
NEI Steam Generator Task Force Divider Plate Cracking Issue Update

Chris Cassino
Westinghouse Electric Company
Chemistry, Diagnostics & Materials
Engineering

Topics for Discussion

- Introduction
- Background: Foreign Crack Indications
- Domestic Fleet: Summary
- EPRI Scoping Study
- Related H*/B* Issues
- Overview of Proposed Phase II
- NRC Staff Concerns & Comments

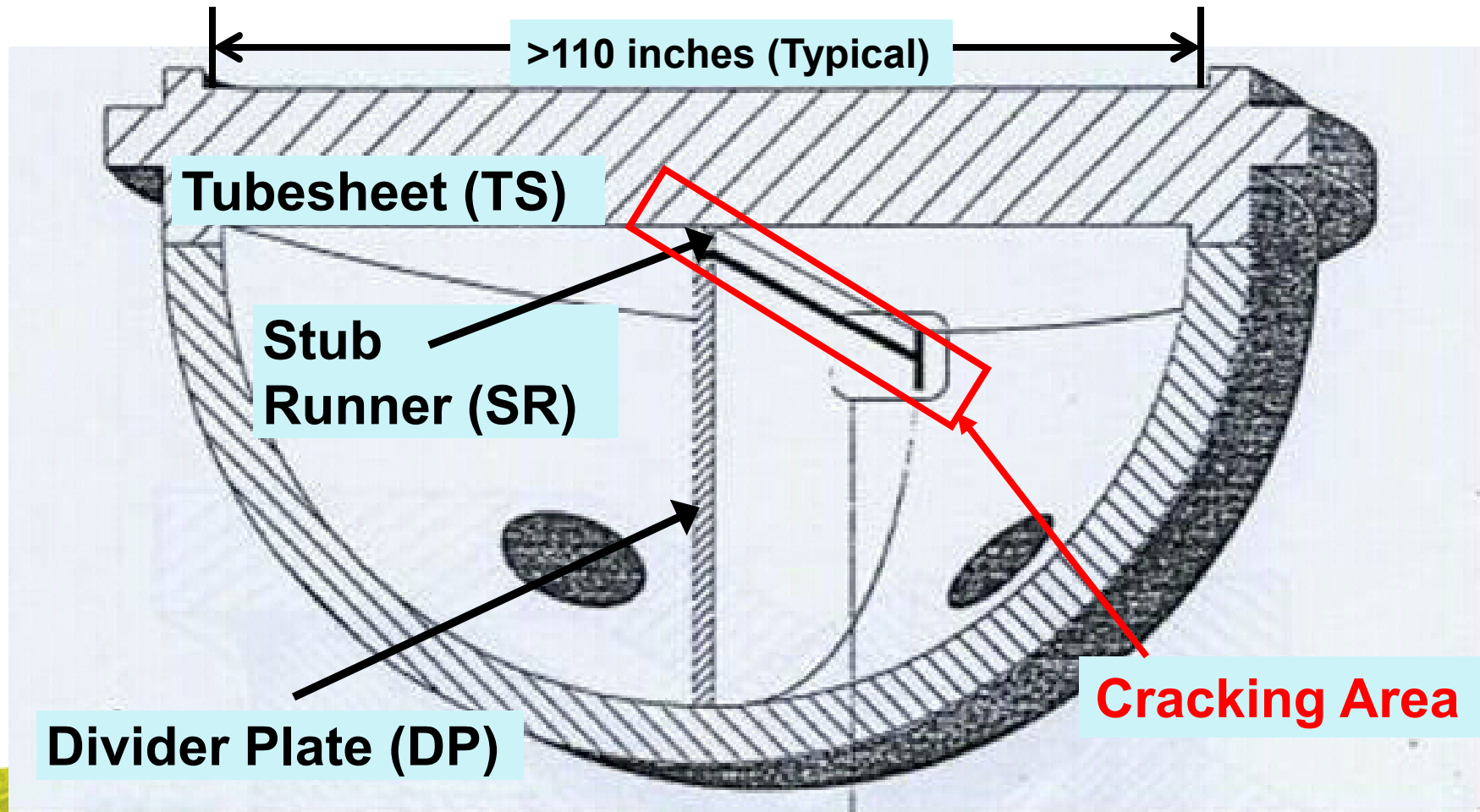
Background: Foreign Crack Indications

- Cracks have been reported in the weld between the divider plate (DP) and the stub runner (SR) in French and Swedish SGs with Alloy 600 DP and Alloy 82/182 weld material.
- Current French assumption is that the limiting cases are due to cold working and defects from manufacturing and installation.

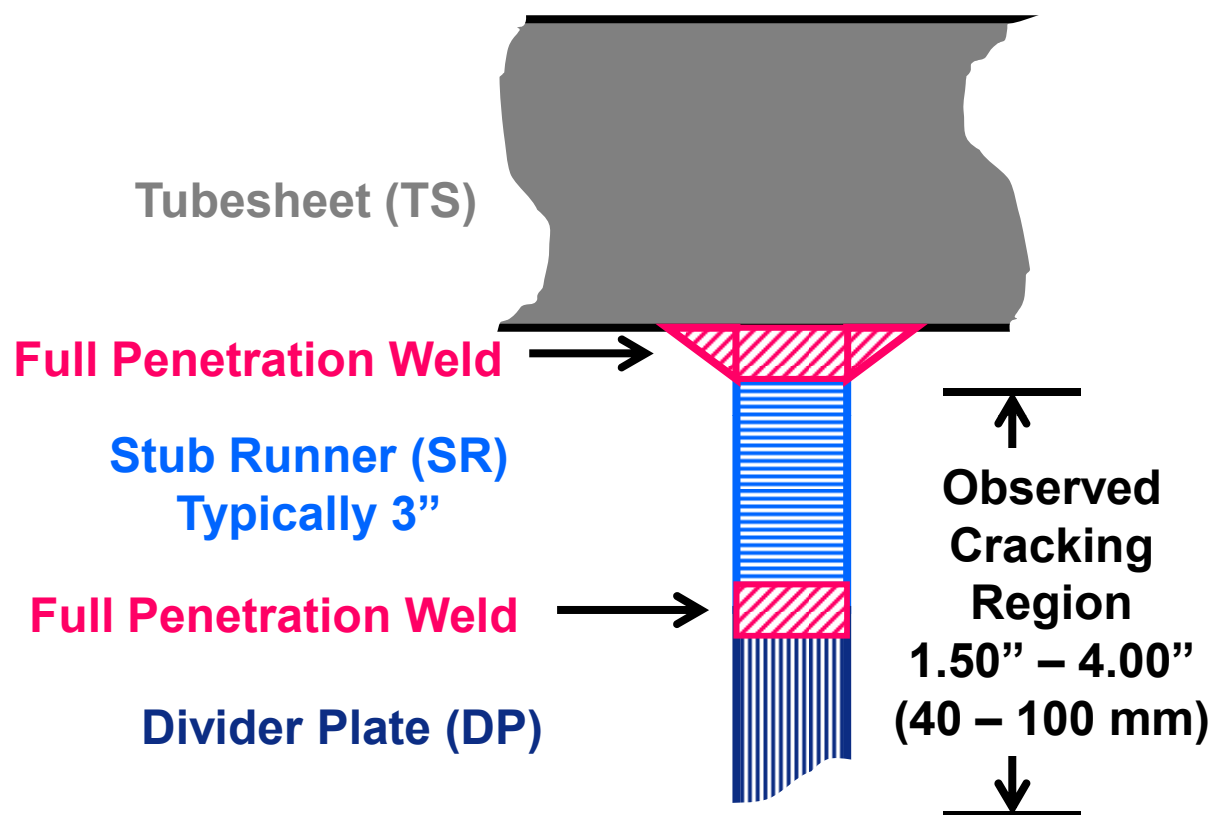
Background: Foreign Crack Indications

- The cracking has occurred in SG's with ***thin*** DP, ≤ 1.5 inches.
 - Model 51 and Model 44F have DP that < 1.5 inch
 - Model F and Model D SG DP's are 1.9 to 2.1 inch
- Cracks occur on ***both*** hot leg (HL) and cold leg (CL) surfaces
- Some of the DP with cracking have:
 - Loose parts damage
 - Cold working from installation process
 - Weld fusion failures

Background: Foreign Crack Indications



Background: Foreign Crack Indications



Background: Foreign Crack Indications

- DP Cracks have been reported in French SG for ~15 years.
- Most cracks are shallow ($\ll 0.10$ inch) and short (3 – 8 inches).
- A few indications are longer (~70 inches) and deeper (~0.25 inch).
 - In SG with history of unique events

Background: Foreign Crack Indications

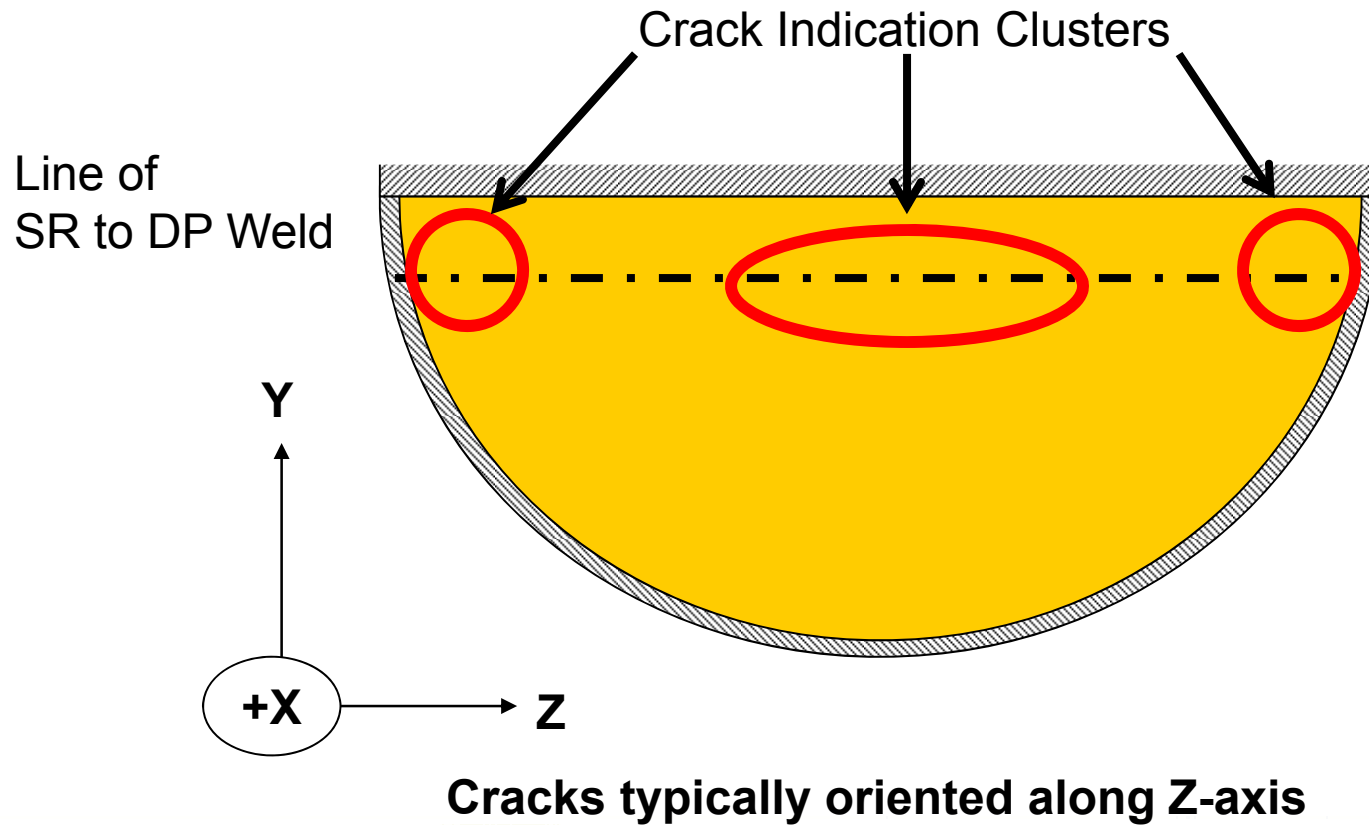
Plant	Year Reported	Length	Max. Depth
		in	in
Blayais	2006	Varies	0.276
Chinon	2002	70.44	0.016
Dampierre	1993	Varies	0.008
Gravelines	1994	Varies	0.011
Ringhals	2004	Varies	Surface Only
St. Laurent-B	1996	Varies	0.0748

- At Chinon, the crack ends grew together.
- At Ringhals, the cracks disappeared when the top surface was ground for inspection.

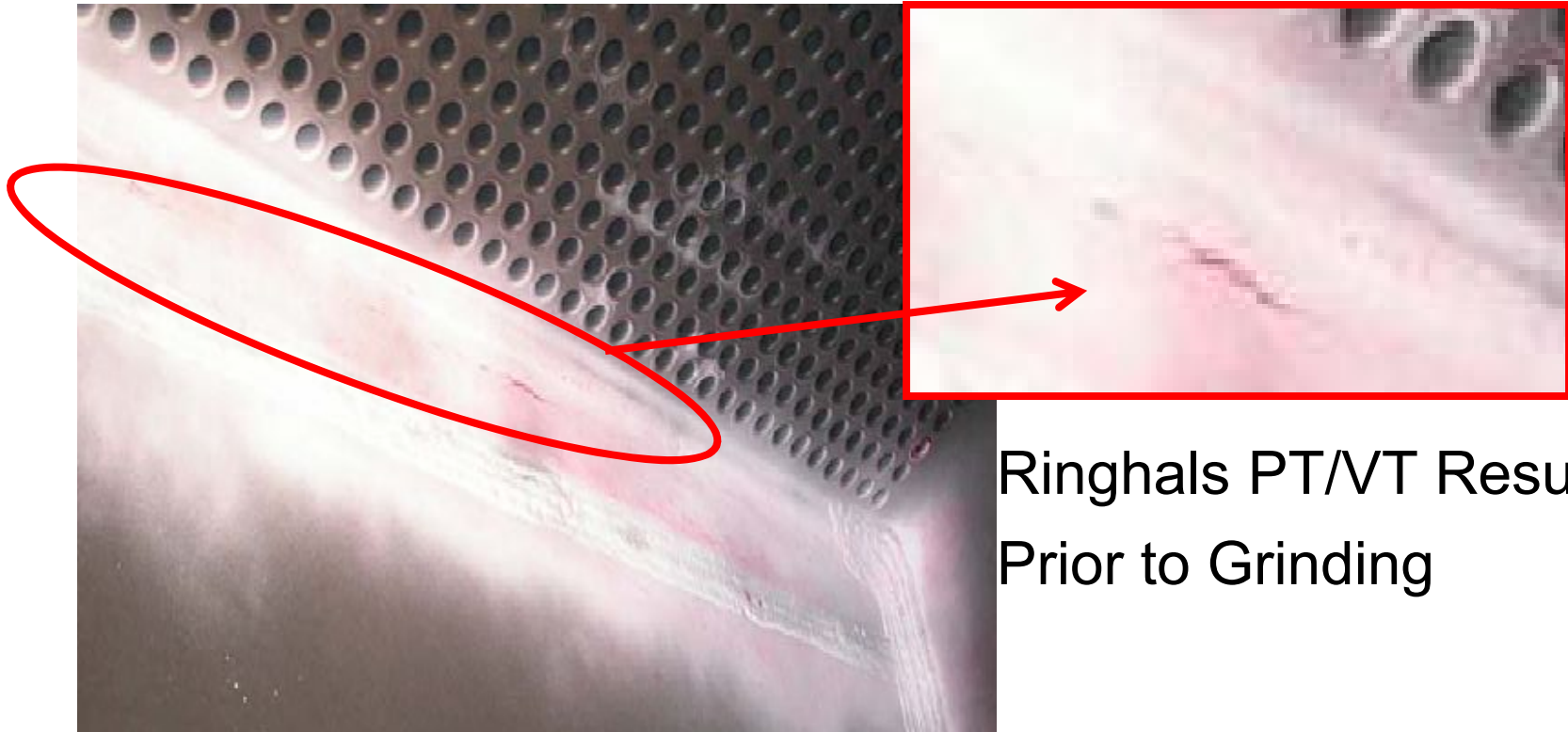
Background: Crack Indications

- Displacements and stress on the DP come from four (4) sources:
 - Tension due to pressure drop across TS
 - Bending across DP from HL to CL
 - Thermal growth of CH, TS and DP
 - Residual stresses in DP to SR weld and HAZ
- The French plants have a load follow schedule
 - Load following increases the number of thermal cycles on the DP and affects fatigue resistance in the weld.

Background: Foreign Crack Indications



Background: Foreign Crack Indications



Ringhals PT/VT Result
Prior to Grinding

Background: Foreign Crack Indications

- The French have been using a combination of auto VT/PT/UT to inspect the DP for cracks
- The VT/PT/UT method resolution limit is 2 mm
- Crack growth is less than 2mm over multiple inspection periods.
 - Crack growth at Chinon B4 (2002 – 2006) indicate no change in crack length over multiple inspections.

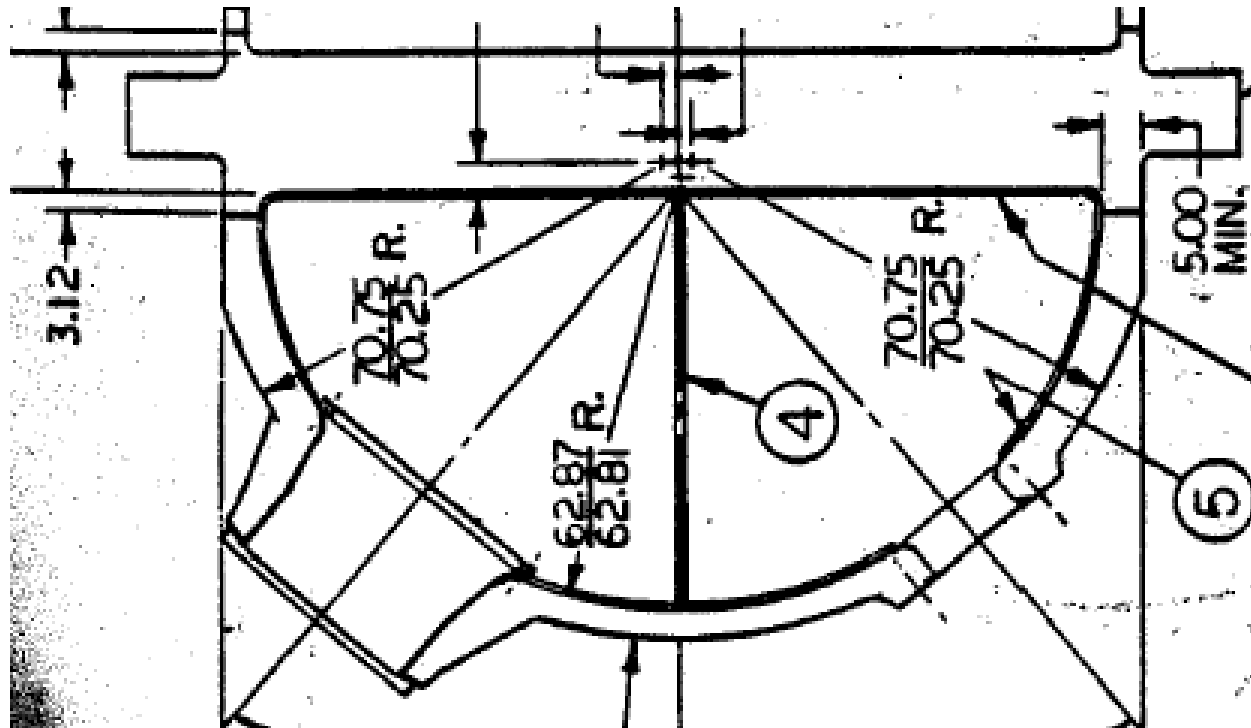
Domestic Fleet: Summary

- Most SG's have **thicker** DP (>1.90 inches)
- Domestic SG's **do not** load follow
 - US DP have different thermal history
 - Thermal ratcheting, fatigue cycling and other effects more prevalent in load follow conditions
- French experience suggests differences in manufacturing processes
 - Limited access to French manufacturing records

Domestic Fleet: Summary

- Typical TS-CH complex assembly process:
 - CH machined and prepared for DP
 - DP welded to CH
 - TS machined and prepared for DP
 - SR welded to TS
 - Z-seam welds TS and CH together
 - TS-CH complex heat treated
 - SR to DP weld applied
 - SR to DP weld ground flush

Domestic Fleet: Summary



Typical Westinghouse TS-CH Complex

Domestic Fleet: Summary

- In the original WEC SG Stress Reports and design analysis:
 - The DP provides a pressure separation between the HL and CL of the SG
 - Is not a primary pressure boundary
 - TS analysis does not credit the DP
- TS junctions do take credit for the DP to reduce TS displacements
 - DP to CH connection alone stiffens the CH
 - Proposed for Future EPRI work

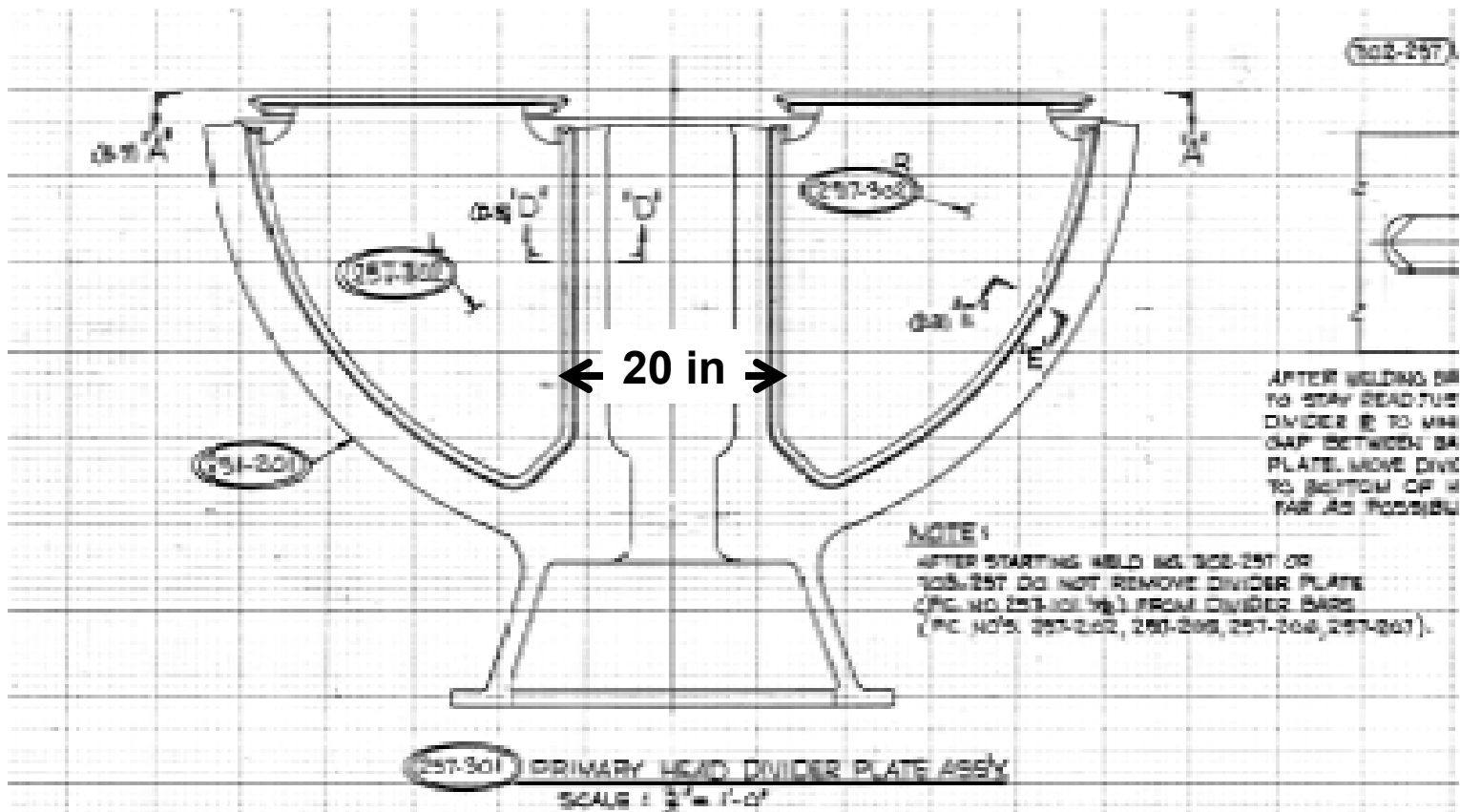
Domestic Fleet: Summary

- Turkey Point, Byron/Braidwood and Wolf Creek have all received DP related RAI on H*/B* ARC.
- The current H*/B* ARC has been revised so that no credit is taken for the DP to resist vertical or radial displacement of the TS.

Domestic Fleet: Summary

- Combustion Engineering (CE) style SG do not have a structurally connected DP
 - The DP is installed with set-screws and partial welds to groove channels
- The center stay in a CE SG connects the TS to the CH directly
- CE SG do not take credit for the DP structurally
- C^* is not affected by structural DP issues

Domestic Fleet: Summary



Typical CE Style Divider Plate and Channel Head Assembly

Domestic Fleet: Summary

- DP are currently examined using a bowl camera
 - There are no qualified US DP inspection or repair criteria.
- There are no qualified US DP inspection tools.
 - We believe some surface prep may be necessary to inspect the DP
 - The surface prep would be dose intensive

Domestic Fleet: Summary

- EPRI conducted an informal survey of DP inspection practices.
 - Most utilities examine the DP using a visual bowl scan to look for abnormalities.
 - None have been reported to date.
- Some utilities have standards for the DP examination.
- French style inspection (auto-VT/PT/UT) has not been attempted in the US

EPRI Scoping Study (Phase I): Purpose

1. To determine the limiting model steam generator with respect to DP cracking.
2. If a DP crack can increase vertical TS displacement by more than 2%
 - If the result of a cracked DP is an increase of $<2\%$, then DP cracking is judged not to be a concern.
3. If a DP crack can propagate 100% through the weld material.

The scoping study was completed in May 2007.

Phase I: Method

- Series of SG model specific 2D finite element analysis (FEA) models to determine limiting SG
- Generic 3D FEA to determine stress and deflection using worst case results
- Conservative mechanical fatigue and PWSCC cracking analysis using FEA results
- The contribution of mechanical fatigue and PWSCC to the cracking were varied

Phase I: Method

- Three (3) design conditions considered:
 - **Design:** Normal Operating, NOP
 - **Accident:** Loss of Load, LOL
 - **Faulted:** Feedline Break or Steam Line Break, SLB or FLB
- Six (6) crack conditions considered:
 - Uncracked
 - 8%, 32%, 64% and 96% cracked
 - SR section removed

Phase I: Method

- TS modeled using transversely anisotropic material properties for a perforated structure [Slot].
- Two (2) TS Conditions:
 - Reinforced by tube material within TS [Terakawa]
 - Unmodified TS stiffness

Phase I: Method

- All materials modeled at **600°F**
 - ***Bounding temperature*** for all conditions
 - ***Weakest Modulus*** values
 - No thermal transients considered
- Operating Pressures taken from E-spec
 - *No dynamic effects* considered
 - SG Model specific values were used
 - ***Bounding operating values*** were used

Phase I: Method

- Several Westinghouse Model SG considered for limiting case:
 - Model F
 - Model D
 - Model 51 Series
 - Model 44F
 - Model 54F
- Initial work suggested that Model 51, Model F and Model 44F were limiting candidates

Phase I: Method

Model 51 Parameters

Category	Condition	Div. Plate DP	Pri. Press	Sec. Press.	DP Thickness
		psi	psi	psi	in
Design	Normal Operating	50	2250	735	1.19
Upset	Loss of Load	45	2531	695	1.19
Faulted	Feed Line Break	0	2650	0	1.19

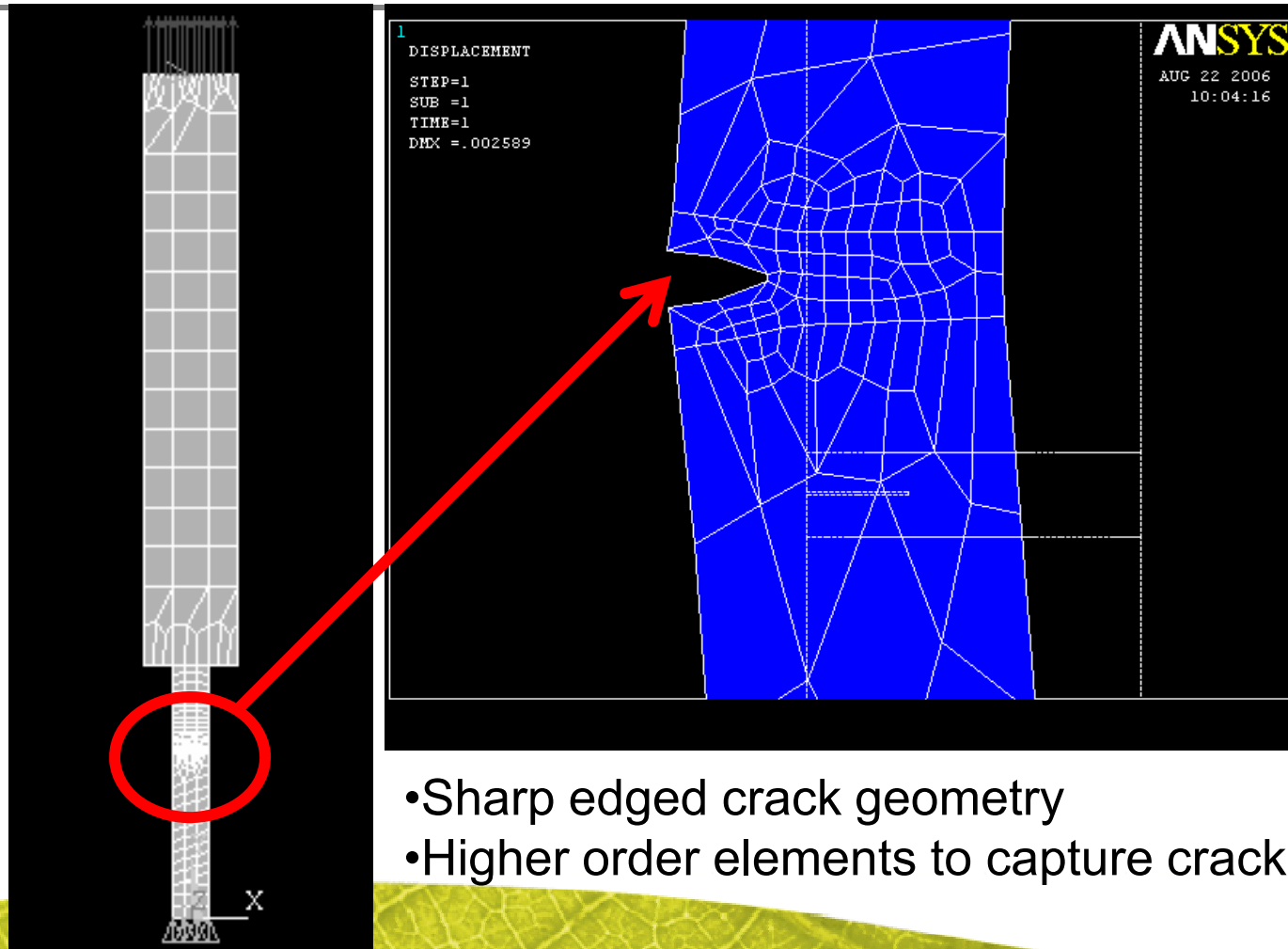
Model 44F Parameters

Category	Condition	Div. Plate DP	Pri. Press	Sec. Press.	DP Thickness
		psi	psi	psi	in
Design	Normal Operating	35	2235	770	1.26
Upset	Loss of Load	35	2735	972	1.26
Faulted	Feed Line Break	0	2560	0	1.26

Model F Parameters

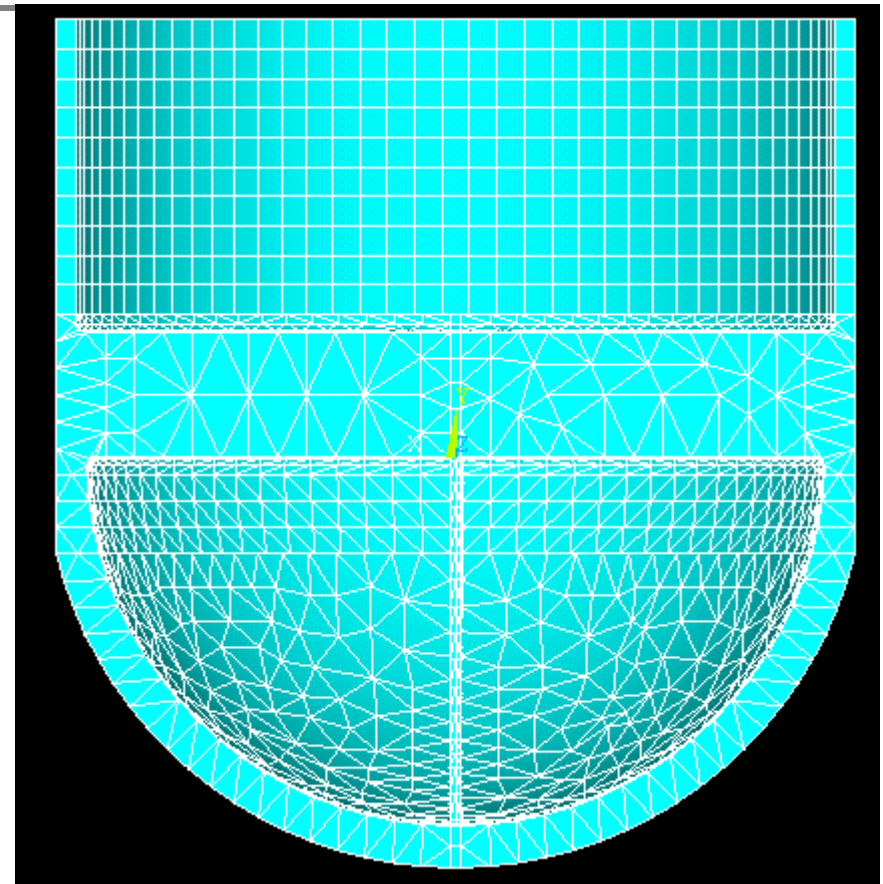
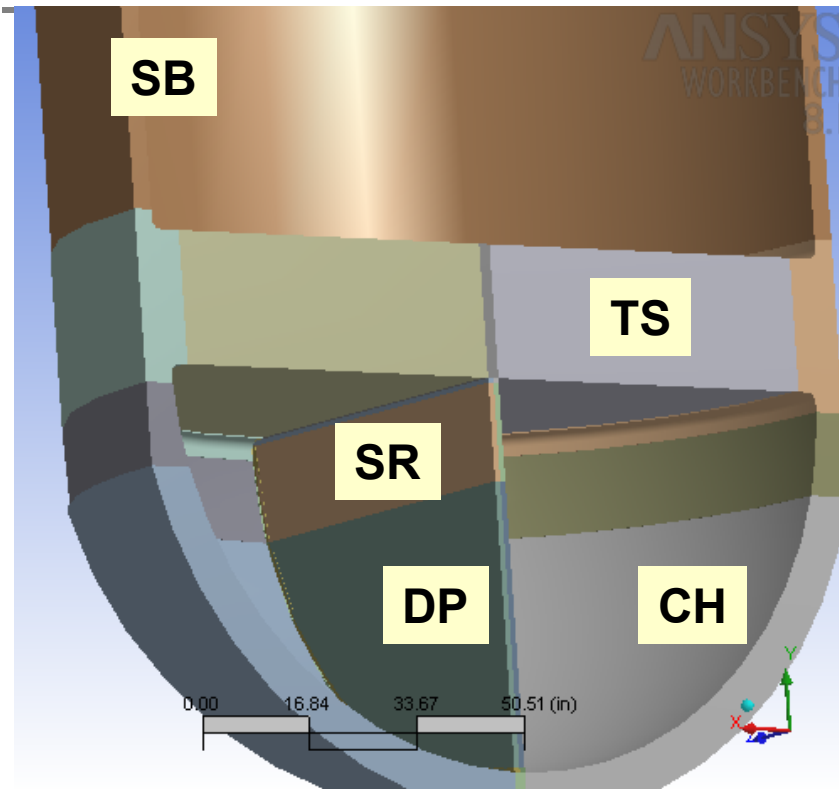
Category	Condition	Div. Plate DP	Pri. Press	Sec. Press.	DP Thickness
		psi	psi	psi	in
Design	Normal Operating	50	2272	870	1.90
Upset	Loss of Load	45	2663	1221	1.90
Faulted	Feed Line Break	0	2560	0	1.90

Phase I: Method



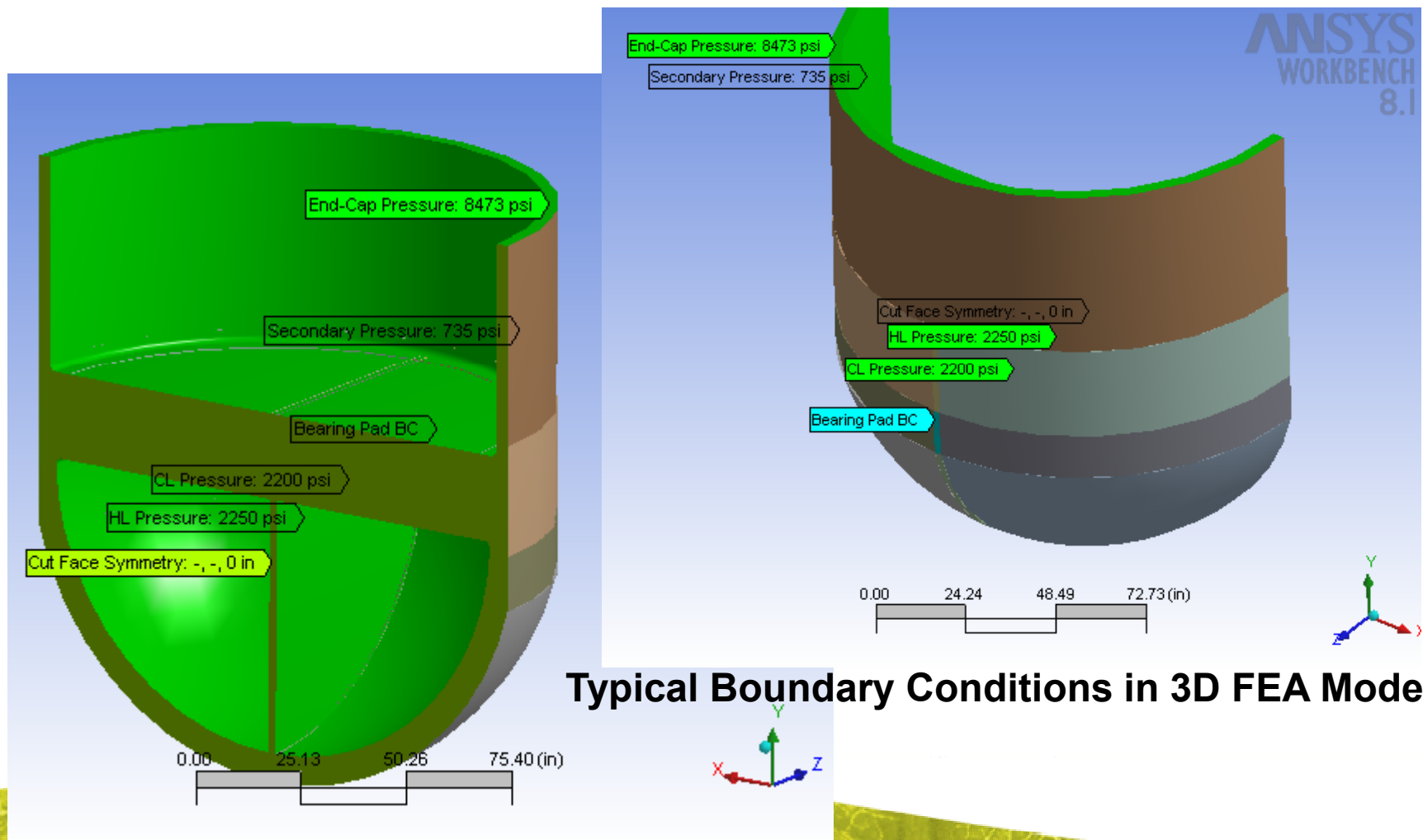
- Sharp edged crack geometry
- Higher order elements to capture crack growth

Phase I: Method



SR region in 3D model includes HAZ and upper portion of DP

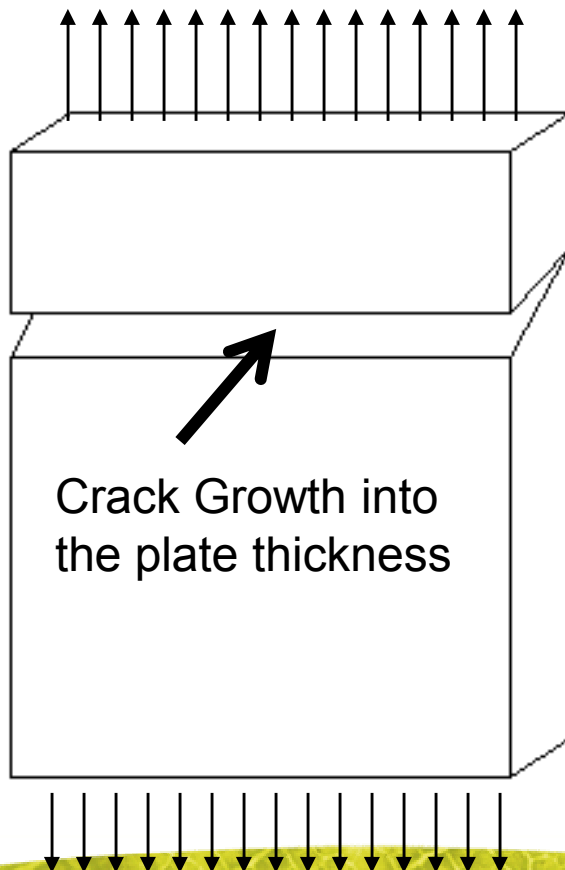
Phase I: Method



Typical Boundary Conditions in 3D FEA Model

Phase I: Method

Applied Tensile Displacement



Crack Growth into
the plate thickness

- Crack geometry in study is **conservative**.
- Cracks between CH and DP were **not** considered in the analysis.
- Real cracks would be **branched**.
- Real cracks would grow in **3D**, not **1D**.

Phase I Model Crack Geometry

Phase I: Assumptions

- Failure of the weld in the study is defined as a crack extending **100% of the plate length** and **100% of the plate depth**.
 - **Plastic yielding** of the weld can occur **before** complete weld failure.
 - A DP with a completely failed SR to DP weld **can still** bear pressure from HL and CL chambers of the CH.

Phase I: Assumptions

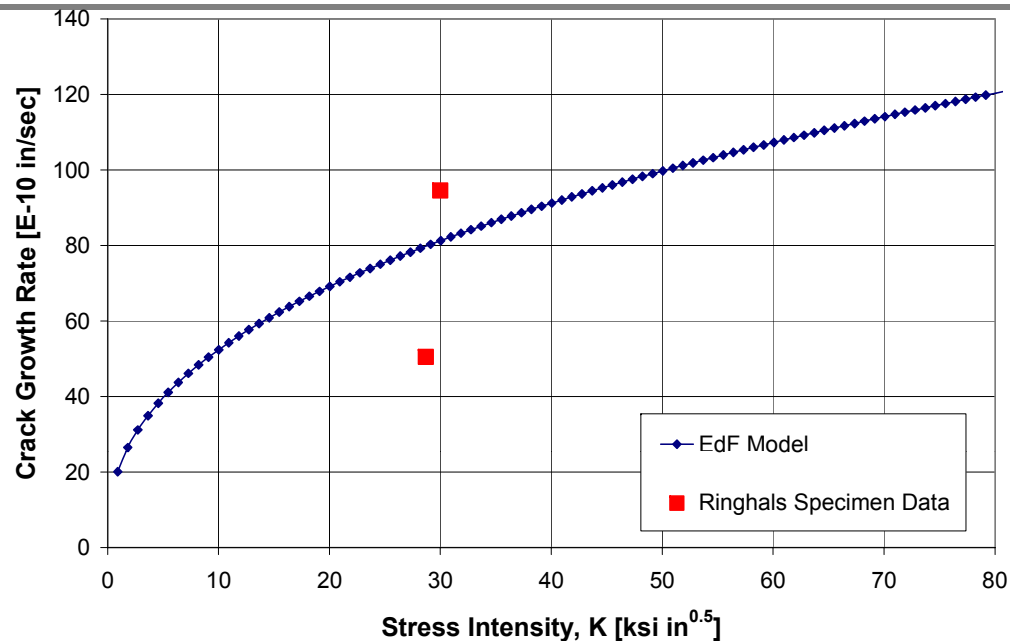
Phase I used very conservative assumptions, such as:

- The entire DP/SR weld surface was cracked (100%).
- A uniform crack front exists.
- No threshold for PWSCC initiation.
- No decrease in crack growth rate from residual stress effects.
- Homogenous weld material.
- 4.5 ksi-in^{0.5} fatigue crack threshold

Phase I: Assumptions

- ***Minimum*** dimensional tolerances on all machined components.
- ***Maximum*** material corrosion loss on all secondary surfaces.
- **1503 applied design transient events** each calendar year.
- ***Full load reversal*** at maximum ΔP for calculating mechanical fatigue effects.
- ***Worst case 2D stiffness result*** from limiting SG applied to typical SG 3D model.

Phase I: Assumptions



- Ringhals specimens from PWSCC sensitized weld nozzle overlay material.
- Most conservative EdF crack growth rate model used [Valliant et al., 2006].

Phase I: Model 51 Comparison

- Model 51 comparison of TS displacements with and without a DP present.
- Original Model 51 Stress Report analysis used FEA and scale models
- The purpose of the original study was to verify plastic limit load conditions in the TS and CH.
- The scale model and original FEA did not include a DP.

Phase I: Model 51 Comparison

- The original FEA predicted vertical deflection of ~0.469 inch at the center of the TS.
- The measured radial strain at the center of the TS in the scale model at 2410 psid was 0.359%. The measured deflection was 0.530 inch.
- It was assumed that not taking credit for the CH to DP connection was highly conservative.

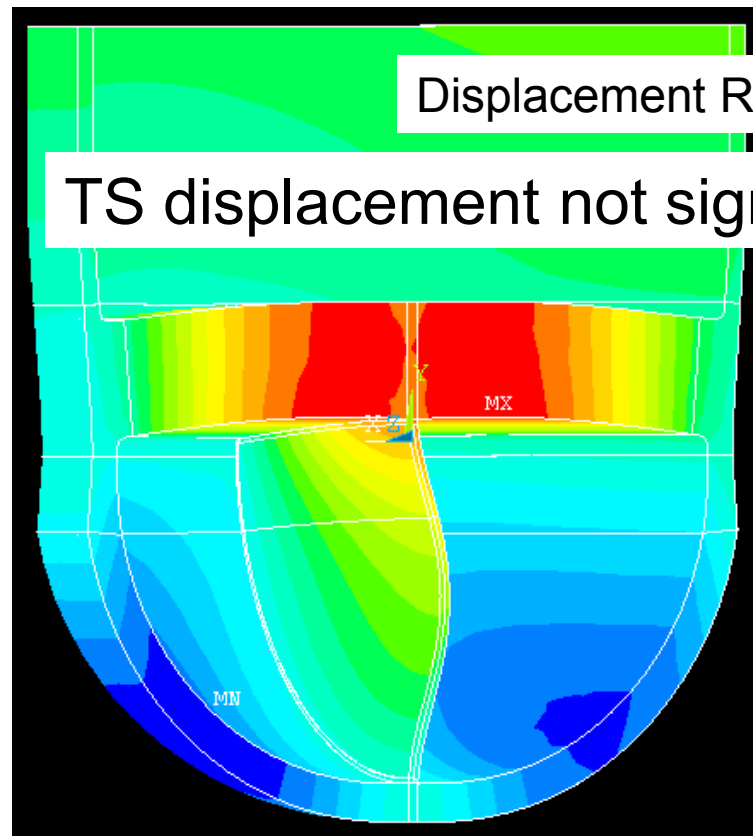
Phase I: Model 51 Comparison

- In the updated FEA model, for a TS with a DP but no SR, at 2410 psid:
 - The radial strain is 0.034%.
 - The vertical displacement is ~0.035 inch.
- The presence of the DP reduced the deflection and strain by an order of magnitude, without the SR present.
- The majority of the stiffening effect of the DP comes from the ***DP to CH connection***, ***not*** the DP to TS connection.
 - This validates the assumption about the DP to CH connection.

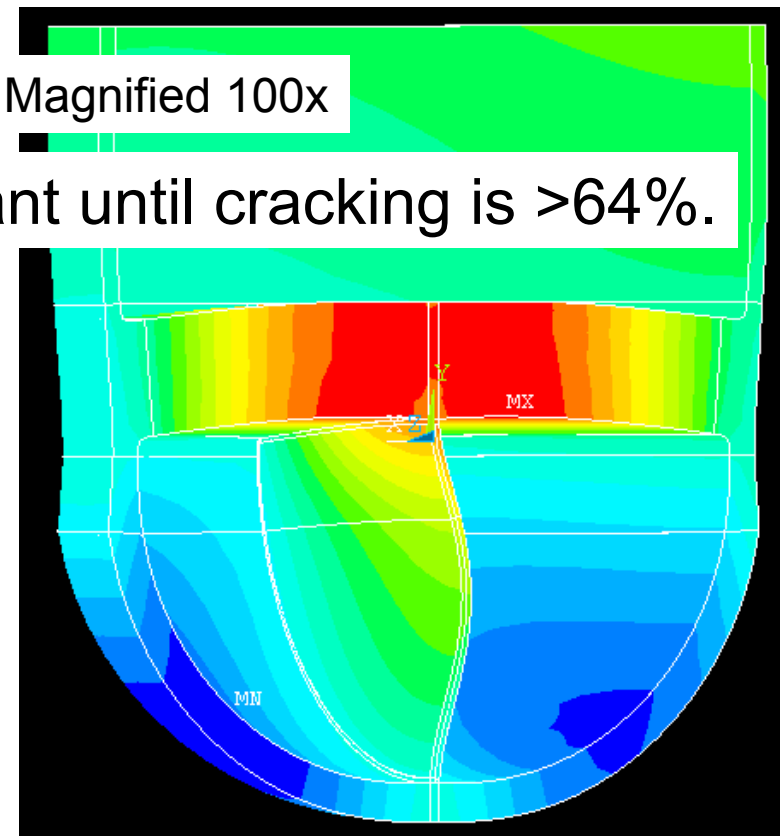
Phase I: Results

- Westinghouse Model 51 SG is the limiting case
 - Thinnest DP section (1.19 inches)
 - Designed with SR
 - Largest vertical TS displacements
 - Similar design to French SG with cracked DP
- Model 44F was the next worst case
- Stiffness of tubes within TS not significant.
 - Due to crack geometry.

Phase I: Results

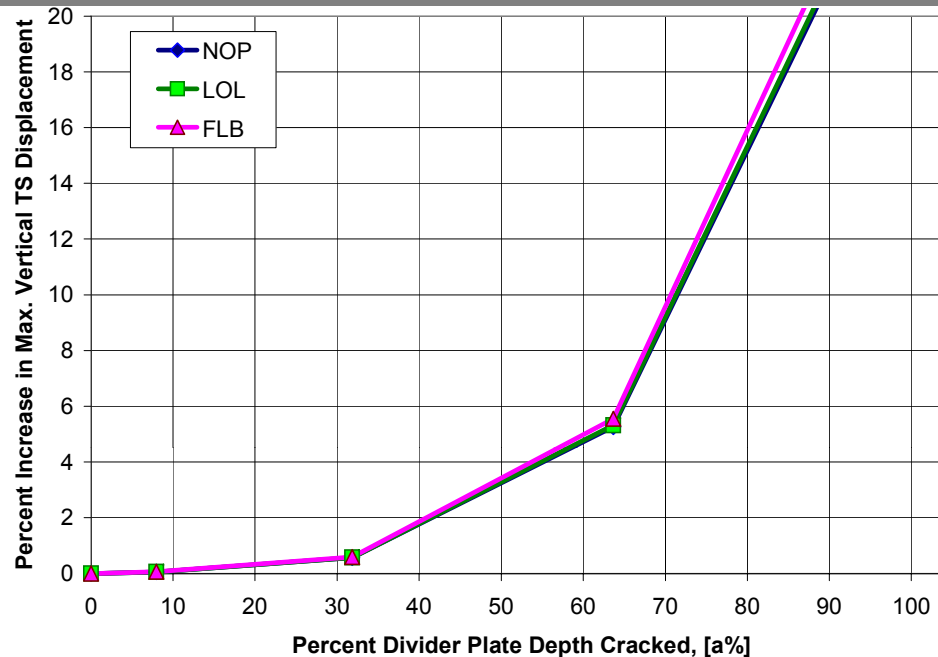


NOP, 8% Cracked, Vert. Displacement



NOP, 64% Cracked, Vert. Displacement

Phase I: Results



- Cracks not a structural concern under normal, accident or faulted conditions until they are **$\geq 40\%$** of the plate depth and **100%** of the plate length.
- Deepest French cracks are 14% of typical DP depth and **do not** occur over 100% of the plate length.

Phase I: Results

Source	Years
FEA w/Ringhals Data	805.1
FEA w/Plastic Failure Limit	751.8
$N_f - N_{CHEM}$	698.6
Finite Element CGR Estimate	5.11

- Assumes NOP conditions only and 1503 Heat-up/Cool Down cycles per calendar year.
- First 3 results assume mechanical fatigue dominates the failure.
- The effect of PWSCC changes in each result; from least to greatest.
- Last result assumes that PWSCC dominates.
- More analysis is needed to refine results of scoping study.

Phase I: Results

Model 51 Crack Growth Rate Summary

Time	Estimated n	Initial Crack Length	Avg. Final K	ΔK	PWSCC CGR	Fatigue CGR	Change in Crack Length	Final Crack Length
Years	#	in	ksi in ^{0.5}	ksi in ^{0.5}	E-10 in/sec	in/cycle	in	in
1	1503	0.16	15.76	15.76	62.82	1.378E-05	0.22	0.38
2	3006	0.16	23.83	23.83	74.12	4.763E-05	0.54	0.70
5	7515	0.16	30.72	30.72	82.61	1.020E-04	1.76	1.92
6	9018	0.16	48.79	48.79	98.72	4.087E-04	2.48	2.64

- A crack in PWSCC sensitized weld could grow through the DP in 5.11 years.
 - Assumes no threshold for crack growth

Phase I: Results

- **Using highly conservative assumptions:**
 - DP cracks ***can grow*** under NOP conditions
 - The analysis suggests that a ***combination of PWSCC and mechanical fatigue*** could fail the weld in time.
 - The currently observed crack indications ***do not*** result in a structural concern under ***normal or accident conditions***.
 - The cracks must be ***very large*** (deep and long) to increase TS displacement >2%.

Phase I: Results

- **93%** of the depth and **100%** of the length of the DP thickness must be cracked to fail during FLB
 - Analysis predicts plastic yielding
- After ~15 years, **the Foreign SG have not approached the 2% TS deflection increase limit.**
- More analysis is planned to refine scoping study.

Domestic Fleet: Conclusions

- Current tube/TS related ARC have been revised so that ***no credit*** is taken for the DP.
- ***More analysis*** is planned to determine if there is an effect on other structures because of a degraded DP.
 - Phase II of the EPRI program is being developed.

The Role of the Divider Plate in the H^*/B^* ARC Analysis

- In H^*/B^* WCAPs prior to 2006 the DP is assumed to provide some restraint to vertical and radial TS deflections.
- Restricting vertical TS deflections limits the radial deflection of the TS because the rotation of the TS due to bowing is reduced.
- Radial deflections are used in the calculation of TS hole dilation.

Recent H*/B* Divider Plate RAI

17. Reference 2, Enclosure 1, Attachment 1 (The Westinghouse Letter Summary of Changes to B* and H*), page 14 - address the status of the divider plate evaluation being performed under EPRI sponsorship, and the schedule for completion of the various topics being addressed in the evaluation. Describe any inspections that have been performed domestically that provide insight on whether the extent and severity of divider plate cracks is bounded by the foreign experience. Discuss the available options for inspecting the divider plates.

Planned Response to RAI 17

- Phase I of the EPRI study is complete.
 - EPRI technical report 1014982
- Phase II of the study is being developed.
 - Is inspection of the DP required?
- General visual examination of the DP is conducted at some plants.
 - No large abnormalities have been observed.
 - There are currently no other viable domestic DP inspection methods.

Recent H^*/B^* Divider Plate RAI

18. Discuss how the ability of the divider plates at Plant A to resist tubesheet deflection (without failure) under operating and accident loads is assured in the short term, pending completion of the EPRI evaluation. Include in this discussion the actions that are planned in the near term to ensure that the divider plates are capable of resisting tubesheet deflection.

Planned Response to RAI 18

- EDF has concluded that the DP to SR cracks do not grow.
 - None of the cracking indications to date have exceeded depth necessary to cause an increase of more than 2% TS deflection.
- The DP to CH weld, **alone**, is capable of limiting the TS deflection.
 - The DPF for the case of a DP to CH connection only is 0.64.

Planned Response to RAI 18, Cont'd.

- There have been no observed indications in the DP to CH weld:
 - The DP to CH weld is heat treated.
- Most Domestic SG have DP that are thicker than the French DP.
- Domestic SG do not load follow:
 - Fatigue usage factor in domestic DP is expected to be lower than French DP.
- The worst French cracking is associated with anomalies.

Proposed Phase II DP Analysis Scope

- Task 1: Perform detailed analysis of multiple crack geometry cases.
 - Reduce over-conservatism from Phase I analysis.
- Task 2: Scoping analysis of effects of a cracked DP during LOCA.
- Task 3: Qualitative evaluation of effects of a cracked DP on performance of SG during other transients.
- Task 4: Development of acceptance criteria for inspections.
 - Input needed from Task 1 – Task 3
 - Task 4 is not necessary if Task 1 – Task 3 show no adverse impact from a cracked DP.
- Task 5: Impact on ASME Code analysis and ARC

The Divider Plate Factor

- Westinghouse ARC originally assumed that the DP could reduce the displacement of the TS.
- Original H^* and B^* analyses take credit for the DP.
- H^* and B^* have been revised to exclude the DP from analysis results.
 - Removes DP from any consideration; DP to TS and DP to CH connections eliminated.

The Divider Plate Factor

- The original DP analysis showed that TS displacements were reduced by 24% with a fully functioning as-designed DP.
- This led to using a DP factor (DPF) of 0.76 to scale TS displacements.
- Recent analysis shows that TS displacements are reduced by nearly 60% with a fully intact DP in a detailed model of the TS-CH Complex.

The Divider Plate Factor

- What does $DPF = 1.00$ mean?
- All of the credit for the DP is removed
 - Vertical, Radial and DP to CH
- Unscaled displacements are used to calculate the contact pressures and TS bow.
 - The result ***would not be different*** even if ***inspection results show that the DP has failed.***

The Divider Plate Factor

- The DPF for the updated case is 0.399.
- Assuming $DPF = 1.00$ means no reduction in TS displacement.
- If only CH contribution is considered...
 - DPF without CH connection = 0.76
 - DPF with CH and TS connection = 0.399
 - DPF without TS connection = $1 - (0.76 - 0.399)$
 - $DPF = 0.639 \sim 0.64$
- Therefore, the TS displacements would still be ***reduced by 36% even if DP to SR connection severed.***

Divider Plate ARC Conclusions

- Current B^*/H^* ARC **does not rely on DP**
 - B^* and H^* use $DPF = 1.00$
- Current ARC **will not change** if cracking is discovered in domestic SG
- **Current B^* and H^* inspection distances will not change if cracking is observed in domestic SG.**

NRC Comments and Questions
