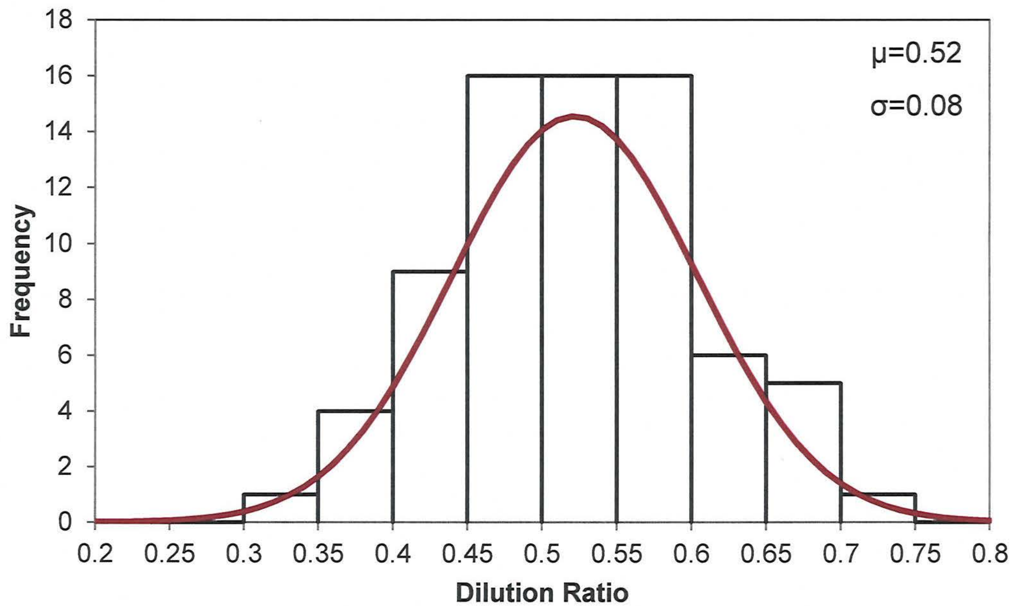

Normal distribution for the Dilution Ratio for 690 tubes welded in 82 cladding




Normal distribution for the Dilution Ratio for 690 tubes welded in 182 cladding

# Analysis of Chromium Content

- The combined dataset was used to determine the mean dilution factor
  - Appropriate estimation of reality for Dilution Equation (below)




$$\%Cr_{weld} = \%Cr_{tube}\,(0.52) + \%Cr_{clad}(0.48)$$

# Results of the Mockup Testing

- An autogenous weld deposit for 690 tubing material and 82 cladding has sufficient chromium content to be resistant to initiation or propagation of PWSCC (exceeds 24% Cr)
  - These welds constitute the majority of the tubesheet
- The weld deposit for 690 tubing material and 182 cladding has less chromium, but the chromium is high enough to be resistant to initiation and slow propagation of PWSCC

Predicted Cr Compositions

| Statistic | % Cr in Weld (82 clad) | % Cr in Weld (182 clad) |
|---|---|---|
| Mean | 25.2 | 22.1 |
| Maximum | 25.8 | 23.2 |
| Minimum | 24.5 | 21.8 |

# Stress Analysis of the Tubesheet

- Finite element analysis of a Westinghouse Model 51 SG channel head was used to determine the stresses during normal, upset, and accident conditions
- Tensile loads are shown to be present in the divider plate region
  - The dominant mechanical bending loads are in the plane that drives a horizontal crack and would not turn the crack vertically.
  - Assuming a crack initiates, it would propagate horizontally
- The Alloy 182 cladding in the center of the tubesheet is the most susceptible to PWSCC
  - This area of concern is in compression
- Results and conclusions were independently verified by third party

# Scenario 3

Concerning the Low Alloy Steel Channel Head

## Stress and Fatigue Analyses

- Finite element model of the steam generator channel head
  - Design transients evaluated
  - Stress paths defined through the channel head wall
  - Through wall hoop and axial stresses mapped along these paths
  - Fracture mechanics and fatigue crack growth evaluations performed
- Maximum stress intensity factor less than the allowable values for all design basis plant conditions up to 75% of the vessel wall thickness
  - Allowable flaw is 3.9" deep and 29.6" long based on flaw tolerance considerations
- Fatigue growth evaluation performed for a postulated flaw 0.25" deep into the low allow steel
  - Evaluated axial and circumferential growth

# Conclusions

- Critical crack depth is 75% of the channel head material - 3.9” deep and 29.6” long
- The bounding crack growth results in a crack depth of 8% of the channel head material
  - The circumferential crack would grow from 0.25” to 0.40” deep and from 1.9” to 3.07” long
- Forty years is chosen because this is typical for fatigue analyses

| Results for 40 Year Crack Growth Period | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Stress Case | Flaw Type | Initial Flaw Depth (inch) | Final Flaw Depth (a) (inch) | Final Flaw Depth/Vessel Thickness (a/t) | Initial K max. (ksi-√in) | Final K max. (ksi-√in) | Allowable K (ksi-√in) | Pass ? |
| Path 1 (with residual) | Circ | 0.25 | 0.4040 | 0.080 | 24.632 | 31.048 | 63.2 | Yes |
| | Axial | 0.25 | 0.2508 | 0.048 | 7.465 | 7.482 | 63.2 | Yes |
| Path 2 (with residual) | Circ | 0.25 | 0.2985 | 0.057 | 21.555 | 23.806 | 63.2 | Yes |
| | Axial | 0.25 | 0.2510 | 0.048 | 10.527 | 10.545 | 63.2 | Yes |
| Path 3 (with residual) | Circ | 0.25 | 0.2524 | 0.049 | 9.954 | 9.998 | 63.2 | Yes |
| | Axial | 0.25 | 0.2514 | 0.048 | 9.555 | 9.579 | 63.2 | Yes |

# Conservatisms in the Fatigue Analysis

- Cracks in divider plate assemblies that have been inspected for years have shown no crack growth and thus have not approached the triple point
- It is not expected that the US fleet has divider plate cracking extending the full length of the divider plate and approaching the triple point
- The assumed initial 0.25" through wall depth primary water stress corrosion crack in low alloy steel is not realistic; but is a conservative assumption
  - Low alloy steel is not susceptible to PWSCC

# Scenarios 1, 2, and 3 Conclusions

- Chromium levels in the tube-to-tubesheet welds are sufficient to resist PWSCC initiation
- Orientation of the dominant stresses associated with the tubesheet to divider plate regions strongly favor horizontal crack propagation in the stub runner or the welds on top and bottom of the stub runner
- The center of the tubesheet is in compression thus the driving force for PWSCC initiation/propagation is not present
- Stresses in the channel head region of the steam generator are insufficient to propagate a crack by fatigue into the channel head and thus would not compromise structural integrity of the channel head
- Final Report 3002002850 published October 2014