SAND2016-3264C

Exceptional service in the national interest

Sandia National Laboratories

Approaches for Validating Container Breach/Failure in Abnormal Thermal Environments

Bonnie Antoun
Mechanics of Materials Department
Livermore, CA

2016 ANALYSIS/TEST HOCWOG TECHNICAL EXCHANGE (JOWOG 31)
Atomic Weapons Establishment, UK
May 9 , 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories

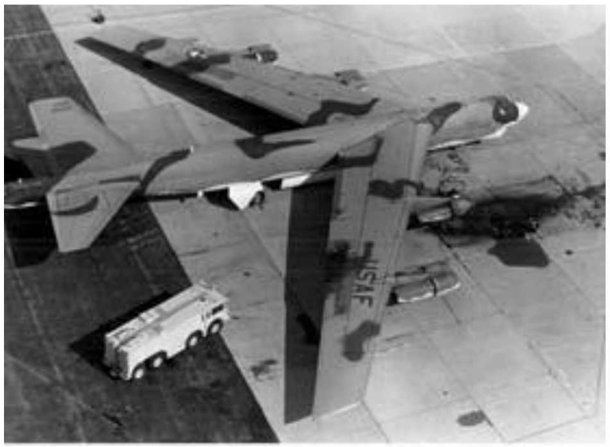
OUTLINE

- Background/Motivation
- Material Characterization
- Evolution of Experimental Approach
  - 1 – Air pressurization of simplified geometry
  - 2 – Sub structure of sectioned geometry
  - 3 – Experimental Approach 3 – Mechanically equivalent loading
- Summary

Background/Motivation

• Abnormal thermal environments include hydrocarbon fuel fires and propellant fires.

• Fully-engulfing and various directed fire scenarios, with and without mechanical damage, are considered when assessing the adequacy of the nuclear safety theme.



Fuel Fire

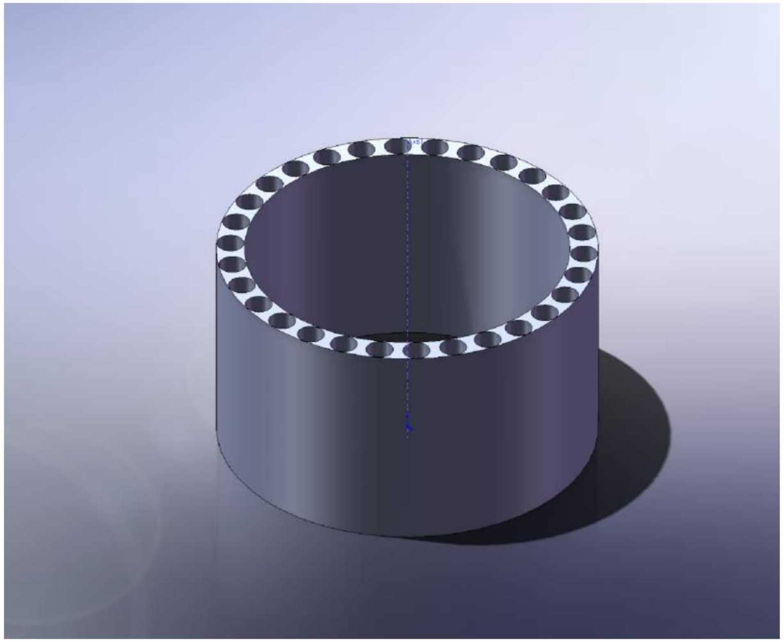
Propellant Fire

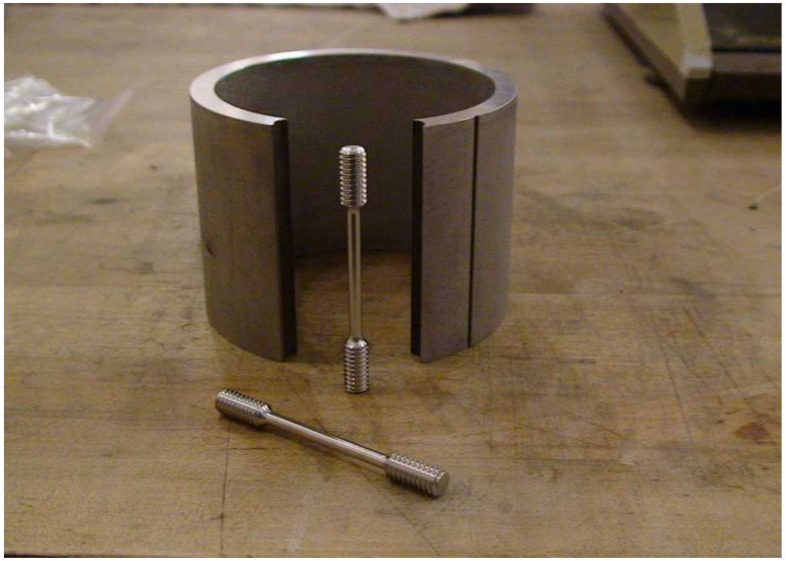
- **Extreme temperatures and temperature gradients are imposed on internal components**
- **Several sealed volumes of interest (exclusion regions and barriers, firing subsystem, etc.) can pressurize due to thermal decomposition of internal foam**
- **High pressures and accompanying thermomechanically imposed stress states can result in a side wall or exclusion region sealing weld failure, which creates a potential path for unintended sources of electrical energy. Similar to the loss of the strong/weak link race, exclusion region breach prior to failure of the weak link is considered a loss of assured safety.**

Material Characterization

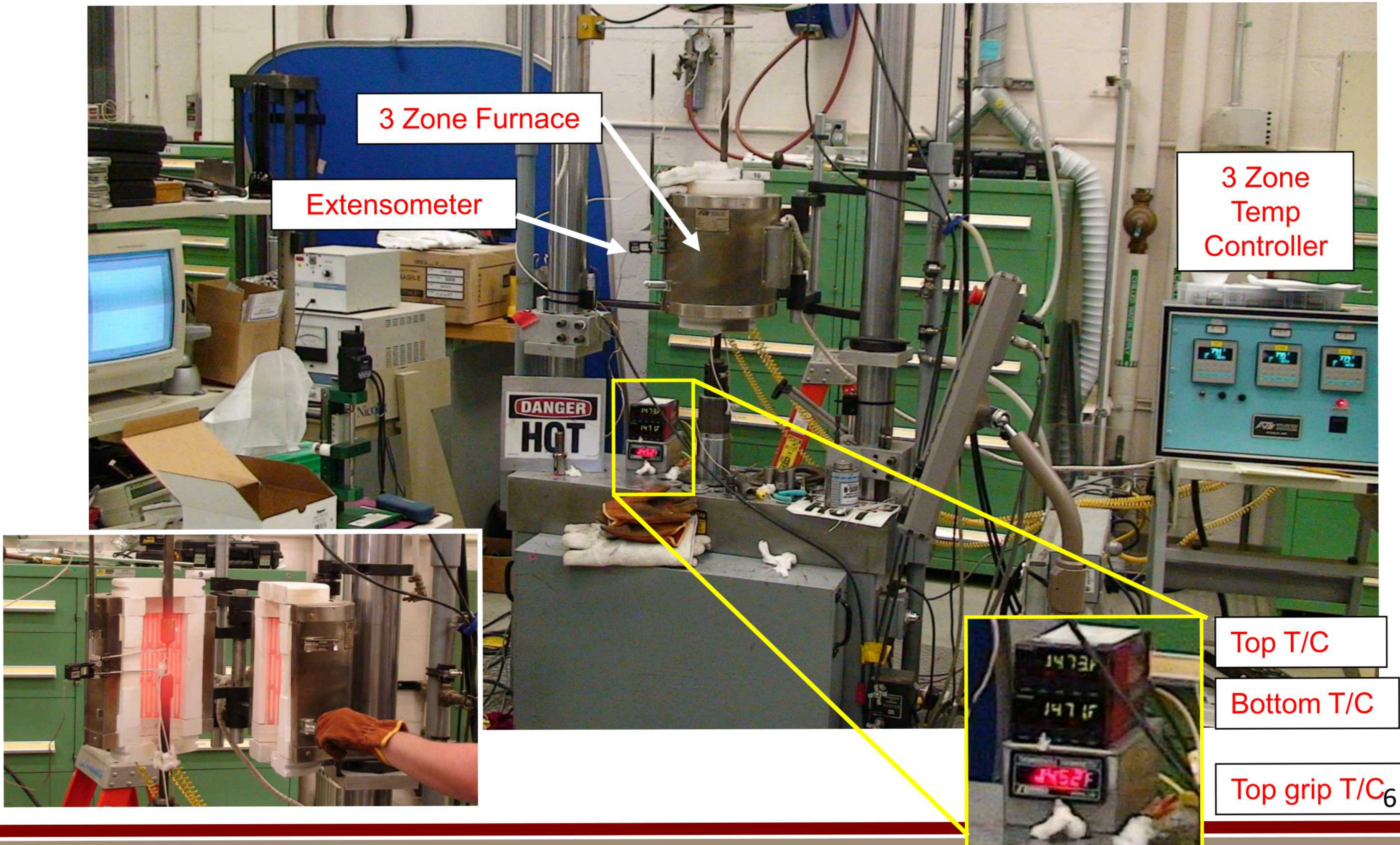
Characterization of 304L Stainless Steel in Tension 3.5" DIA Tube Material

- Material for Pressurized Validation Experiments is 304L Stainless Steel Tube (not 3.5" DIA bar stock used for previous data)
- 40 Tensile specimens have been machined and annealed for additional tests as a function of temperature (0.001/s)

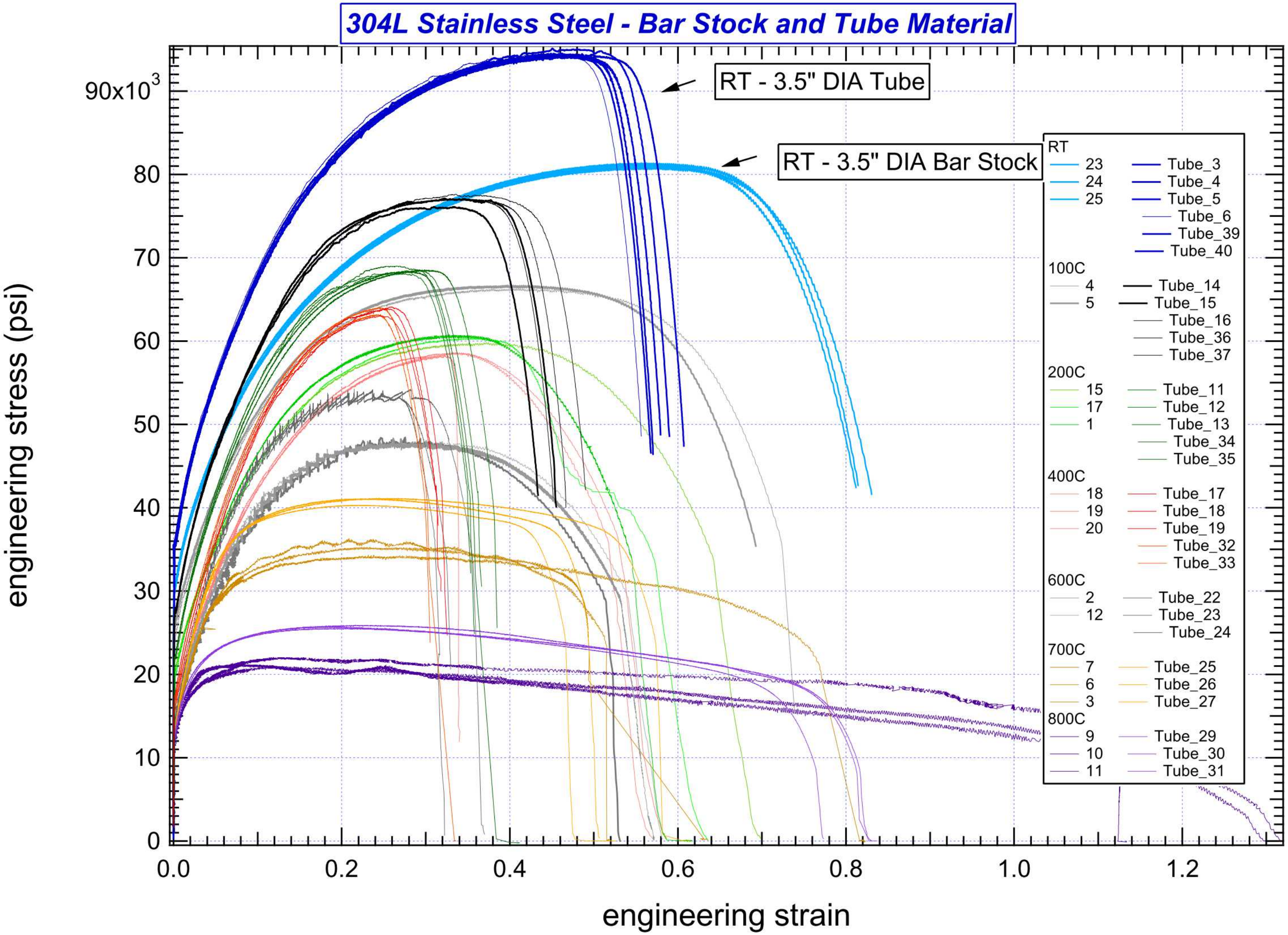




Experimental Setup on 50Kip A/T MTS Servohydraulic Frame



Characterization of 304L Stainless Steel in Tension



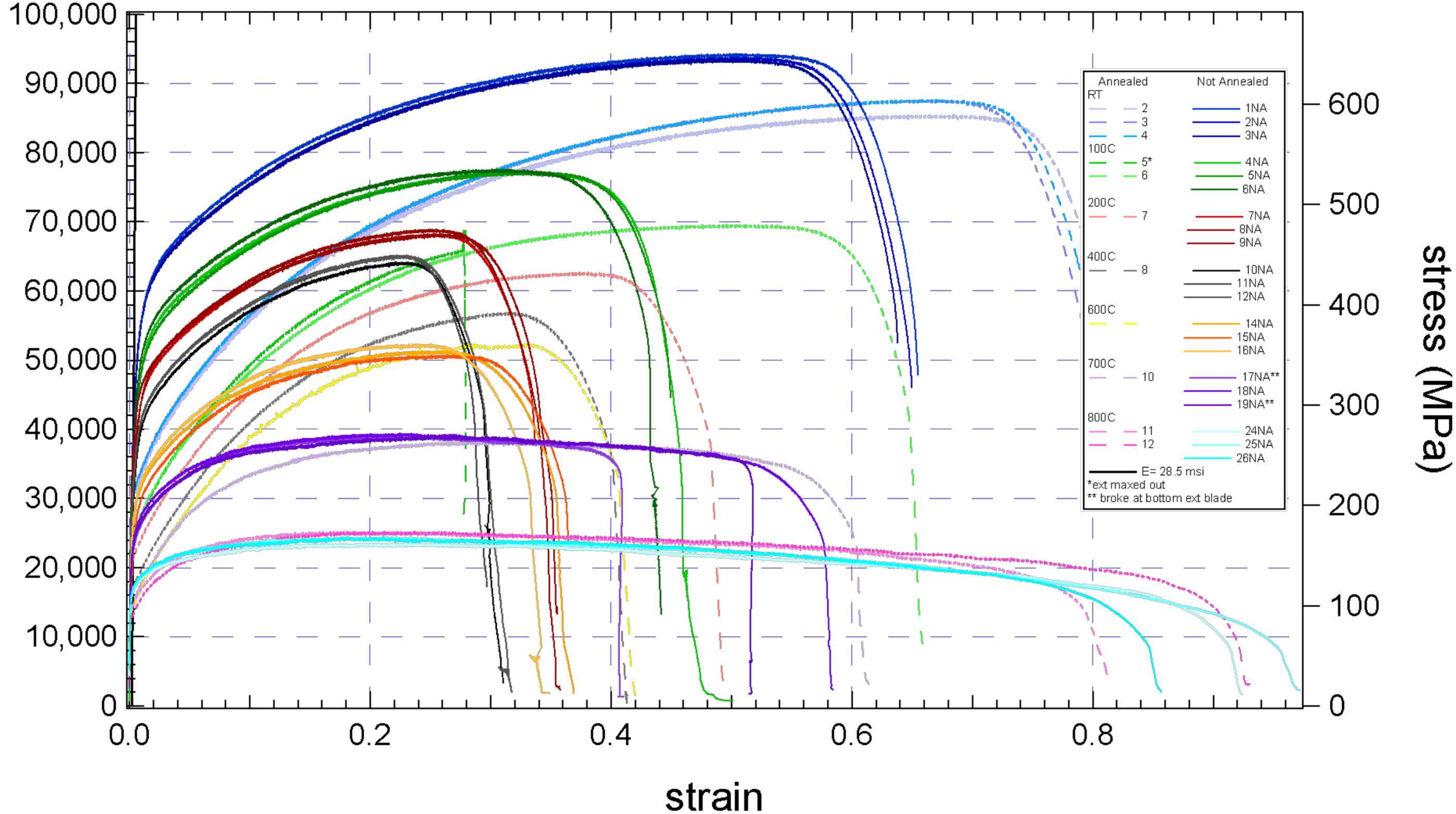
- At every temperature, the 304L tube material behavior was substantially different from the bar stock material behavior

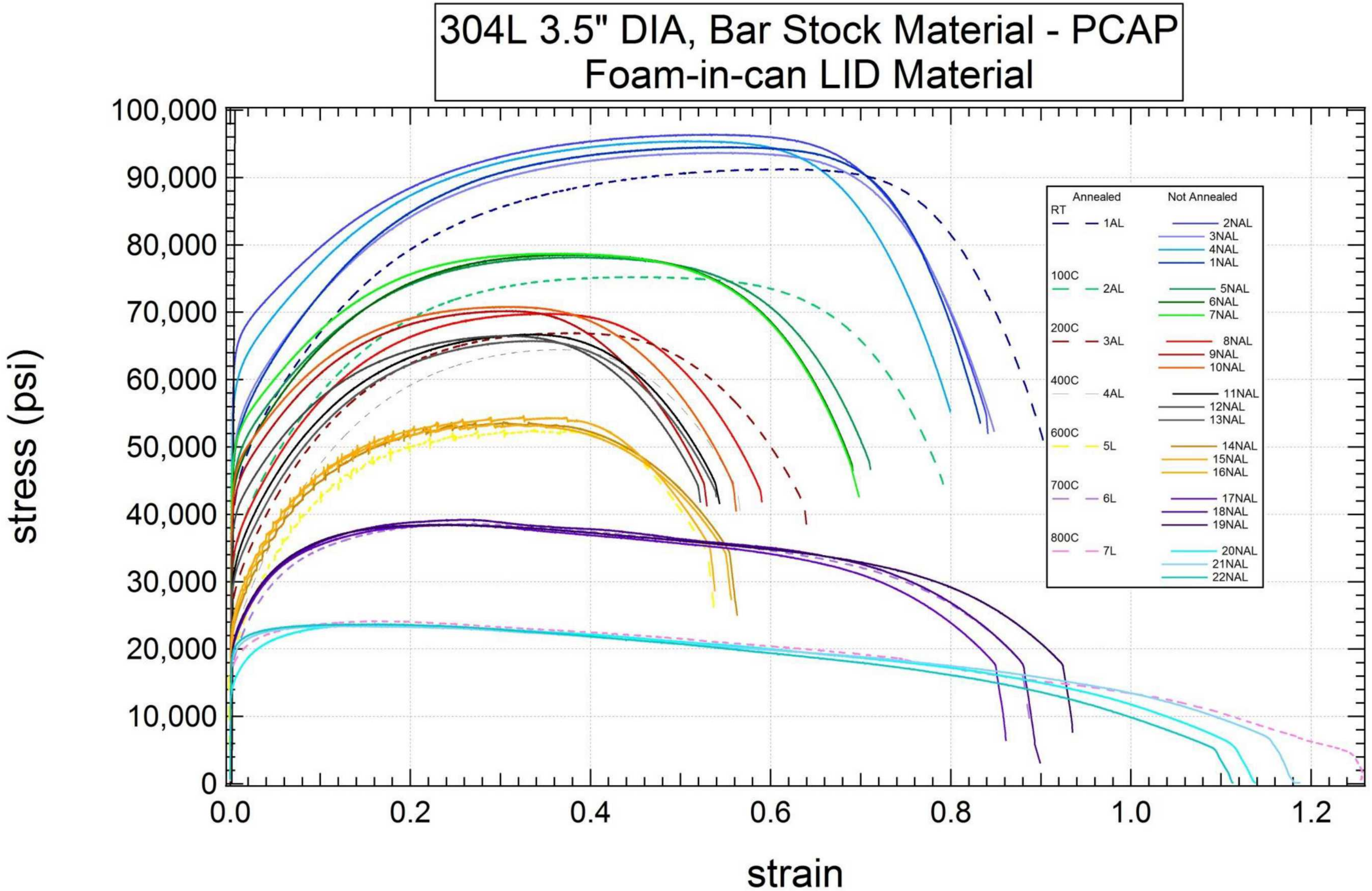
Comparing tube to bar stock:

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

Sandia National Laboratories

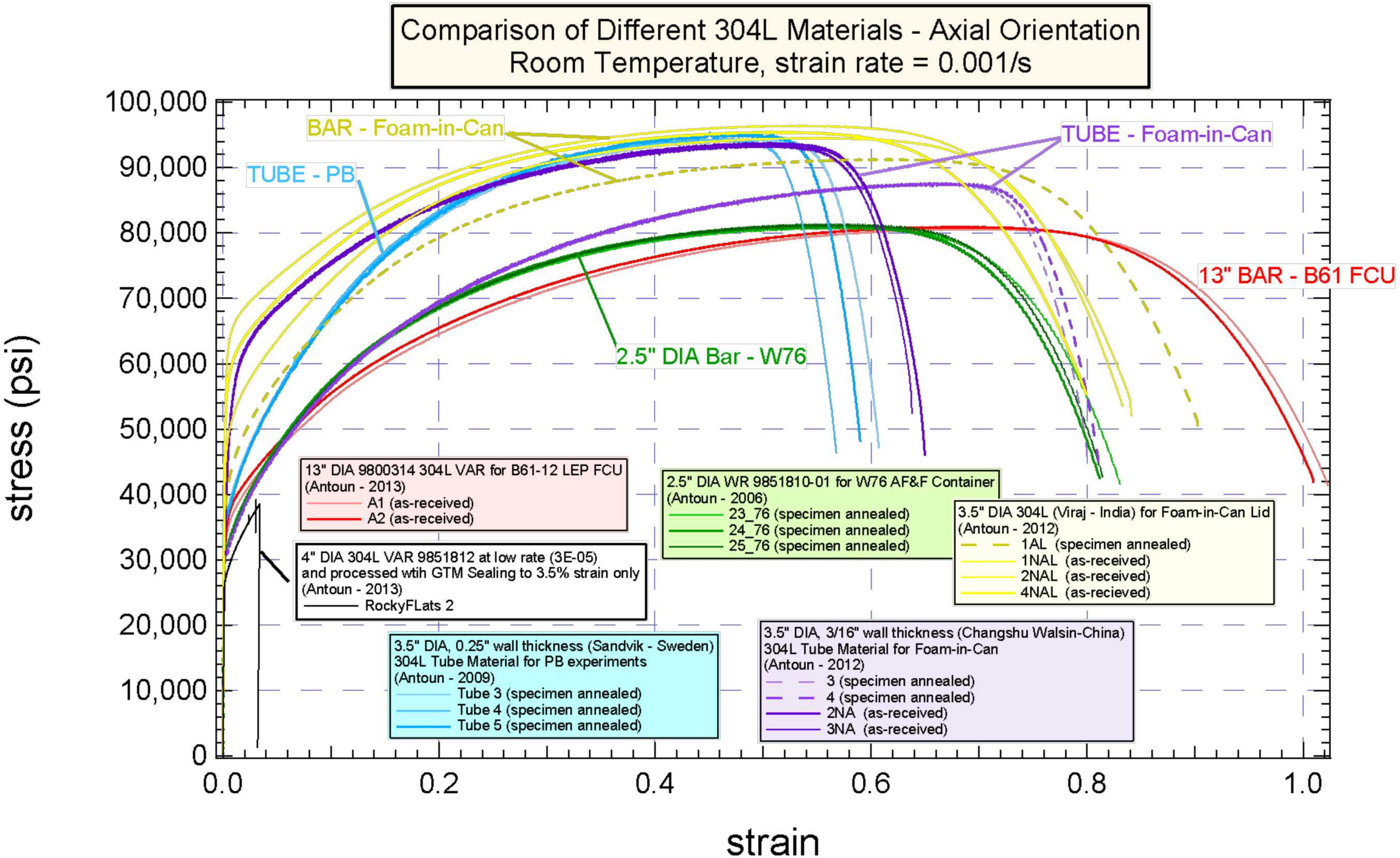
304L 3.5" DIA, 3/16" wall thickness Tube Material - PCAP





304L 3.5" DIA, Bar Stock Material - PCAP
Foam-in-can LID Material
stress (psi)
strain
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Annealed
Not Annealed
RT
1AL
2NAL
3NAL
4NAL
1NAL
100C
2AL
5NAL
6NAL
7NAL
200C
3AL
8NAL
9NAL
10NAL
400C
4AL
11NAL
12NAL
13NAL
600C
5L
14NAL
15NAL
16NAL
700C
6L
17NAL
18NAL
19NAL
800C
7L
20NAL
21NAL
22NAL

304L Stainless Steel: A Complex Material that is Sensitive to Form, Composition and Processing



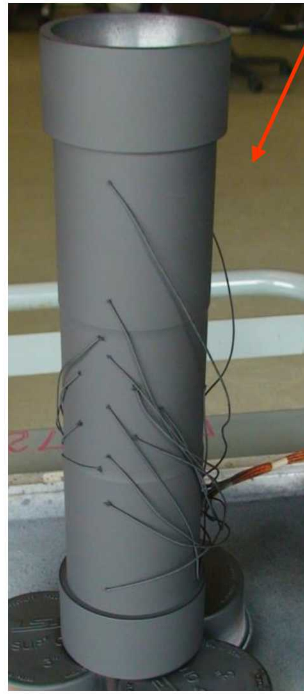
Evolution of Experimental Approach

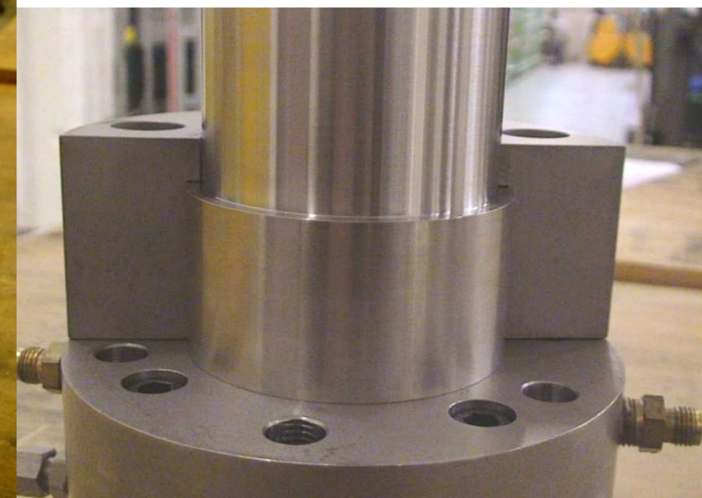
- 1 – Air pressurization of simplified geometry
- 2 – Sub structure of sectioned geometry
- 3 – Experimental Approach 3 – Mechanically equivalent loading

Internally Pressurized PB Validation Specimens

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)





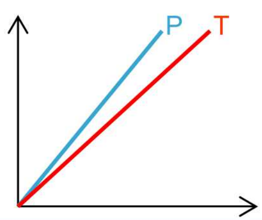
3" Reduced section, from 0.050" to 0.020"

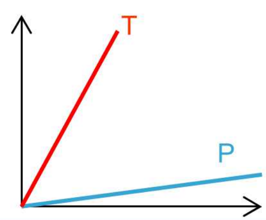
TC count increased # from 16 to 23

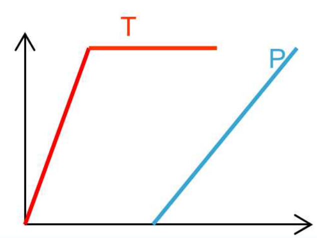
Ceramic slug replaced with stainless steel

Fixture and specimen geometry modified to allow loading in tension

Thermomechanical Coupling

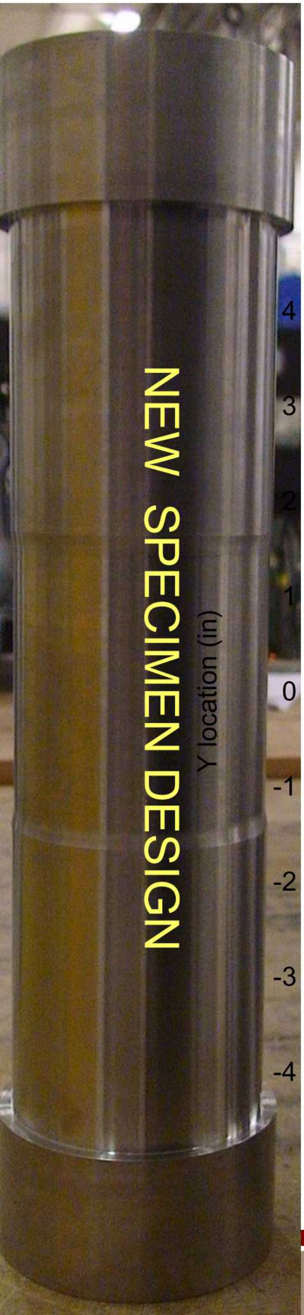


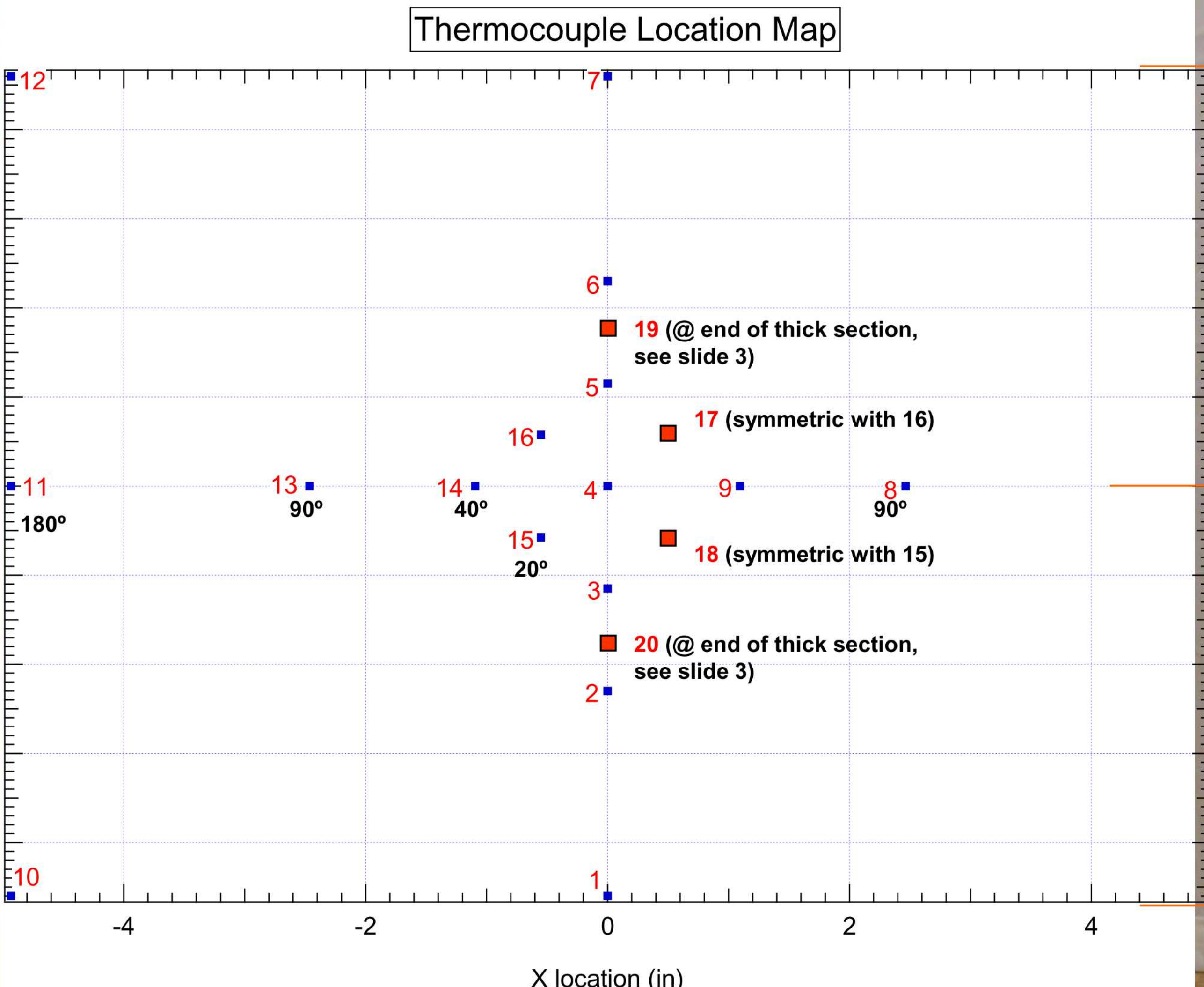


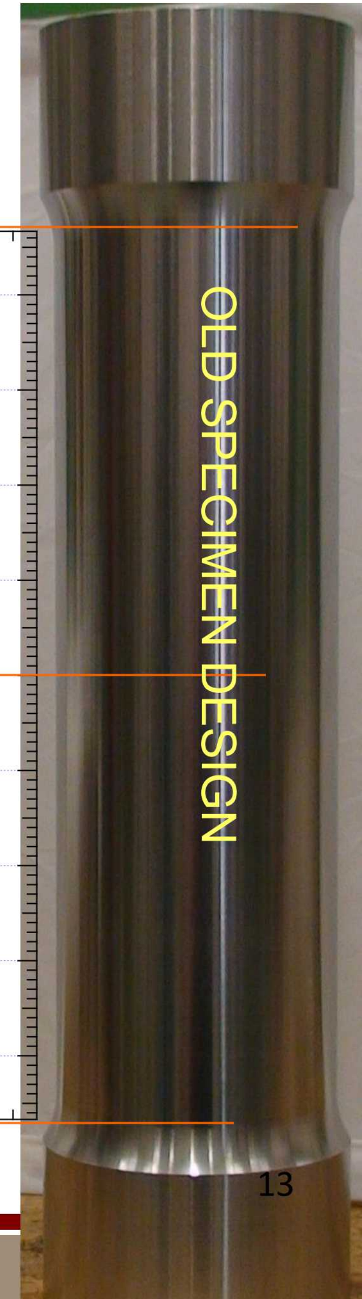


Mapping of 20 Thermocouples onto Validation specimen surface

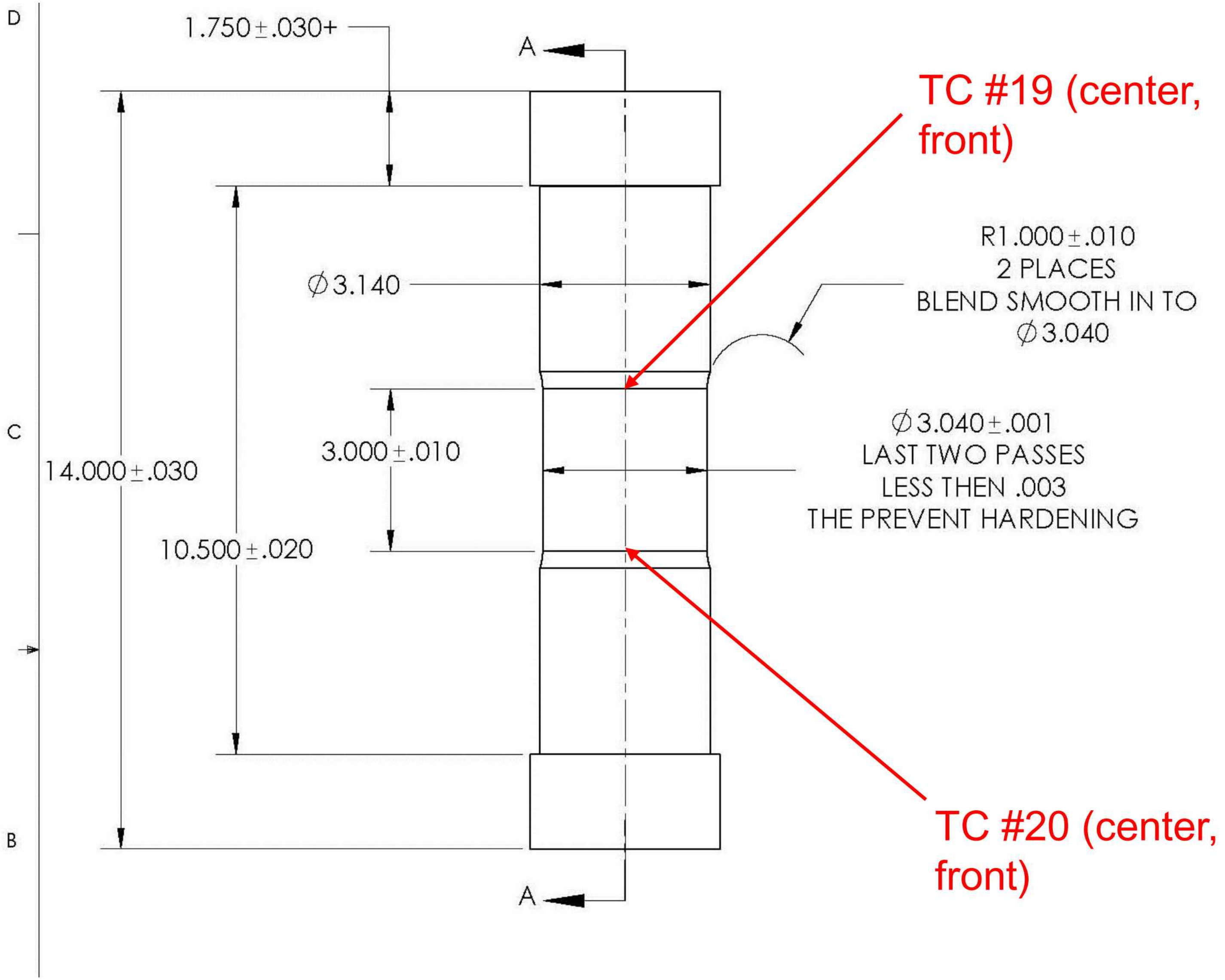
Sandia National Laboratories





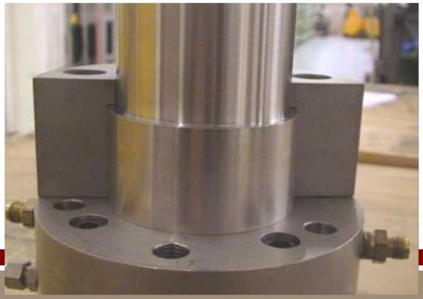


PB Validation Specimen Geometry

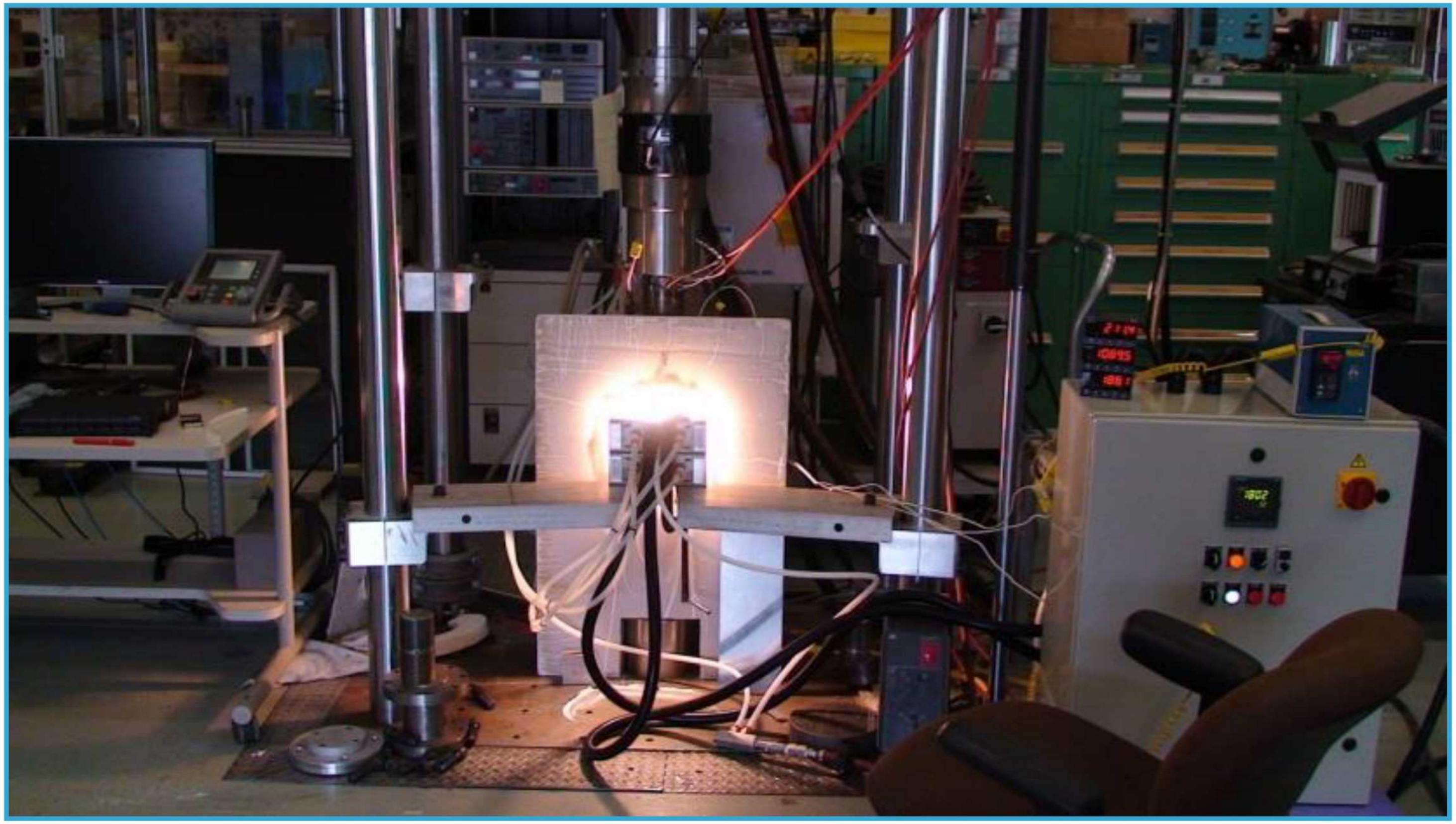


Mechanical Pressurization of PB Specimens

- **Controlled linear or non-linear ramp via MTS computer control system**
- **Uses 2500 psi Nitrogen gas bottle, Dome regulator, pressure regulator and several safety features (bleed off valve, burst disk)**

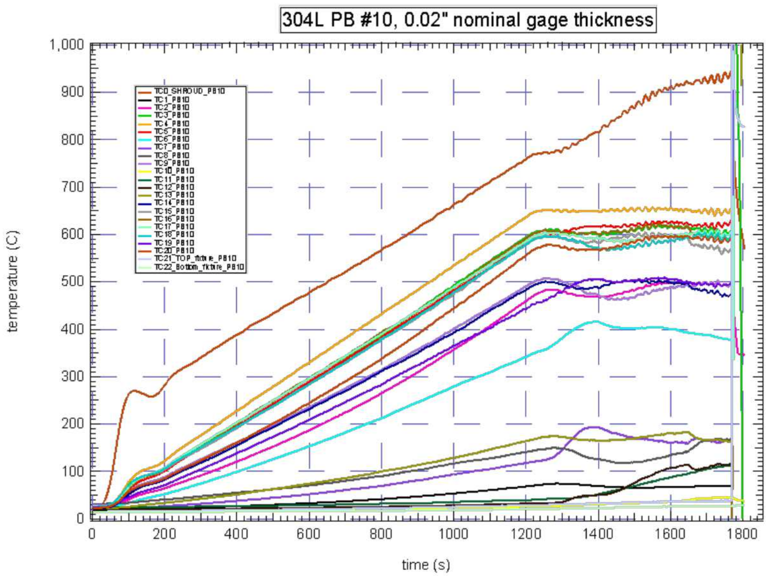


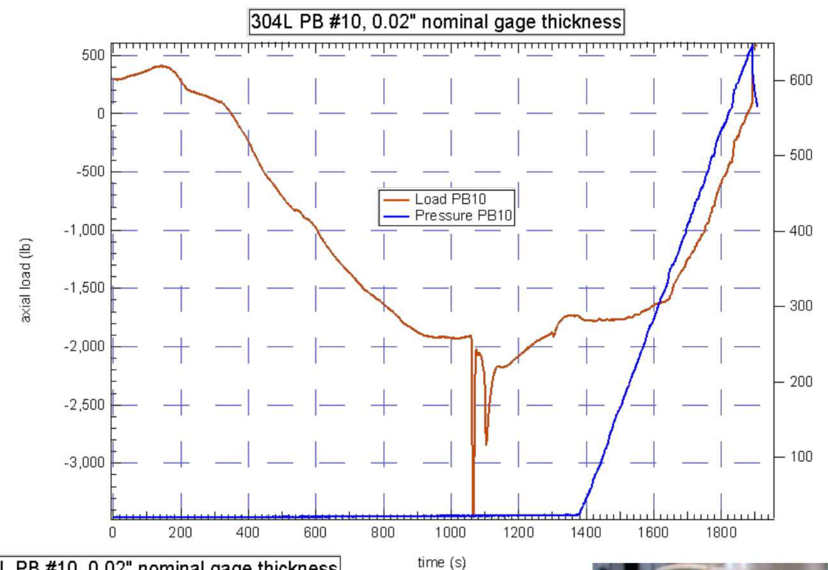
Coupled Thermomechanical Experimental Setup

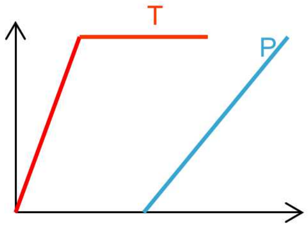


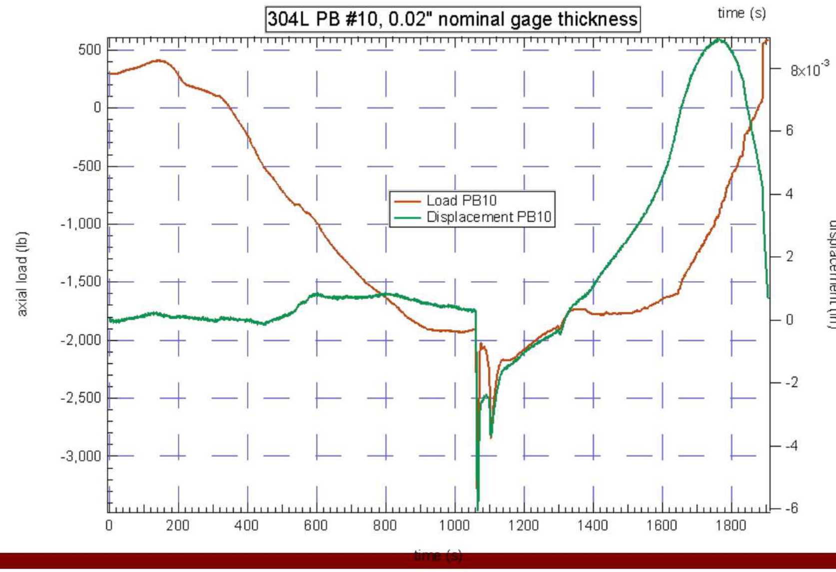
- Setup is within 220Kip MTS load frame
- Control axial displacement, temperature profile and pressurization profile
- Measure axial force, full thermal field (24 TC), deformation (optically), control parameters

Results from Coupled Thermomechanical Failure PB Validation Experiments

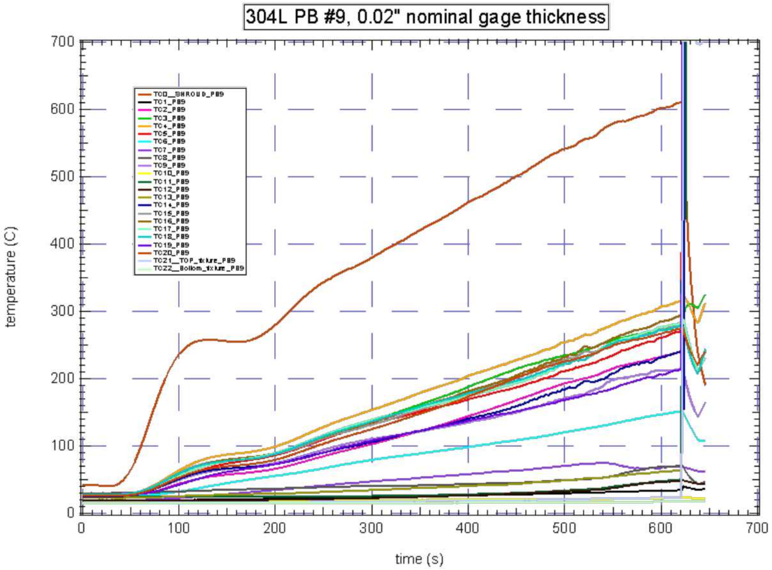


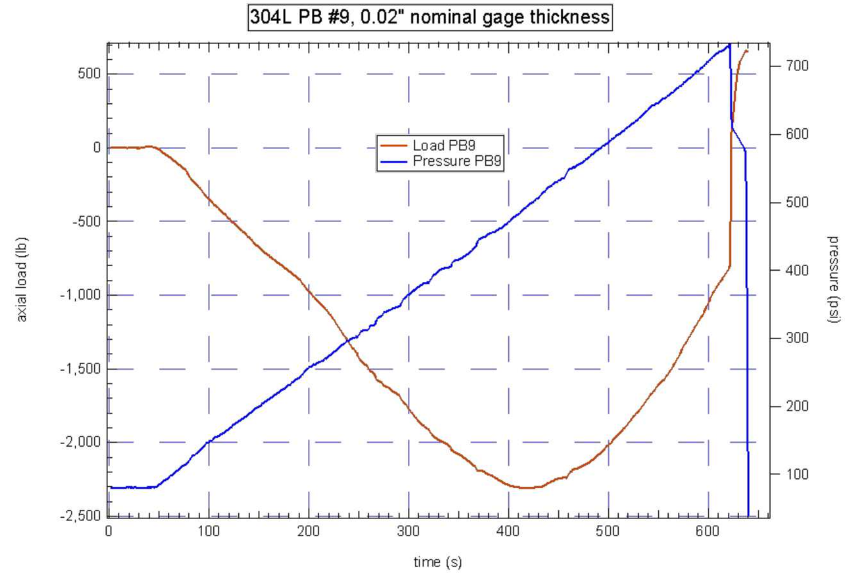


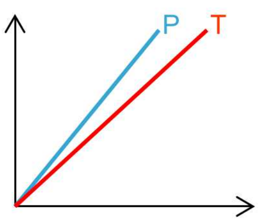


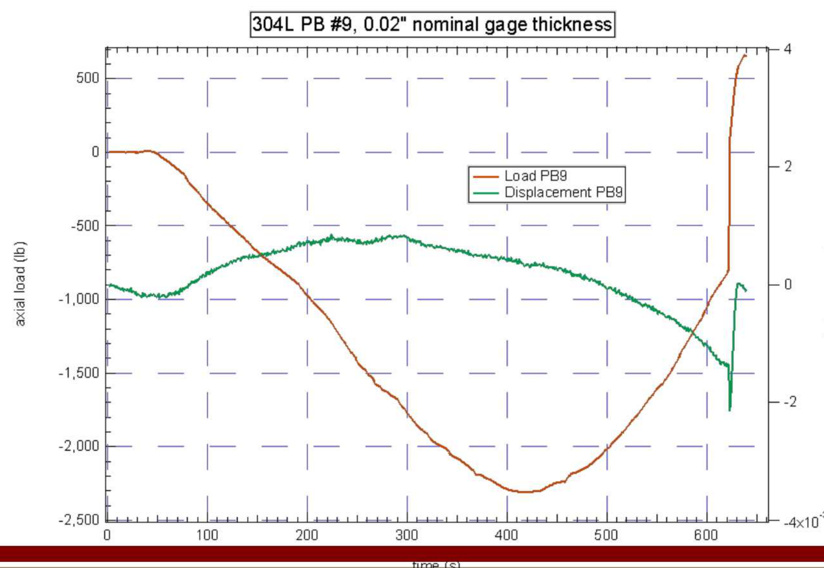


Results from Coupled Thermomechanical Failure PB Validation Experiments



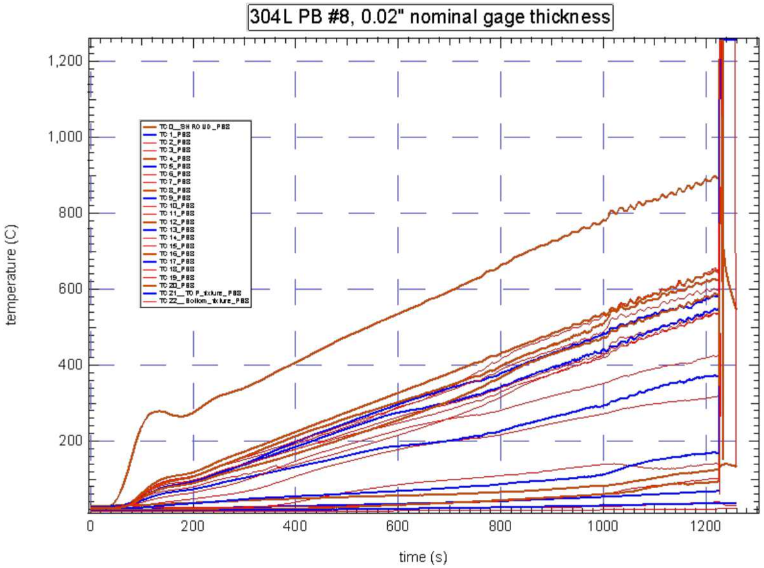


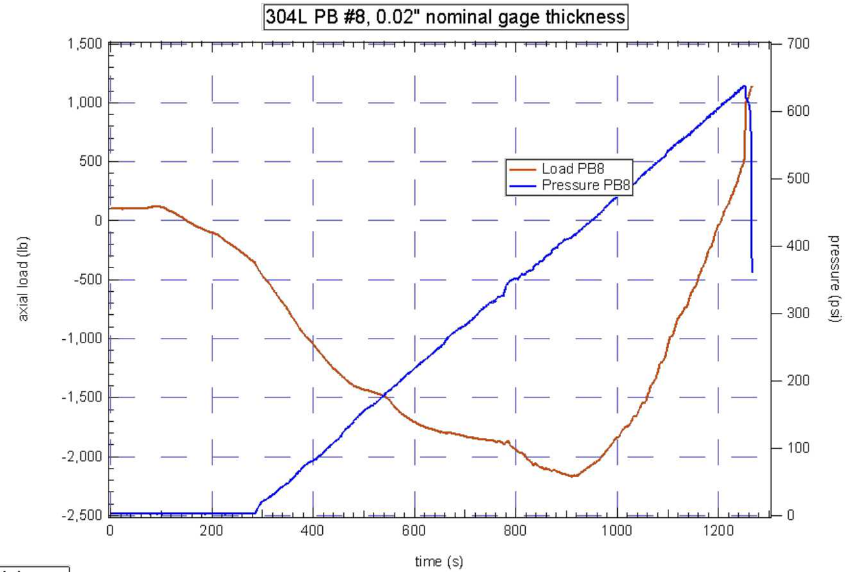


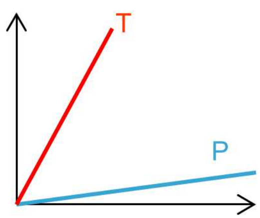


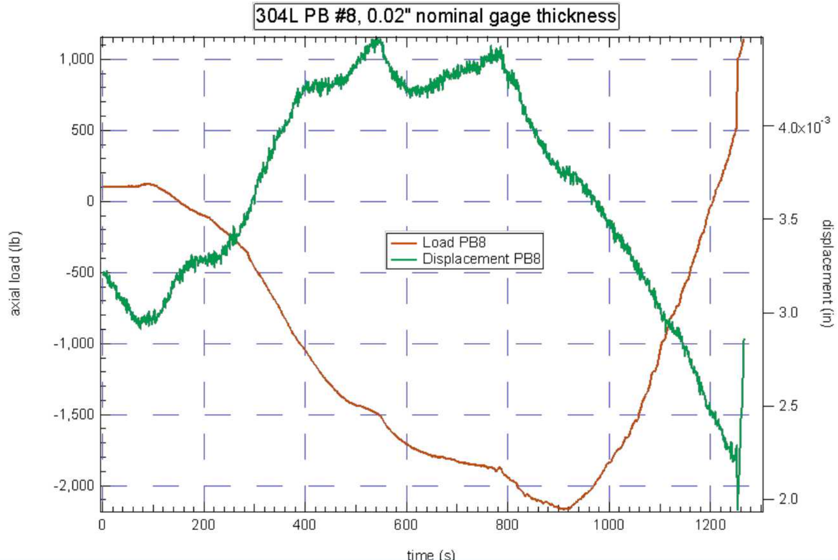
Results from Coupled Thermomechanical Failure PB Validation Experiments

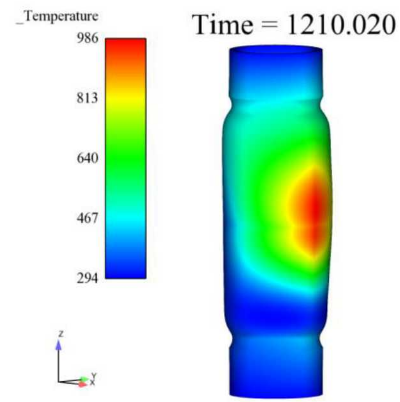
Sandia National Laboratories











Coupled simulation of thermal-mechanical failure validation experiment

Sandia National Laboratories

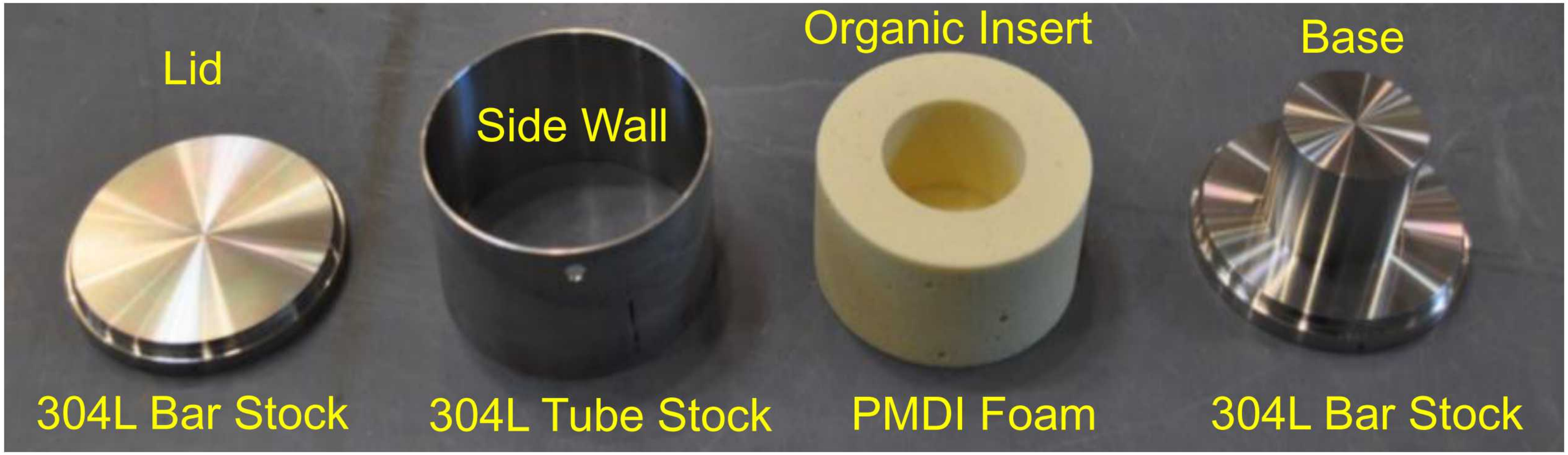
PB Validation Specimens Failed under Various Thermomechanical Loading Conditions

Evolution of Experimental Approach

- 1 – Air pressurization of simplified geometry
- 2 – Sub structure of sectioned geometry
- 3 – Experimental Approach 3 – Mechanically equivalent loading

Background: Sub-level Experiments are Related to Larger Scale Validation Tests

- **Response of stainless steel structures sealed by laser welding was of interest**
- **Cylindrical can structures were constructed of two base materials, 304L stainless steel in tube and bar form**
- **Joining was accomplished by partial penetration laser welding.**

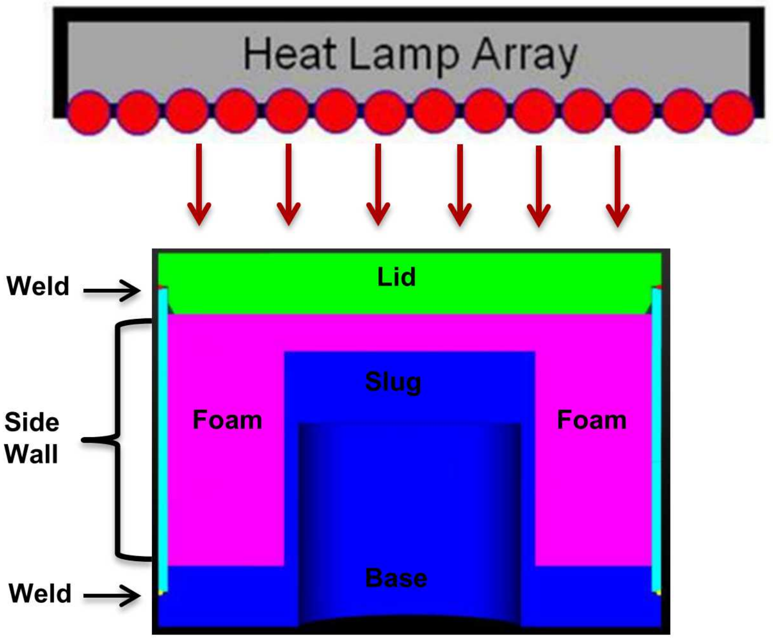


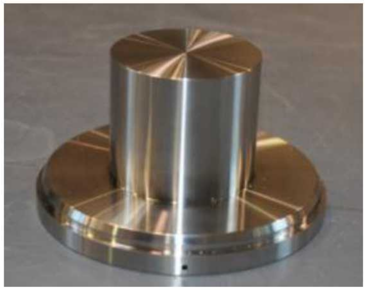
Laser welded can structure geometry before assembling

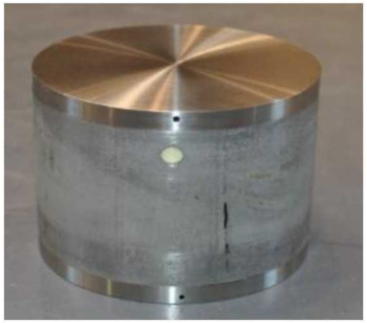
3.5"Dx2.25"H Foam in Can Validation Specimen

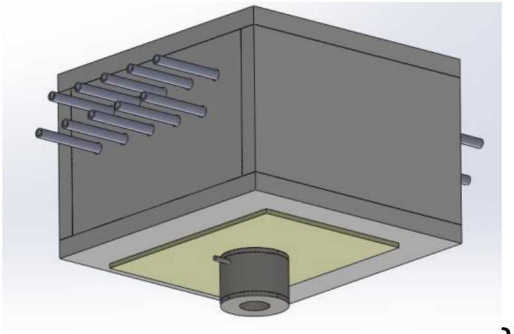
Validation Experiments (J. Suo-Anttila)

- Test Variables: Can Orientation and Heating Rates
- Response Quantities:
  - Thermocouples (Temperature)
  - Pressure Gauges (Pressure)
  - X-Ray Imaging (Displacements & Foam Decomposition)
  - Time to Breach
- 5 upright tests at 150^{o}C/min to 800^{o}C Lid Temperature





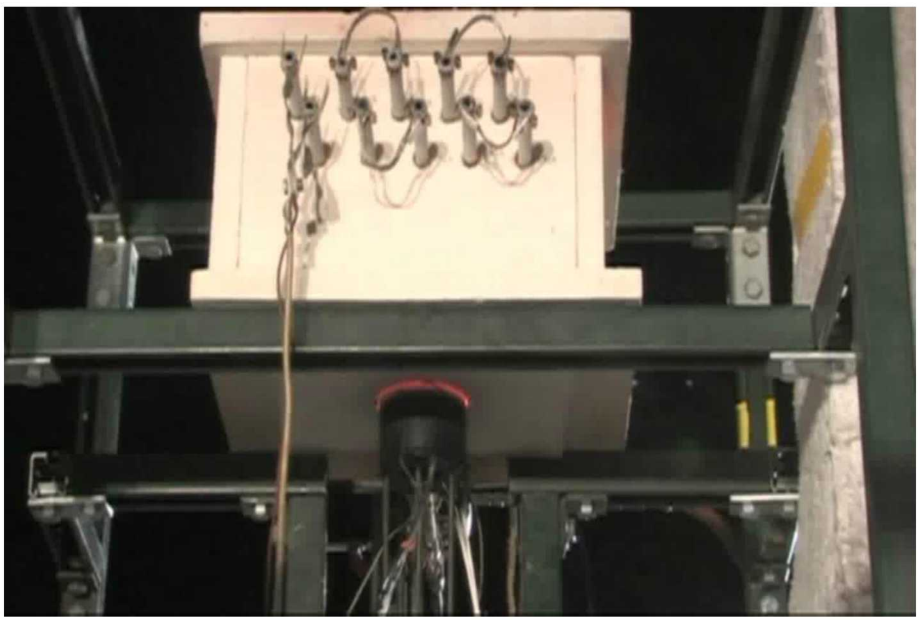




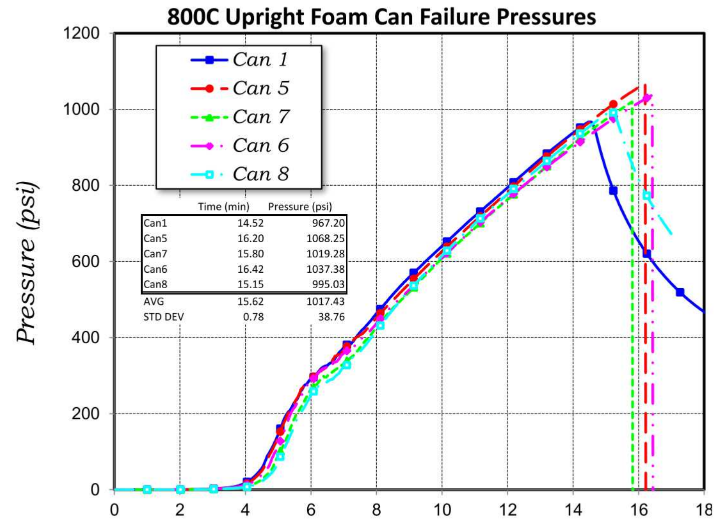
Validation Experiments (J. Suo-Anttila)

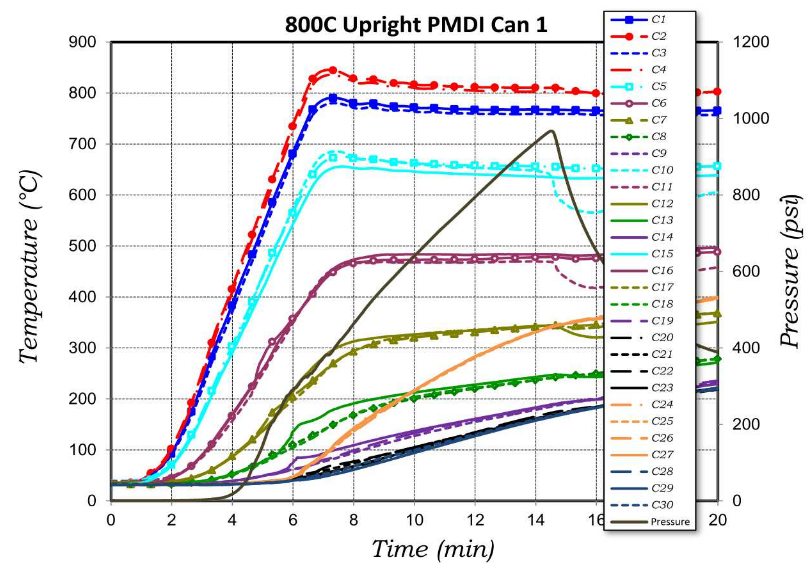
Sandia National Laboratories

- Failure pressure of 1017 ± 39 psi
- Time to failure of 15.6 ± 0.8 min
- Weld temperature at failure, 650°C < T < 750°C
- Two failure modes observed, venting or abrupt weld failure

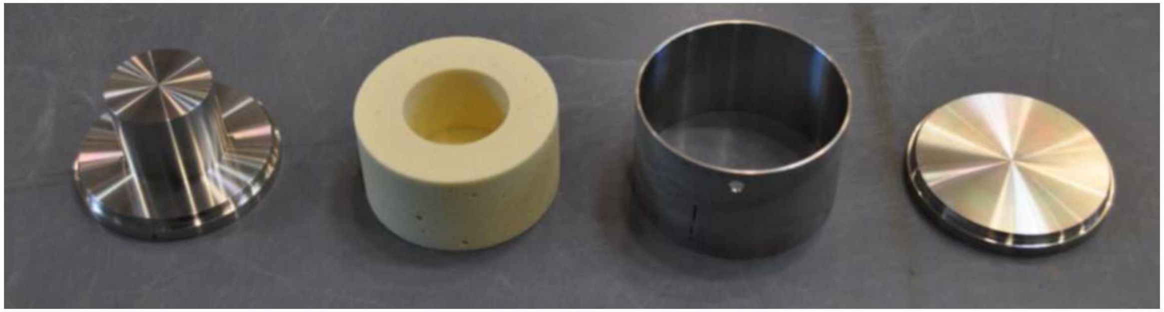


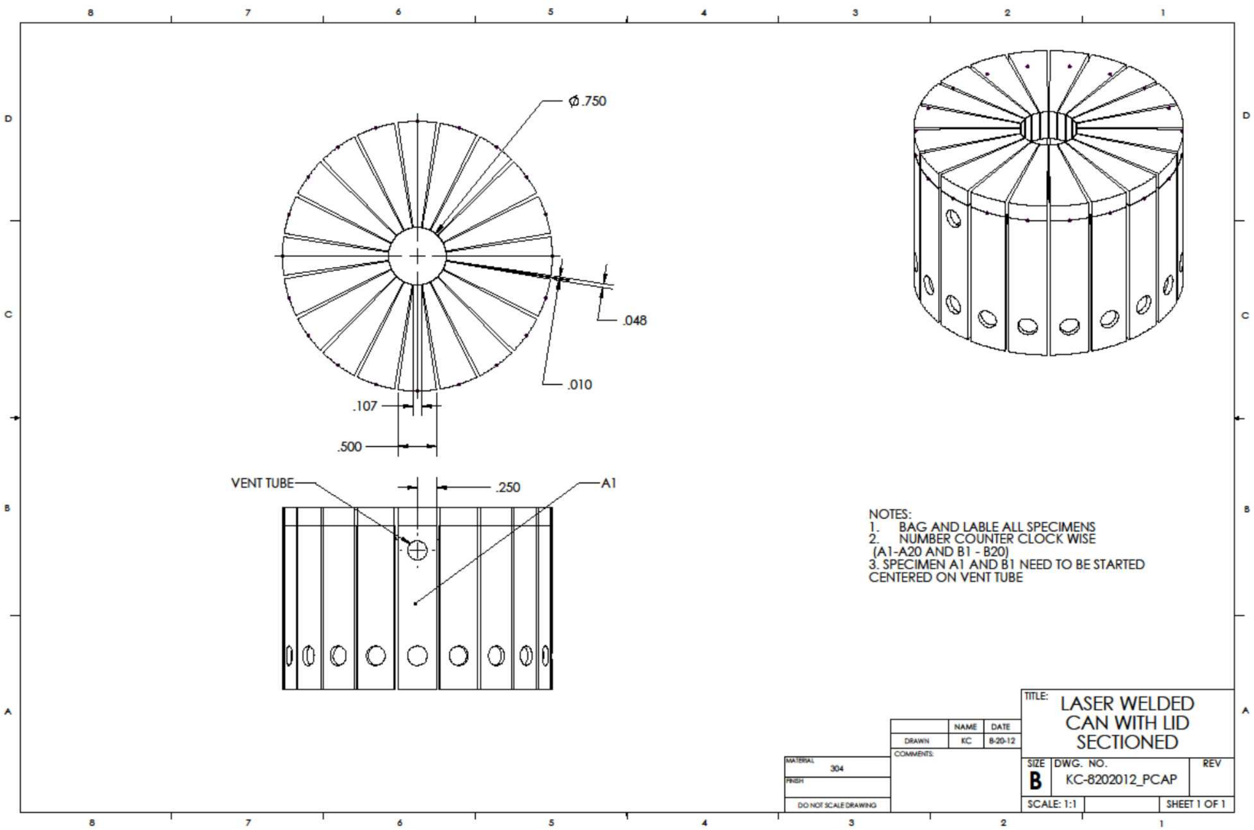
Can 5 Upright 800C Video

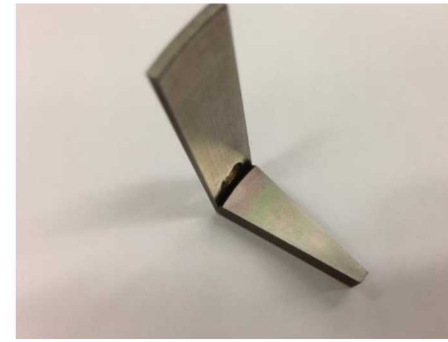




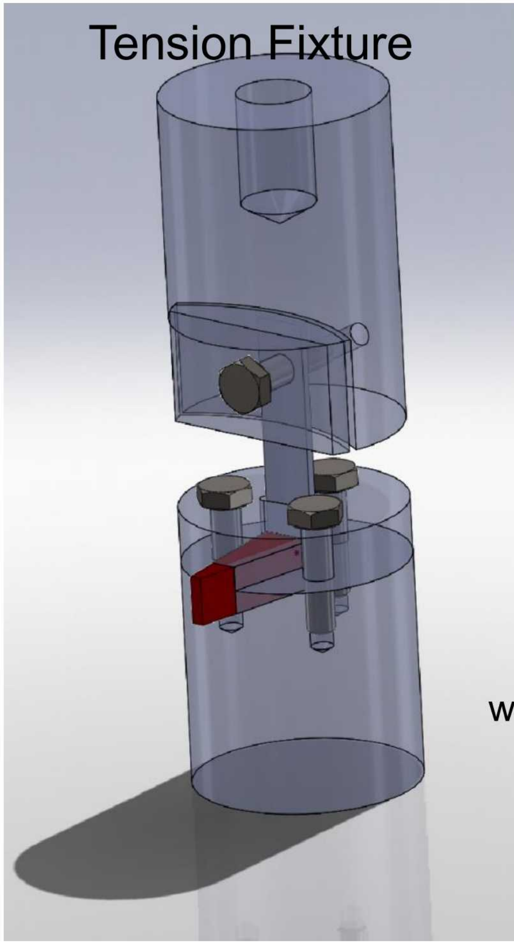
3.5”Dx2.25”H Foam in Can Validation Specimen Sectioned into Calibration Specimens

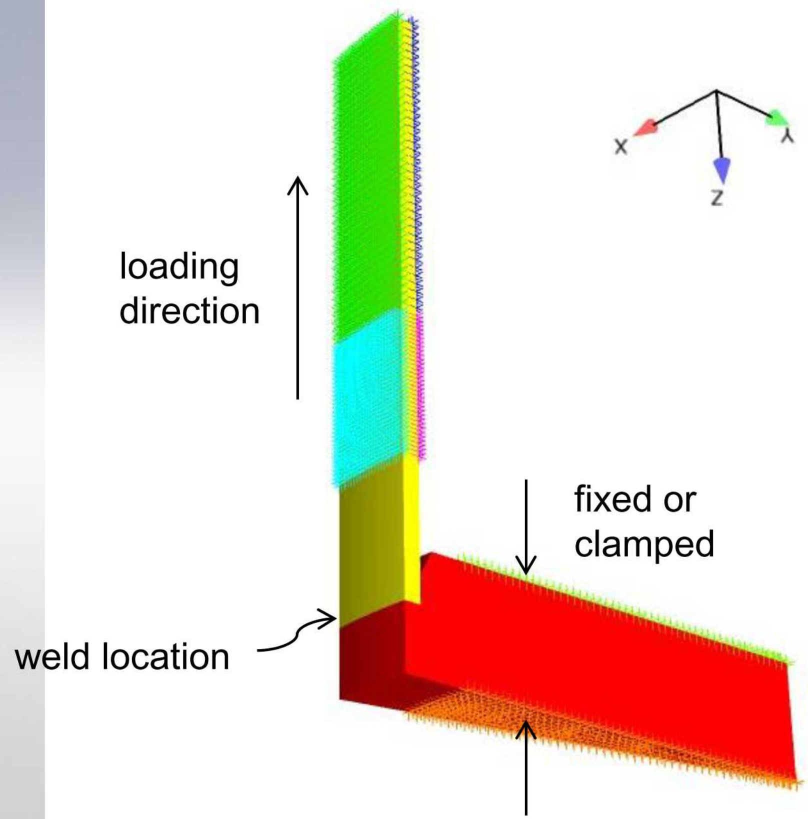






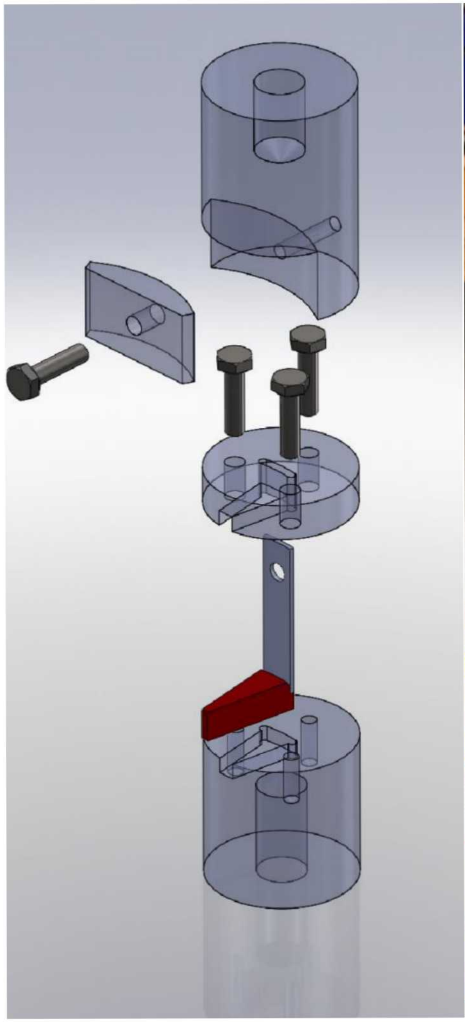
High Temperature Fixtures for Weld Characterization/Calibration Tests in Tension





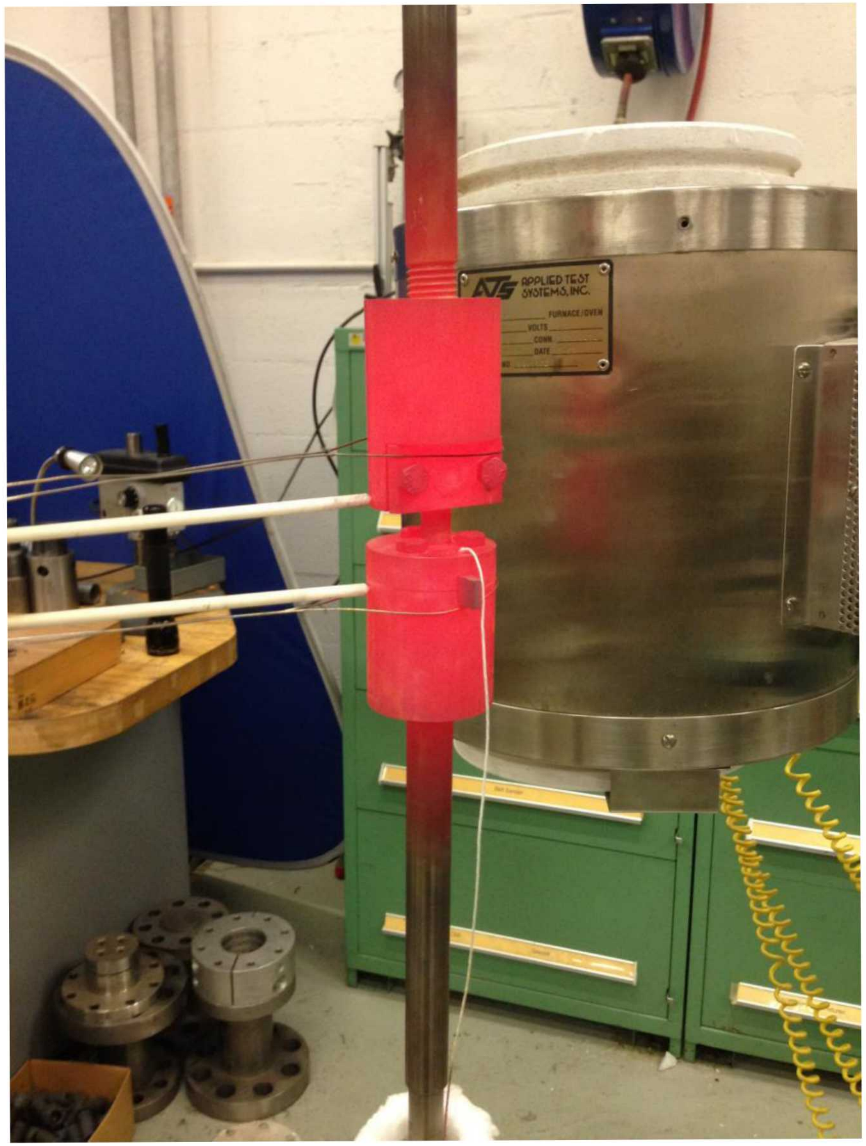
- **Goal is to have 2 sets of weld tests, 1 set for calibration and 1 for validation**
- **The calibration tests should be primarily tension loading of the weld**
- **The validation tests should be a different stress state, preferably with bending and shear in the weld**

High Temperature Fixtures for Weld Characterization/Calibration Tests in Tension

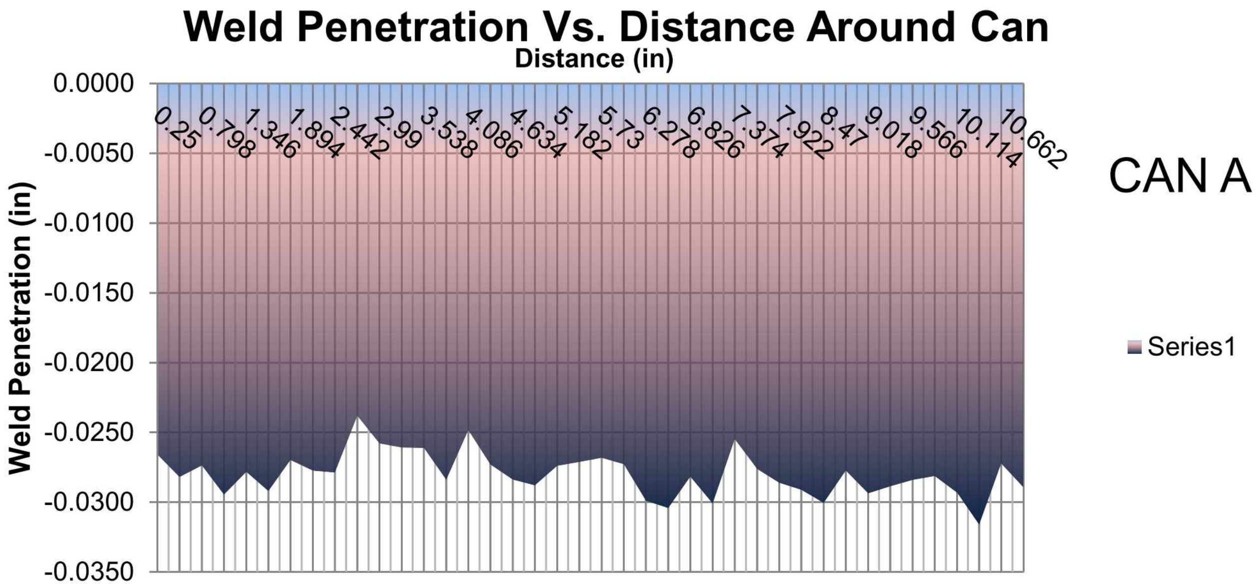


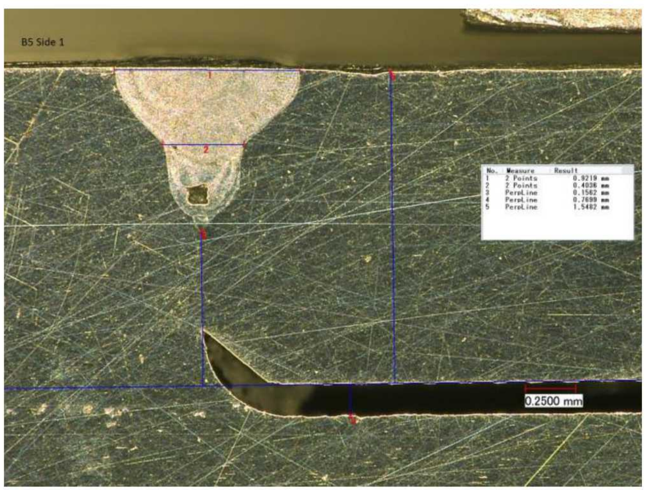
Weld Characterization/Calibration Test – 800C (after failure)

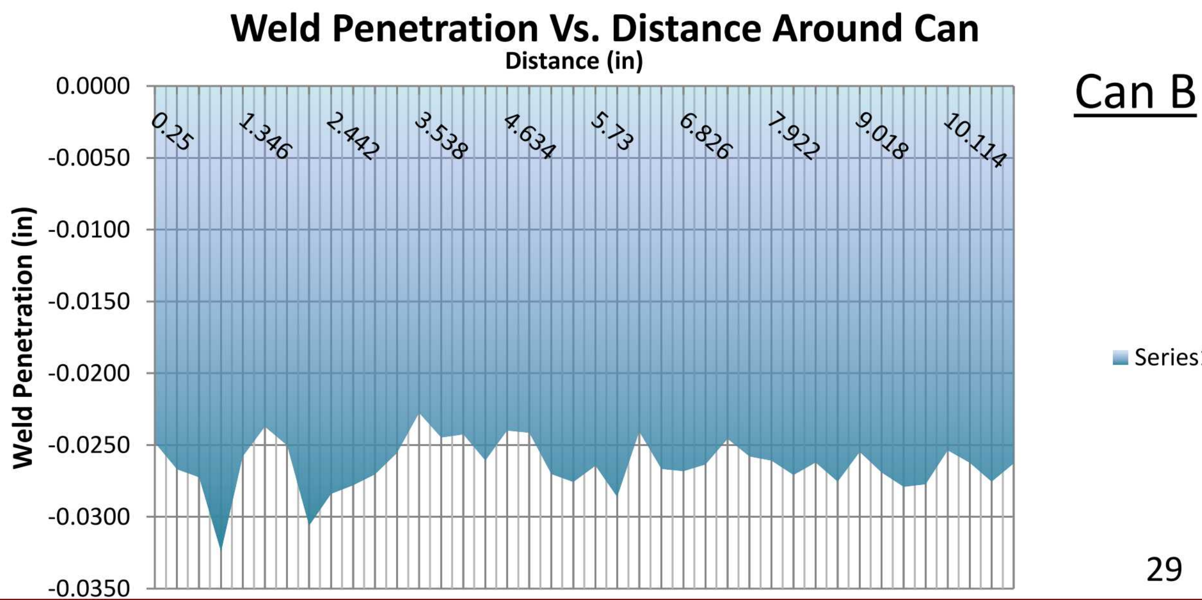
Sandia National Laboratories



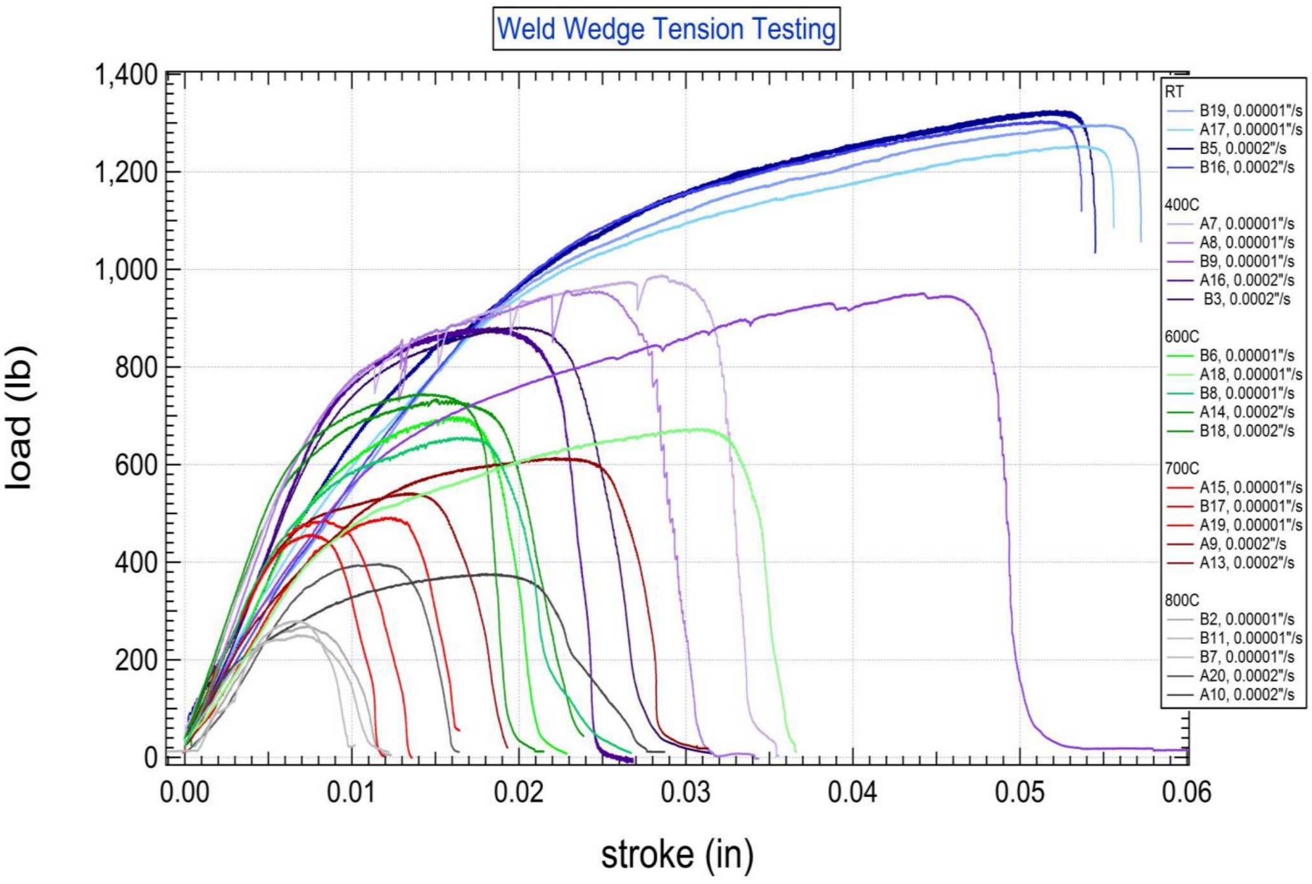
Measurement of Weld Penetration and Variability







Wedge Tension Results as a Function of Applied Rate and Temperature



- Bend tests (not shown) were ineffective
- Rate reversal effect (DSA) – higher rate results in lower loads
- Direct evidence of DSA at 400C and 600C (load ratcheting)
- Analysts were never able to match these results
- Did not shed any light on full can results (low ductility/fracture in welds) – these results were ductile
- Poor boundary condition choice, as warned by experimentalist
- Calibration tests should be avoided, in general – better to use another level of validation experiment

Sandia National Laboratories

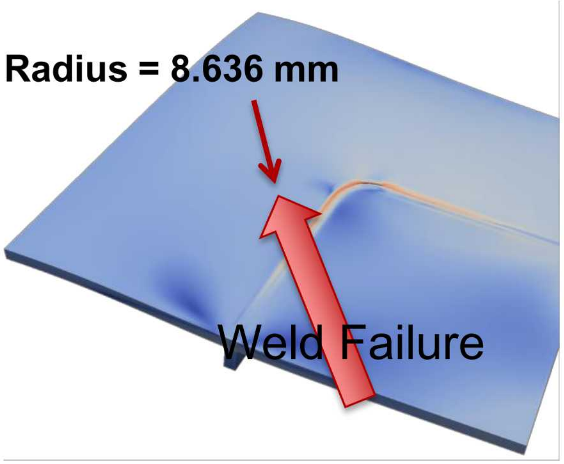
Evolution of Experimental Approach

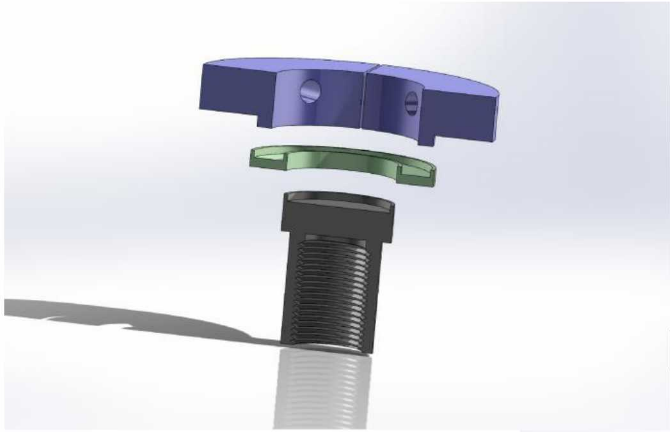
- 1 – Air pressurization of simplified geometry
- 2 – Sub structure of sectioned geometry
- 3 – Experimental Approach 3 – Mechanically equivalent loading

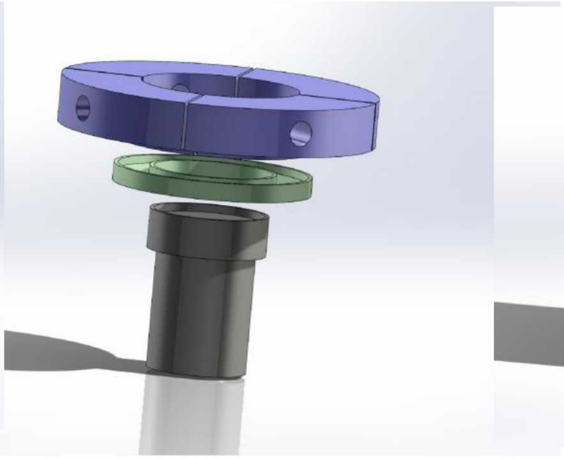
Design of Multi-Axial Laser Welded Specimens
Combined Axial-Radial Loading
Combined Axial-Torsional Loading

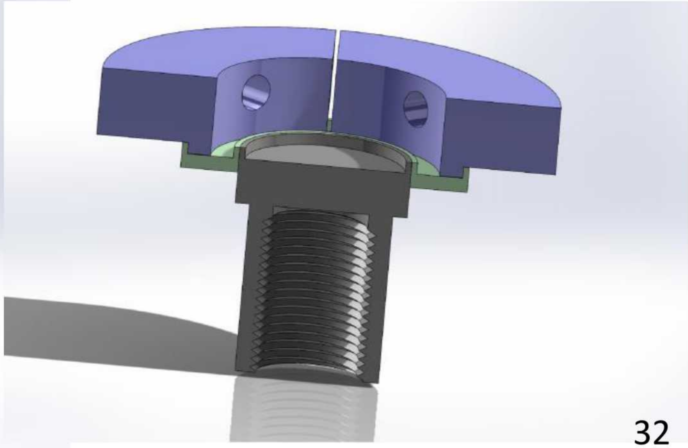
Mechanically Imposing a Range of Application Stress States

- Uniaxial Tension or compression loading
- Additional radial loading mechanically simulates pressurization
- [Or Additional torsional loading imposes shear loading along weld]
- Laser weld loaded in shear across weld depth (0.030”)
- Simple geometry changes will have large effect on applied stress state
- Geometry to match observed corner weld failures
- Elevated temperature to 800ºC
- Variable applied rates of loading
- DIC on weld surface



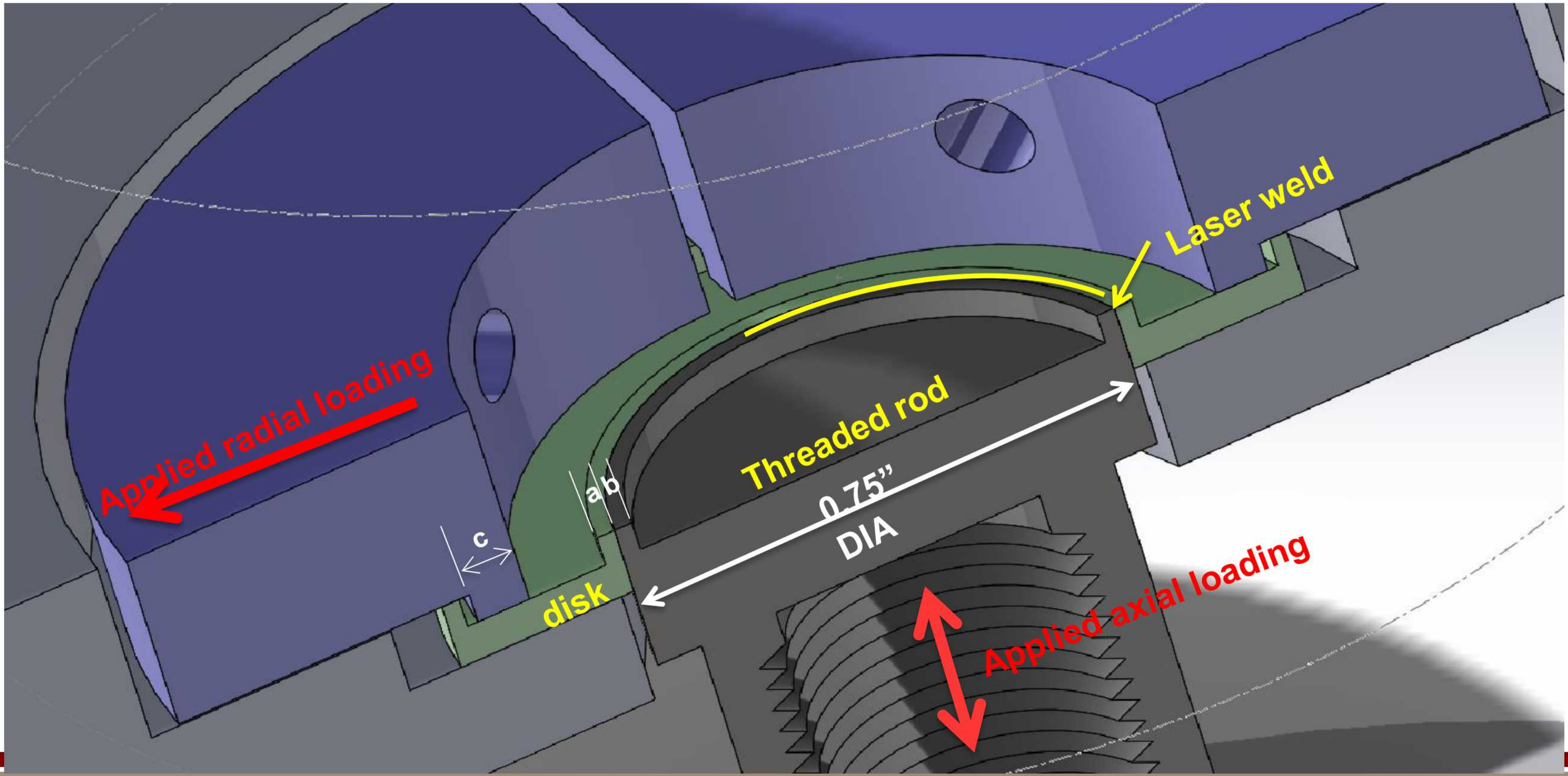




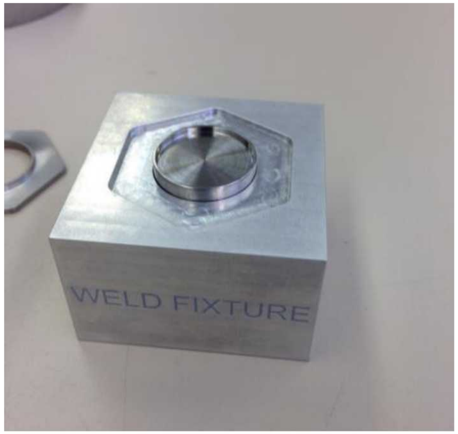


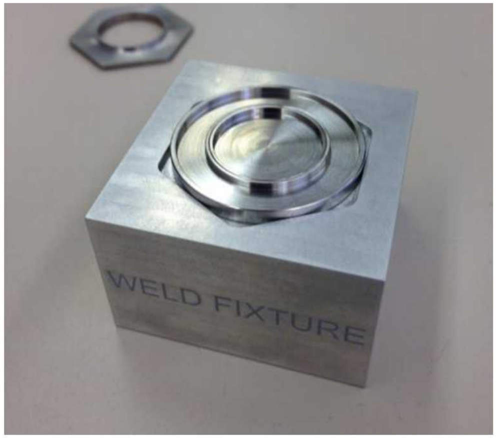
Notes to Analysts to Assist in Geometrical Designs to Match Stress States during Pressurization of Exclusion Region

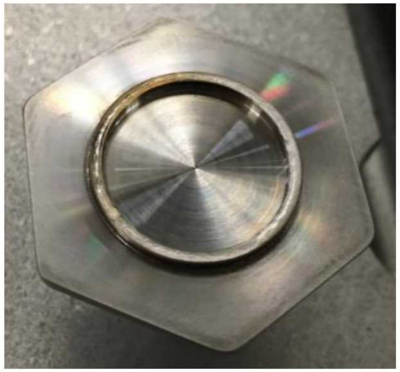
- **Partial penetration laser weld connects threaded rod to disk - between a and b, around top surface of where they touch**
- **a and b are currently drawn at 0.10”**
- **Changing b will vary relative amounts of bending/shear loading on laser weld – could be from 0.050” to a solid center**
- **Dimension of c is important for compression loading (pushing up on pin) – will affect bend/shear loading on laser weld. For mostly shear, inner edge of c should be very close to outer wall of a.**
- **Need analyses to size the two 304L VAR parts (green disk and charcoal threaded rod), 0.75” DIA is fixed. Would like to match stress state in critical portions of exclusion region.**
- **It would be okay to have a few variations to vary applied stress state, but more than a few is not feasible, so bounding application stress state is important.**

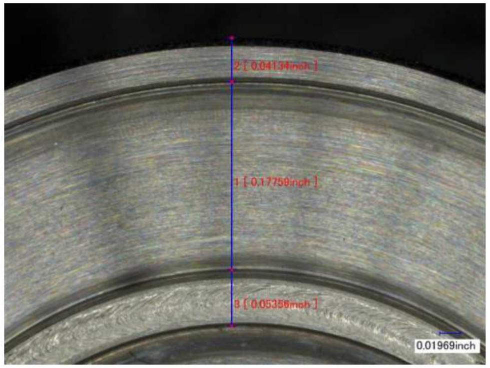


Partial Penetration Laser Weld Setup



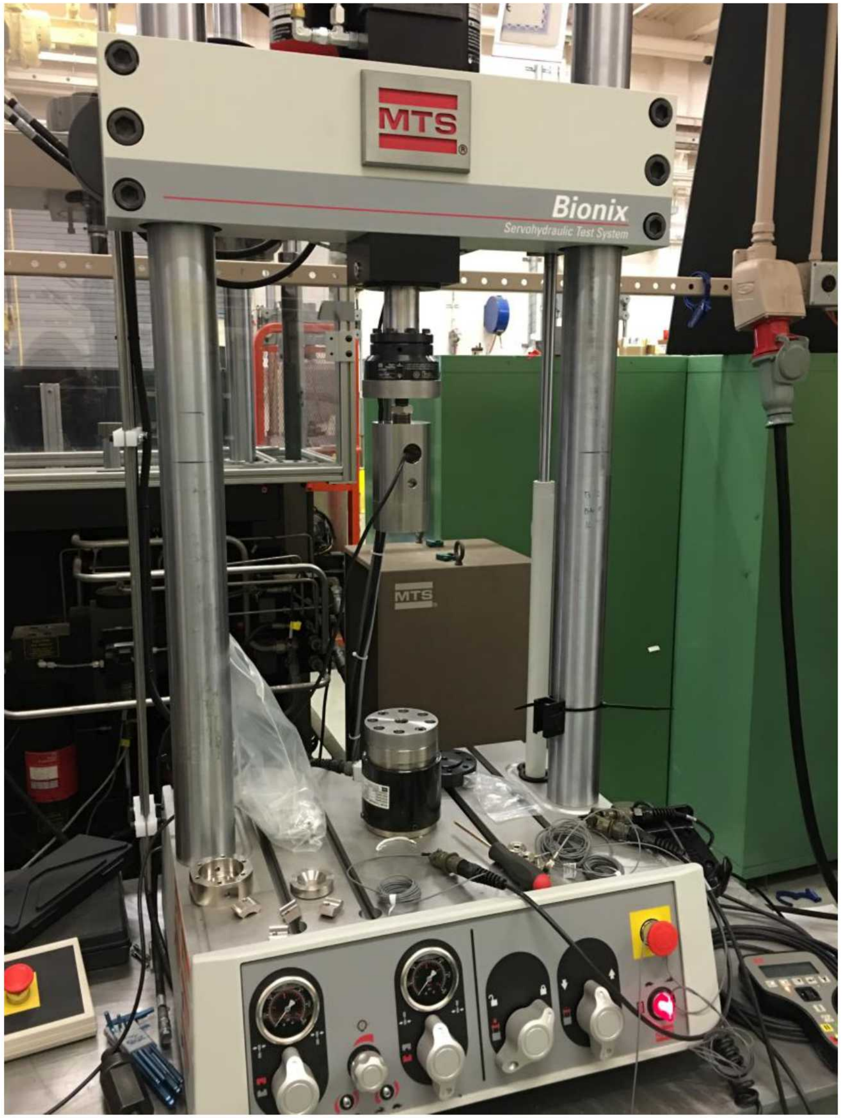






Customizable laser weld specimen for triaxial loading to failure at elevated temperatures, radial loading (left) and torsional loading (right).

Experimental Setup for Multi-Axial Loading of Laser Welded Specimens: 3Kip A/T MTS Test frame



- Setup includes camera to view laser weld during loading/deformation, DIC possible
- Isothermal testing up to 800C, custom induction coil and heating
- Additional 4 load cells to monitor radial load response
- Tension/Compression + Radial
- Tension/Compression + Torsional

- Several advantages:
  - Eliminated runaway failure (pressure – load controlled)
  - Controlled failure, can measure more than pressure and time
- Testing in progress, results soon

Summary

Sandia National Laboratories

- Pressurization/Breach scenarios require coupled thermo-mechanical characterization and validation experiments
- Each time a new validation scheme was proposed/developed a new material stock or form was used – full characterization required each time due to variability of 304L with specification and form
- Temperature, Rate and (preferably) History dependent constitutive model required to adequately describe material behavior in validation simulations
  - Temperature, strain rate space
  - Using tension data only may not work well in predicting failure in multi-axial loaded structures
- Experimental Approach 1 was quite successful, data continues to be used
- Experimental Approach 2 was agreed to after much reservation, which turned out to be warranted
- Experimental Approach 3 has significant advantages and we have high hopes for the results
  - No pressurization (less safety concerns)
  - Can run in load or displacement control (not runaway pressure failure)
  - Can measure local stress response
  - Completely tailorable stress state using geometry and loading parameters