SAND2012-0870C

JOWOG 31 – Engineering Analysis HOCWOG
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Thermo-Mechanical Failure Prediction in a Complex Temperature Environment

"Pipe Bomb" Analysis and Experiments

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G. W. Wellman, 1525 – Failure Model

W. M. Scherzinger,1524 – Constitutive Model, Lamé

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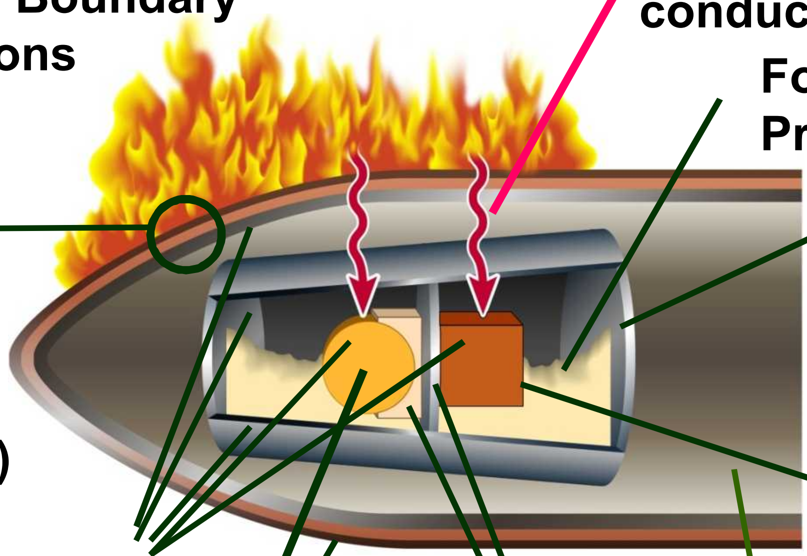
Motivation


Heating Boundary Conditions
Thermal radiation, conduction, convection
Foam Vaporization, Pressure Production
Weapon-Envelope Response (charring, melting, vaporization, etc. of various mtl. layers)
Thermal Weakening and Pressure driven Breach of compartments
Inside component: contact resistance, emissivity evolution, failure modes/ characterization
Emissivity Evolution (thermal radiation paths)
Heat-Conduction, contact resistance
Highly anisotropic material properties, failure characterization of component
explosive, reactive, energetic materials

Approach

- **Develop and validate Thermal EP Fail constitutive model**
  - Use a simple geometry
    - Pipe Bomb (load controlled)
      - 14” x 3” x .020” machined 304L sstl tube
      - Side heated and internally pressurized
- **Perform C6 validation experiments**
  - Perform tensile material tests with temperature
  - Run Pipe bomb experiments with repeats
    - Pressure and temperature ramp combinations (~20 minutes)
    - Explore thickness variations, hot spot buckling, creep
- **Build and validate a thermal pressurization breach model**
  - Quasi-static constitutive model w/ tearing parameter
  - Materials definition
  - Coupled thermo-mechanical modeling
  - Temperature mapping and UQ

Constitutive Model

Elastic-plastic –

Temperature dependent elastic parameters

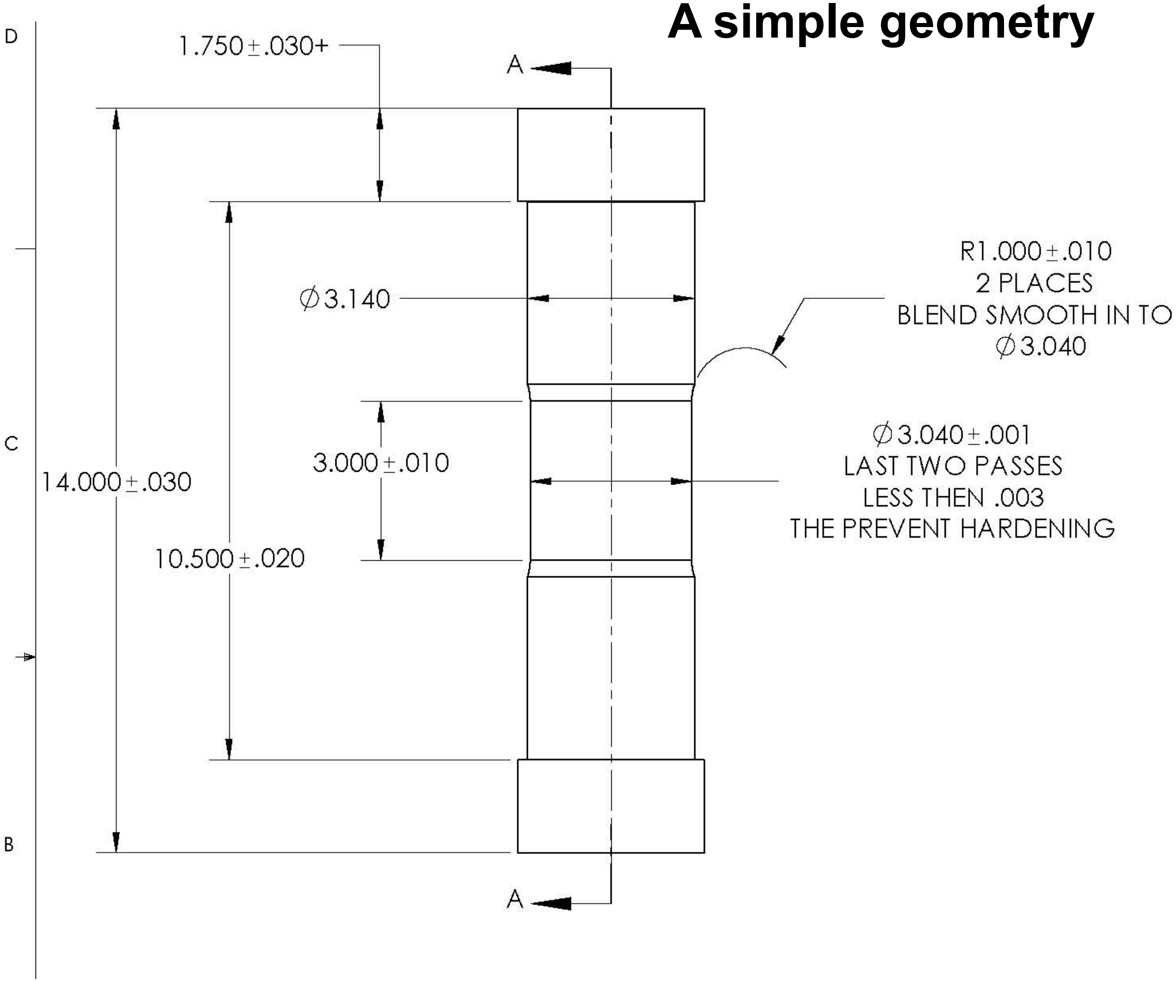
Temperature dependent strain hardening

- Defined by piecewise linear function at each temperature
- Interpolation in temperature between strain hardening functions

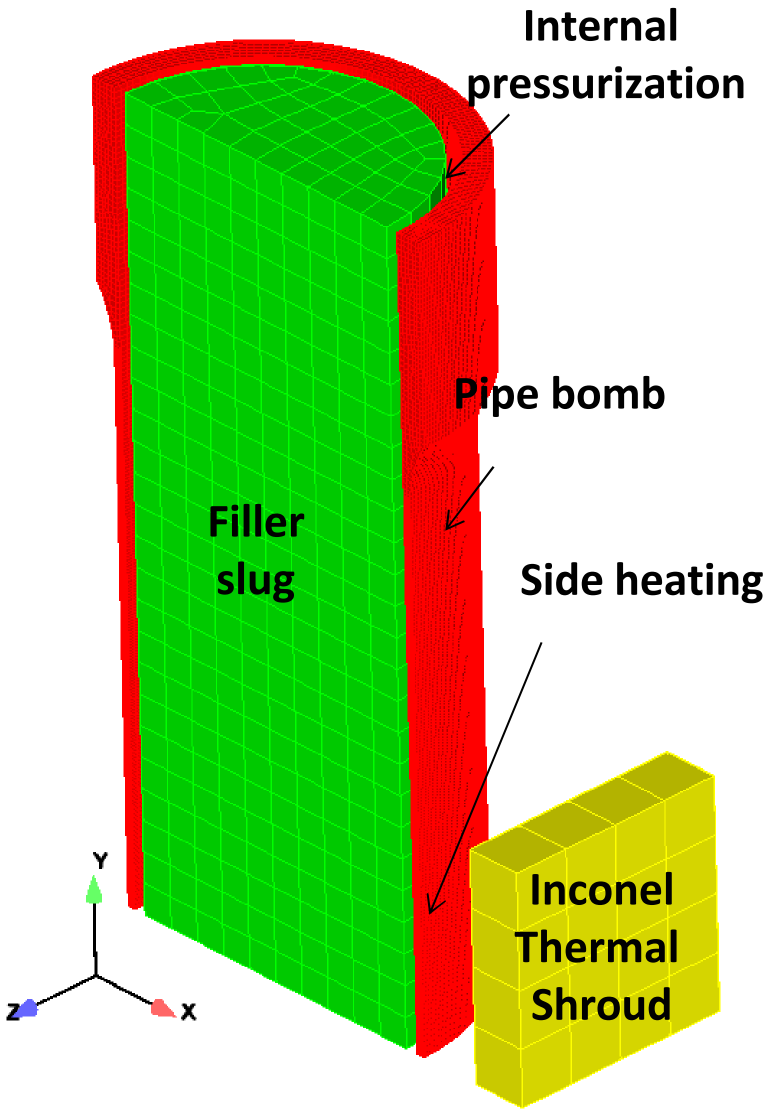
Temperature dependent failure criterion - strongly coupled to strain hardening

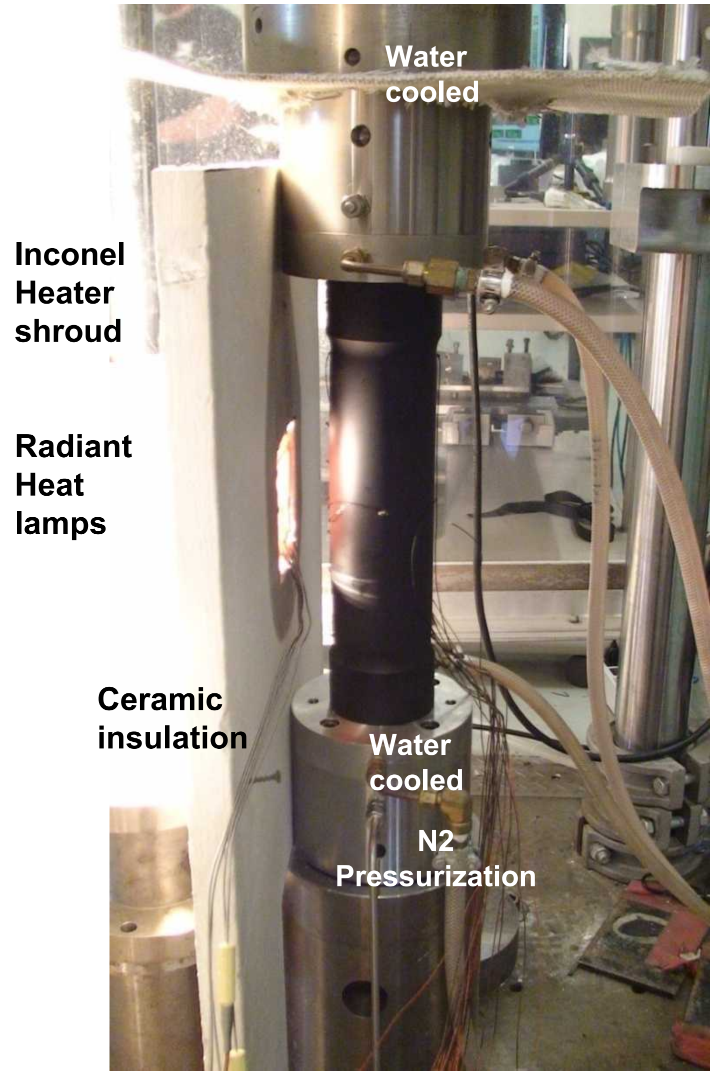
The Pipe Bomb

A simple geometry



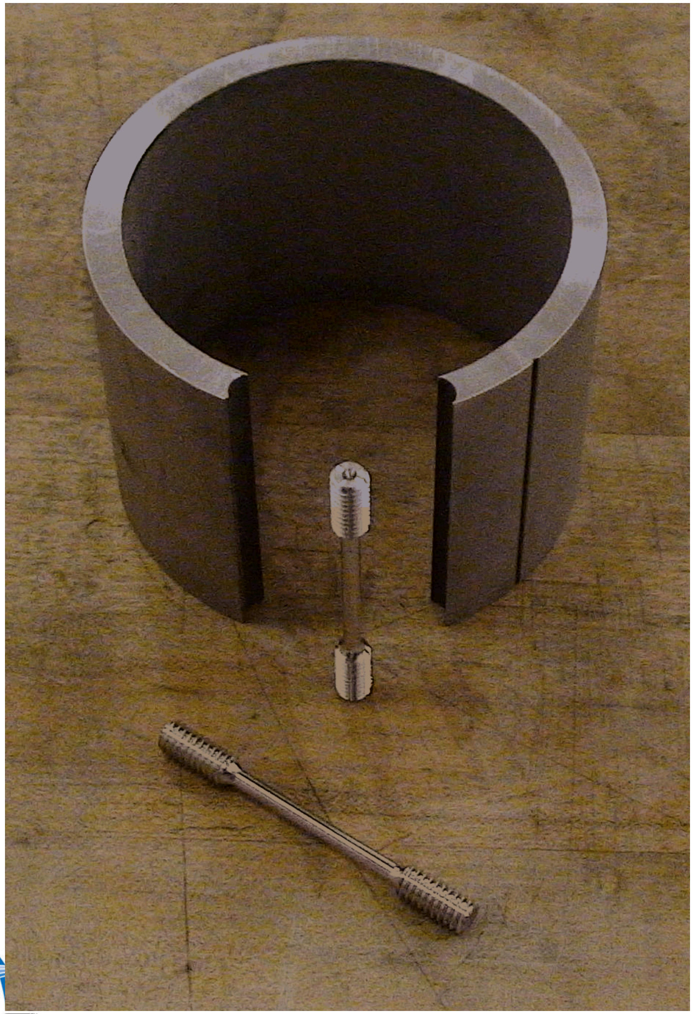
Model & test setup





Mechanical Characterization of 304L Stainless Steel Tube Material

Specimen Extraction from 3.5” OD, 3.0” ID 304L Stainless Steel Tube



- The maximum size tensile specimens that could be removed from the tube thickness (t = 0.25 inch) was a ¼”-20 threaded specimen.
- Specimens were designed with a long gage section for elevated temperature test considerations.
- 44 tensile specimens were removed and machined.
- Specimens were vacuum annealed at 1000C for 30 minutes to produce the same anneal conditions that will be present in the large validation (PB) specimens.

Summary of Experimental Conditions for Mechanical Characterization

Specimen dimensions: gage DIA = 0.125” (nominal), gage length = varies

Test Temperatures:

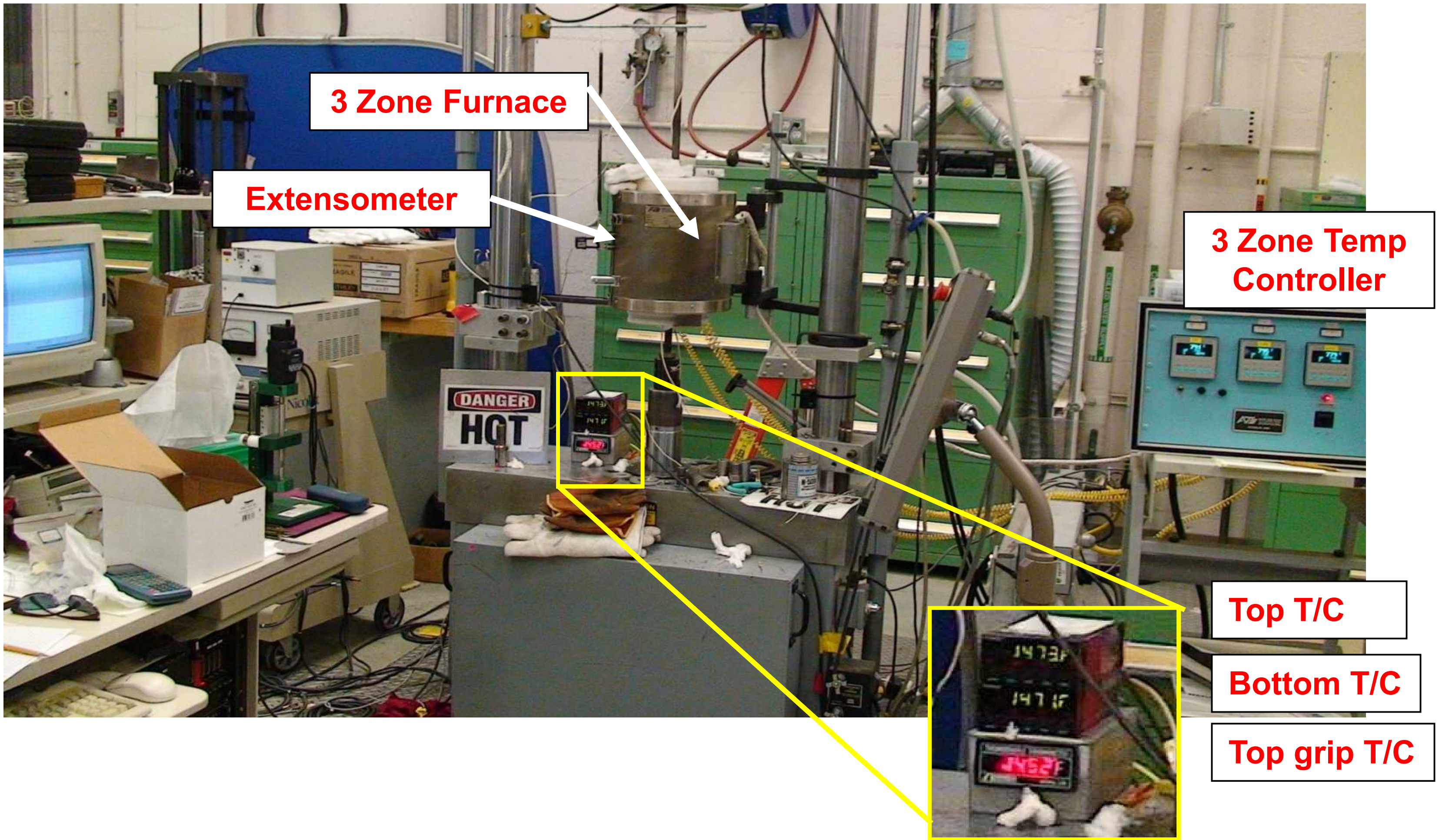
20C
100C
200C
400C
600C
700C
800C

Tensile experiments were all conducted in displacement control at 0.0015 in/s to produce a strain rate of 0.001/s (same rate as bar stock material data shown for comparison on plots).

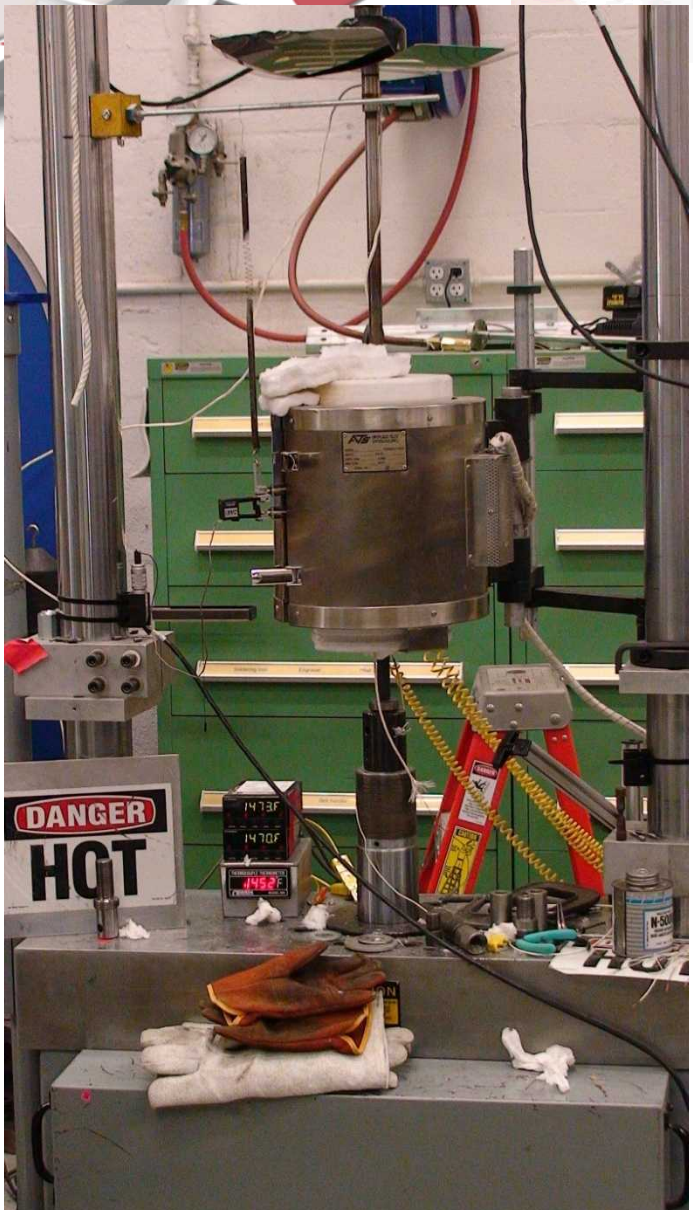
Decision was made to conduct extra repeats (up to a total of 5) at temperatures of RT, 100C, 200C and 400C to provide useful data for QMU calculations. Other temperatures have three repeats each.

Experimental Setup on 50Kip A/T MTS Servohydraulic Frame

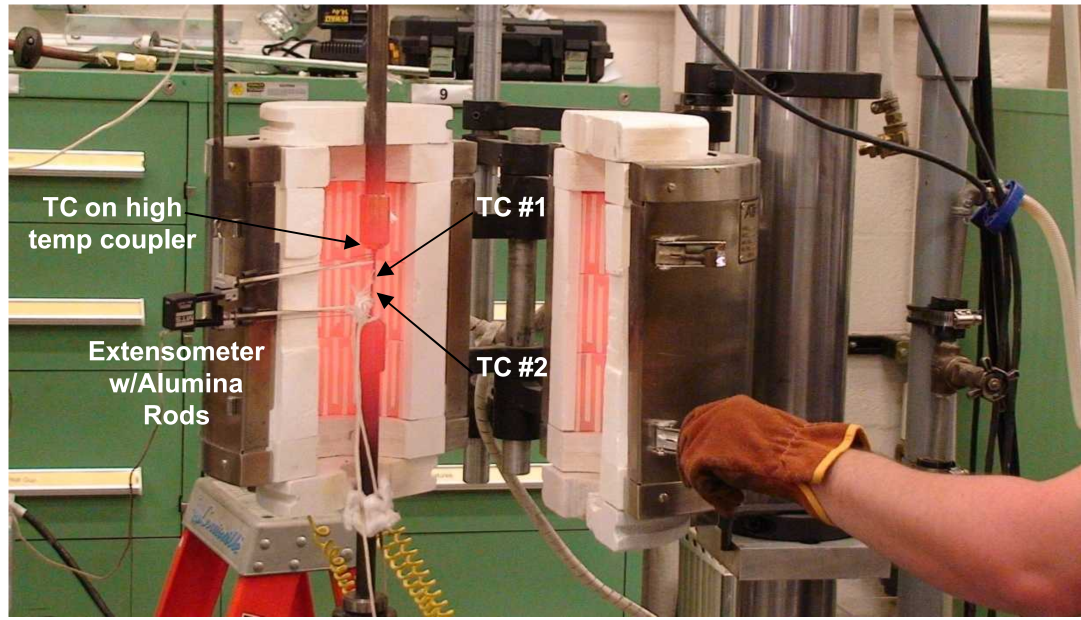
- Computer controlled displacement
- Direct specimen strain measurement with extensometer fitted with alumina rods
- Three zone furnace and controller
- Two Type K T/Cs on each specimen
- One additional Type K T/C on top threaded adapter (grip)

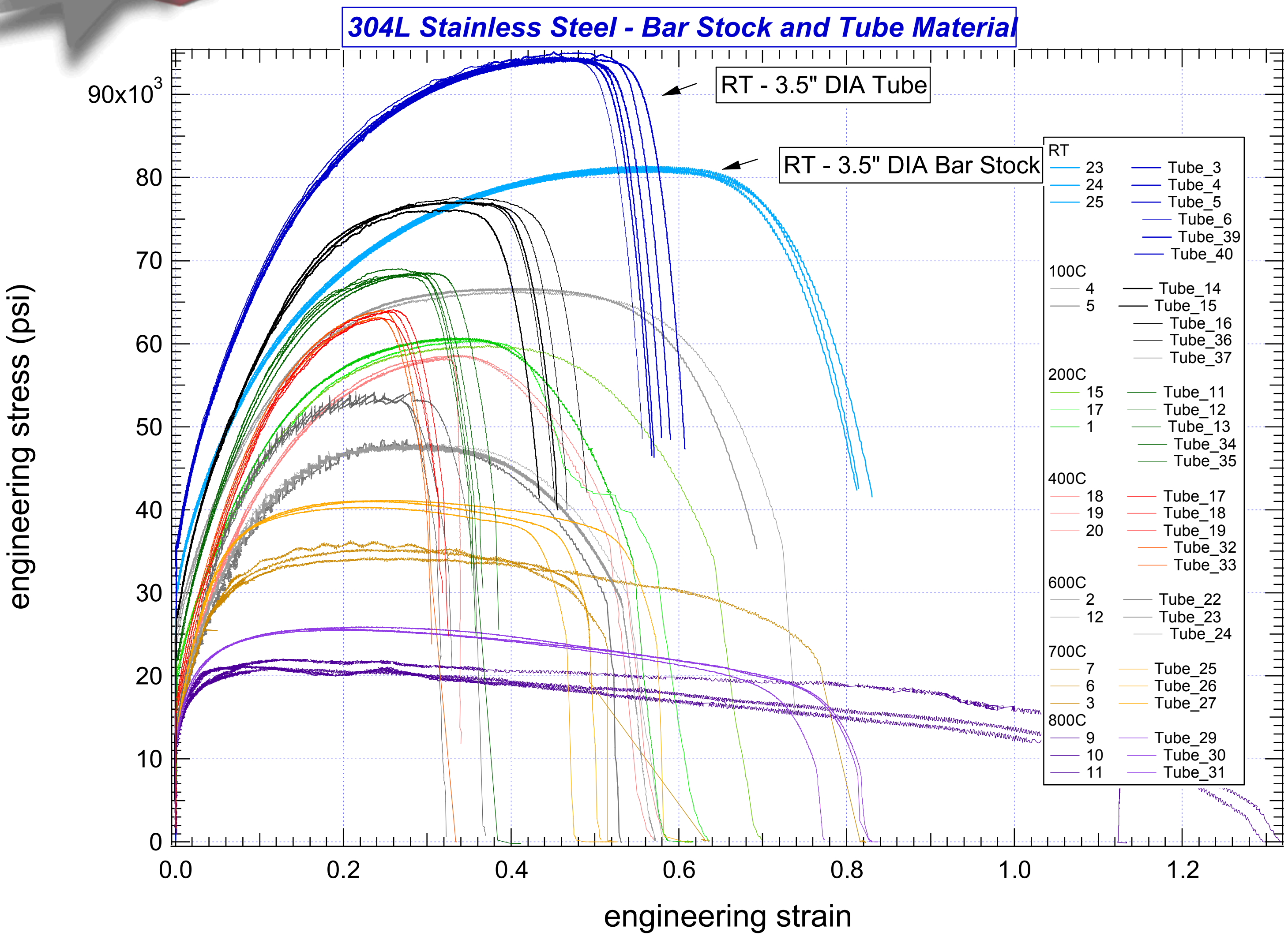


During an 800C Experiment



Immediately after an 800C Experiment



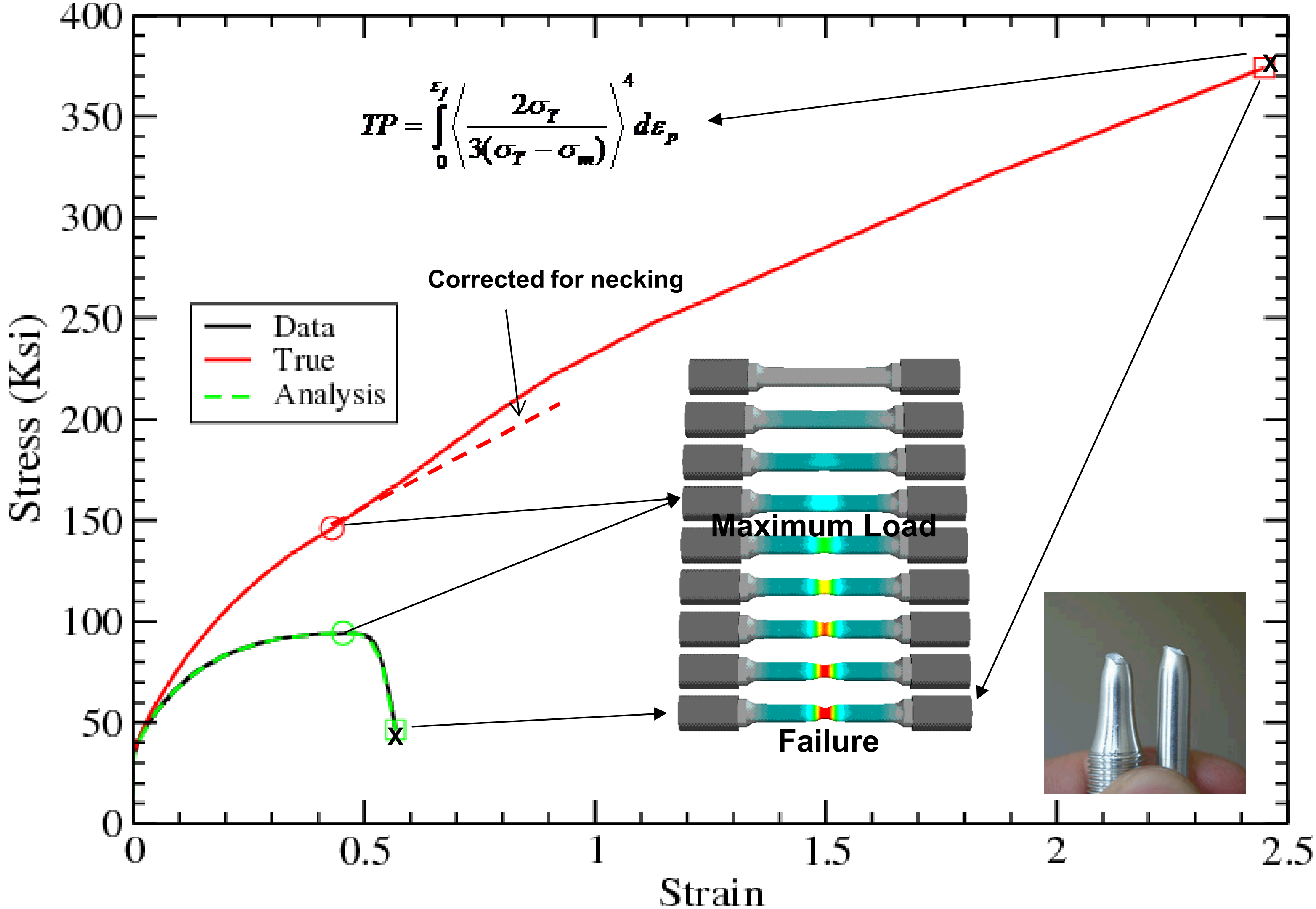


- **At every temperature, the 304L tube material behavior was substantially different from the bar stock material behavior**

Comparing tube to bar stock:

- **Higher yield stress, especially at lower temps**
- **Higher flow stress**
- **Substantially lower strain to failure (lower ductility)**

Extract Cauchy-Stress; Logarithmic Strain from Experimental Data



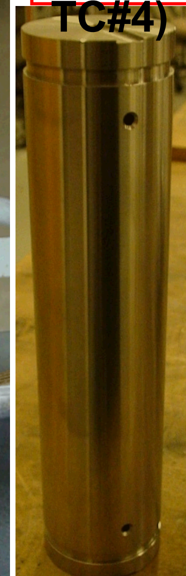
Validation experiments

20 TC on specimen + 1 shroud + 1 top grip + 1 bottom grip = 23 TC

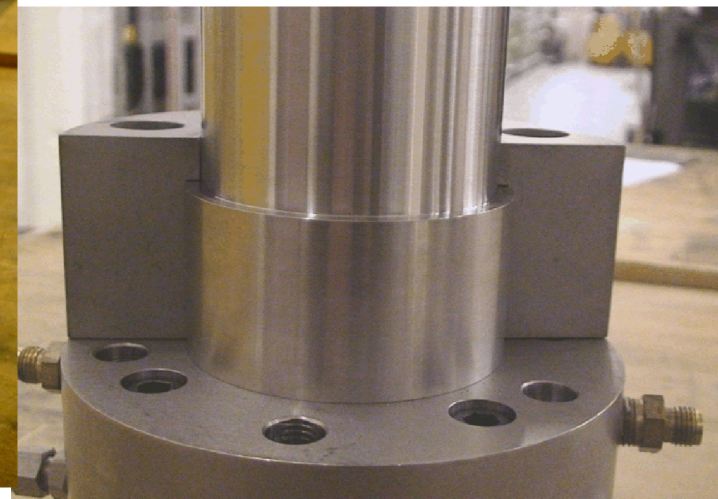
(control TC is separate and not recorded in data, location identical to TC#4)

3" Reduced section, from 0.050" to 0.020"

TC count increased # from 16 to 23

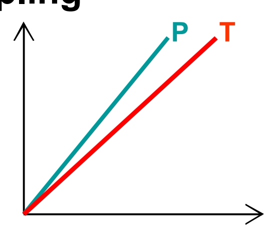


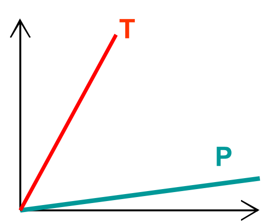
Ceramic slug replaced with stainless steel

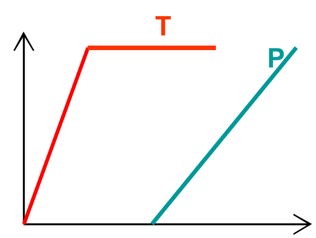


Fixture and specimen geometry modified to allow loading in tension

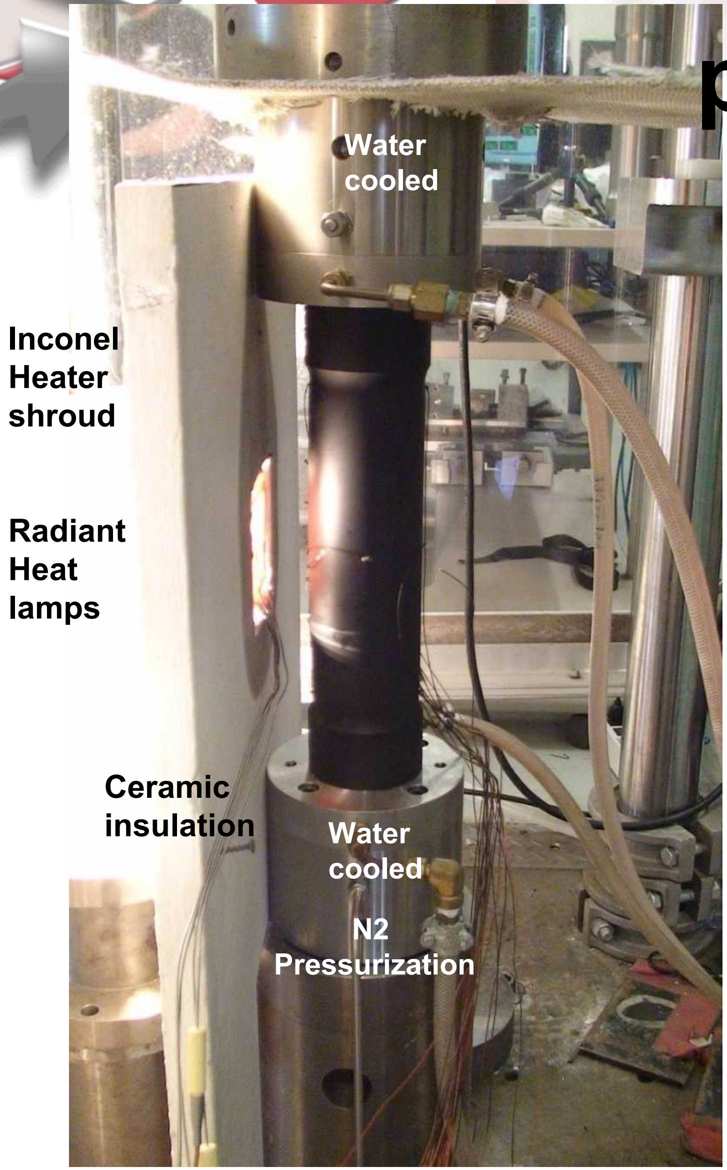
Thermo mechanical Coupling



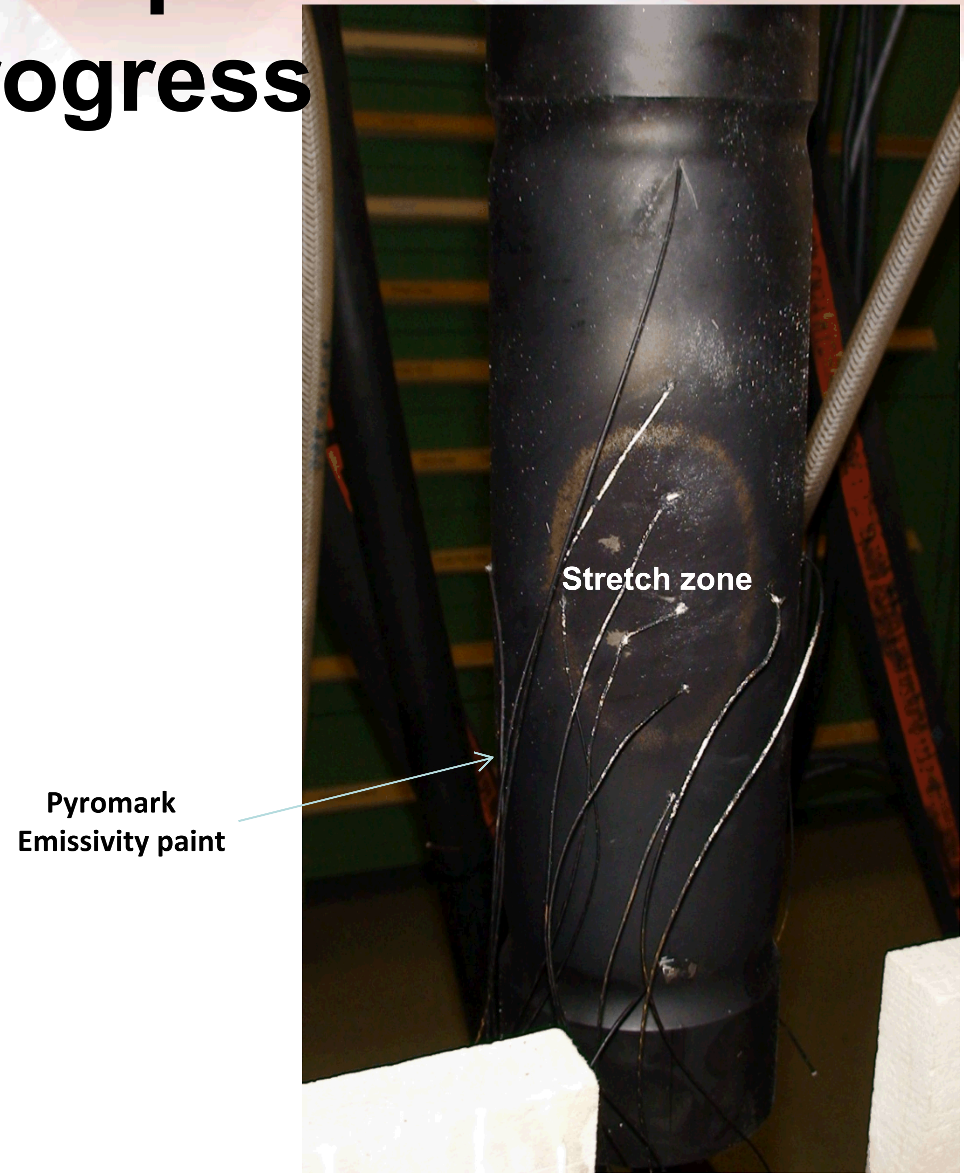




Validation experiment in progress

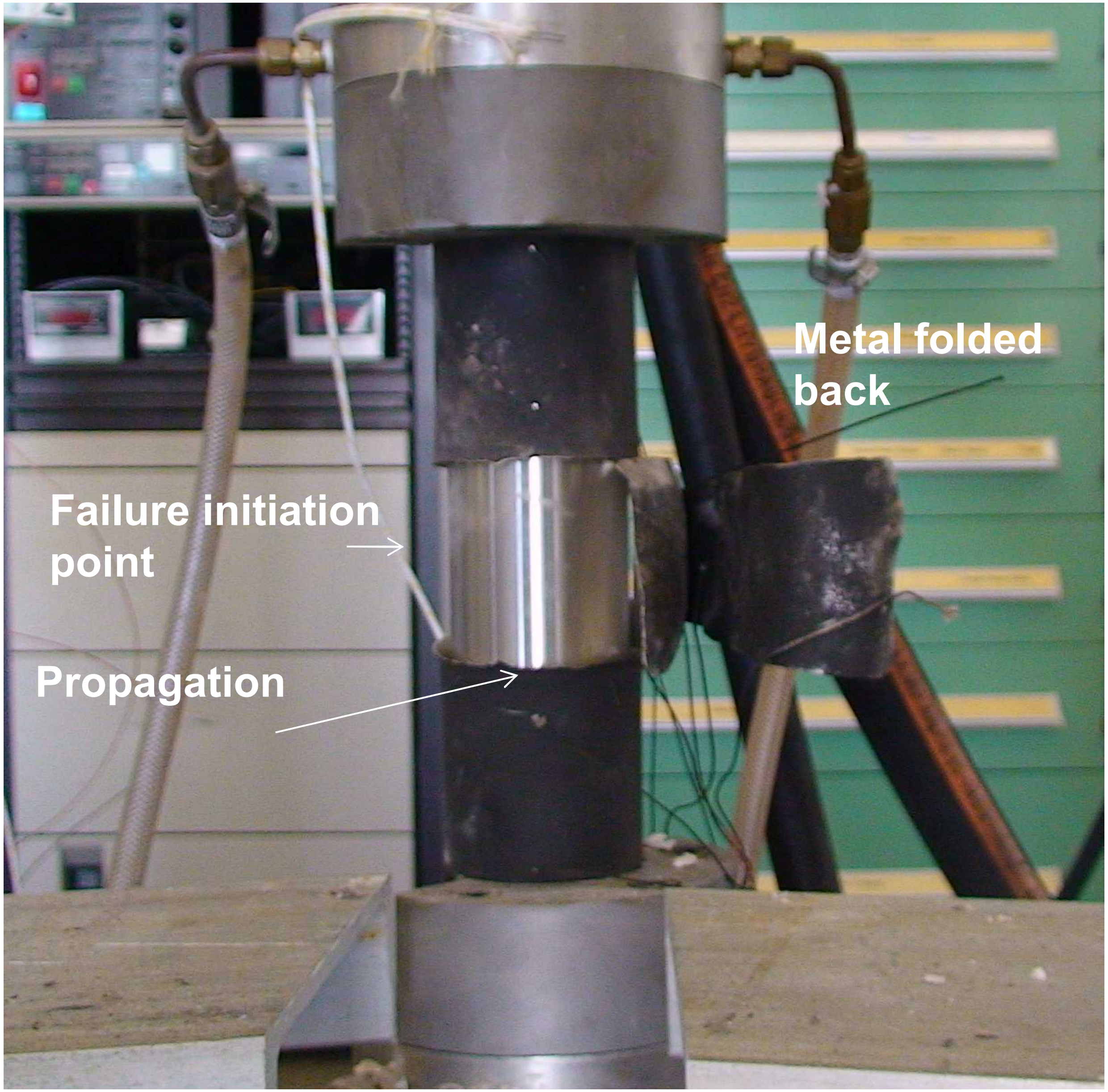


Side view of Specimen during heating

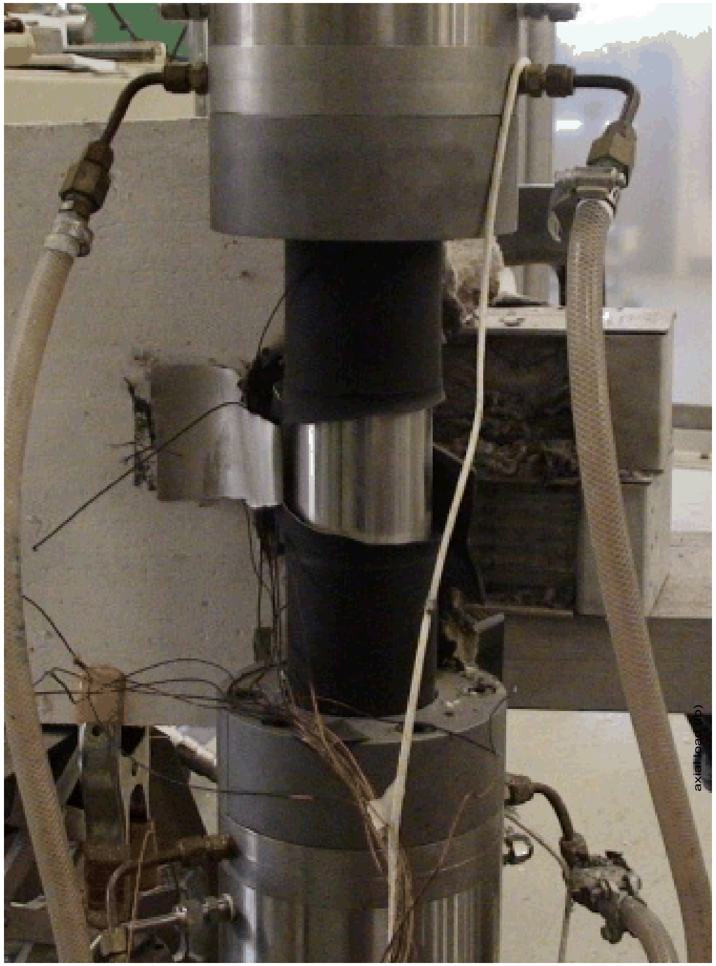


Specimen bulged and deformed after heating and pressurization

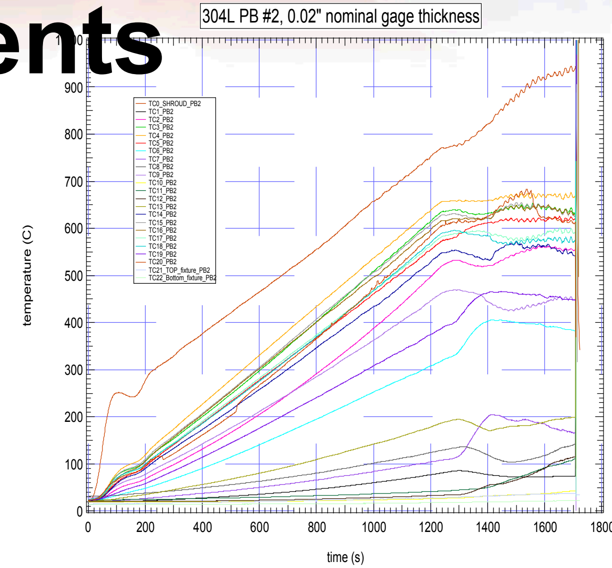
Completion of a Validation experiment



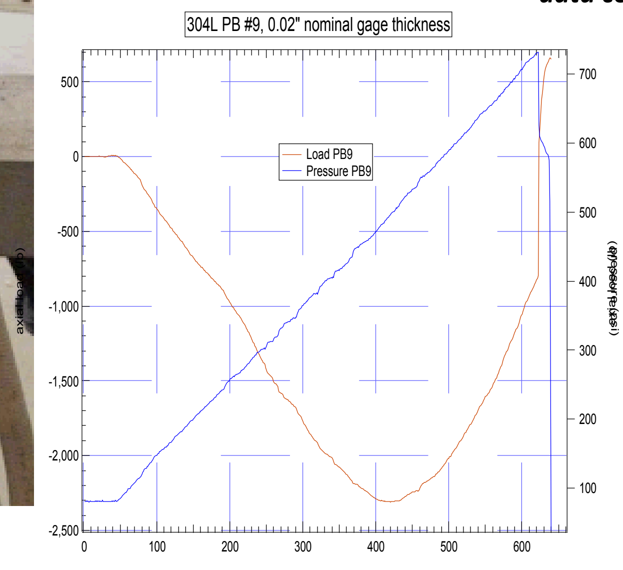
Validation experiments



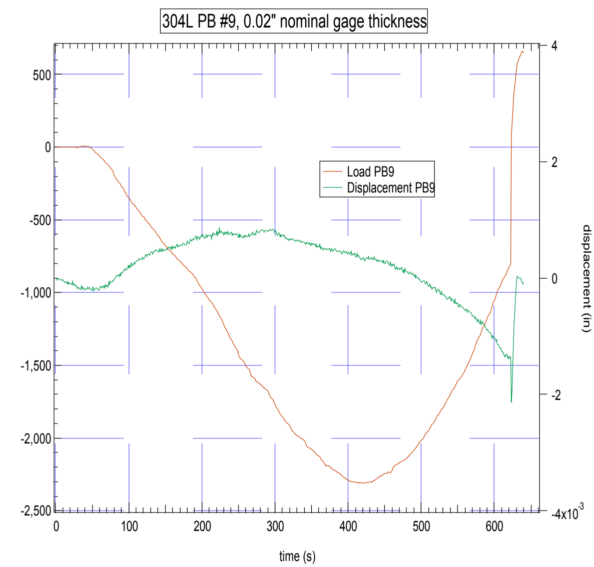
Validation specimen after failure



Full-field temperature data collected



Applied internal pressure and measured axial force response



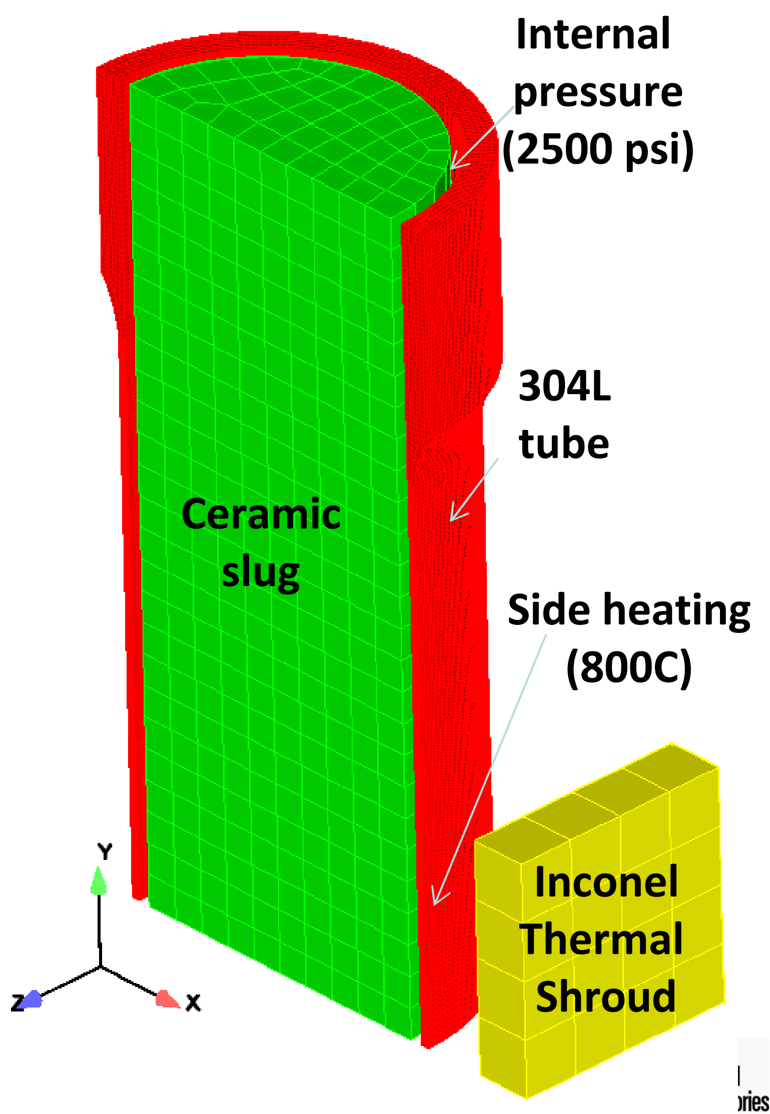
Measured axial response: load and displacement

Validation Specimens Failed under Various Thermo/mechanical Loading Conditions

Thermal/Mechanical "Pipe Bomb" model validation
Pressurization breech and failure

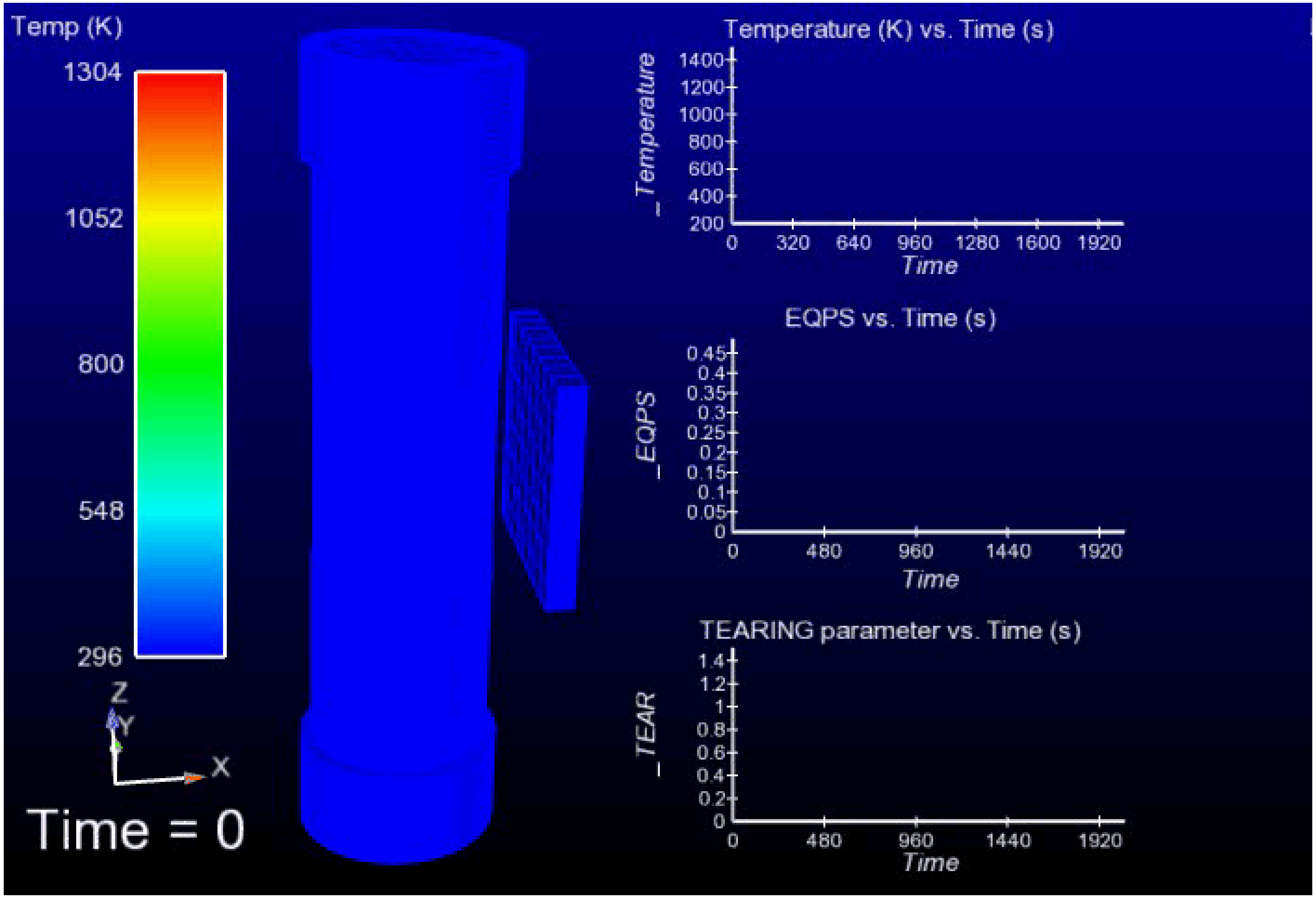
Arpeggio <u>Fully coupled</u> analysis and <u>temperature mapped</u> with experiments

- Aria – Heat transfer with symmetry
    - Conduction
    - Convection
    - Dynamic enclosure radiation
- Adagio mechanics with symmetry
    - Thermo-elastic-plastic-hard/fail
    - Tearing parameter method
    - Adaptive time stepping
- Mesh types
    - Hex-8, Tet-4, Tet10, Nodal based



Simulate the experiment

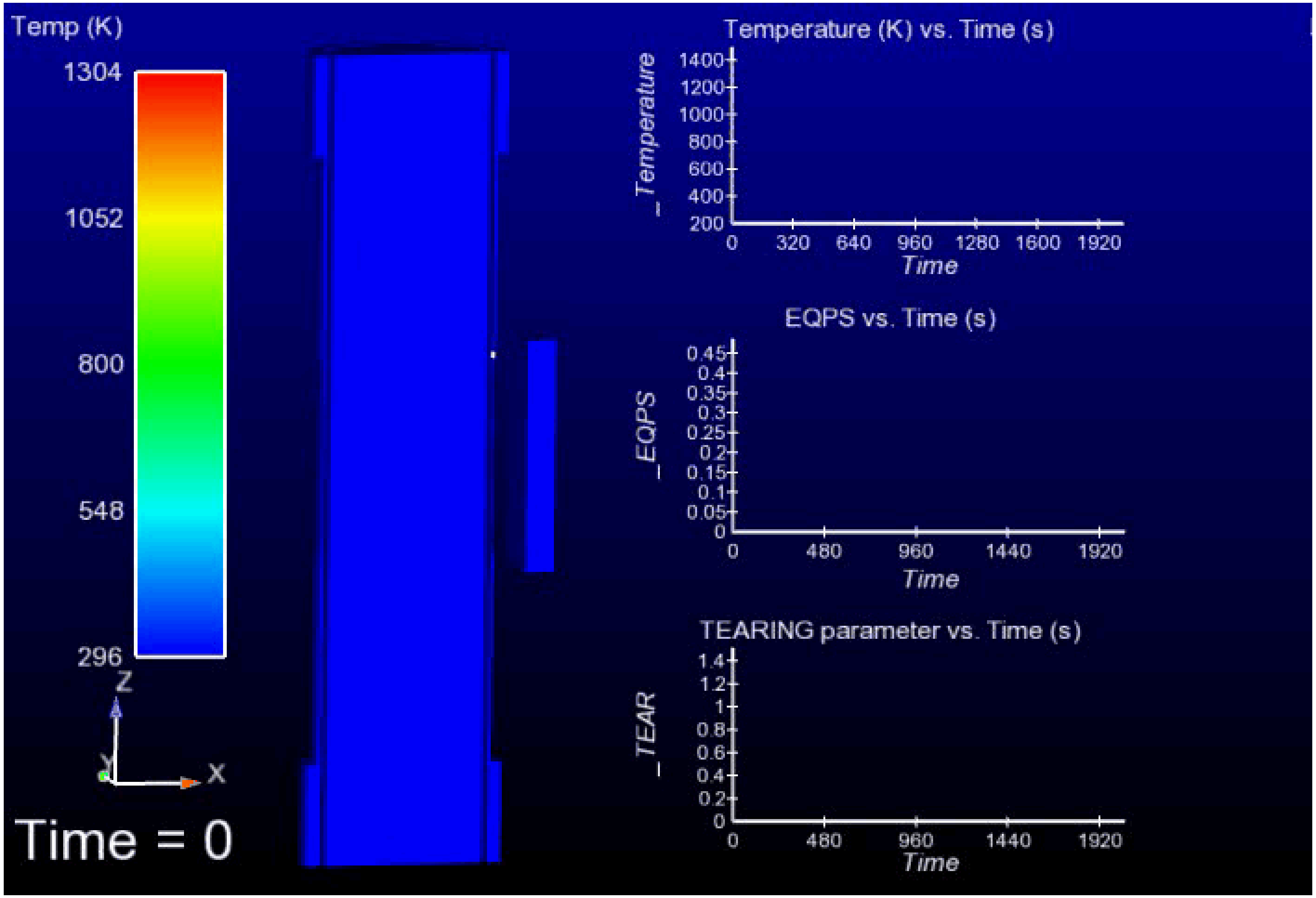
Thermal/Mechanical coupled response of a pressurized heated tube



Full view

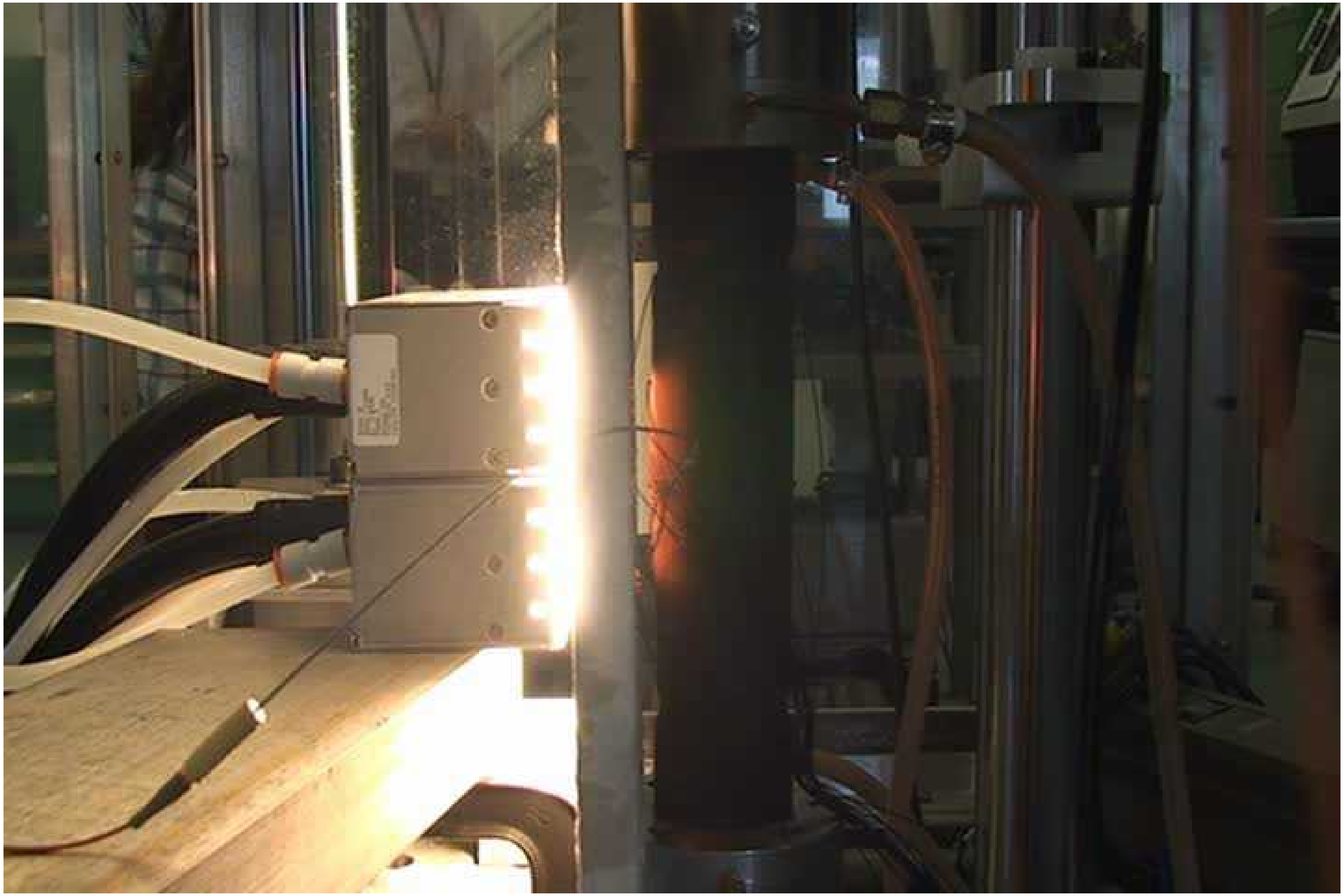
Simulate the experiment

Thermal/Mechanical coupled response of a pressurized heated tube



Sectioned view

Big bang



Initiation to propagation
Adagio to presto handoff

Simulation – Used quasi-statics (Adagio) to predict failure initiation to the point where the solution becomes unstable. At this point, it is restarted with explicit dynamics (Presto) with inertia terms to continue and compute the failure propagation.

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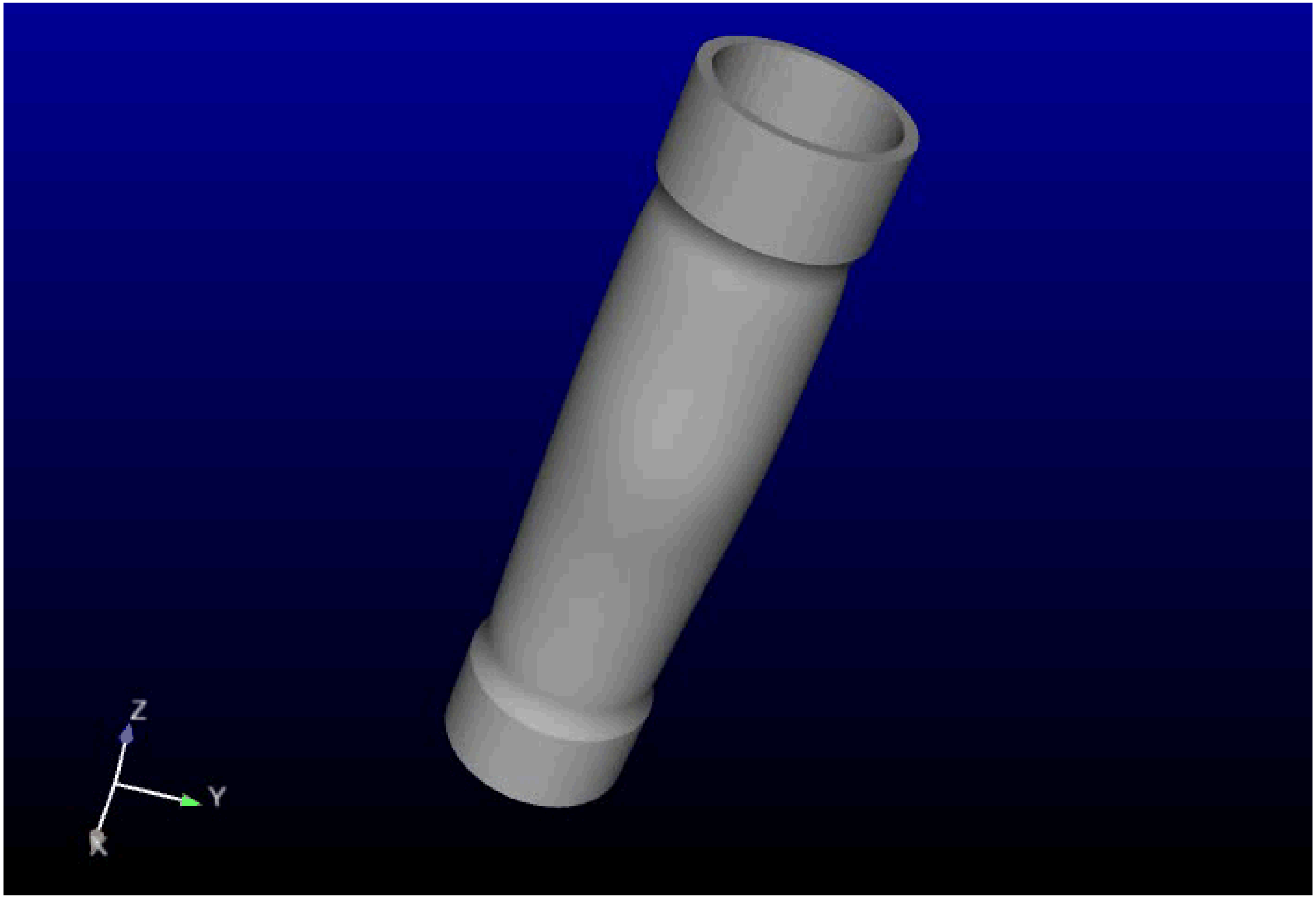
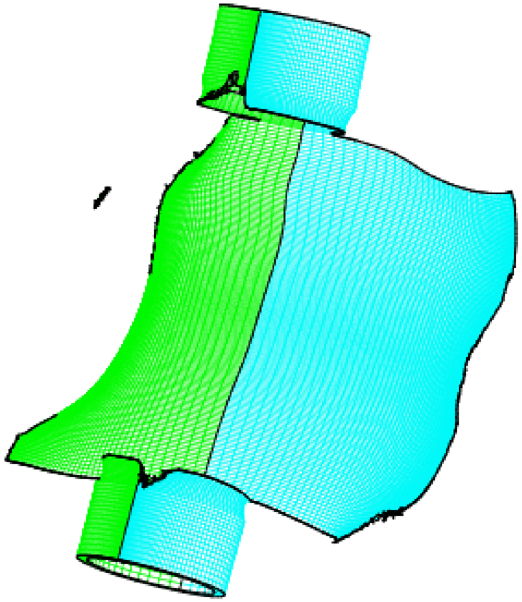
Initiation to propagation
Adagio to presto handoff



Results summary

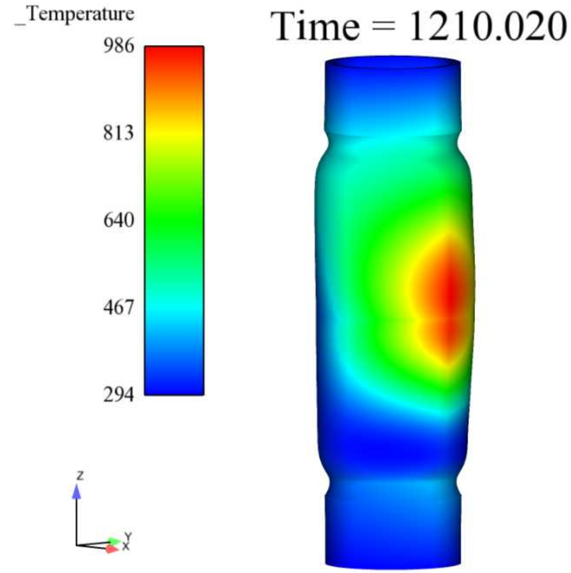


Simulation – Used quasi-statics (Adagio) to predict failure initiation to the point where the solution becomes unstable. At this point, it is restarted with explicit dynamics (Presto) with inertia terms to continue and compute the failure propagation.

Experiment

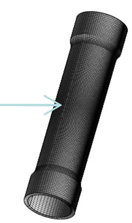
Post-Failure Photograph

Analysis model results



Quasi-static "Adagio"
Failure initiation Simulation

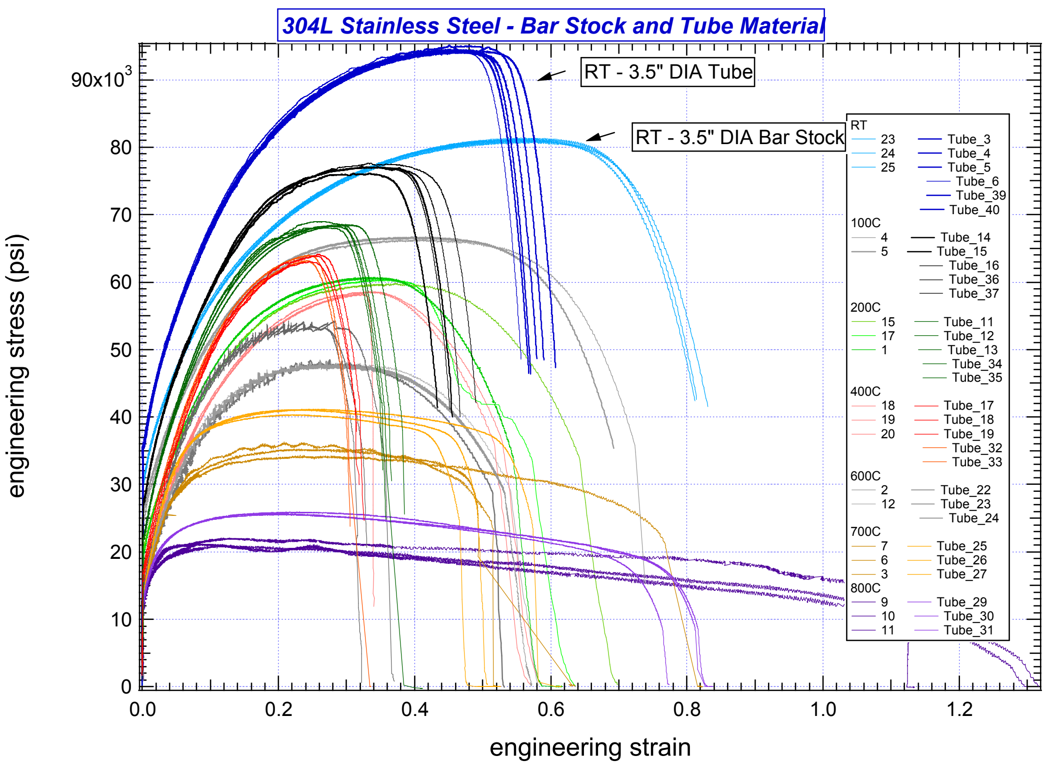
Number of Elements T-T	Exp	2	4	6	8
Number of Elements		52,080	190,368	412,200	1,195,680
Time to Fail (s)	1188	1329.3	1310.4	1298.5	1283.0
Pressure at Fail (MPa)	10.32	11.57	11.41	11.30	11.17
Temperature at Fail (K)	949	1050	1039	1033	1024



Uncertainty Quantification

material strength ranking

304L material data ranking complete



Temp.	LowStrengthCurve	HighStrengthCurve
25C	try39-rt	try5-rt
100C	try15-100	try16-100
200C	try35-200	try11-200
400C	try17-400	try19-400
600C	try22-600	try24-600
700C	try26-700	try27-700
800C	try30-800	try31-800

Note: An isothermal response was calculated to rank high/low materials for additional UQ on experiments. (see next slide).

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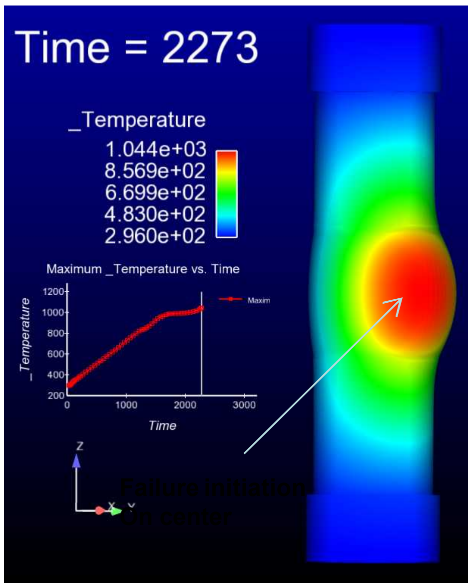
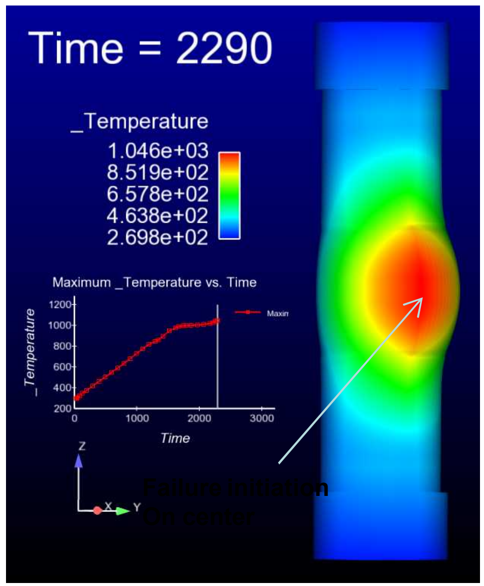
Uncertainty Quantification

Coupled experiment to mapped
(Self check)

Special UQ on TC mapping algorithm with hi/low material ranking and emissivity variance for final UQ on full set of C6 experiments.



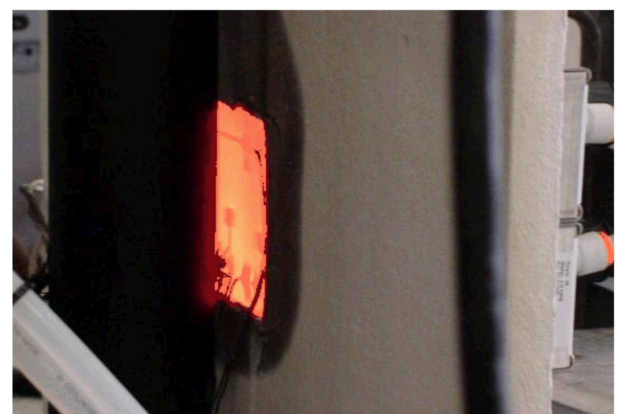
Coupled experiment calculation High strength, Nominal Emissivity with TC outputs for self check (right)



TC interpolation check calculation Using coupled TC outputs (left)

Results

Run case	Time Seconds	Temp K	Pressure psi	TP ref
Coupled High 0.86	2273.50	1043.64	1183.09	4.12
Coupled Low 0.86	2204.50	1040.90	1110.06	5.28
Coupled High 0.7	2310.40	988.96	1222.16	4.03
Coupled Low 0.7	2259.70	977.26	1168.49	3.28
Interp High 0.86	2290.10	1043.55	1200.66	4.36
Interp Low 0.86	2231.10	1040.77	1138.21	5.93
Interp High 0.7	2328.60	988.89	1241.41	4.39
Interp Low 0.7	2274.90	977.18	1184.58	3.52



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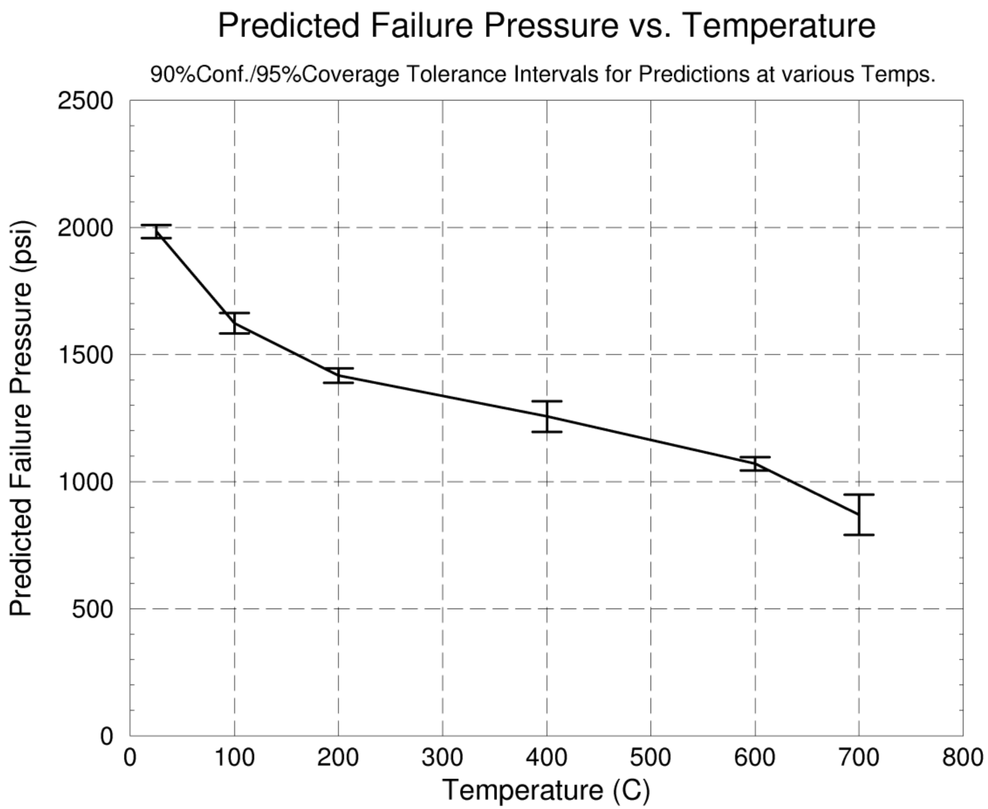
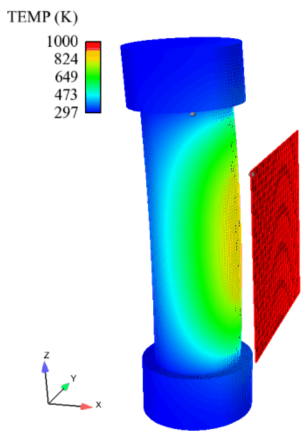
Uncertainty Quantification —Predicted Range of Failure Pressures Due to Variability of Material Stress-Strain Curves at Tested Temps.

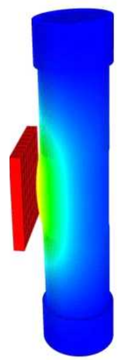




Material stress-strain variability at discrete temperatures will be used for temperature-path integrated variability in predicted failure pressure for temperature transients applied to pressurizing pipe

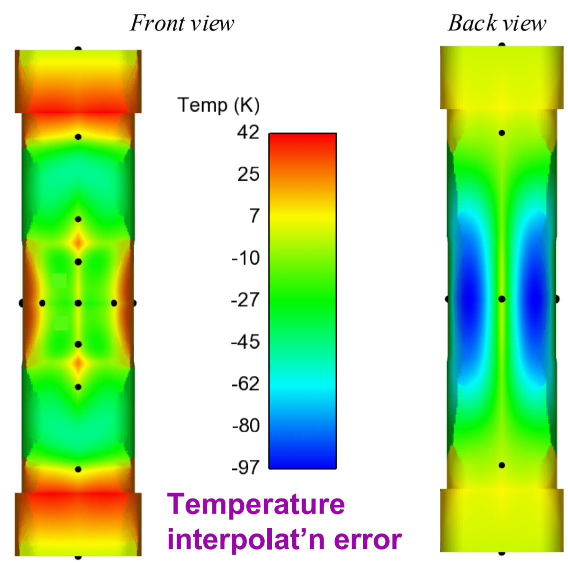
A more difficult and involved *Data Conditioning* example — "Pipe-Bomb" validation problem

Coupled thermal-mechanical model has radiative heating, thermal expansion, & pressure induced deformation, but no convection ➡ a thermally "*nearby problem*" to experiment



- Temperature field on pipe surface must be modeled from limited thermocouples on pipe, placed to best work with quasi-Hermite bi-cubic interpolation scheme to recreate temperature field as closely as possible

- Estimate of spatial error in reconstructed experim. temperature field is obtained from *nearby problem* with approx. same temperature field as in the experiments (see model above)



interpolation error is zero at TC locations and where yellow fades to green

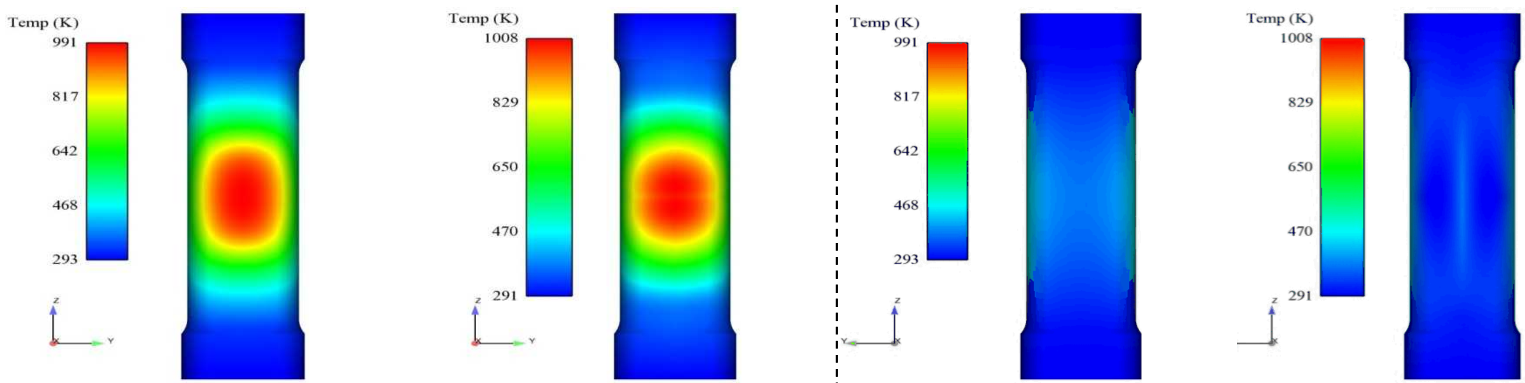
Uncertainty Quantification
—Temperature Mapping/Interpolation and Error Correction

Exact Temperature Field
Front view, 3390sec.

Interp. Temperature Field
Front view, 3386 sec.

Exact Temperature Field,
Back view, 3390sec.

Interp. Temp. Field
Back view,3386sec.

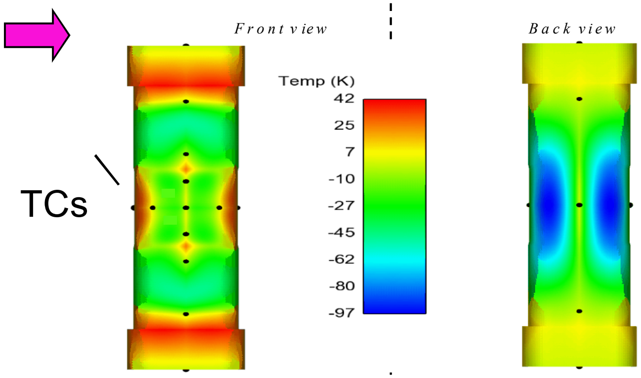


Difference (error) Plots

- **temperature interpolation error is characterized and corrected for validation predictions**
- **a ~2% error in predicted failure pressure if not corrected for interp. error**

offset angle front view

offset angle back view



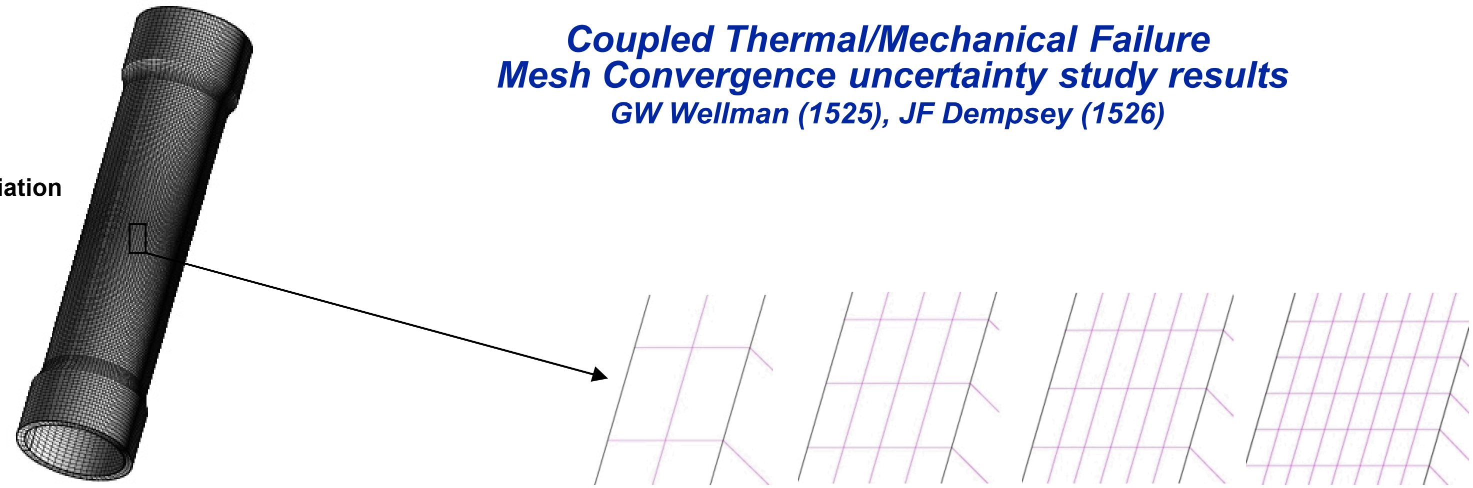
Verif of Coupled Thermal/Mechanical Capability FY11 Q3 Update – V&V

Frank Dempsey, Org. 152665755/002.01.24

Coupled Thermal/Mechanical Failure
Mesh Convergence uncertainty study results

GW Wellman (1525), JF Dempsey (1526)

Failure initiation
On center



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Pressure at Fail (MPa)	10.32	11.57	11.41	11.30	11.17
Temperature at Fail (K)	949	1050	1039	1033	1024

Benchmarks

- Completing 8 Validation tests with repeats
  - Modeled all tests
  - Modeled .02” & .05” wall thicknesses
  - In progress - .035 wall thickness w/ repeats
- Completing material screening – high/low UQ margins
- Completing thermocouple mapping error UQ, ~3%
- Explored Arpeggio 2-way coupling
  - Emissivity variance and high/low material margins
- Predictions higher than experiments by 10-20%
- Temperature interpolation - ~3%
- Creep behavior
  - Fast pressure test -
- Buckling observations/modeling – not an issue

Unresolved Issues

- Mesh convergence when instability is quantity of interest
- Mesh convergence under severe mesh distortion (ductility)
- Adaptive remeshing (not just mesh refinement)
- Mesh refinement versus initial element bias

Summary

- "Adagio" quasi-static FEA techniques with experimental validation were used successfully to predict ductile failure initiation in complex thermal environments for load controlled systems.
- "Presto" explicit dynamics FEA techniques were coupled to Adagio quasi-statics to propagate the failure.
- Ongoing PCAP to demonstrate ductile failure with foam chemistry pressurization with V&V for 2-way coupling.