Recent H* Results Summary

3D Tubesheet Displacement Analysis Results
Radius Dependent Tubesheet Stiffness Results
Combined Applied Loading
Axisymmetric vs. 3D Results
Residual Contact Pressure Sensitivity Study

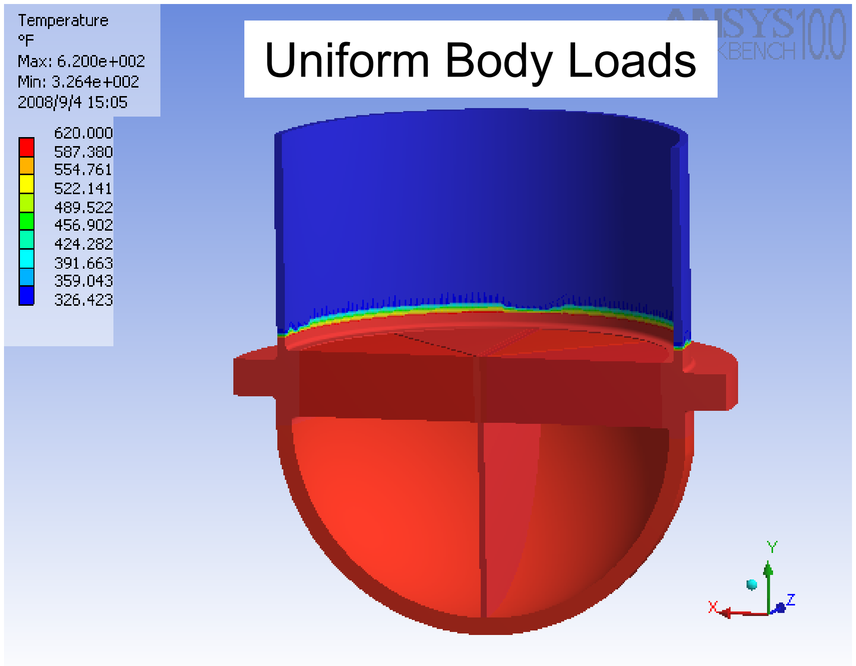
Progress Since July 2008

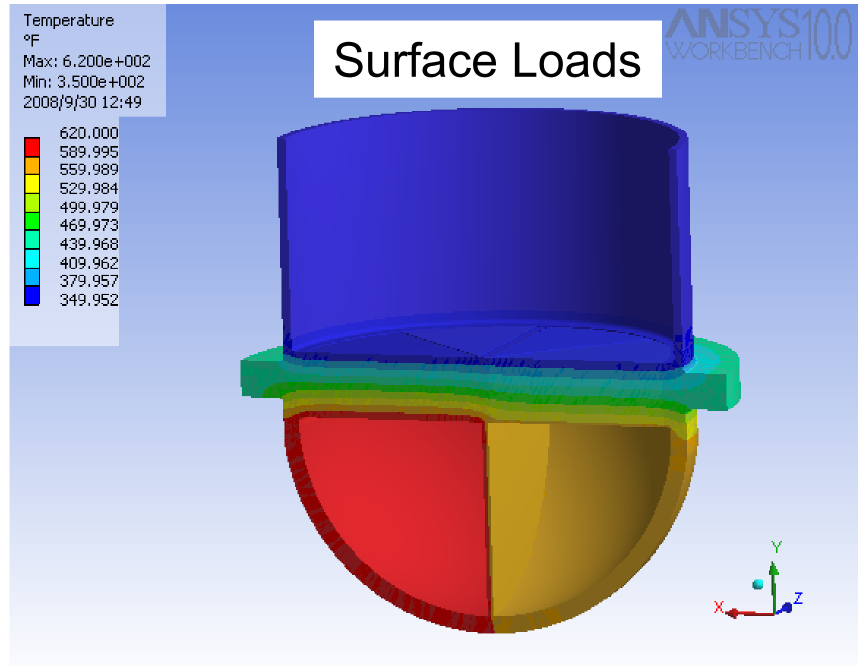
- Preliminary “Beta Factor”/Tubesheet Stiffness Study Results
- 3D Tubesheet Displacement H* Study
- Axisymmetric Linear Superposition (ALSP) Tubesheet Displacement Study
- Updated H* Analysis Tool
- Residual Contact Pressure (RCP) Sensitivity Study

3D Tubesheet Displacement Results

- 3D TS Displacements much smaller than ALSP.
- TS Displacements vary with respect to radius and angle.
  - Maximum TS Displacements due to pressure loading occur perpendicular to DP.
  - Minimum TS Displacements due to pressure loading occur parallel to DP.
- TS Displacements due to thermal loads are similar throughout the TS.
- Reduced TS Displacements lead to increased Tube-TS Contact Pressure.

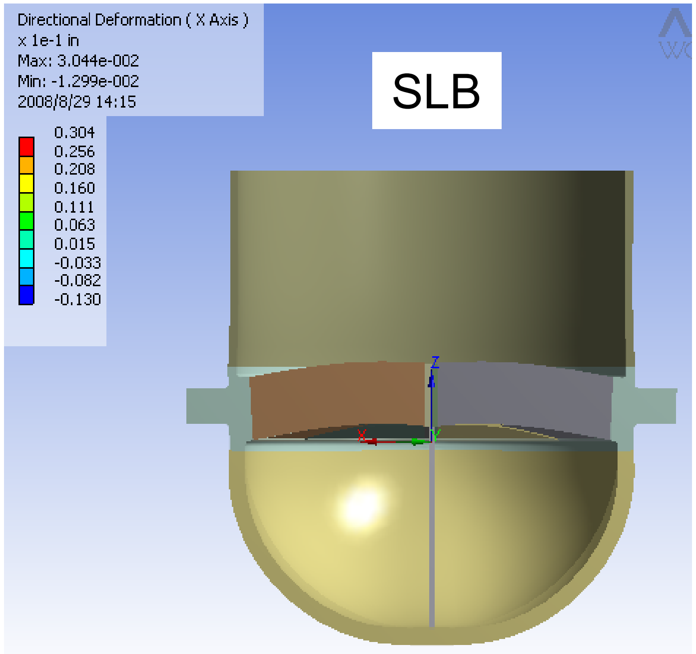
Application of Thermal Loads

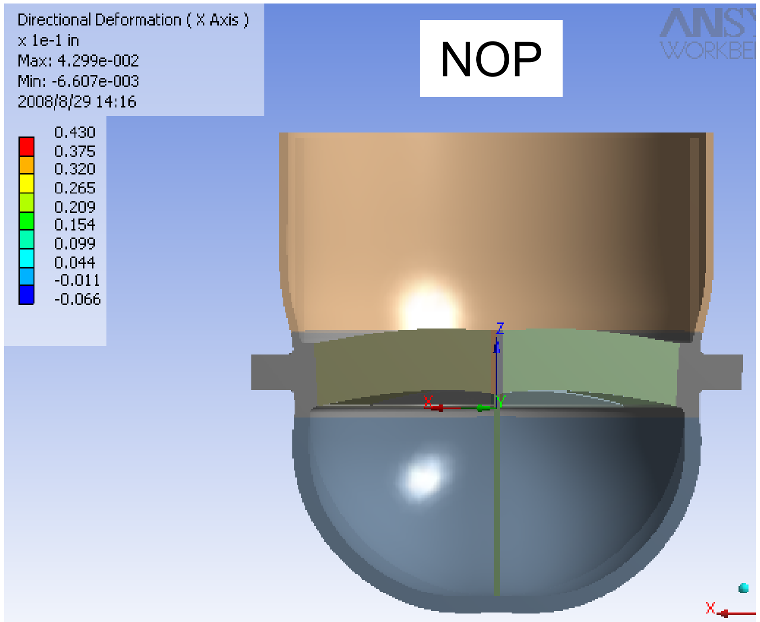




- Typical NOP Temperature Distributions
- Uniform Body Loads produce Greater TS Displacements
- ALSP uses Uniform Body Loads

Application of Pressure Loads





- 3D Applied Load Cases prove that axisymmetric loading is conservative.
- ALSP approach does not capture 3D mode shape of TS.
- 3D Applied Load TS Disp. << Axisymmetric Unit Load TS Disp.

Original Tubesheet Stiffness Study

- Original TS Collar wall thickness determined by pressurizing single tube in square pitch bundle.
- No other TS bore pressurized.
- Minimum material properties used.
- Appropriate for calculation of TS displacements around a single hole.
- Underestimates TS bore stiffness in bundle.

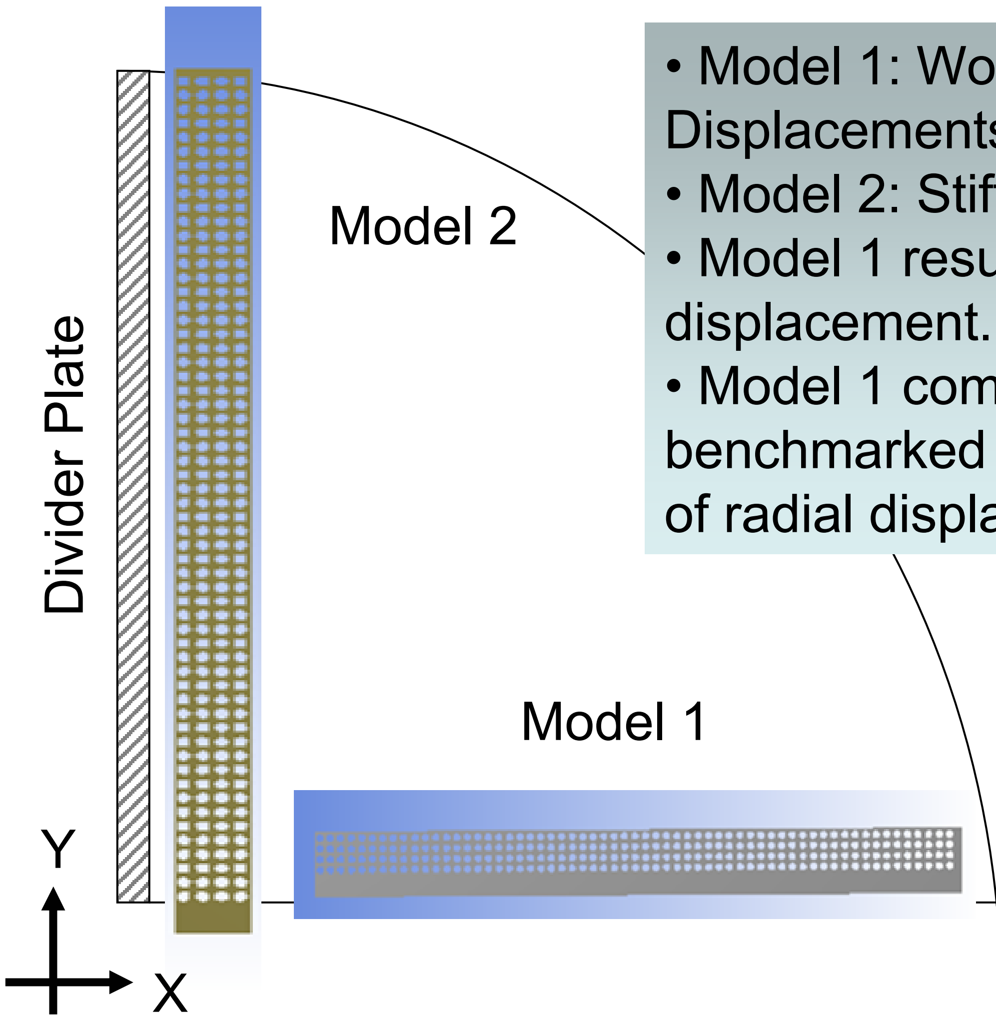
Updated Tubesheet Stiffness Study

- Original Concept for Pressurized Bore in Bundle was "Beta" Factor
- EP agreed that effect needed to be considered.
- EP recommended different approach.
- Redefinition of "Beta Factor" as radius dependent TS stiffness study.
- Tubesheet stiffness coefficient (TS collar OD) can now vary with radius based on constraint from boundary conditions.

Tubesheet Stiffness Study

- Two Plane Stress Finite Element Models used:
  - Model 1: Represents limiting region in bundle, perpendicular to DP
  - Model 2: Represents stiffest region in bundle, parallel to DP.
- Two cases considered:
  - All tubes pressurized.
  - Three “tubes of interest” pressurized.
- Two pressure cases used on tube bore:
  - SLB: 2560 psi, P_{sat} = 358 psi
  - NOP: 2250 psi, P_{sat} =1418 psi

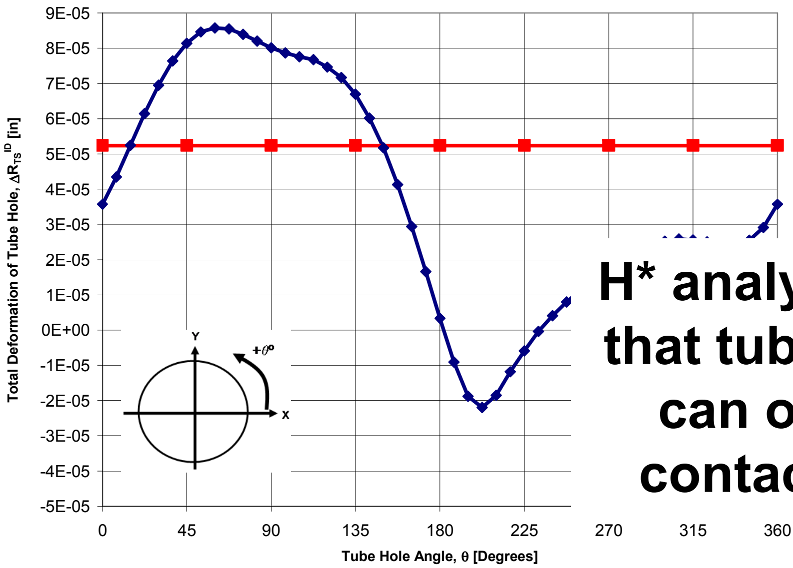
Tubesheet Stiffness Study



- Model 1: Worst Case TS Displacements
- Model 2: Stiffest TS Sector
- Model 1 results show greatest displacement.
- Model 1 combined load case benchmarked against 3D TS within 1% of radial displacement.

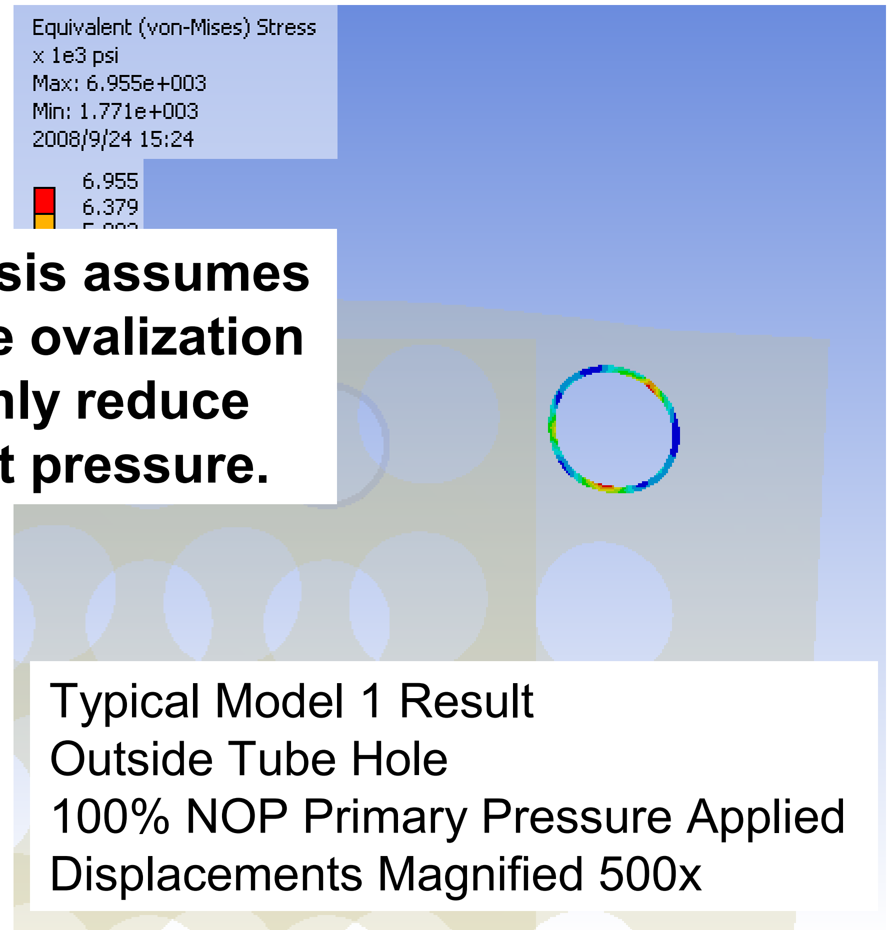
Additional edge material added for conservatism and to separate tube bore from BCs.

Tubesheet Stiffness Study



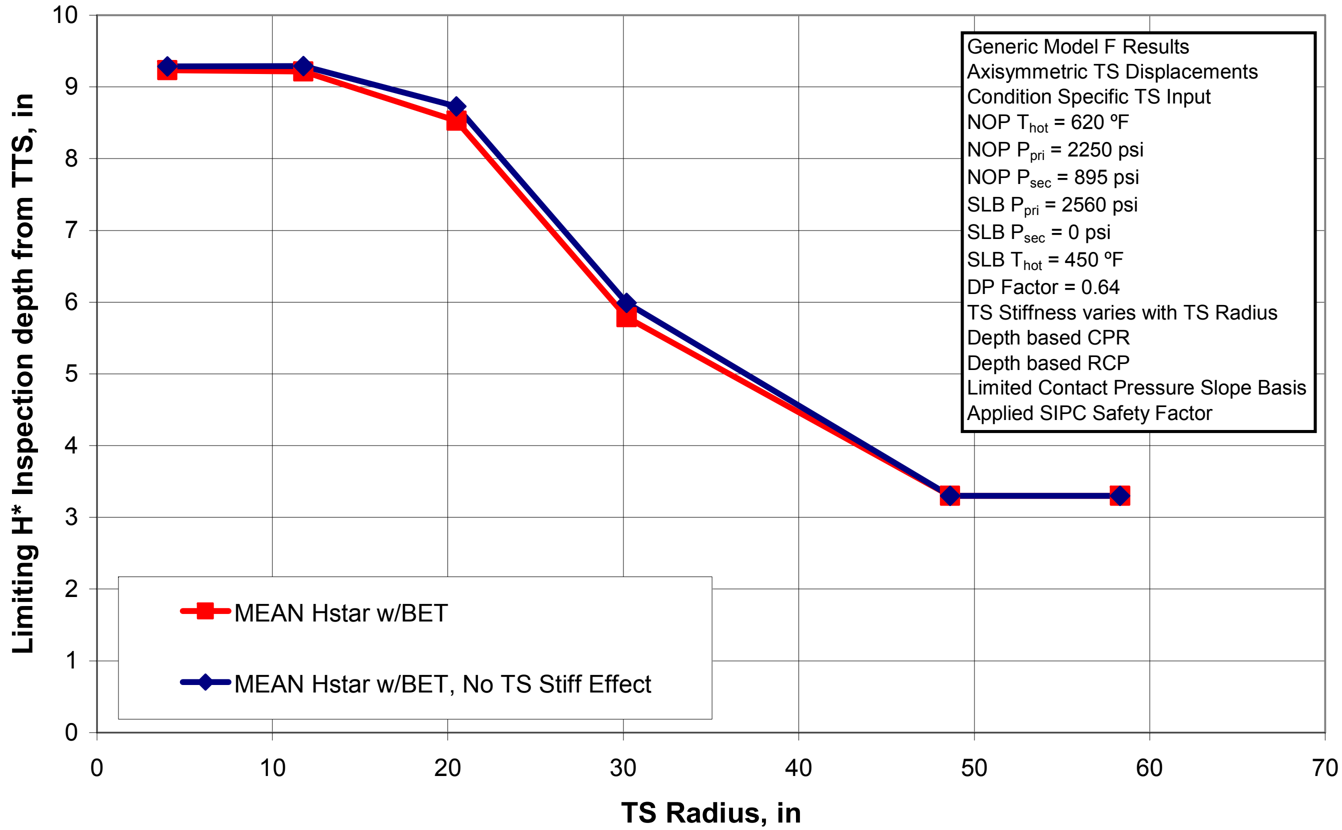
H* analysis assumes that tube ovalization can only reduce contact pressure.

Typical tubesheet bore deformation for a pressurized tubesheet shows significant ovalization of the bore.



Typical Model 1 Result
Outside Tube Hole
100% NOP Primary Pressure Applied
Displacements Magnified 500x

Tubesheet Stiffness Study



Radius specific tubesheet stiffness modification has small effect on mean H*.

Tubesheet Stiffness Study

- Same contact pressure equations used with adjusted TS Stiffness.
- TS Interaction coefficients and TS Collar thickness vary with TS Radius.
- EP review by end of October 2008.

Residual Contact Pressure Study

- Original study (spider plot) has been determined to be unrealistic.
  - Considered variations on the order of ±50%
  - Did not use statistical basis for parameter variation.
  - Assumed unrealistic variation in post-yield behavior.
- Updated Study addresses these concerns and uses updated modeling.

Residual Contact Pressure Study

- H* analysis tool can accommodate any RCP distribution.
- Test results will be used to establish the mean RCP.
  - Variability to be based on sensitivity study
- Friction model can be applied as constant value or non-linearly varying model.
- Recent literature results are considered.
  - Soler, Bazergui et al., Allam et al., etc.

H* FEA Residual Contact Pressure Sensitivity Preliminary Results

- Sensitivity study considers the following set of parameters:
  - Unexpanded Tube OD
  - Tubesheet Hole ID
  - Tube Yield Stress
  - Tube Elastic Modulus
  - Tubesheet Elastic Modulus
  - Expansion Pressure
  - Level of Strain Hardening
- End result of sensitivity study will be a distribution of residual contact pressure due to $\pm 2\ \sigma$ variation of each parameter

H* FEA Residual Contact Pressure Sensitivity Preliminary Results

- Full 360^{o}, concentric cylinder, 2-D plane stress representation of tube and tubesheet
- Surface-to-surface contact between tube OD and tubesheet hole ID
- Pressure load applied to tube ID
- Multi-linear isotropic strain hardening

H* FEA Residual Contact Pressure Sensitivity Preliminary Results

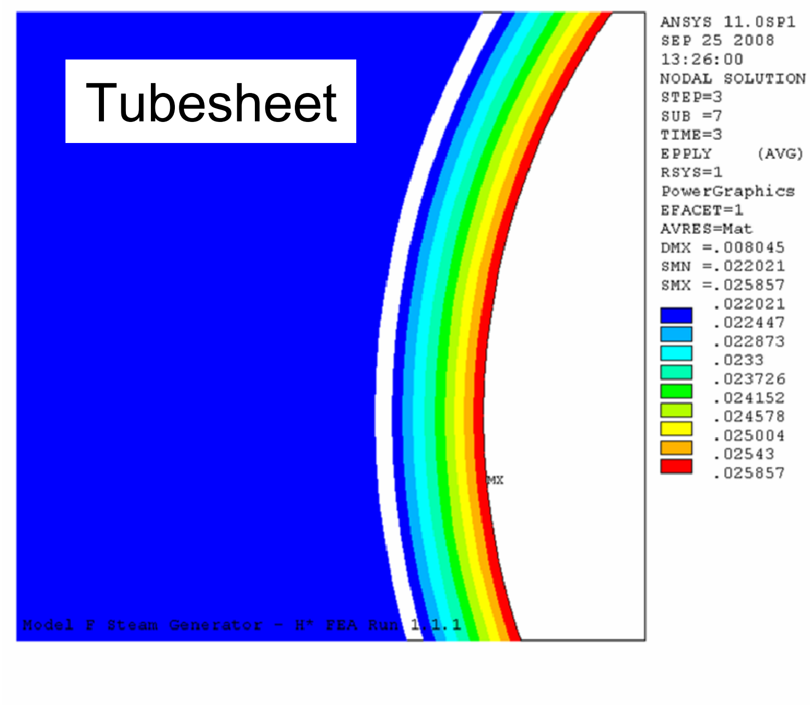
	Mean Value (psi)	-2σ Value (psi)	+2σ Value (psi)
Tube OD	537	314	683
TS ID	537	671	338
Tube Y_S	537	835	250
Tube E	537	469	604
TS E	537	604	472
Expansion Pressure	537	366	710
Strain Hardening Curve	537	537	537

H* FEA Residual Contact Pressure Sensitivity Preliminary Results

Variable Parameters							
Unexpanded Tube OD	Tubesheet ID	Tube Yield Stress	Tube Elastic Modulus	Tubesheet Elastic Modulus	Expansion Pressure	Strain Hardening Curve	Residual Contact Pressure
(in)	(in)	(ksi)	(psi)	(psi)	(psi)		(psi)
0.688	0.703	51.4	3.10E+07	2.95E+07	31000	AVG	537
0.6840	0.703	51.4	3.10E+07	2.95E+07	31000	AVG	314
0.6906	0.703	51.4	3.10E+07	2.95E+07	31000	AVG	683
0.688	**0.7004**	51.4	3.10E+07	2.95E+07	31000	AVG	671
0.688	**0.7070**	51.4	3.10E+07	2.95E+07	31000	AVG	338
0.688	0.703	**43.6**	3.10E+07	2.95E+07	31000	AVG	835
0.688	0.703	**59.0**(1)	3.10E+07	2.95E+07	31000	AVG	250
0.688	0.703	51.4	**3.047E+07**	2.95E+07	31000	AVG	469
0.688	0.703	51.4	**3.153E+07**	2.95E+07	31000	AVG	604
0.688	0.703	51.4	3.10E+07	**2.900E+07**	31000	AVG	604
0.688	0.703	51.4	3.10E+07	**3.000E+07**	31000	AVG	472
0.688	0.703	51.4	3.10E+07	2.95E+07	**30318**	AVG	366
0.688	0.703	51.4	3.10E+07	2.95E+07	**31682**	AVG	710
0.688	0.703	51.4	3.10E+07	2.95E+07	31000	**-1s**	537
0.688	0.703	51.4	3.10E+07	2.95E+07	31000	**+1s**	537
0.688	0.703	51.4	3.10E+07	2.95E+07	31000	**-2s**	537
0.688	0.703	51.4	3.10E+07	2.95E+07	31000	**+2s**	537

Notes: 1) For convergence purposes, 59.0 ksi tube yield stress value used for +2s value in lieu of actual value of 59.2 ksi.

H* FEA Residual Contact Pressure Sensitivity Preliminary Results



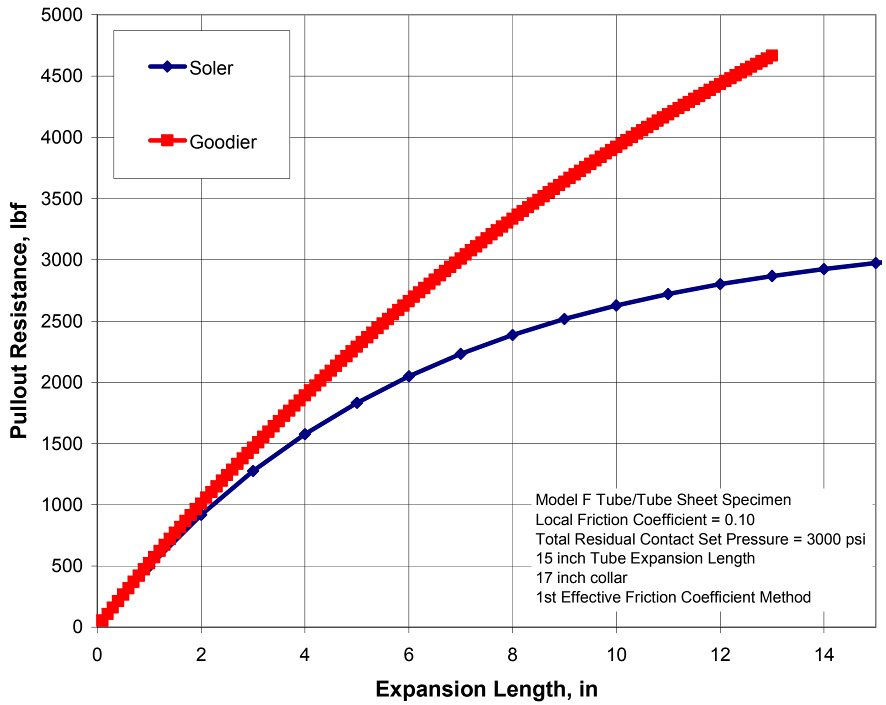
Typical Plastic Strain contours for Mean Case plotted on undeformed configuration.

- Finite element model can accommodate radial springback.
- Finite element model conservatively applies expansion pressure to minimize resulting contact pressure distribution.
- Values for plastic strain and deformation in the expanded tube are similar to original study results.

H* FEA Residual Contact Pressure Sensitivity Preliminary Results

- Average residual contact pressure approximately 500 psi
  - H* analysis currently assumes 300 psi
- Residual contact pressure most sensitive to variations in the tube yield stress
- Residual contact pressure relatively insensitive to variations in post-yield strain hardening behavior (under review by EP)

Residual Contact Pressure Study



- Goodier: Assumes constant coefficient of friction.
- Soler: Effective coefficient of friction that varies with expansion length.
- Both models require test data to benchmark values.

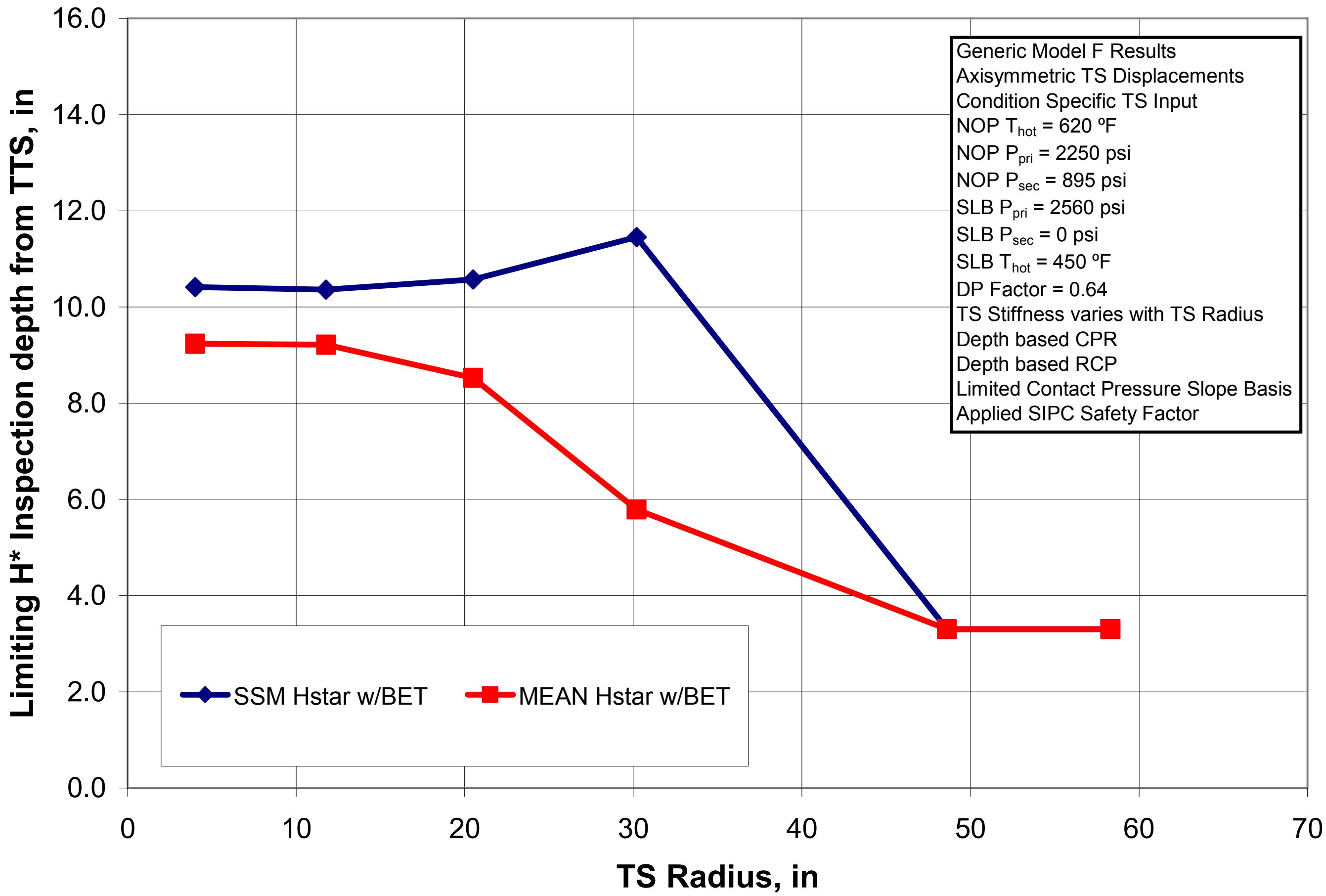
H* Study Results

- Axisymmetric and 3D TS Disp. Compared
- Simplified Statistical Method (SSM) from Guidelines used to combine variability at 95/50 confidence level
- Minimum H* set at 3 in. because of leakage limit
- BET conservatively added to 3 in. minimum and all other values after uncertainties are considered.

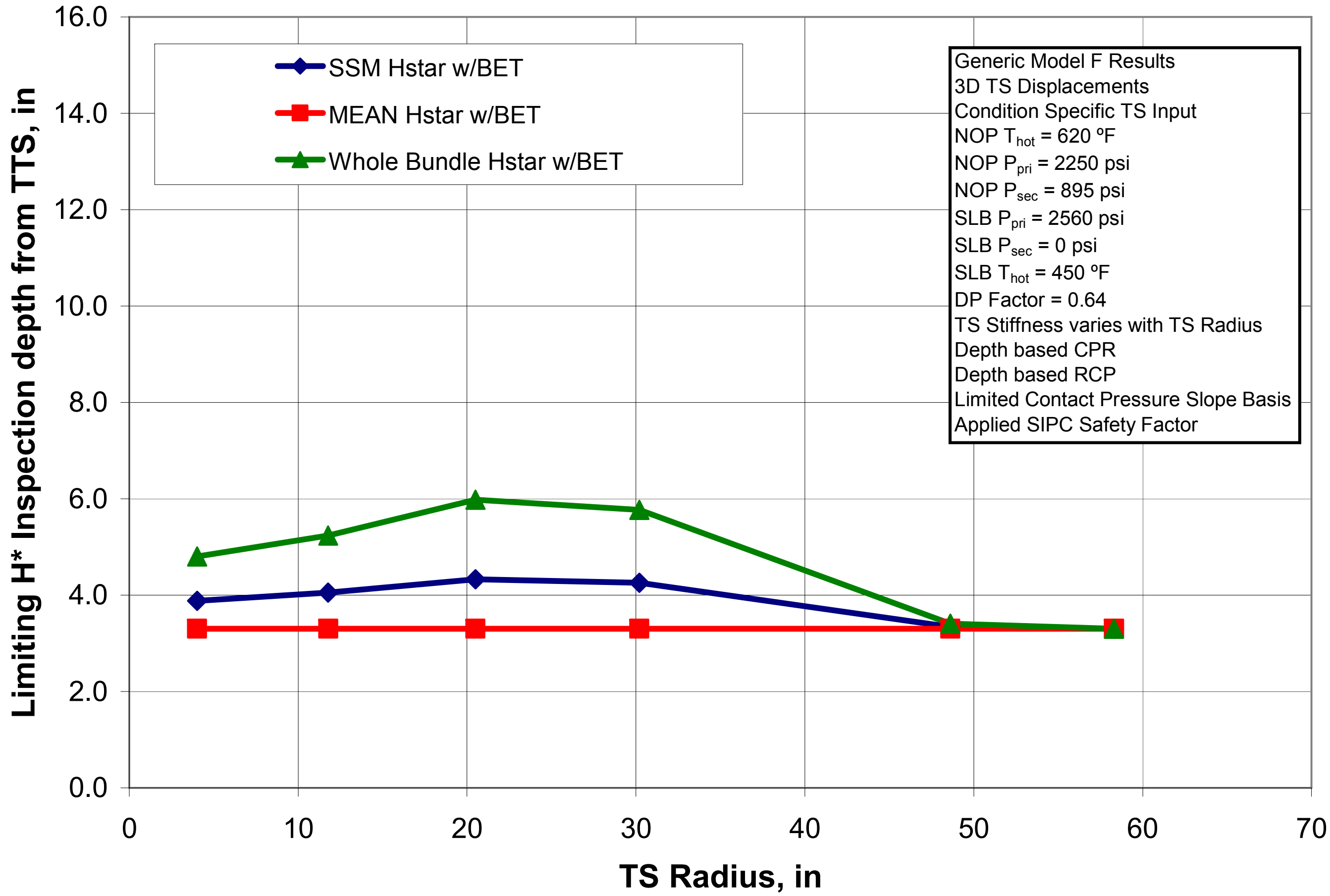
H* Results

- Bounding Model F Operating Conditions
- 6 Parameters in H* study:
  - Coefficient of Friction (μ = 0.3, 1σ = 0.1)
  - Residual Contact Pressure (μ = 200 lbf/in, 1σ = 50 lbf/in)
  - Tubesheet Young's Modulus (1σ = 0.85%)
  - Tube Young's Modulus (1σ = 0.85%)
  - Tubesheet CTE (1σ = 1.75%)
  - Tube CTE (1σ = 2.3%)
- Linear RCP model applied.
- Each parameter varied independently

Axisymmetric H* Results
(Worst case single tube)

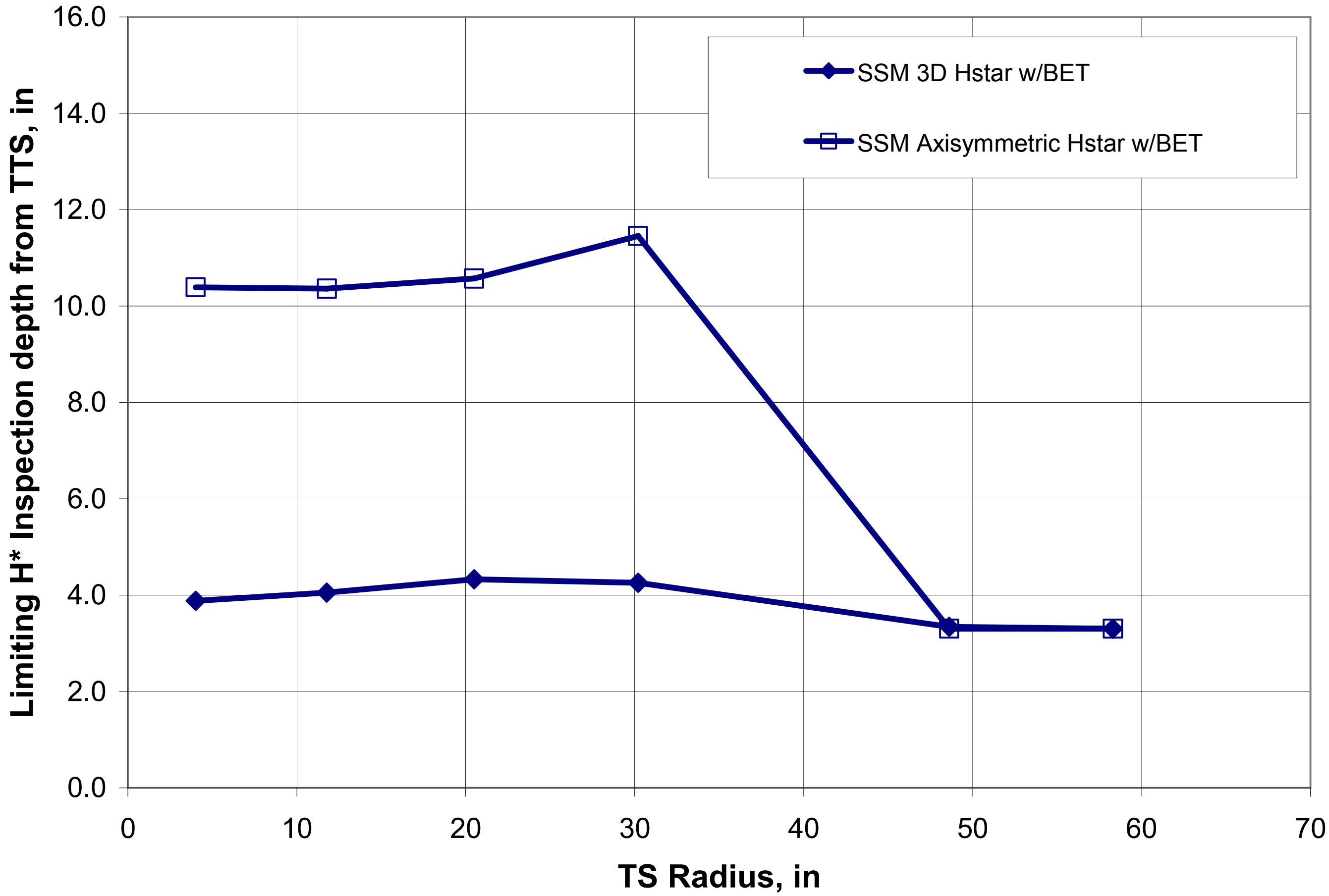


3D H* Results



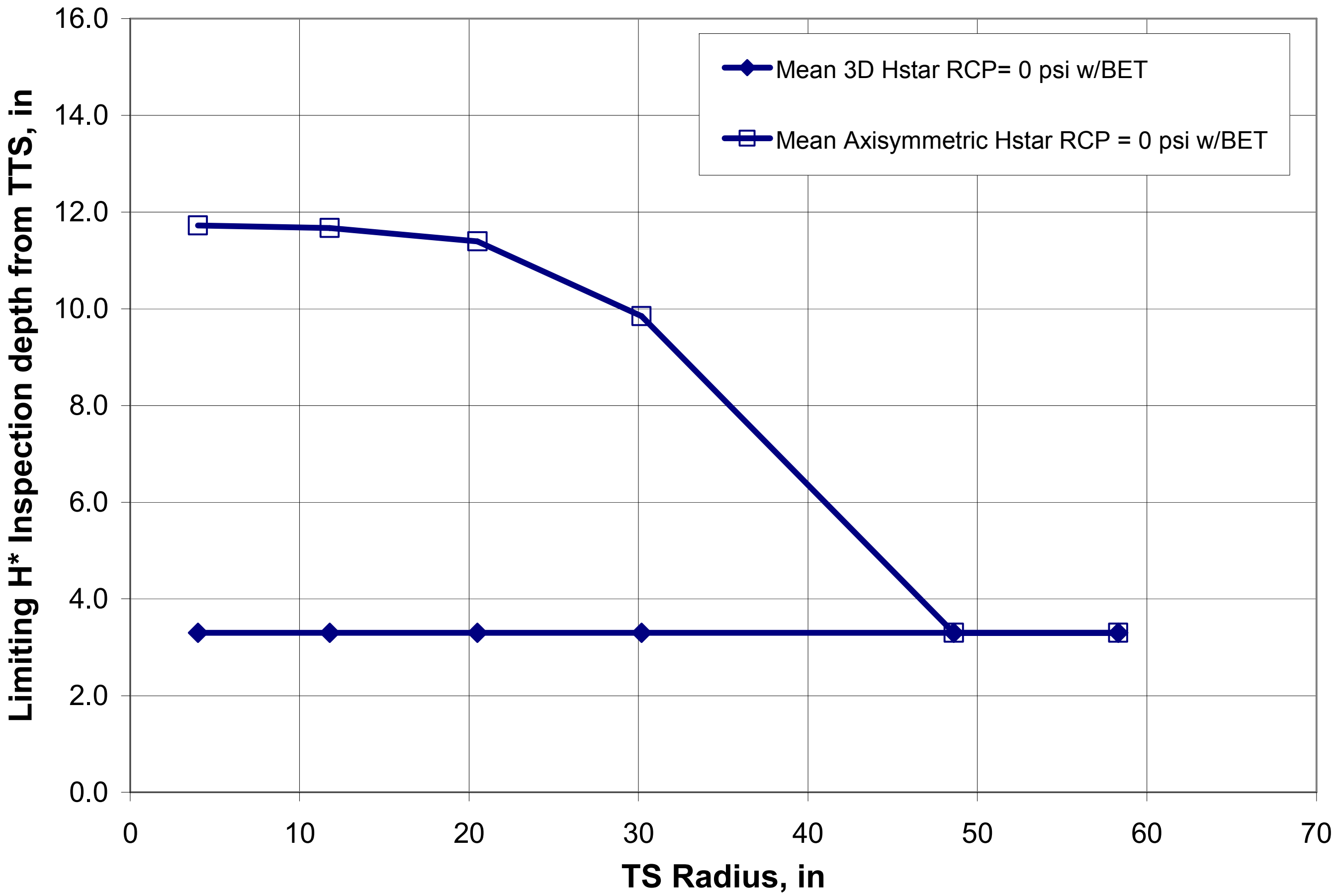
3D TS Displacements much less sensitive to variability

Comparison of SSM H* Results
(Worst case single tube)



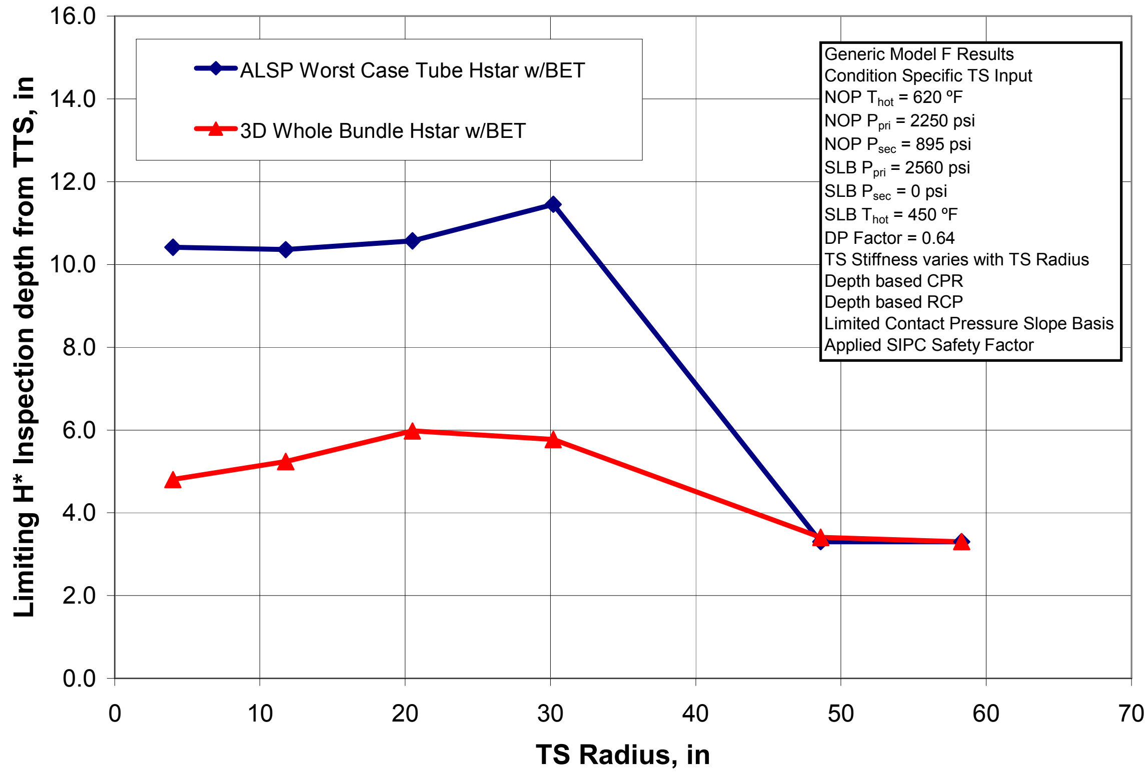
Axisymmetric SSM H* Bounds at all radii 3D SSM H*

Comparison of H* RCP = 0 psi



- 3D Mean H* Results insensitive to RCP = 0 psi case
- Axisymmetric Mean H* Results increase by 3 in for RCP = 0 psi

Preliminary Results - Option D



- Whole bundle analysis based on 5500 tubes in Model F bundle.
- Worst case tube H* defined using SIPC, limiting TS sector, worst condition result.

Future Work

- Response Surface Study for H* Variability with 3D tubesheet displacements.
- Monte Carlo Analysis H* study for updated ALSP and 3D results.
- Establish Residual Contact Pressure models based on test data.
- EP to verify 3D TS Displacements and Tubesheet Stiffness Study Results
- Update other SG Model analysis tools.

Conclusions

- H* analysis approach and equations have not changed.
  - H* analysis inputs have been refined based on EP comments.
- H* analysis tools have been updated to reflect EP comments.
- Bounding Model F ALSP SSM (worst case single tube) H* results less than 12 in.
- Bounding Model F 3D SSM (whole bundle) H* results less than 6 in.