Probabilistic Risk Assessment of Layered Pressure Vessels

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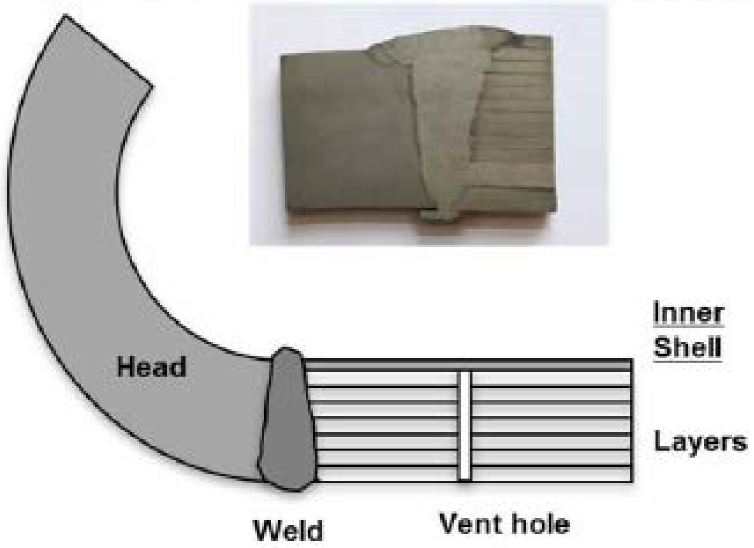
Background and Motivation

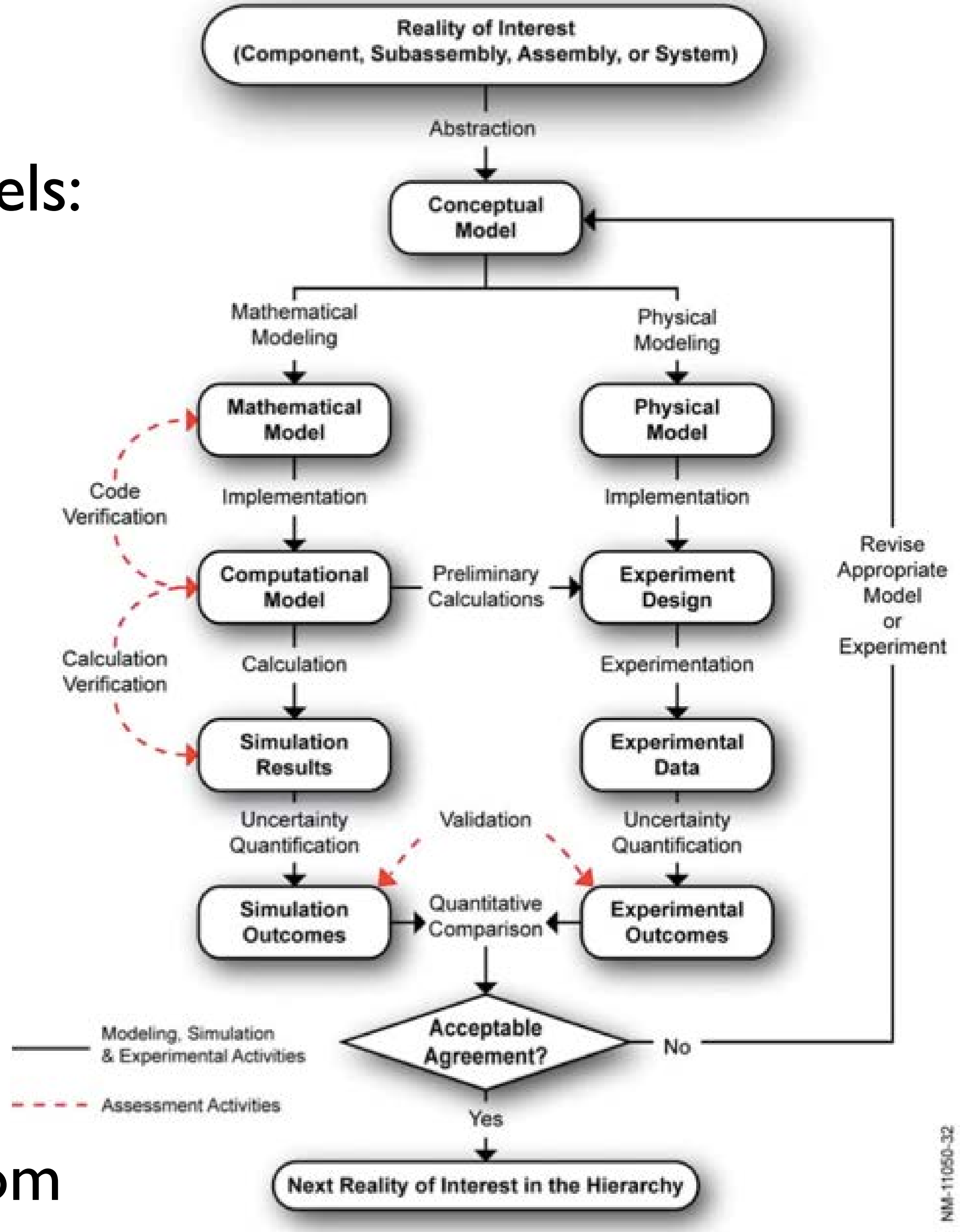
- NASA operates ≈ 300 aging layered pressure vessels (LPVs) that were fabricated prior to ASME B&PV code requirements
- Performing traditional fitness for service is challenging and may be overly conservative due to many unknowns in these LPVs:
  - Use of proprietary materials in fabrication
  - Missing construction records
  - Geometric discontinuities
  - Weld residual stress (WRS) uncertainty
  - Complex service stress in and around welds



- **Developed probabilistic framework that can capture variability and uncertainty in LPV fleet and assess risk of fracture in regions of interest**

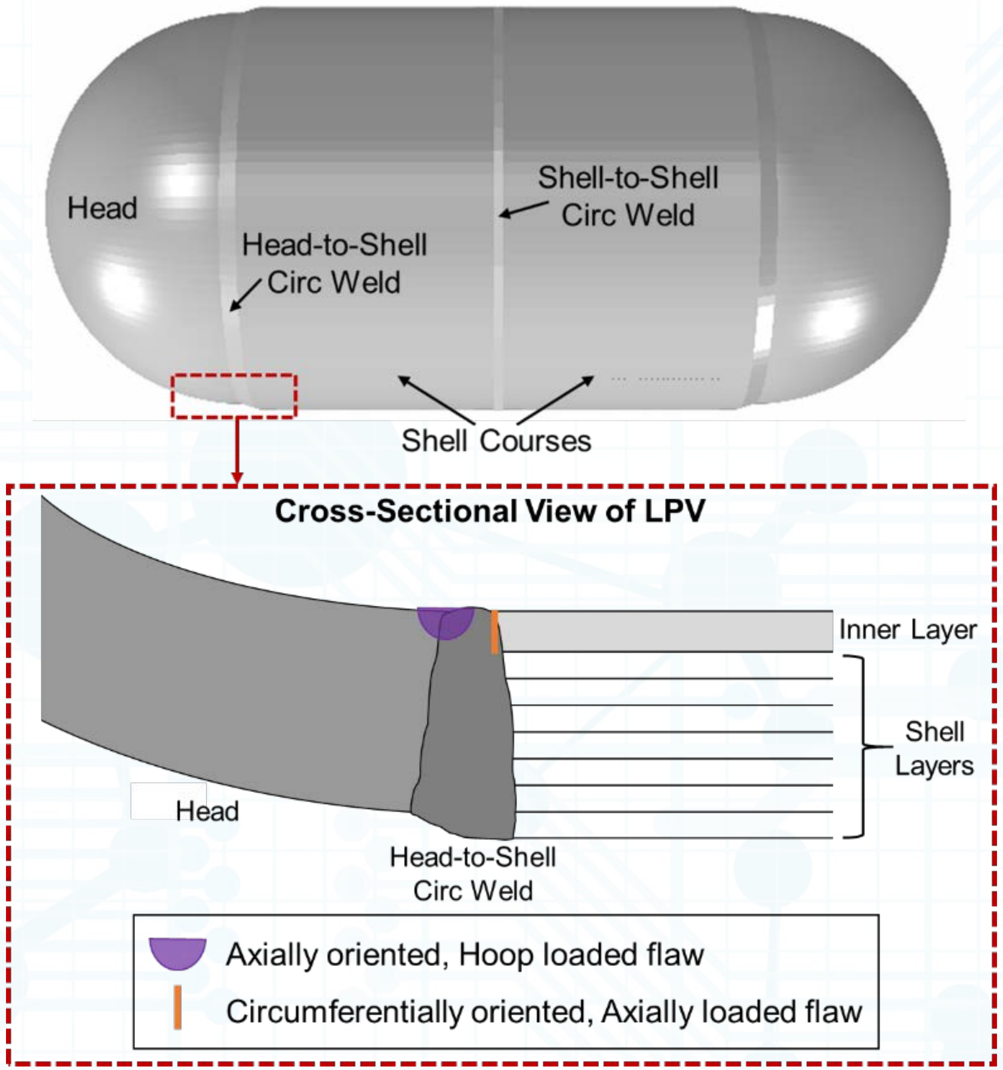
Framework Development

- The probabilistic framework is comprised of multiple models:
  - Vessel geometry
  - Service stress
  - Weld residual stress
  - Stress intensity factor
- Model development was performed using verification and validation (V&V) approach:
  - Identify important phenomena
  - Quantify uncertainties and approximations
  - Establish evidence about predictive accuracy of the models
- NESSUS® probabilistic software makes model inputs random variables, exercises the models, and links model outputs



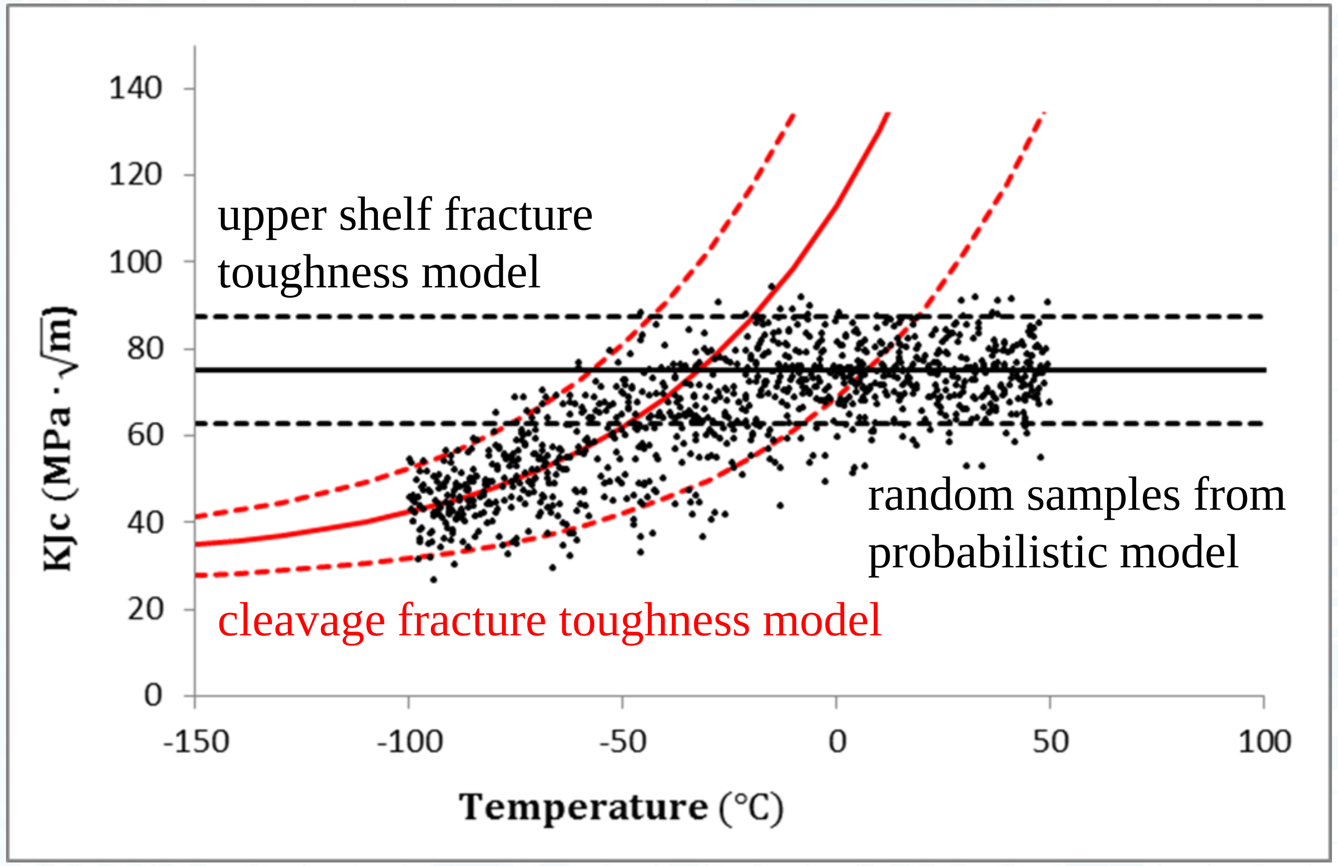
Demonstration Cases and Probabilistic Analysis

- Predict stress intensity factor (SIF) for two flaws in head-to-shell (H-S) circumferential welds for 4-layer (small) and 14-layer (large) LPV to demonstrate framework
  - H-S welds have unique geometry and stress → interlayer gaps introduce bending stress + complex WRS from fabrication
  - H-S weld non-destructive evaluation (NDE) is challenging → use models in probabilistic framework to guide NDE
- <u>Perform probabilistic studies</u>: (1) full cumulative distribution function and (2) global sensitivity analysis
- <u>Compute probability of failure based on limit-state function</u>: $g = K_{JC} - K_I = 0$
  - $\boldsymbol{p_f} = P[g < 0] = P\left[K_{JC} - K_I < 0\right] = \boldsymbol{P}[\boldsymbol{K_{JC}} < \boldsymbol{K_I}]$
  - Integrate joint PDF (f_X) of all random variables (X) over failure region: $\boldsymbol{p_f} = \int_{g<0} \cdots \int \boldsymbol{f_X(x)dx}$



Vessel Materials and Geometry

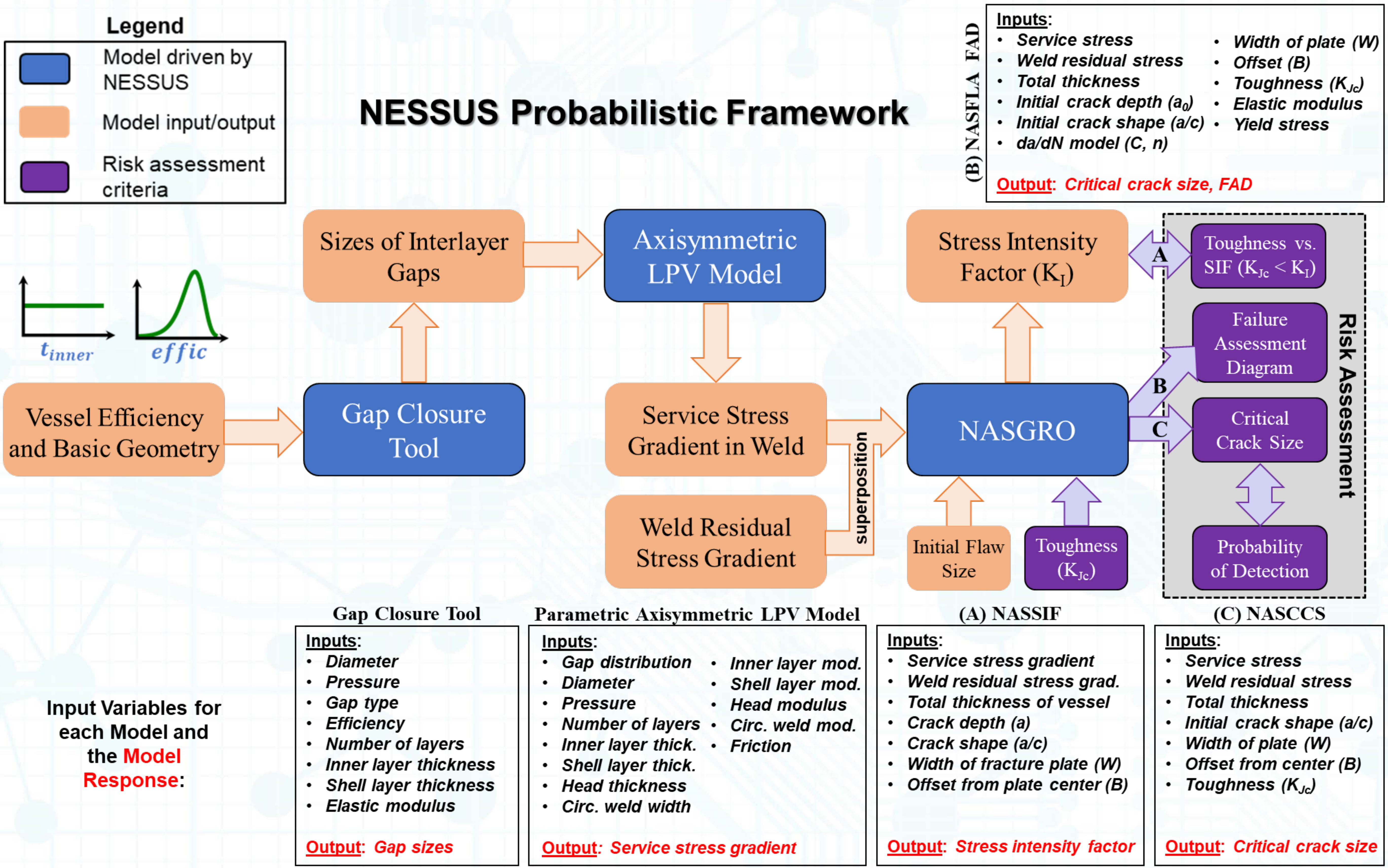
- 4-layer (1 inner + 3 shell layers) and 14-layer (1 inner + 13 shell layers) vessel:
  - Manufactured in 1963 by Chicago Bridge and Iron Company
  - Inner layer rolled from 1143 Mod. steel
  - Shell layers rolled from 1146 steel
  - Head fabricated from A-225 Grade B FBX steel
- Uncertainty in inner shell and head thickness estimated based on construction records
- Variation in vessel efficiency estimated from pi tape measurements of other vessels in fleet
- Fracture toughness determined experimentally
  - ASTM E-1921 → cleavage toughness model
  - Uncertainty in cleavage transition to upper shelf
    → use lower of cleavage or upper shelf toughness



Cleavage and upper shelf fracture toughness models with 5% and 95% tolerance bounds

*Note: tables listing geometry and loading/boundary conditions for the 4- and 14-layer vessel are provided in backup slides

Probabilistic Framework


NESSUS Probabilistic Framework
Legend
Model driven by NESSUS
Model input/output
Risk assessment criteria
Sizes of Interlayer Gaps
Axisymmetric LPV Model
Stress Intensity Factor (K_I)
Toughness vs. SIF (K_Jc < K_I)
Failure Assessment Diagram
Critical Crack Size
Probability of Detection
Risk Assessment
A
B
C
t_inner
effic
Vessel Efficiency and Basic Geometry
Gap Closure Tool
Service Stress Gradient in Weld
Weld Residual Stress Gradient
superposition
NASGRO
Initial Flaw Size
Toughness (K_Jc)
(B) NASFLA FAD
Inputs:
• Service stress
• Weld residual stress
• Total thickness
• Initial crack depth (a_0)
• Initial crack shape (a/c)
• da/dN model (C, n)
• Width of plate (W)
• Offset (B)
• Toughness (K_Jc)
• Elastic modulus
• Yield stress
Output: Critical crack size, FAD
Input Variables for each Model and the Model Response:
Gap Closure Tool
Inputs:
• Diameter
• Pressure
• Gap type
• Efficiency
• Number of layers
• Inner layer thickness
• Shell layer thickness
• Elastic modulus
Output: Gap sizes
Parametric Axisymmetric LPV Model
Inputs:
• Gap distribution
• Diameter
• Pressure
• Number of layers
• Inner layer thick.
• Shell layer thick.
• Head thickness
• Circ. weld width
• Inner layer mod.
• Shell layer mod.
• Head modulus
• Circ. weld mod.
• Friction
Output: Service stress gradient
(A) NASSIF
Inputs:
• Service stress gradient
• Weld residual stress grad.
• Total thickness of vessel
• Crack depth (a)
• Crack shape (a/c)
• Width of fracture plate (W)
• Offset from plate center (B)
Output: Stress intensity factor
(C) NASCCS
Inputs:
• Service stress
• Weld residual stress
• Total thickness
• Initial crack shape (a/c)
• Width of plate (W)
• Offset from center (B)
• Toughness (K_Jc)
Output: Critical crack size

Gap Closure Tool

- Excel-based tool developed at NASA's Marshall Space Flight Center
  - **Inputs:** basic vessel geometry, linear elastic material properties, vessel efficiency, internal pressure, and through-thickness distribution of gaps
  - **Outputs:** through-thickness size of interlayer gaps and closure pressure
  - Uses thin walled vessel theory and Excel's Goal Seek function
- Uniform through-thickness distribution of gaps used in this study → conservative assumption

Input basic vessel parameters

Vessel	d inner	20	in.
	t total	1.750	in.
	E	29500000	psi
	# Layers	6	
	MAWP	5500	psig
	Gapping Type *	1	
Target Efficiency		85	Macro

	Mono Equivalent					Layered Response		
	P (psi)	σi (ksi)	σo (ksi)	C (in)	D (in)	D (in)	Efficiency	
Initial	0	0	0	73.8274	23.5	23.5053		
Closure	825.00	5.16	4.33				85.00	From P
Final	5500.00	34.40	28.90	73.8947	23.5214	23.5235		
			delta:	0.0673	0.0214	0.0182	85.00	From D

Given a target efficiency, computes equivalent layer gapping

						3D				All	
										σa (ksi)	P actual
Layer #	T layer	Gap	R Layer	T closure	P closure	P closure	R Mono	C closure	D Closure	0	0
0	0.5	0.000530	10.251	0.500	76.396	87.54	10.250	65.977	21.001	0.230	87.54
1	0.25	0.000530	10.626	0.750	113.331	128.17	10.375	67.551	21.502	0.567	215.71
2	0.25	0.000530	10.877	1.000	149.476	166.85	10.500	69.125	22.003	1.005	382.56
3	0.25	0.000530	11.127	1.250	184.883	203.68	10.625	70.699	22.504	1.540	586.24
4	0.25	0.000530	11.378	1.500	219.602	238.76	10.750	72.273	23.005	2.167	825.00
5	0.25	0.009103	11.637	1.750	4376.813	4675.00	10.875	73.901	23.524	14.450	5500.00
6	0	0.000000	11.762	1.750	0.000	0.00	10.875	73.901	23.524	14.450	5500.00
31	0	0.000000	11.762	1.750	0.000	0.00	10.875	73.901	23.524	14.450	5500.00
Proof	0	0.005355	11.767	1.750	2581.881	2750.00	10.875	73.935	23.534	21.675	8250.00

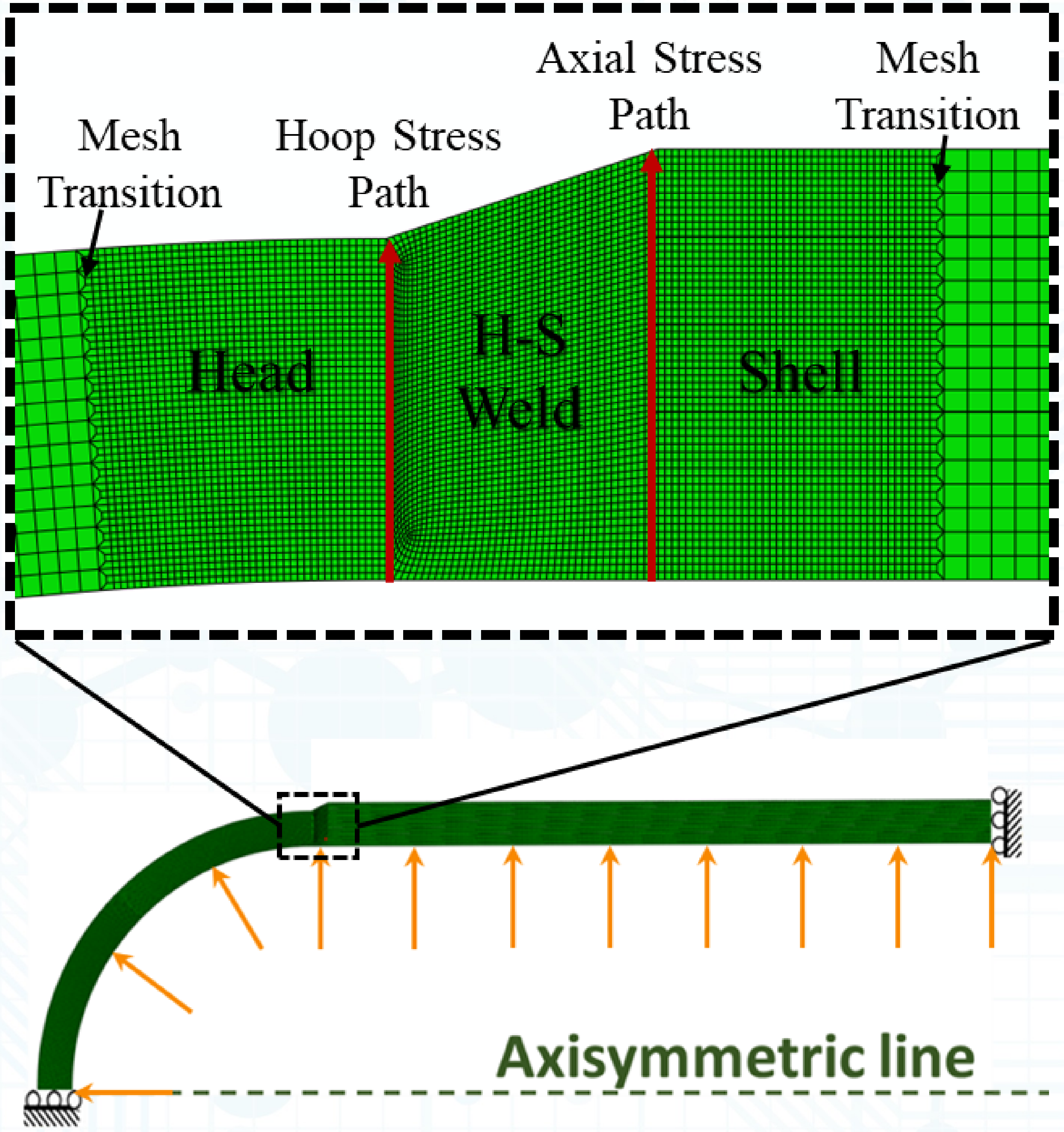
#	Multiplier	* Gapping Type
1	1	uniform
2	0.5	linear change through thickness
3	0	inner only (most conservative for inner layer)
4	0.8	linear change through thickness
5		

Calculates pressure-consistent stress history for all layers

Adjustable presumed gap distribution

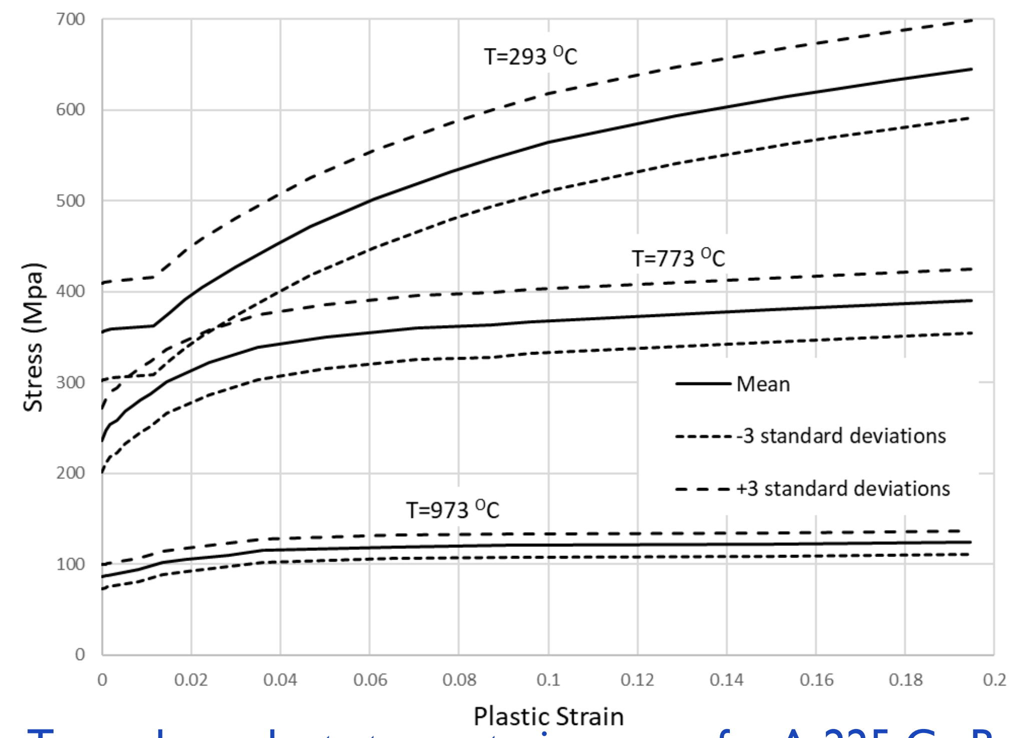
Parametric Axisymmetric LPV Model

- Linear elastic finite element model in Abaqus
  - Parametric → capable of simulating all LPVs in fleet
  - Axisymmetric → takes advantage of axisymmetric nature of circumferential welds to reduce order of simulation and computational cost
  - **Inputs:** vessel geometry, material properties, service pressure, gap sizes from Gap Closure Tool
  - **Outputs:** linear elastic stress field during service (univariate stress gradient extracted along path)
- Limitations of the model:
  - Does not consider effect of longitudinal welds
  - Does not include weld backing plate in geometry

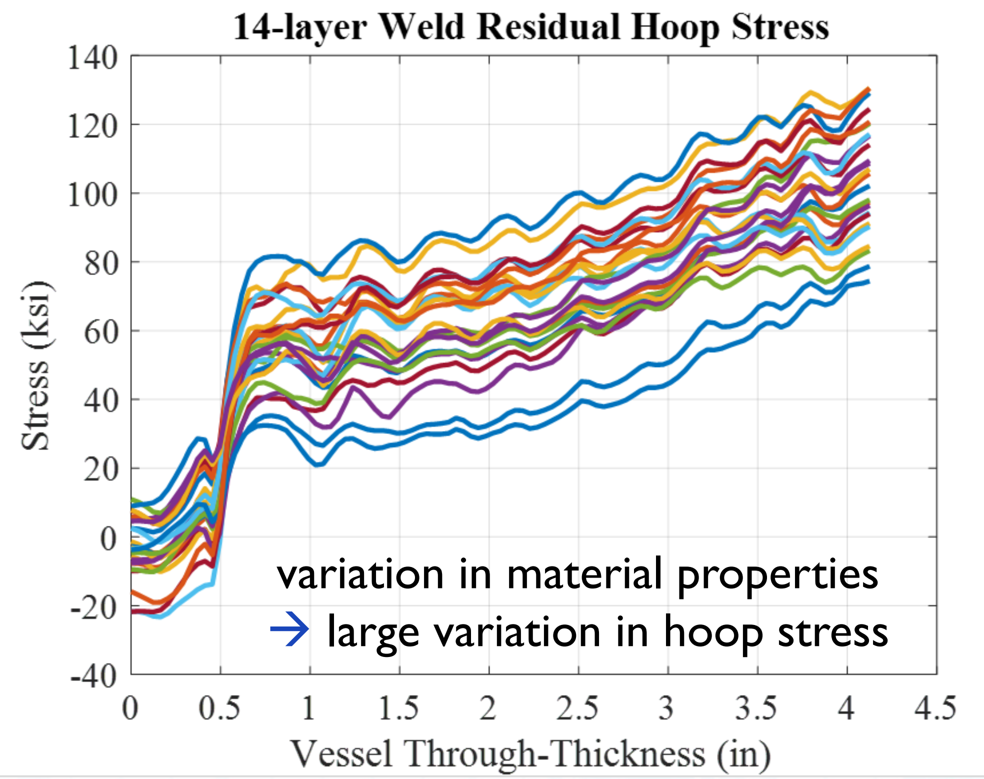


Thermo-mechanical Weld Simulations

- Multi-pass weld simulations of 4- and 14-layer H-S welds performed by Engineering Mechanics Corporation of Columbus using VFT™ (Virtual Fabrication Technology) code[1]
  - Sequentially coupled thermo-mechanical FEA → elastic-plastic WRS field prediction
  - Include hydro test at 1.5 times max pressure in simulation → univariate stress gradient extraction after hydro
- Temp-dependent stress-strain curves determined experimentally for materials in vessels
- Temp-dependent CTE and stress-strain curves (yield stress) are random variables
- Generated 25 WRS gradients to train surrogate model
  - PCA-based model
  - Predicts WRS variability
  - Reduces computational cost vs. FEA



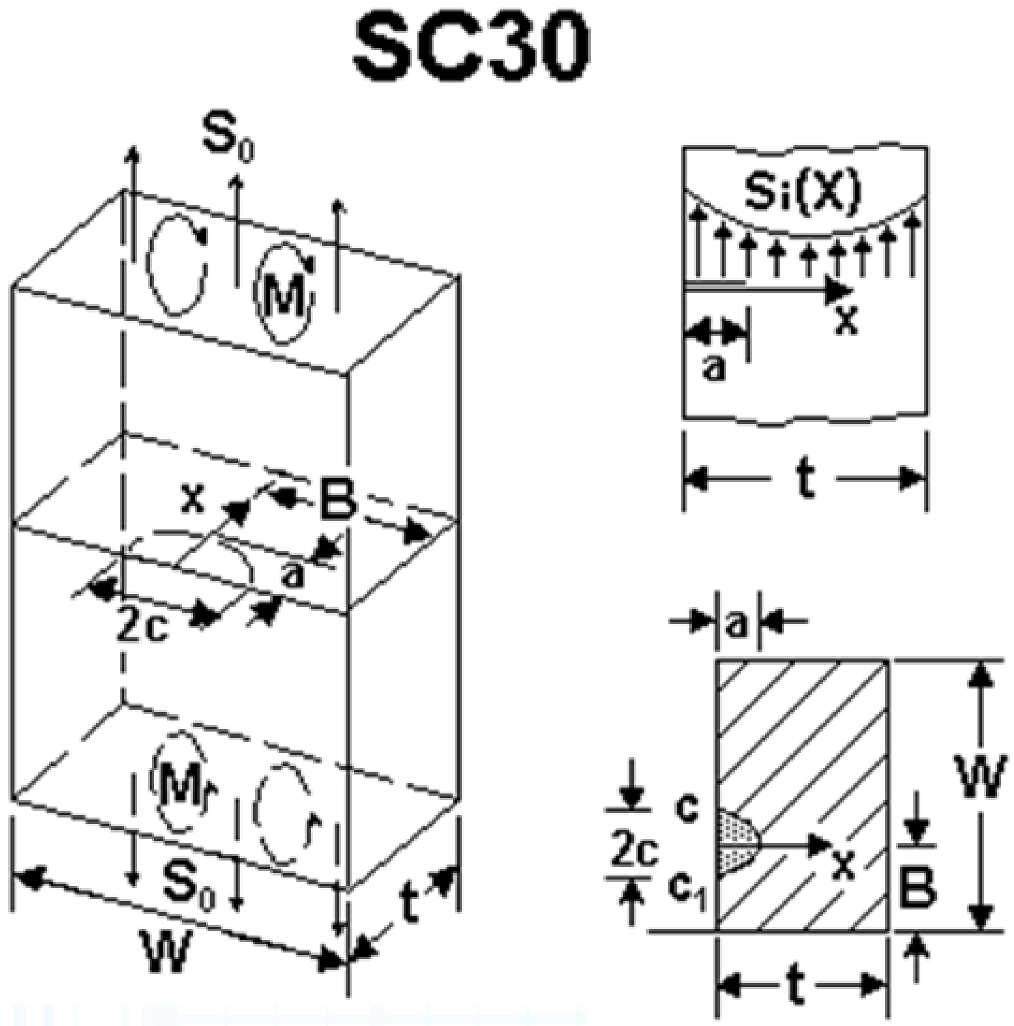
Temp-dependent stress-strain curves for A-225 Gr. B



[1]User Manual for VFT – Virtual Fabrication and Weld Modeling Software by Engineering Mechanics Corporation of Columbus (EMC2), Battelle Memorial Institute and Caterpillar Inc., April 2016.

Fracture Mechanics Model

- Used NASGRO® fracture mechanics software[2] to perform LEFM
- Model reference flaws as semi-elliptical surface crack in flat plate (SC30 weight function solution)
- In this study:
  - Width of plate (W) = ½ vessel circumference
  - Thickness of plate (t) = thickness of vessel
  - Cracks centered in the plate ($B = \frac{W}{2}$)
- Univariate service stress and WRS superimposed to create stress field for computing SIF
- NASGRO® capabilities include fatigue crack growth, FAD, and CCS



[2]NASGRO® Fracture Mechanics and Fatigue Crack Growth Analysis Software, Version 9.0, NASA Johnson Space Center and Southwest Research Institute, May 2018.

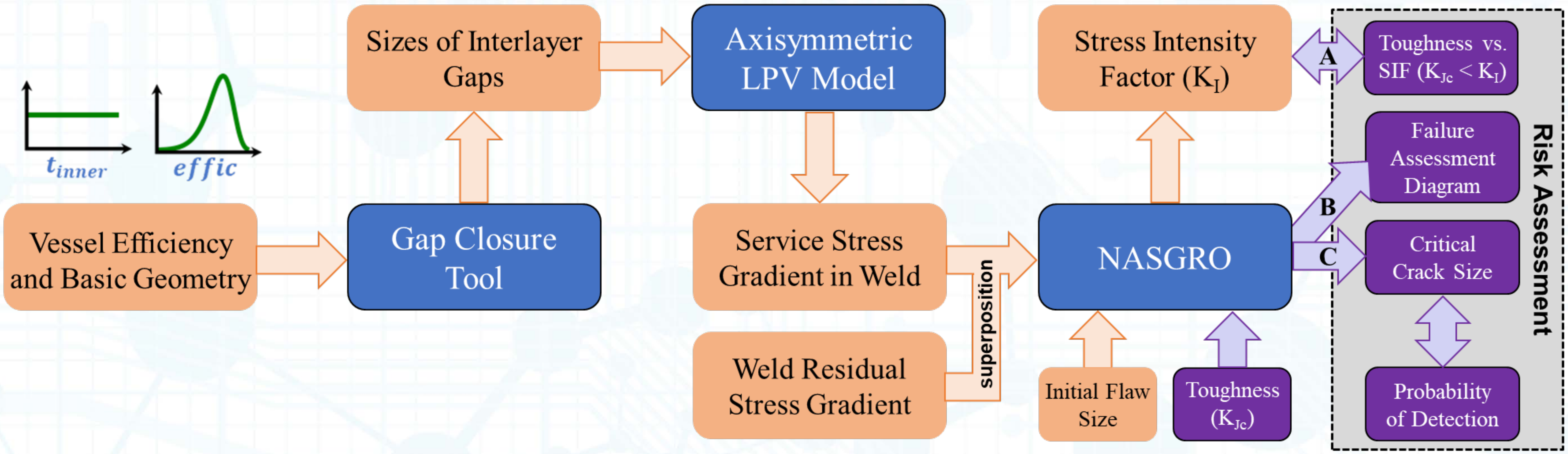
NESSUS Probabilistic Framework

Legend
- Model driven by NESSUS
- Model input/output
- Risk assessment criteria

(B) NASFLA FAD

Inputs:
- *Service stress*
- *Weld residual stress*
- *Total thickness*
- *Initial crack depth (a_0)*
- *Initial crack shape (a/c)*
- *da/dN model (C, n)*
- *Width of plate (W)*
- *Offset (B)*
- *Toughness (K_{Jc})*
- *Elastic modulus*
- *Yield stress*

Output: *Critical crack size, FAD*



Input Variables for each Model and the Model Response:

Gap Closure Tool

Inputs:
- *Diameter*
- *Pressure*
- *Gap type*
- *Efficiency*
- *Number of layers*
- *Inner layer thickness*
- *Shell layer thickness*
- *Elastic modulus*

Output: *Gap sizes*

Parametric Axisymmetric LPV Model

Inputs:
- *Gap distribution*
- *Diameter*
- *Pressure*
- *Number of layers*
- *Inner layer thick.*
- *Shell layer thick.*
- *Head thickness*
- *Circ. weld width*
- *Inner layer mod.*
- *Shell layer mod.*
- *Head modulus*
- *Circ. weld mod.*
- *Friction*

Output: *Service stress gradient*

(A) NASSIF

Inputs:
- *Service stress gradient*
- *Weld residual stress grad.*
- *Total thickness of vessel*
- *Crack depth (a)*
- *Crack shape (a/c)*
- *Width of fracture plate (W)*
- *Offset from plate center (B)*

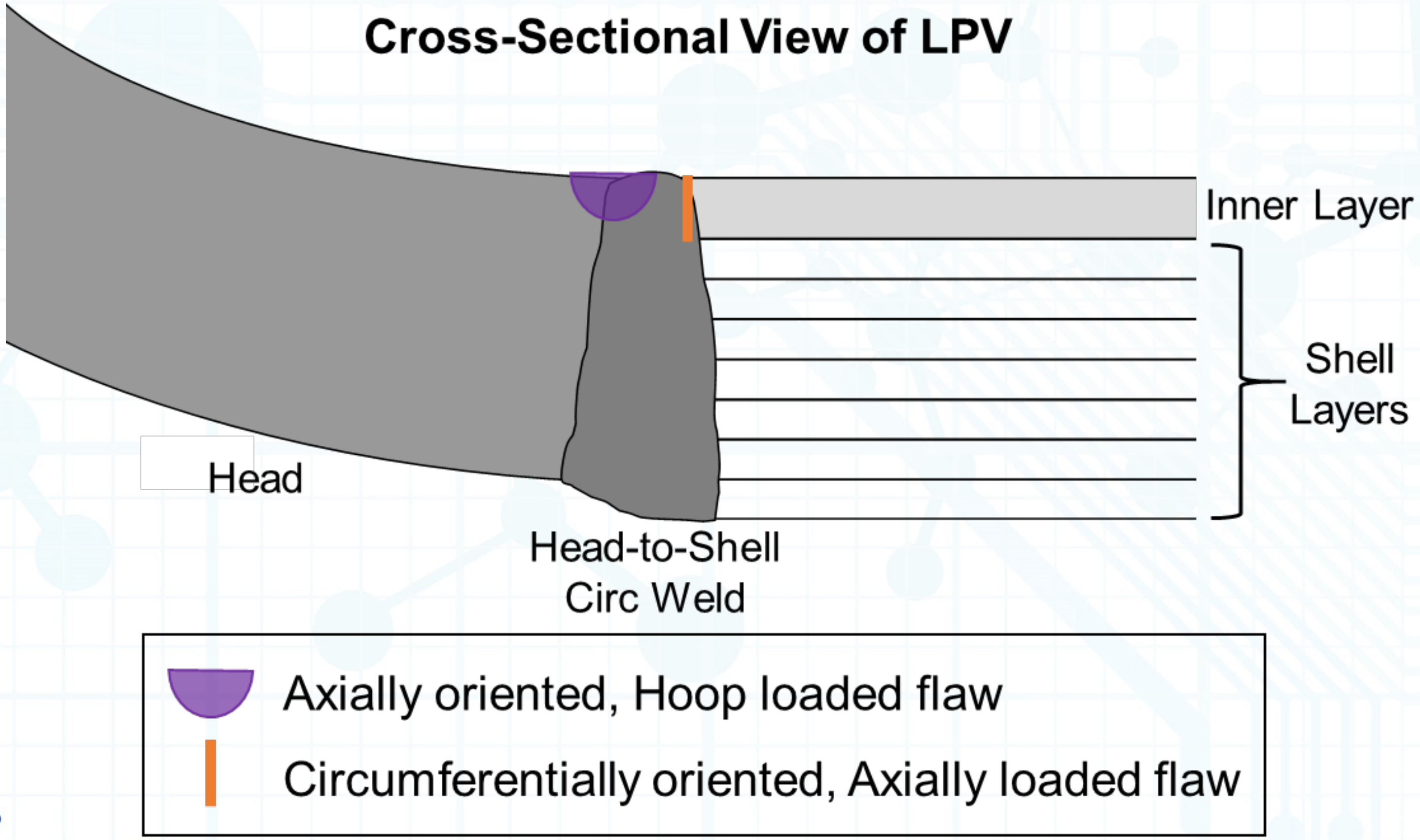
Output: *Stress intensity factor*

(C) NASCCS

Inputs:
- *Service stress*
- *Weld residual stress*
- *Total thickness*
- *Initial crack shape (a/c)*
- *Width of plate (W)*
- *Offset from center (B)*
- *Toughness (K_{Jc})*

Output: *Critical crack size*

Preliminary Results

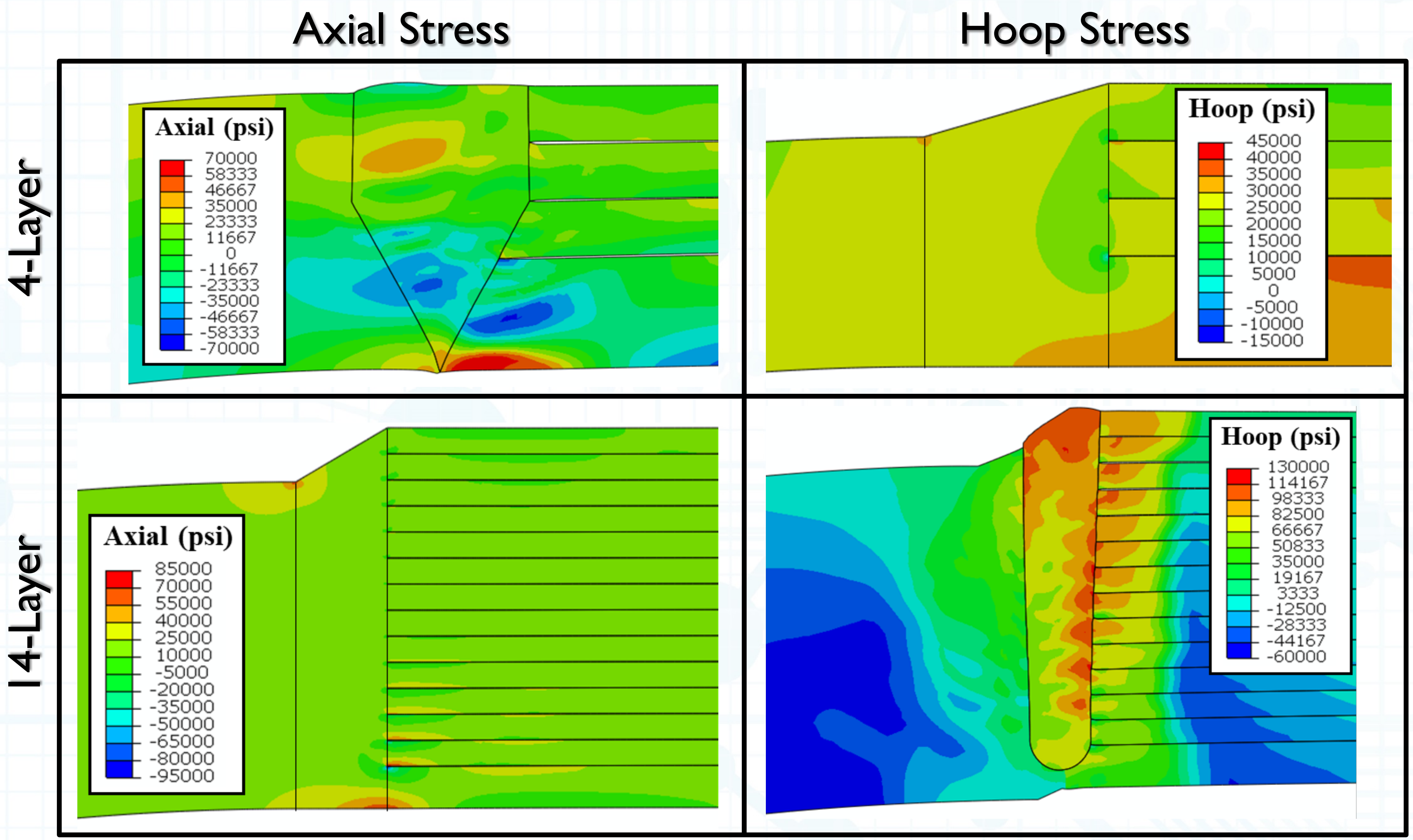


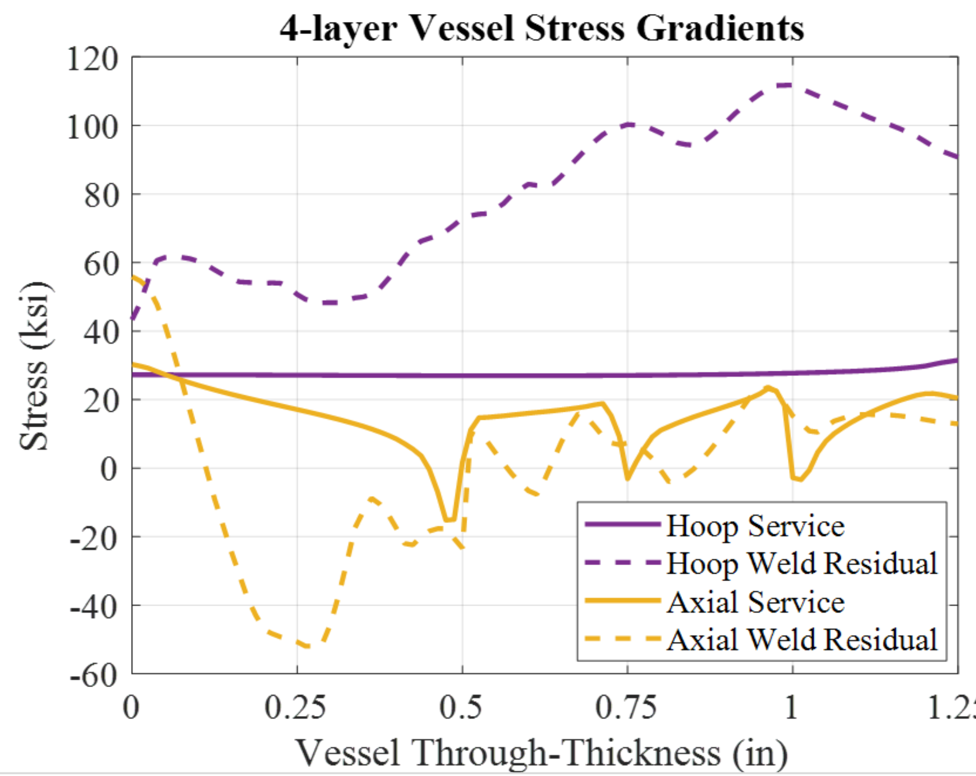
Reference Flaw Sizes

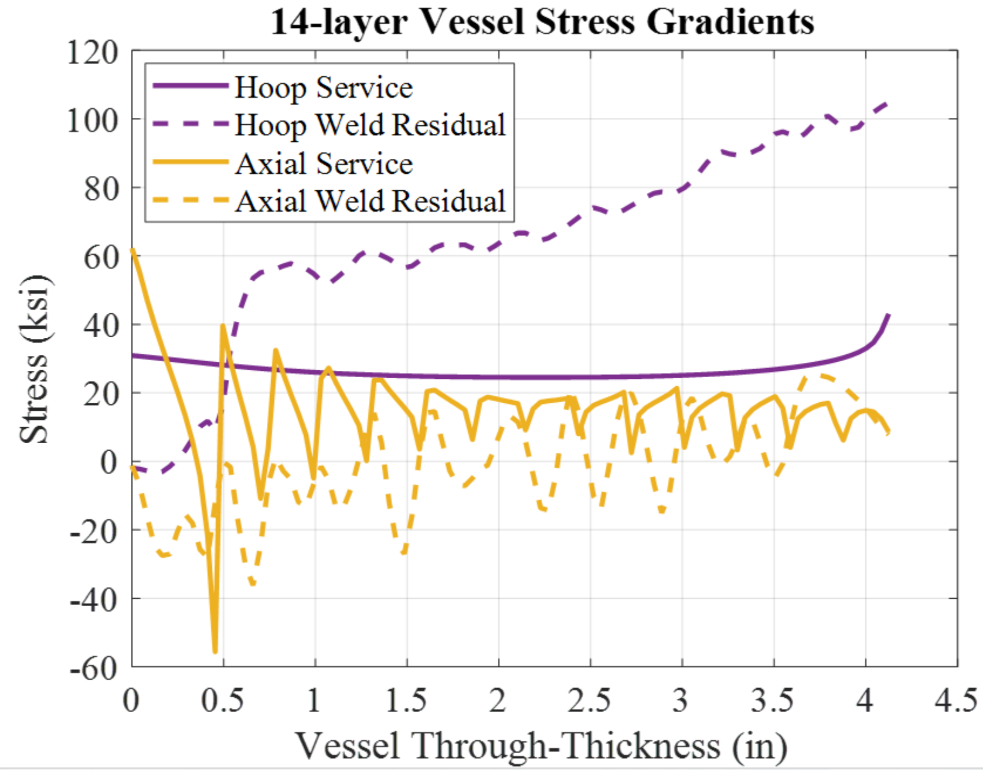
a = 0.25 in, a/c = 1

a = 0.2 in, a/c = 2/3

Nominal Stress Plots

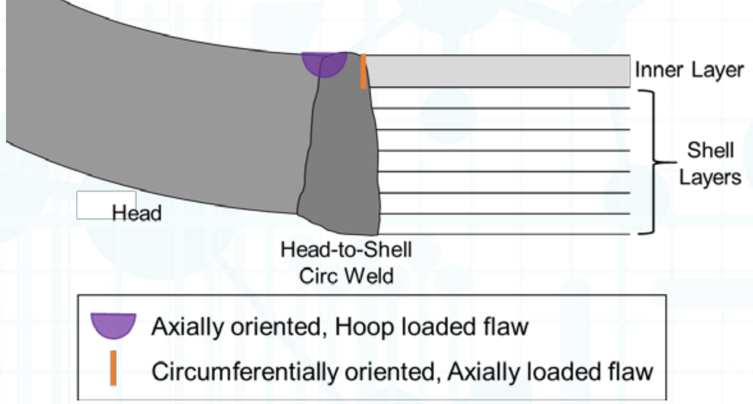




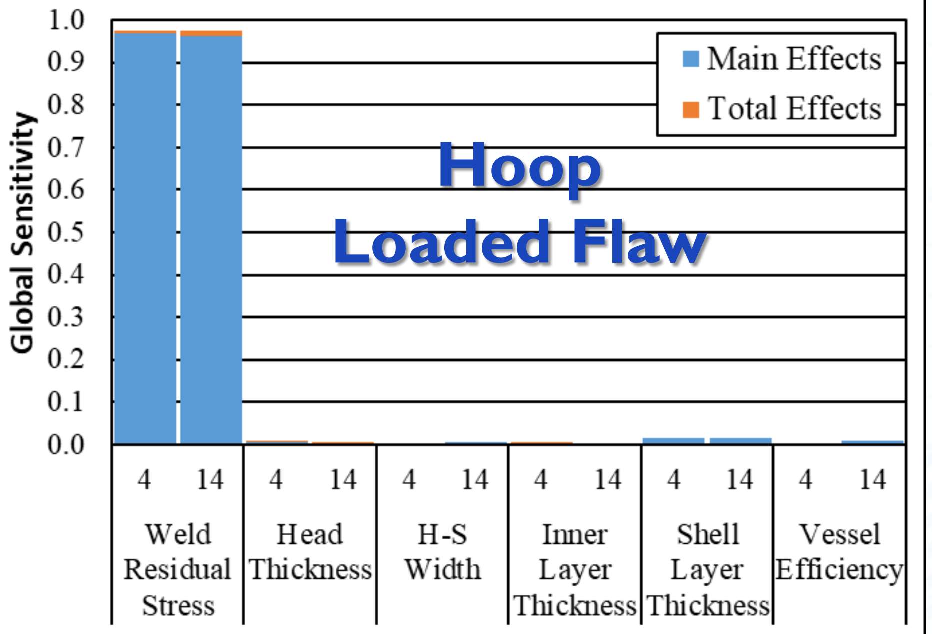


*Weld geometry differences have minimal effect on stress gradient predictions
*Stress predictions are more sensitive to gap size and through-thickness distribution

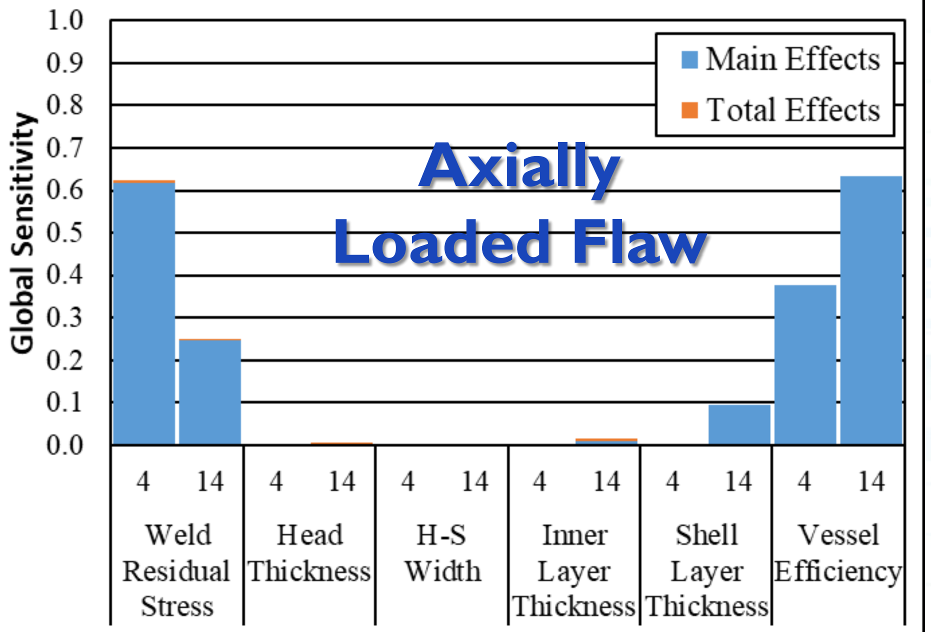
Sensitivity Studies



- <u>Axially oriented, hoop loaded flaw</u>:
  - Variability in SIF is primarily the result of variation in WRS
- <u>Circumferentially oriented, axially loaded flaw</u>:
  - Variability in SIF is primarily the result of variation in WRS and vessel efficiency → interlayer gaps
- Flaw size did not have a significant effect on sensitivity analysis
- Sensitivity analysis more dependent on flaw location
  - Flaw on shell-side is more sensitive to efficiency (interlayer gaps)
  - Relative influence of weld material properties is dependent on flaw location
- Thickness and weld width variation have minimal contribution to SIF variability



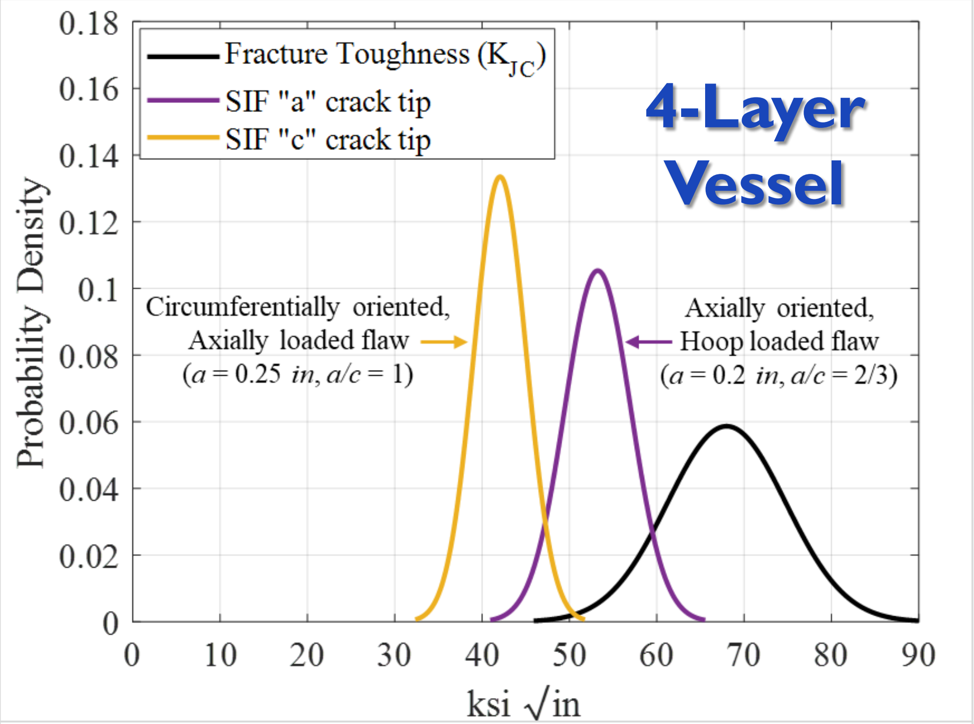
Axially Oriented, Hoop Loaded Flaw
a = 0.25 in, a/c = 1

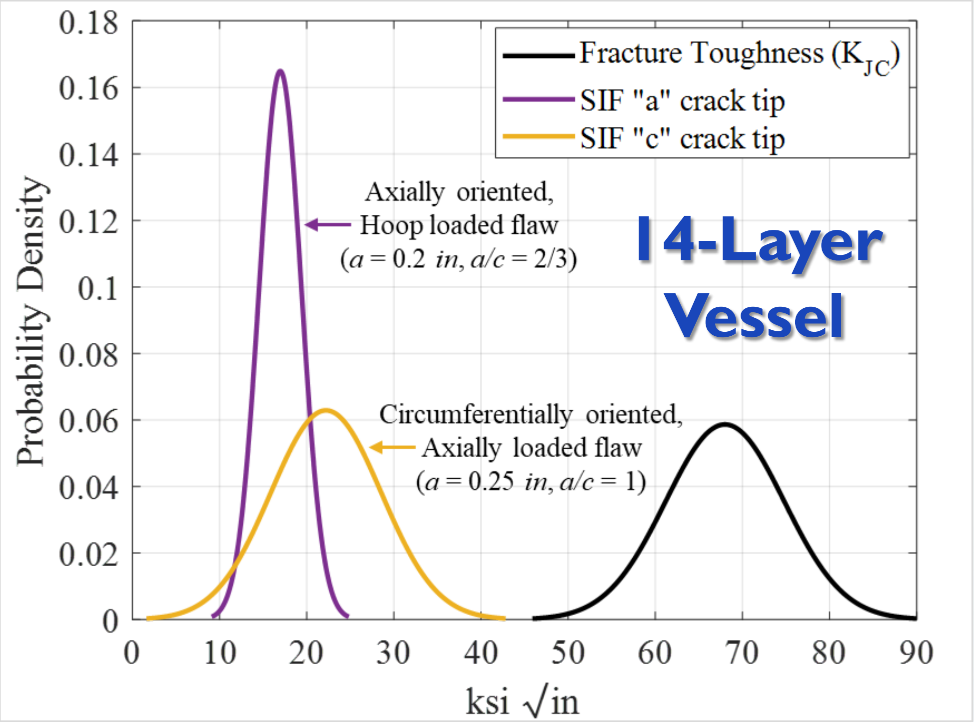


Circumferentially Oriented, Axially Loaded Flaw
a = 0.2 in, a/c = 2/3

Stress Intensity Factor vs. Toughness

- NESSUS® used to generate CDF of K_I → converted to PDF to compare to K_{JC} in heat-affected zone
- Monte Carlo sampling used to perform integration:
  $p_f = \int_{g<0} \dots \int f_X(x)dx$
- **4-layer vessel**
  - "a" crack tip probability of $K_I > K_{JC} = 0.027$
  - "c" crack tip probability of $K_I > K_{JC} = 0.0002$
- **14-layer vessel**
  - Separation of K_I and K_{JC} PDFs: probability of $K_I > K_{JC} \approx 0$
- Predictions largely driven by uncertainty in WRS models/data and assumptions of fracture toughness variation





Conclusions

- Developed probabilistic framework to predict fracture risk in regions of interest
  - Includes models for WRS, service stress, SIF, and fracture toughness
  - Model development using V&V approach
  - Framework can utilize fatigue crack growth and failure assessment diagram capabilities in NASGRO®
- Probabilistic studies performed to predict variability in SIF and global sensitivities
  - Results are preliminary → used to demonstrate framework and guide resource allocation
  - WRS and vessel efficiency variation and uncertainty are largest drivers of SIF variability
  - Considerable variation and uncertainty in fracture toughness as well
- Further development and evaluation of this probabilistic framework are underway as one part of NASA's strategy to evaluate safety of LPV fleet

Acknowledgements

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- Special Thanks to NASA Marshall Space Flight Center Personnel:
  - Brian Stoltz
  - Doug Wells
  - Joel Hobbs
  - Levi Shelton

Questions?

Backup Slides

4-layer Vessel Geometry and Loading/Boundary Condition (BC) Information

	Design	Distribution	Parameters
Geometry			
Head Thickness	1.056[c] in	uniform[d]	a=1.056 b=1.1088
Diameter	24 in	deterministic	
Length[a]	118 in	deterministic	
Inner Layer Thickness	0.50[c] in	uniform	a=0.50 b=0.54
Shell Layer Thickness	0.25[c] in	uniform	a=0.25 b=0.29
Efficiency	≥ 50%	beta	α=7.8207 β=3.0674 L=50 U=100
H-S Weld Width	0.875 in	uniform[e]	a=0.7437 b=1.0063
Loads/BCs			
Pressure[b]	3500 psi	deterministic	
Coefficient of Friction	0.7	deterministic	

[a]tangent-to-tangent vessel length
[b]maximum allowable working pressure (MAWP)
[c]minimum
[d]variable range: -0, +5% from design
[e]variable range: ±15% from design

$$E = 2.95 \times 10^7\ psi$$
$$\nu = 0.3$$

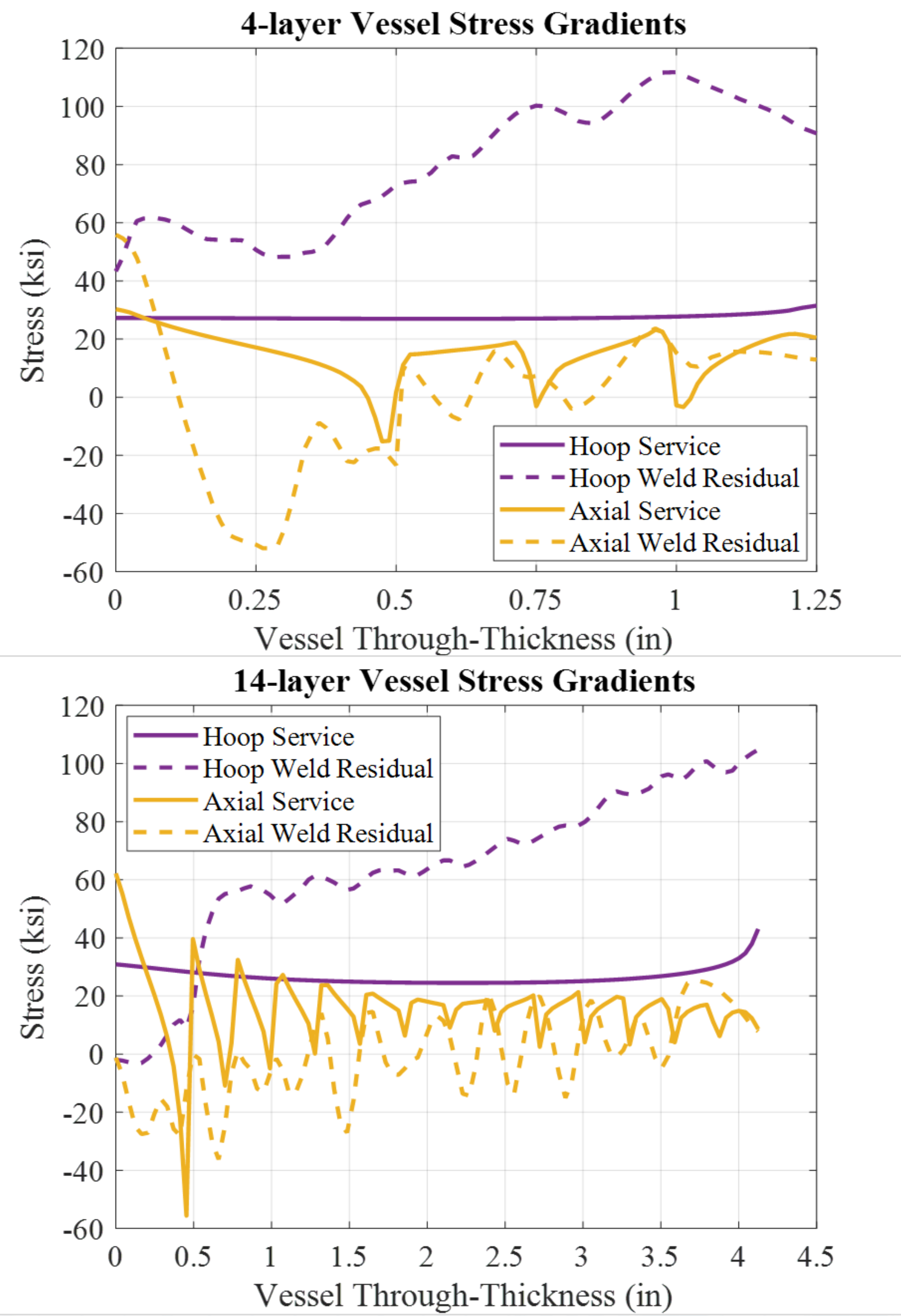
14-layer Vessel Geometry and Loading/Boundary Condition (BC) Information

	Design	Distribution	Parameters
Geometry			
Head Thickness	3.699[c] in	uniform[d]	a=3.699 b=3.8840
Diameter	60.25 in	deterministic	
Length[a]	720 in	deterministic	
Inner Layer Thickness	0.46875[c] in	uniform	a=0.46875 b=0.50875
Shell Layer Thickness	0.28125[c] in	uniform	a=0.28125 b=0.32125
Efficiency	≥ 50%	beta	α=7.8207 β=3.0674 L=50 U=100
H-S Weld Width	1.0625 in	uniform[e]	a=0.9031 b=1.2219
Loads/BCs			
Pressure[b]	5000 psi	deterministic	
Coefficient of Friction	0.7	deterministic	

[a]tangent-to-tangent vessel length
[b]maximum allowable working pressure (MAWP)
[c]minimum
[d]variable range: -0, +5% from design
[e]variable range: ±15% from design

Surrogate Modeling Approach

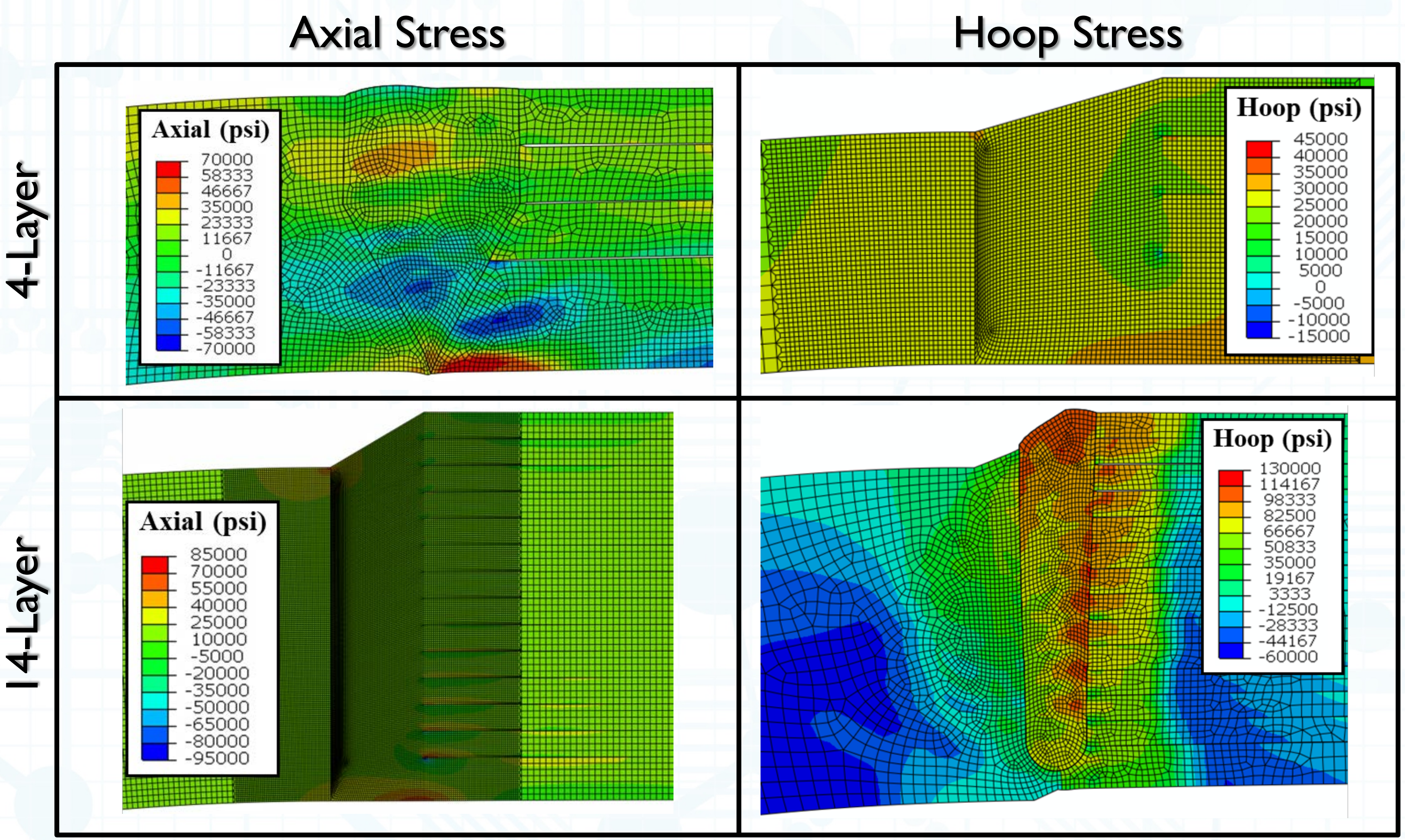
- Principal component analysis (PCA) technique used to create surrogate model for service & WRS stress gradient
  - Predicts stress at multiple points (gradient) vs. single location
  - PCA reduces dimensionality of model output[3]
  - Greatly reduces computational time vs. FEA
- Surrogate Model Development Procedure:
  1. Run FE model based design of experiments to generate training data
  2. PCA used to express variation in gradients as linear combination of shape vectors → retaining only most important shape vectors reduces dimensionality
  3. Response surface to predict individual principal component score (eigenvalue) based on inputs → then reconstruct stress gradient as linear combination of most important shape vectors



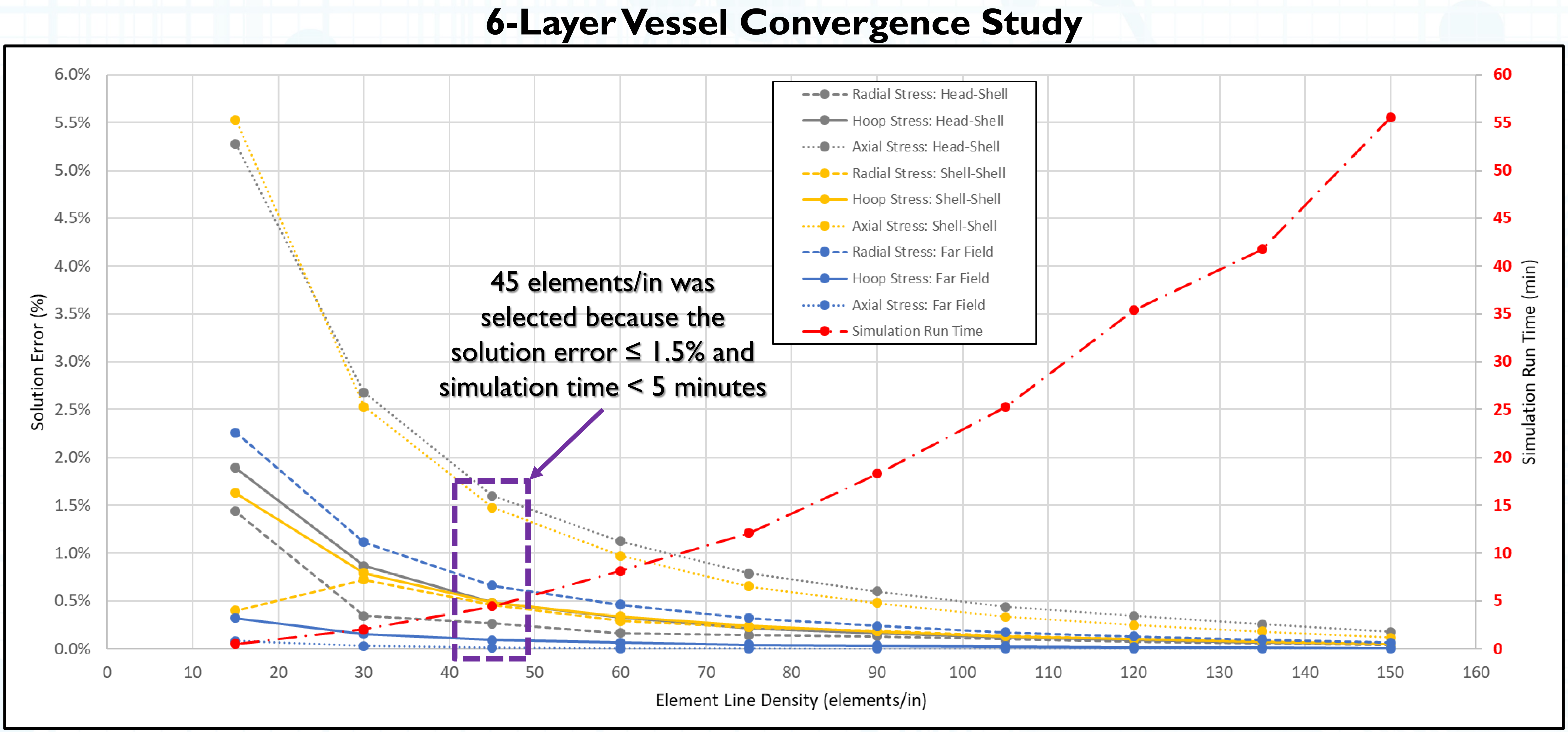
[3]Higdon, D., Gattiker, J., Williams, B., and Rightley, M., "Computer model calibration using high-dimensional output", Journal of the American Statistical Association, Vol. 103, No. 482, pp. 570-583, 2008.

Nominal Contour Plots (with mesh shown)

- **<u>Axial stress</u>:**
  - Largest stress at inner surface
  - Gaps result in bending stress
- **<u>Hoop stress</u>:**
  - Largest stress at outer surface
  - Gaps result in stress concentrations
- Weld geometry differences have minimal effect on stress gradient predictions
- Stress predictions are more sensitive to interlayer gap size and through-thick distribution



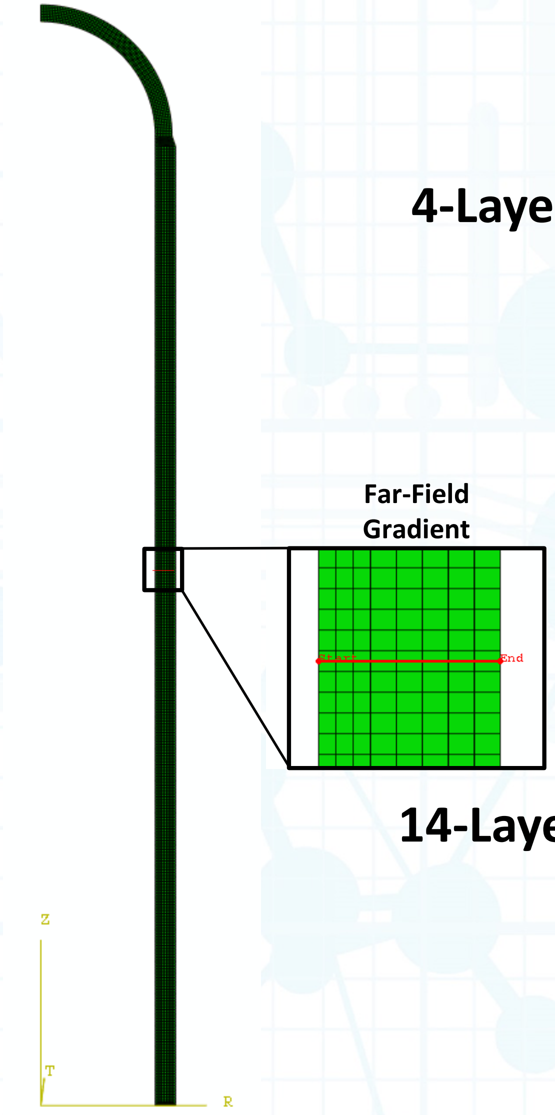
Mesh Convergence



*Solution uses element line density of 200 elements/in

Axisymmetric Model Verification

4-Layer Vessel



Far-Field Gradient

14-Layer Vessel