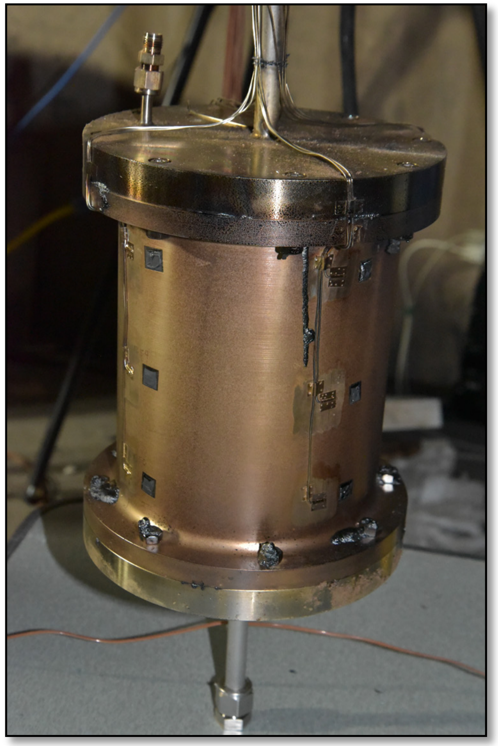
SAND2022-3311C

Minimally Invasive Instrumentation for Mock Fire Scenarios


post-test w/o x-ray DIC


post-test with x-ray DIC

Brent C. Houchens, Elizabeth M.C. Jones, Ethan T. Zepper, Andrew W. Murphy, Enrico Quintana

Sandia National Laboratories

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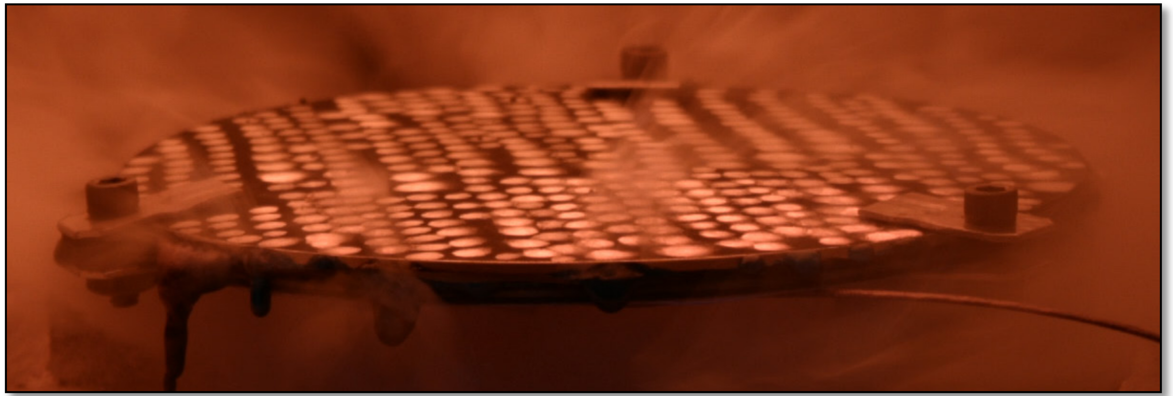
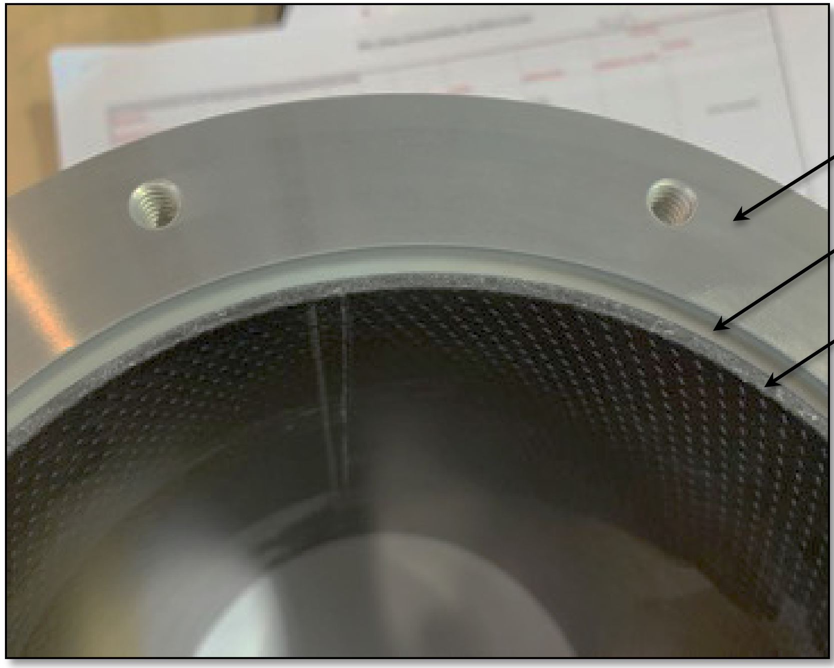
Motivation and Research Questions



- Motivation
  - Develop minimally invasive instrumentation and diagnostics for fire environment research
  - Explain observed melting phenomena from flat plate tests
- Research questions
  - Can x-ray DIC (digital image correlation) be used on a surface without significant impact to radiant heat transfer?
  - Are spring-loaded thermocouples effective for temperature measurements on a moving, decomposing organic surface?
- Approach
  - Single repeat of an aluminum-clad composite pressure vessel subject to a mock fire environment
  - One test with x-ray DIC and reduced thermocouples, and one test without x-ray DIC
- Outline
  - Test article and oven description
  - Instrumentation with focus on spring-loaded interior TCs and exterior x-ray DIC with tantalum
  - Results and post-test model comparison

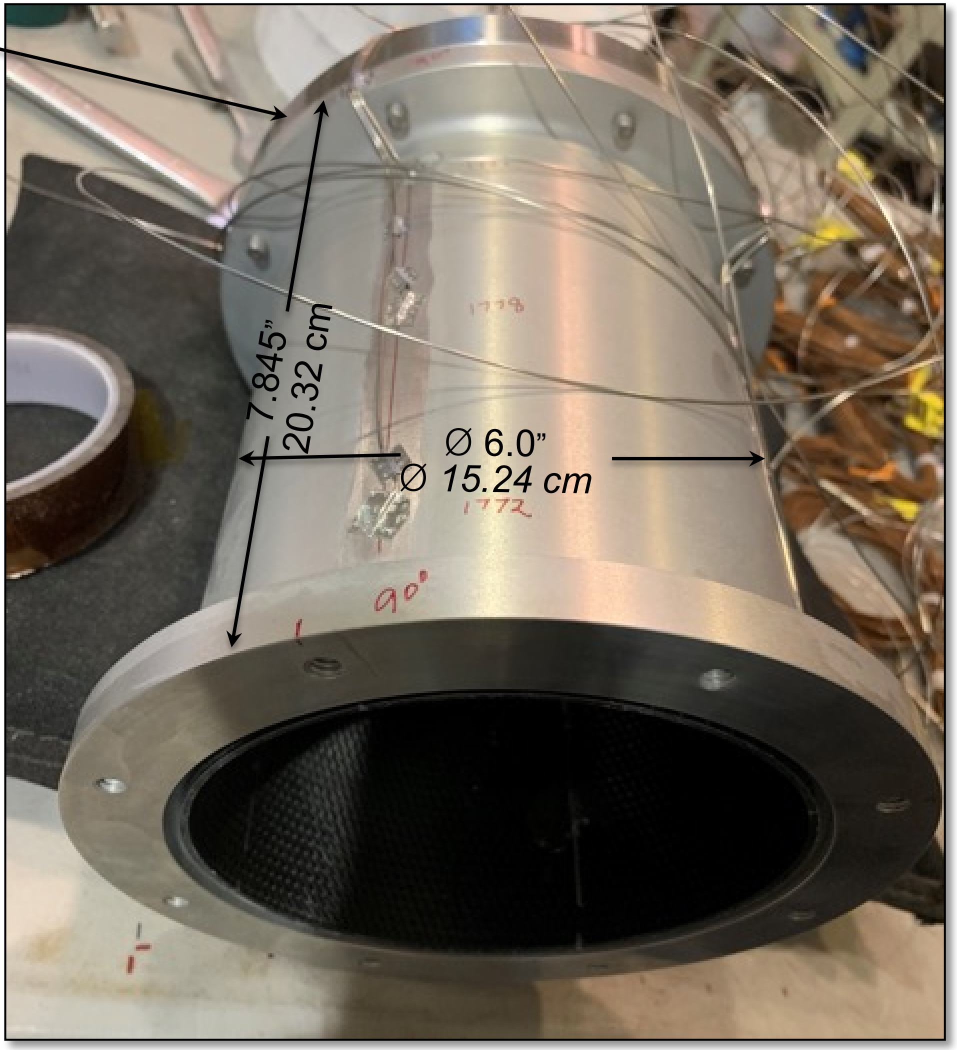
Test Article Design: Size and Carbon Fiber Layup

- Al-clad composite cylinder
  - sealed and backfilled with nitrogen (10 purges)



composite layup by Brian McKay, infusion resining by April Nissen

Part	Thickness (in.)	Thickness (mm)
Al-6061 Case	0.09375	2.4
Infusion Resin	0.120	3.0
Composite	0.090	2.3



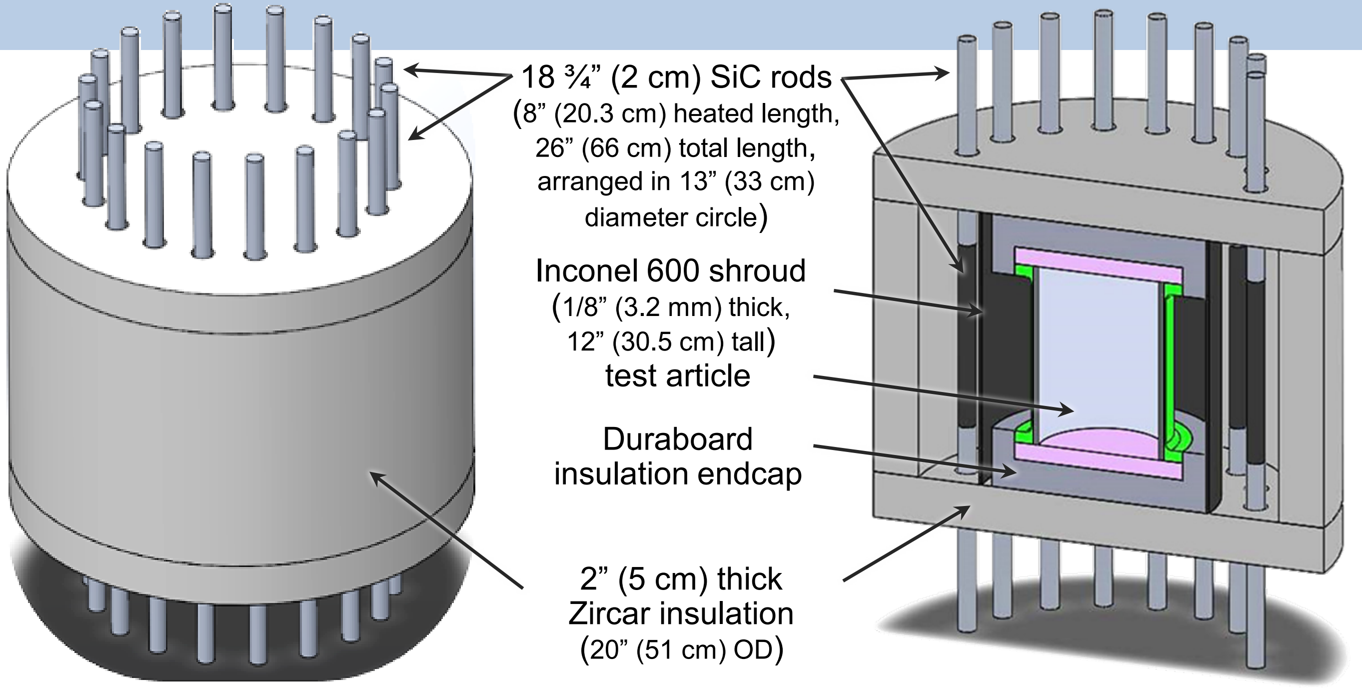
Al-cladding / SS endcap design courtesy of Kevin Connelly

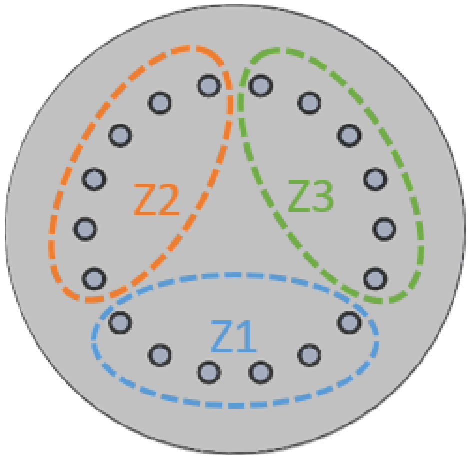
Oven Design and Thermal Insults

- Oven
  - silicon carbide fast-response rod heater
  - heat 1/8” (3.2 mm) -thick Inconel shroud which re-radiates to test unit
    - provides axisymmetric boundary condition
  - 2” (5 cm) Zircar Alumina-Silica AXL insulation

- Boundary Conditions
  - total test of 2.5 hours
  - target quasi-steady temperatures of
    - 250 °C
    - 270 °C
    - 285 °C
    - 300 °C

    - note organics begin to decompose ~275 °C





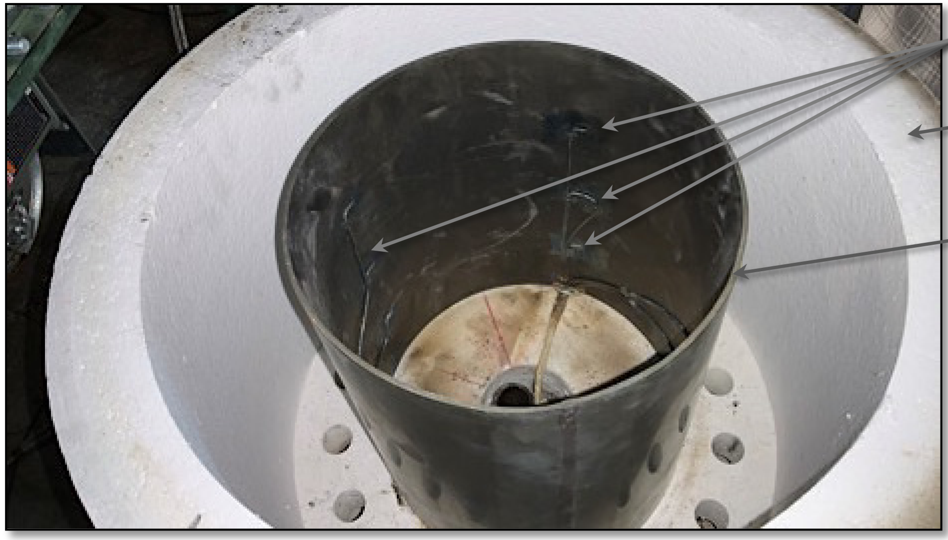
3 zones of 6 rods

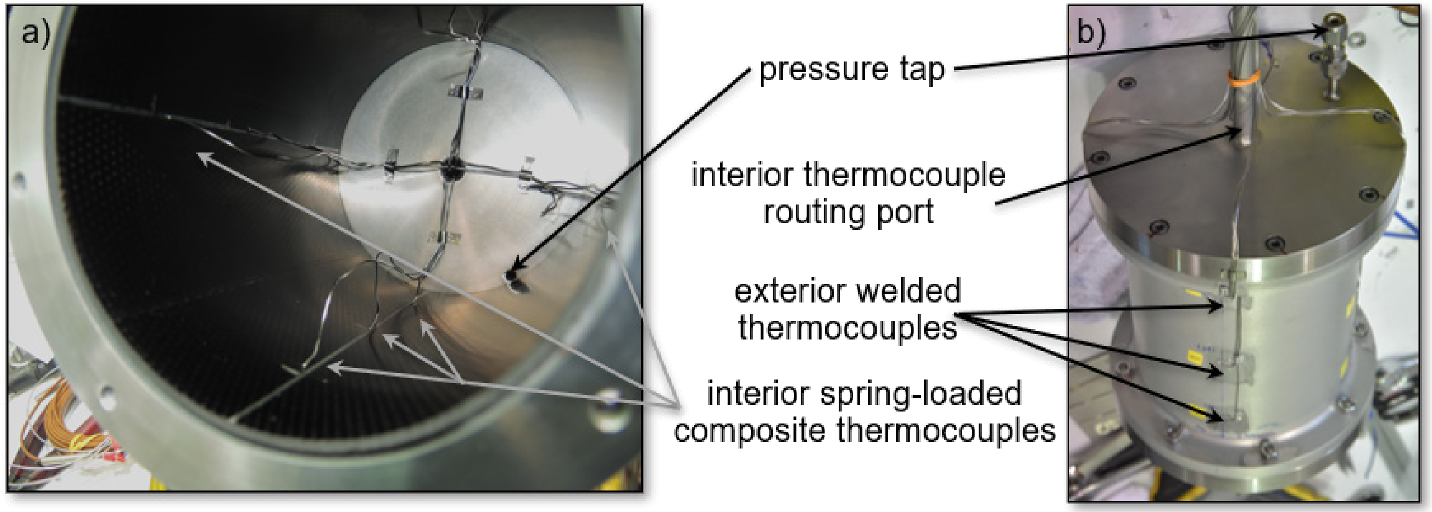
Each bank pulls a maximum of 12.4kW at 110W/in^2 surface loading or 3.4kW at 30W/in^2.

Utilizes a 240V/70A or 480V/70A controller.

Instrumentation: Temperature and Pressure

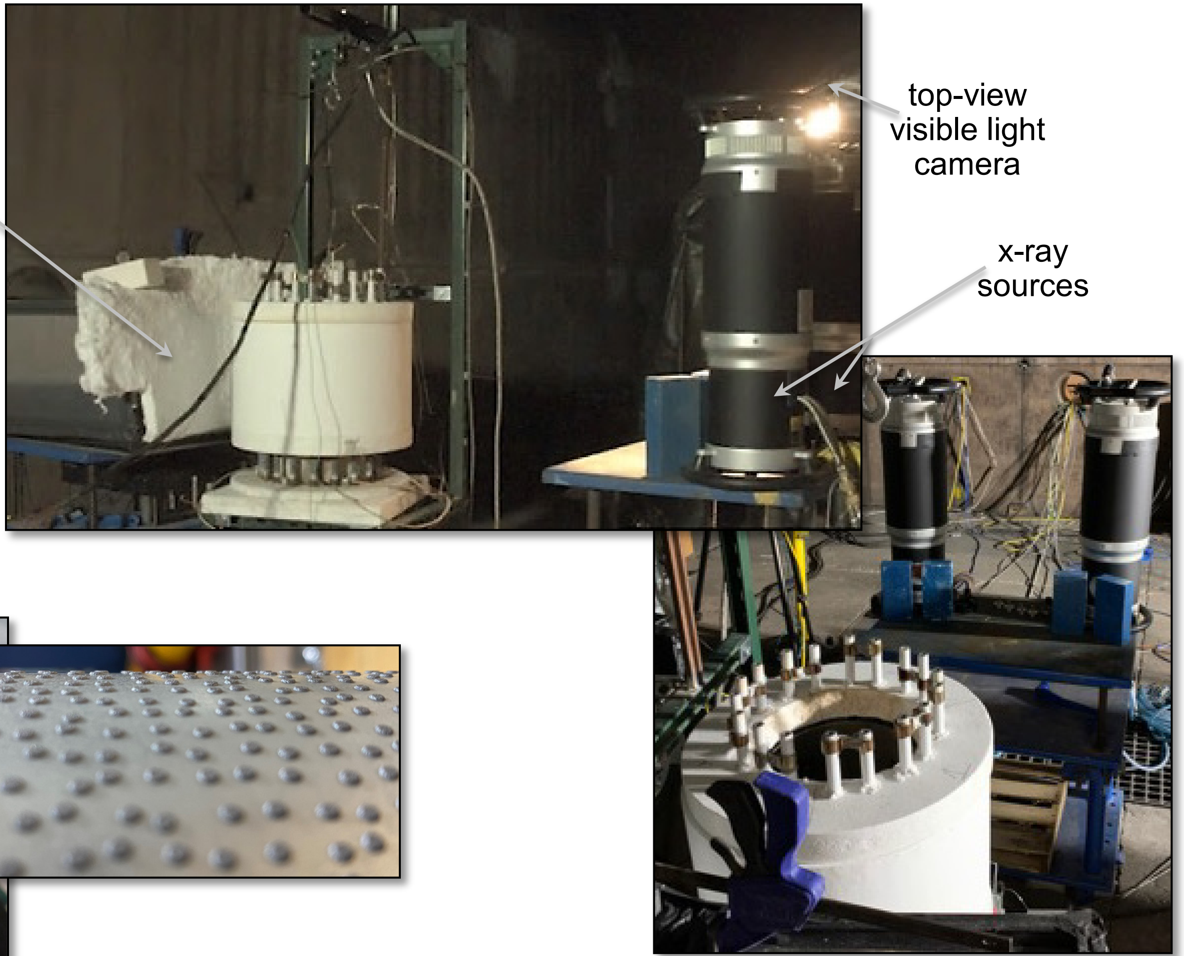
- Thermocouples (TCs) on oven
  - oven shroud interior
  - oven insulation (not shown)
    - 1" deep into wall from exterior
  - ambient (air) below oven (not shown)
- TCs on test article
  - exterior test article surface
    - 4 azimuthal locations on unit w/o DIC
    - 2 azimuthal locations on unit with x-ray DIC
  - interior composite surface spring-loaded
    - 4 azimuthal locations on unit w/o DIC
    - 2 azimuthal locations on unit with x-ray DIC
  - interior void space
  - stainless steel endcap
- Pressure gauges
  - redundant (2) gauges to internal void space
    - 500 psig and 1000 psig max scales

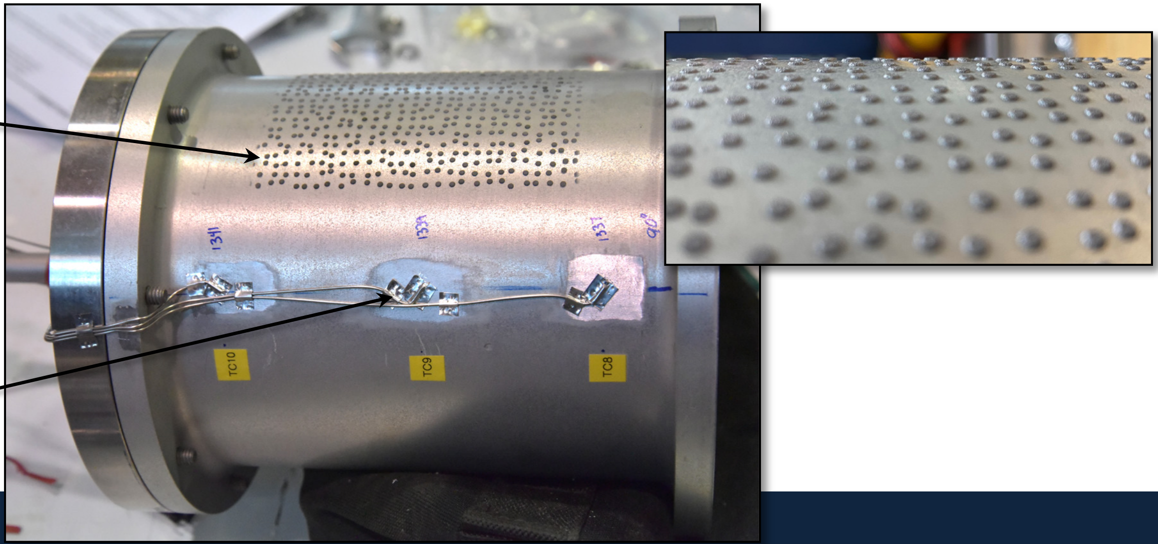




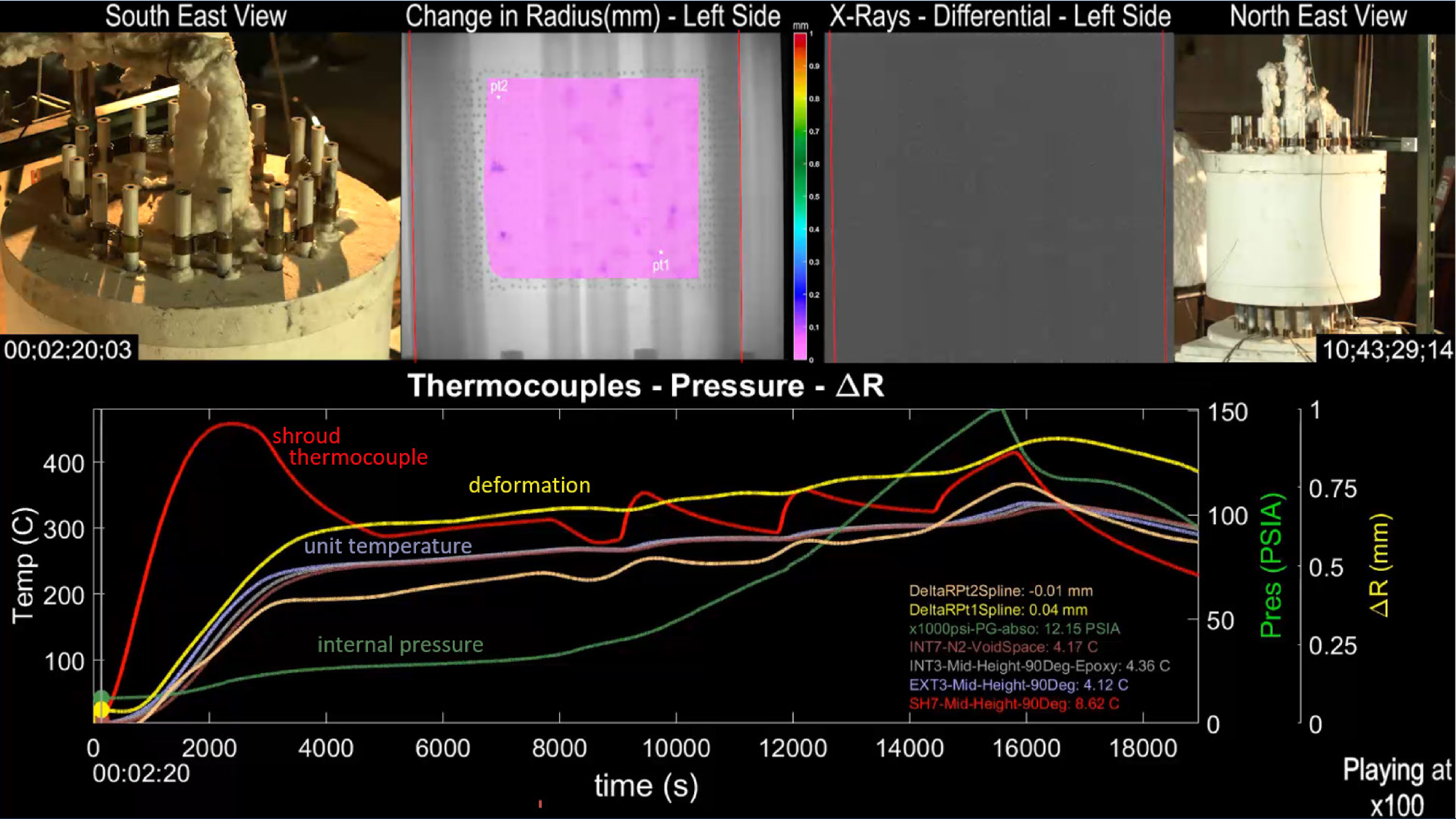
Instrumentation: X-ray with DIC and Photometrics

- Photometrics
  - two visible light video cameras
- x-ray
  - real-time x-ray used in both tests to observe unit inside oven
- Stereo x-ray DIC with Tantalum used in one test
  - real-time visualization of surface deformation due to thermal expansion and/or pressurization
    - test suite represents first application of x-ray DIC to material characterization test



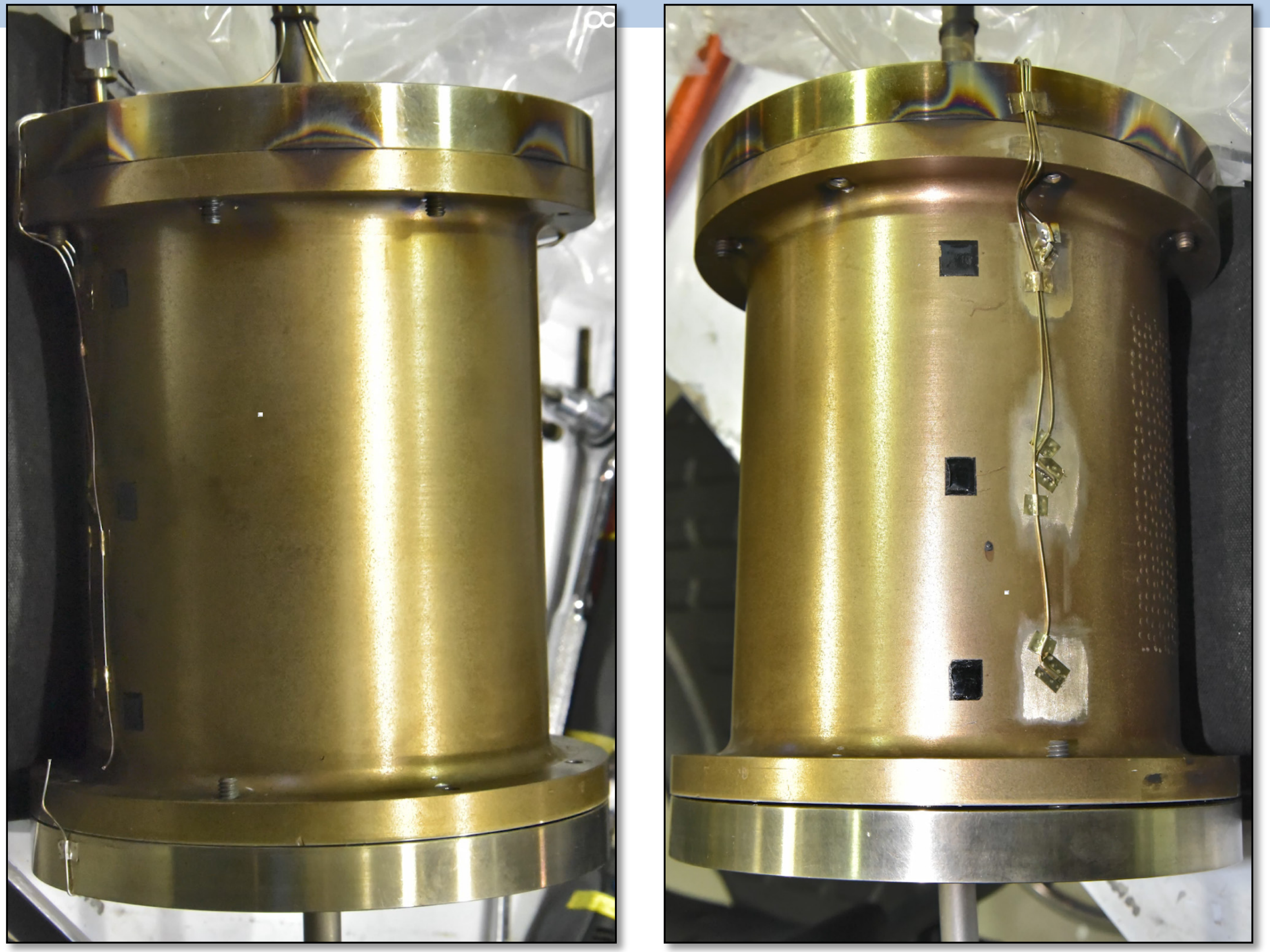


TEST WITH X-RAY DIC


South East View
Change in Radius(mm) - Left Side
X-Rays - Differential - Left Side
North East View
mm
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
pt2
pt1
00;02;20;03
10;43;29;14
Thermocouples - Pressure - ΔR
shroud
thermocouple
deformation
unit temperature
internal pressure
DeltaRPt2Spline: -0.01 mm
DeltaRPt1Spline: 0.04 mm
x1000psi-PG-abso: 12.15 PSIA
INT7-N2-VoidSpace: 4.17 C
INT3-Mid-Height-90Deg-Epoxy: 4.36 C
EXT3-Mid-Height-90Deg: 4.12 C
SH7-Mid-Height-90Deg: 8.62 C
Temp (C)
400
300
200
100
Pres (PSIA)
150
100
50
0
ΔR (mm)
1
0.75
0.5
0.25
0
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
00:02:20
time (s)
Playing at
x100

Notable Test Highlights

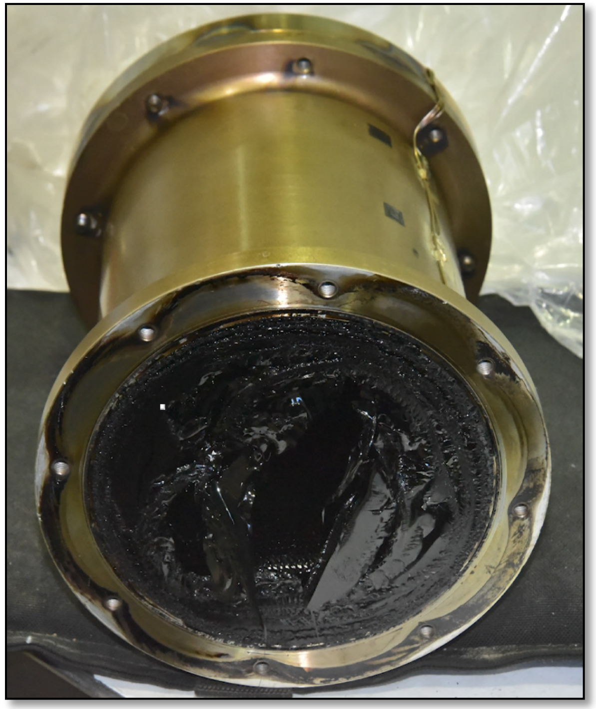
- Four quasi-steady holds achieved
  - 247 °C: minimal pressurization likely from water vapor and unreacted volatiles in composite
  - 268, 284.5, and 303.5 °C: significant pressurization from decomposing organics
- No measurable plastic deformation
  - all deformation seen in x-ray DIC due to reversible thermal expansion
- External case max temperature ~328 °C at onset of leak (151 psia)
  - venting between bolts when al-flange softens
- External TCs and Tantalum pattern survived

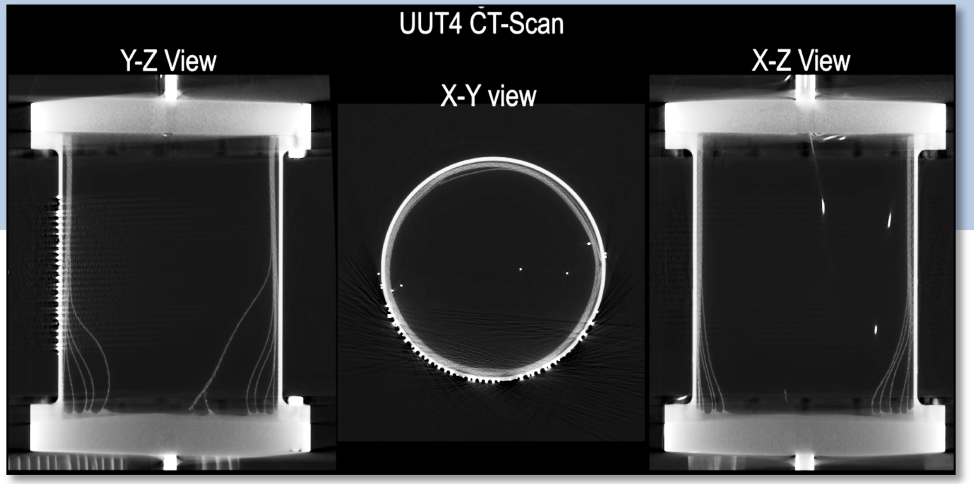


post-test scan showing leak pattern at top endcap, and survival of welded external TCs and Ta pattern

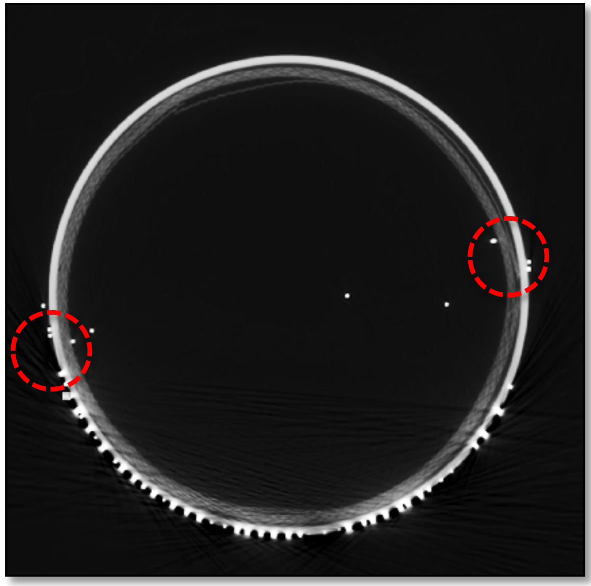
Interior Features

- Melted infusion resin verified at bottom lid
- Spring-loaded TCs remained in contact with composite

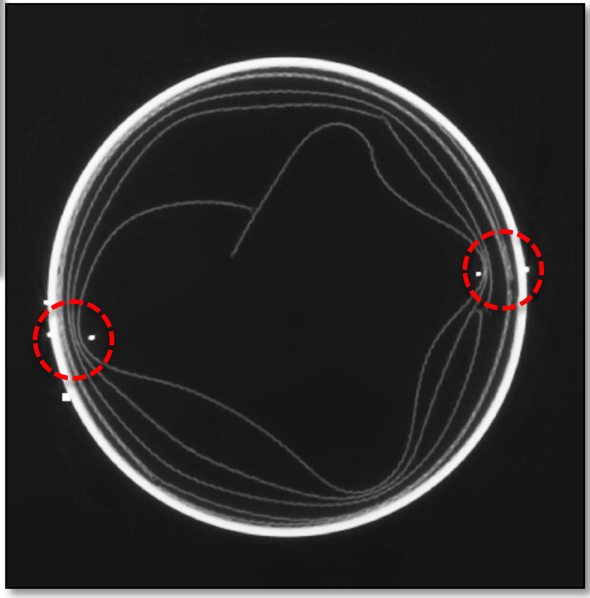




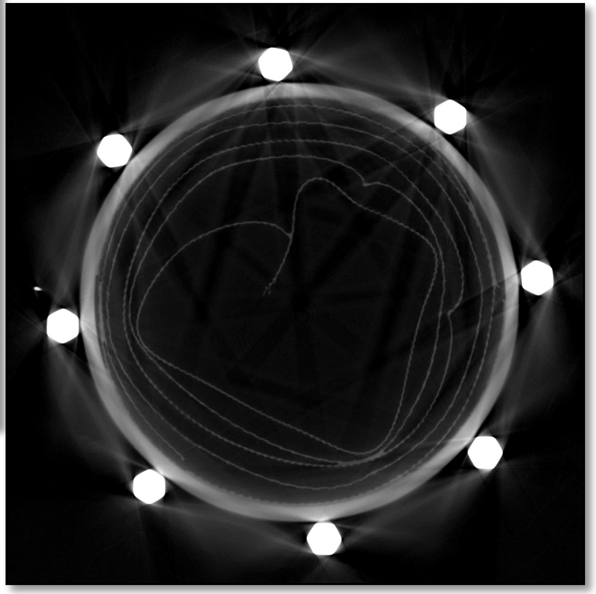
post-test CT scans, near bottom of unit



middle TCs

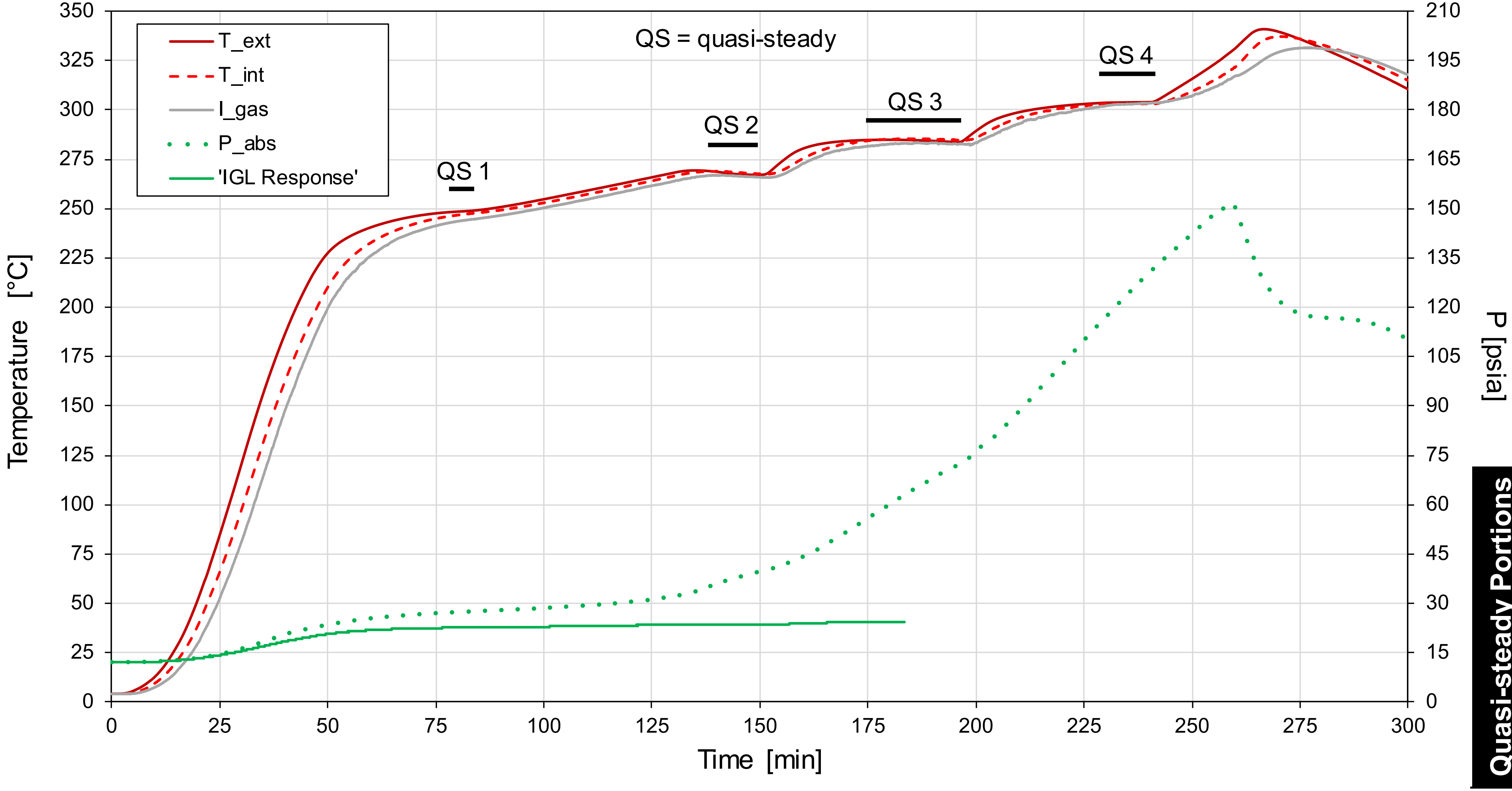


lower TCs



near bottom of unit

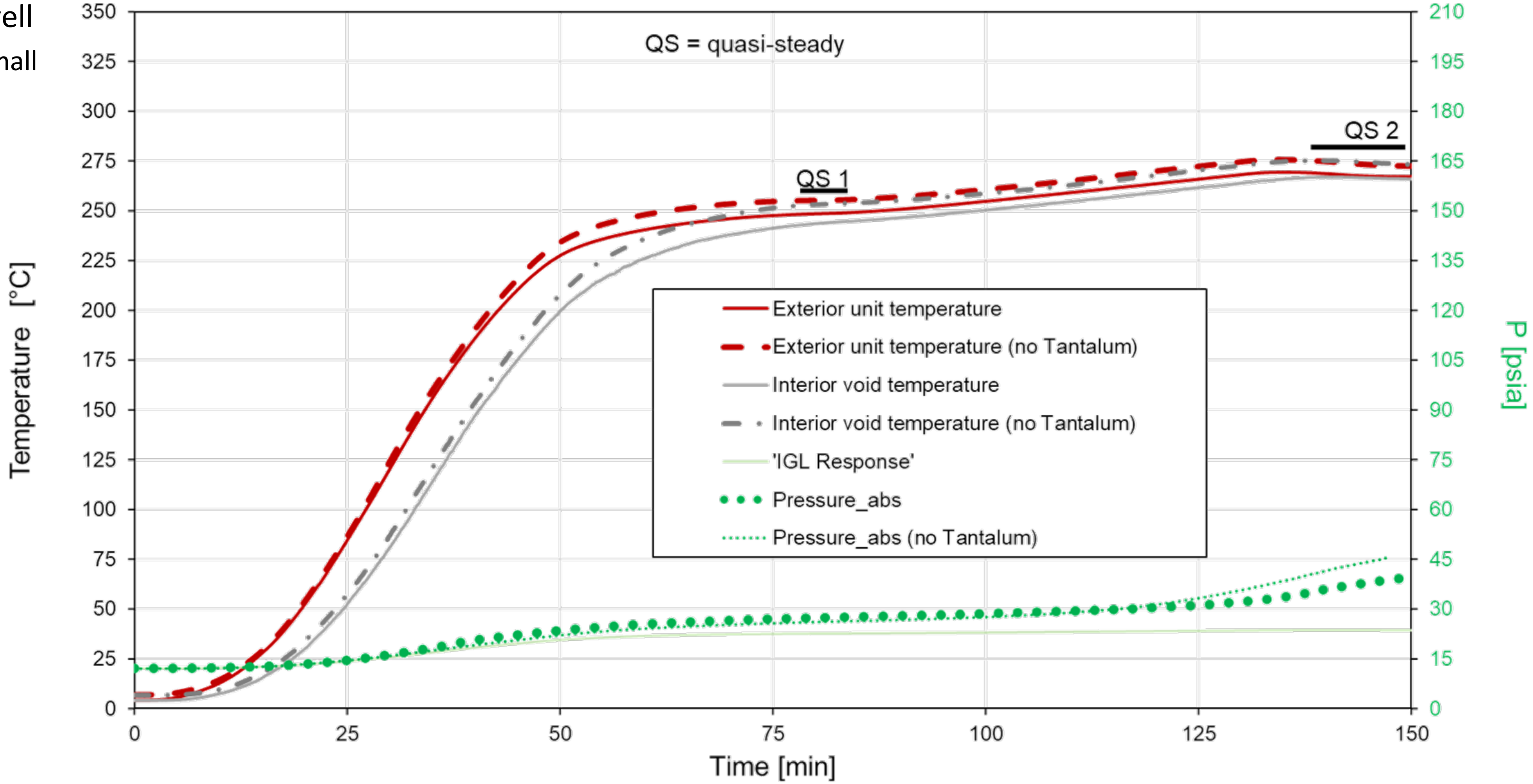
Test with X-ray DIC - Unit Temperatures and Pressure



		T_{ext_mid} [°C]	Time Range [min]
Quasi-steady Portions	1st	247 (± 1)	78.5 - 83.5
	2nd	268 (± 1)	138.5 - 149
	3rd	284.5 (± 1)	175 - 196
	4th	303.5 (± 1)	229 - 241

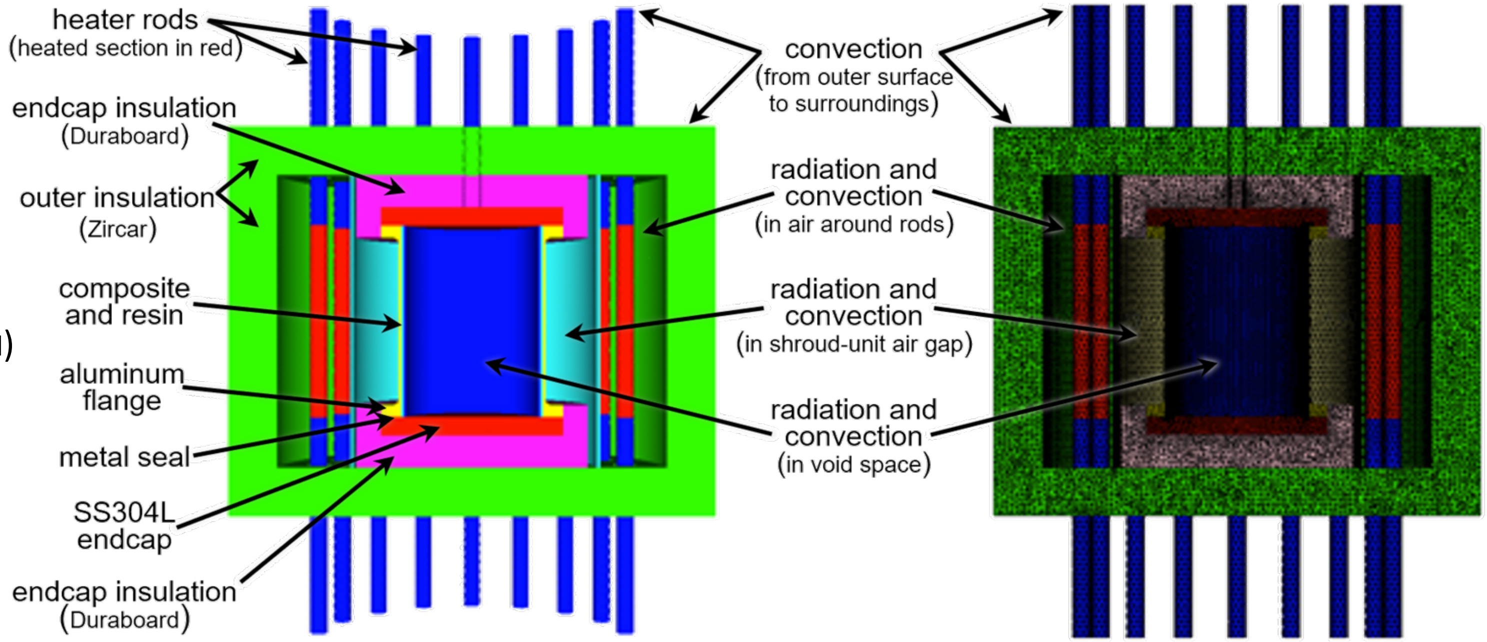
Repeat Test Comparison for 150 minutes

- Oven power was the same up to 150 min (2 hr, 30 min)
  - compares relatively well
    - likely Ta impact is small
  - Exterior QS soaks
    - QS 1: 255 vs 247 °C
    - QS 2: 275 vs 268 °C



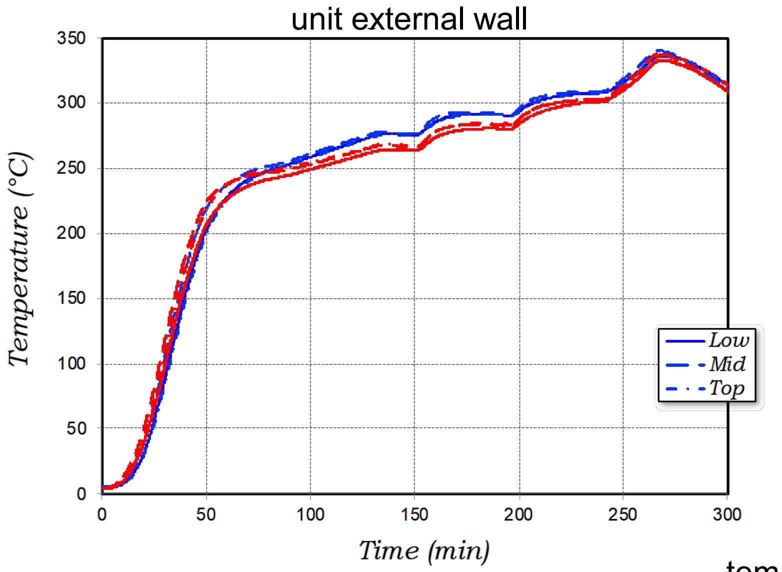
Pre- and Post-Test Simulations

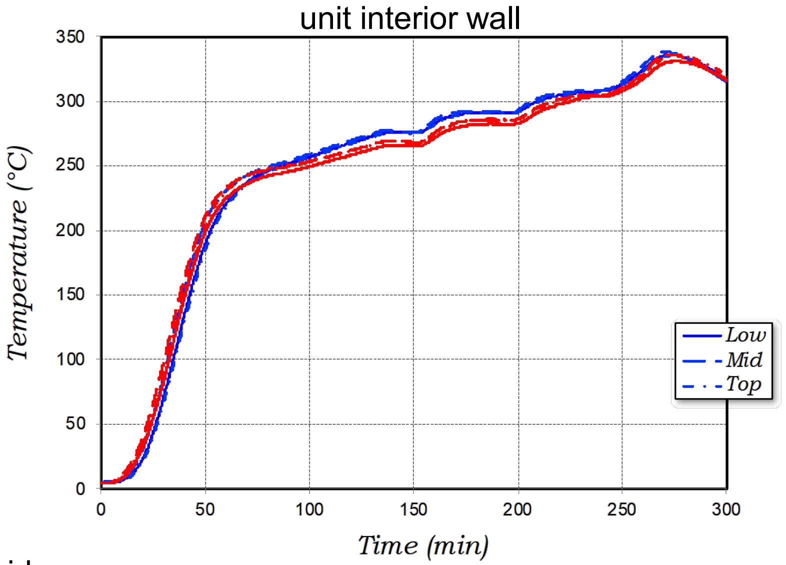
- Transient simulations in Sierra Thermal/Fluids (Aria)
  - ~4.75 M tet element mesh
    - average element size = 2mm
    - ~3.1 M tet elements in solids
    - ~1.6 M tet elements in voids
  - Governing equation: $\rho c_P \frac{\partial T}{\partial t} = k\nabla^2 T + \dot{Q}$
    - Conduction in all solid bodies and internal voids
    - Convection on all exposed surfaces (internal and external)
      $$q = h(T)(T_s - T_b)$$
    - Radiation on all internal surfaces
      $$q_n = \sigma\epsilon T^4 - \alpha G$$
  - Adaptive time-stepping (maximum timestep = 15s)
- Pre-test simulations provide
  - heater power profiles for target thermal response
  - pressure estimates for decomposing organics
  - instrumentation recommendations and safety estimates
- Post-test simulations use actual heater power from experiments



see Murphy *et al.*, Response of Aluminum-skinned Carbon-Fiber-Epoxy to Heating by an Adjacent Fire, *12th US National Combustion Meeting*, 2021 for details

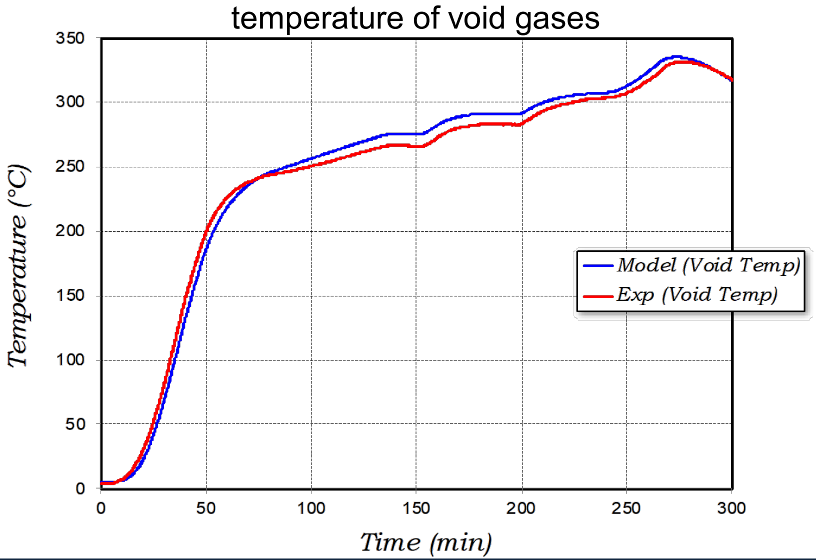
Post-test Simulations Compared to Experiments

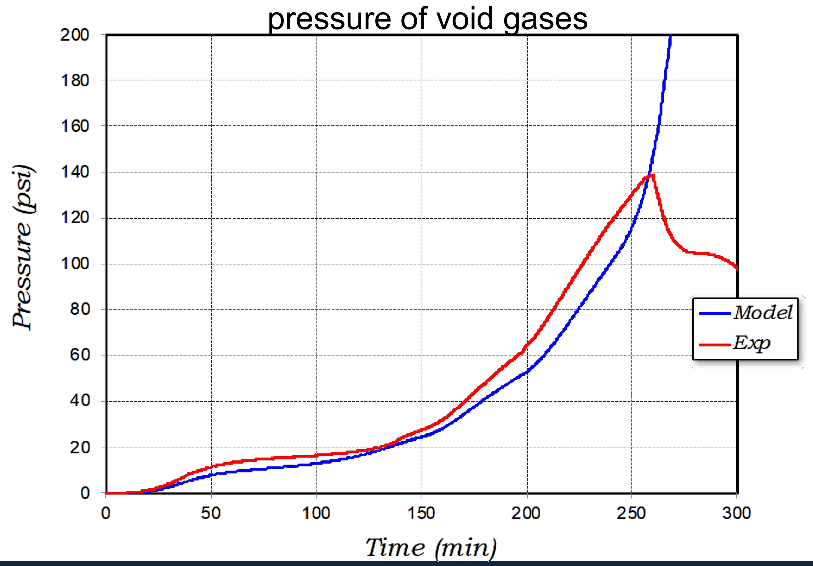




red (experiments), blue (simulation)

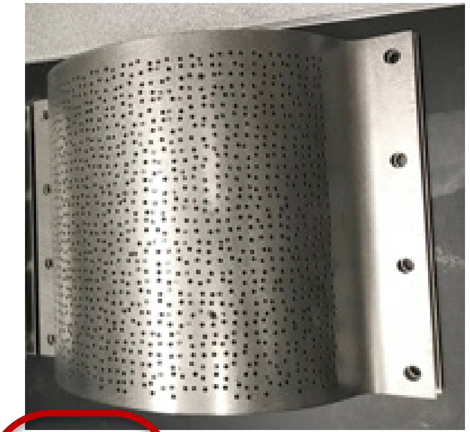
- Quasi-steady temperatures slightly overpredicted
  - may be due to insulation c_P modification from first test

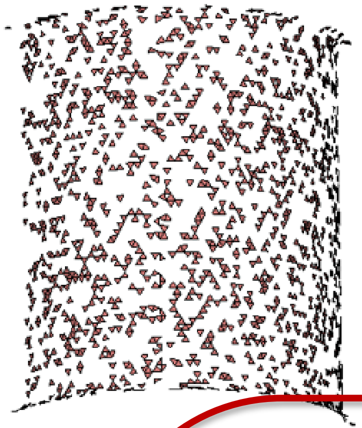




Modeling Tantalum Patterning Effects

- Python script randomly selects X% of tet element faces on unit surface to become a shell of tantalum dots
  - Based on mesh size, modeled “diameter” of TA dots = ~3mm
  - Using shell feature in Aria, Ta dots assigned material model
    - investigated high, low and nominal thermal diffusivity α values $\frac{\partial T}{\partial t} = \alpha \nabla^2 T$
    - note emissivity of anodized aluminum is ~0.69 at temperatures studies





Property	Nominal Value (Units)
Thermal Conductivity	58 W/m-K
Specific Heat Capacity	138.1644 J/kg-K
Density	16607.9 kg/m^3
Emissivity	0.45

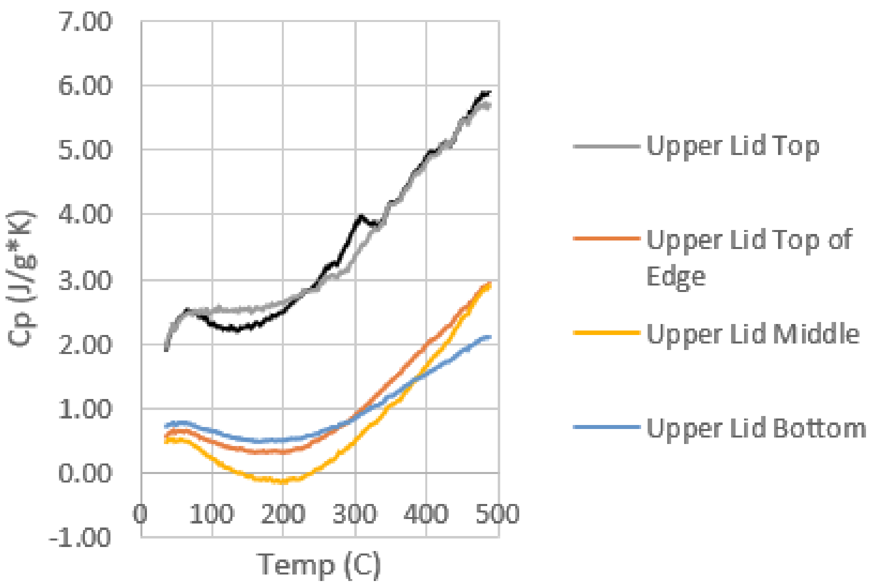
base Ta properties

Scenario represented	Properties	Expected outcomes	Emissivity (-)	Thermal conductivity k (W/m-K)	Density ρ (kg/m³)	Thermal Diffusivity $\alpha = k/\rho c_p$ (m²/s)	Thickness (μm)	Surface Coverage
Nominal Ta dot properties thought to be closest to truth	Nominal thermal diffusivity	True impact of surface temperature due to Ta dots	0.285	0.33 * base Ta	0.97 * base Ta	8.6×10^{-6}	210	18%
Highly reflective, low thermal conductivity, thick Ta dots, high coverage	Low emissivity (low absorptivity via Kirchhoff's law), and slightly lower diffusivity	Cold spots on surface under Ta dots compared to nominal	0.1	0.33 * base Ta	base Ta	8.3×10^{-6}	400	18%
Higher emissivity, high conductivity, lower density, thin Ta dots with low coverage	Much higher thermal diffusivity, with much higher emissivity and much thinner dots	Overall reduced influence of Ta dots compared to no dots	0.45	base Ta	0.90 * base Ta	2.8×10^{-5}	150	12%

⇒ all scenarios have less than a 1 °C influence on the maximum outer case temperature below the melting point of aluminum

Other Dominant Sources of Uncertainty

- comparisons between repeats were relatively good
  - w/o Tantalum dots, quasi-steady soaks at 255 °C and 275 °C
  - with Tantalum dots, quasi-steady soaks at 247 °C and 268 °C
    - less than 4% difference between tests
- modeling showed Ta dots unlikely source of difference between tests
- focus shifted to other sources
  - insulation was reused to minimize disturbance of test/shroud geometry
    - insulation thermal properties surprisingly degraded after just 2 tests at modest (≤ 500 °C) temperatures
  - shroud emissivity another potential source of uncertainty
    - strong, proportional impact on results
  - both warrant additional consideration and further testing



black curve is pristine insulation

measurements by Jacob Maher

Conclusions and Future Work

- tantalum used for x-ray DIC seems to have minimal impact on temperature field
  - highly promising, minimally invasive measurement technique
- spring loaded TCs proved effective throughout decomposition
  - avoids additional organics introduced by traditional epoxy methods
- more work on thermal degradation of insulation is needed

HUGE Thanks…

to the test team and everyone who supported this project

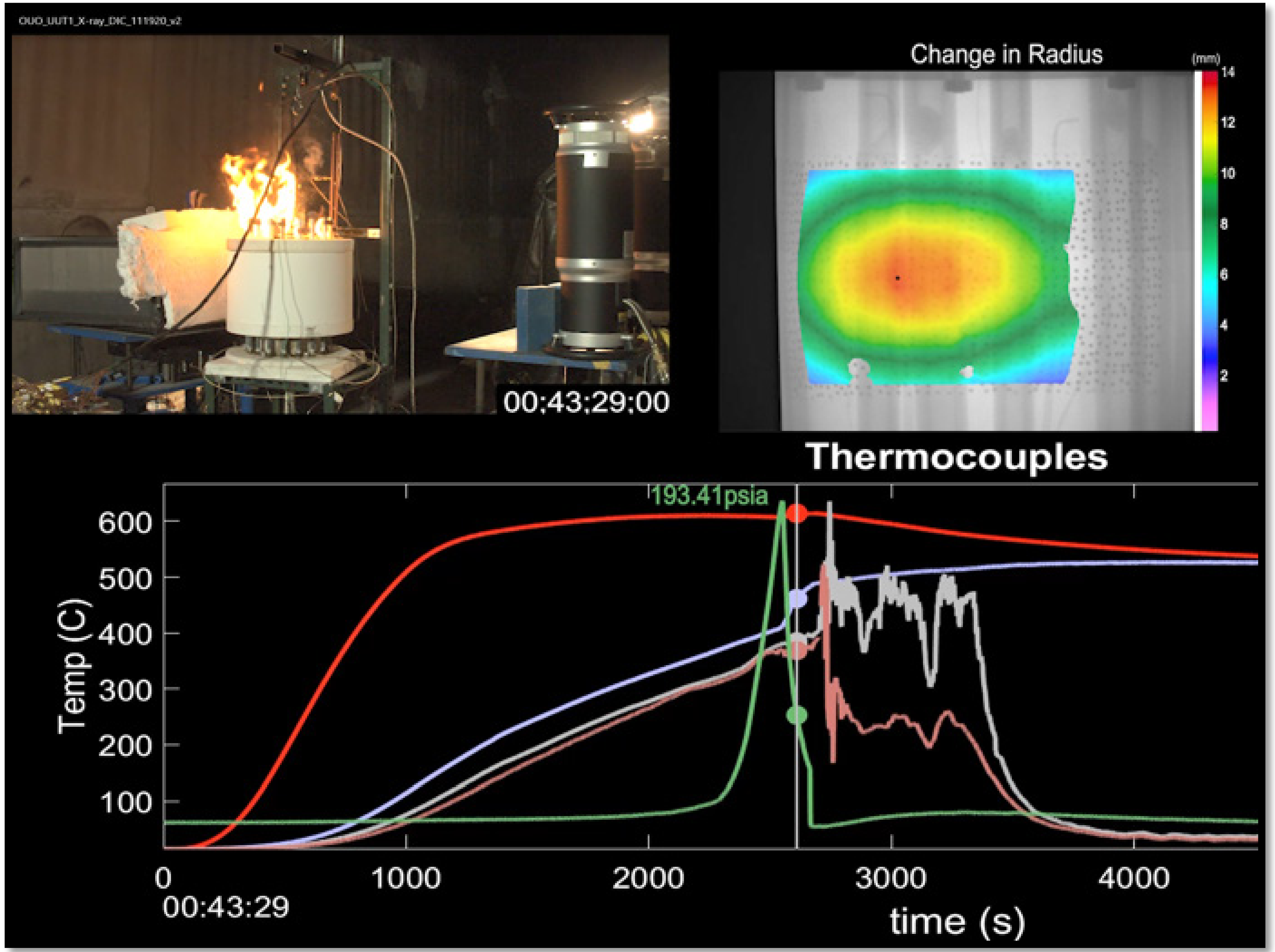
first and foremost, Daniel Roybal and Randy Foster, who set up the experiment and diagnostics

- Thermal Test Complex support and experiment backup
  - Jerry Koenig, Jason Goar, June Stanley and Caroline Winters
- Photometrics
  - Ryan Flanagan, Alvaro Cruz-Cabrera, Rana Weaver, Ed Bystrom
- Expertise
  - Terry Johnson, Walt Gill, Jill Suo-Anttila, Vince Valdez
- Modeling
  - John Hewson, Sarah Scott, Ari Frankel, Ryan Keedy
- Leveraged unit design / models from DE/ASC collaborators
  - Bonnie Antoun, Kevin Connelly, Lauren Beghini
- Sealing design support
  - Alex Hanson for bolt loading, Terry concepts and brainstorming
- Modeling and experimental support
  - Chris Dillon, John Tencer, Rad Bozinoski
- Spray lab
  - Jake Mahaffey and Joe Padilla
- Aluminum emissivity measurements
  - Mike Montoya
- Unit manufacturing
  - Ken DeMone (ABQ machinist)
- TGA/DSC
  - Karla Reyes, Adriana Pavia-Sanders, Sean Maharrey (among others)
    Analysts and Modelers: Ari Frankel, Sarah Scott, Ryan Keedy, Ellen Wagman, Matt Kury
    Sample Prep: April Nissen, Brian McKay, Caleb Lystrup

QUESTIONS?

BACKUP SLIDES

Notable Features

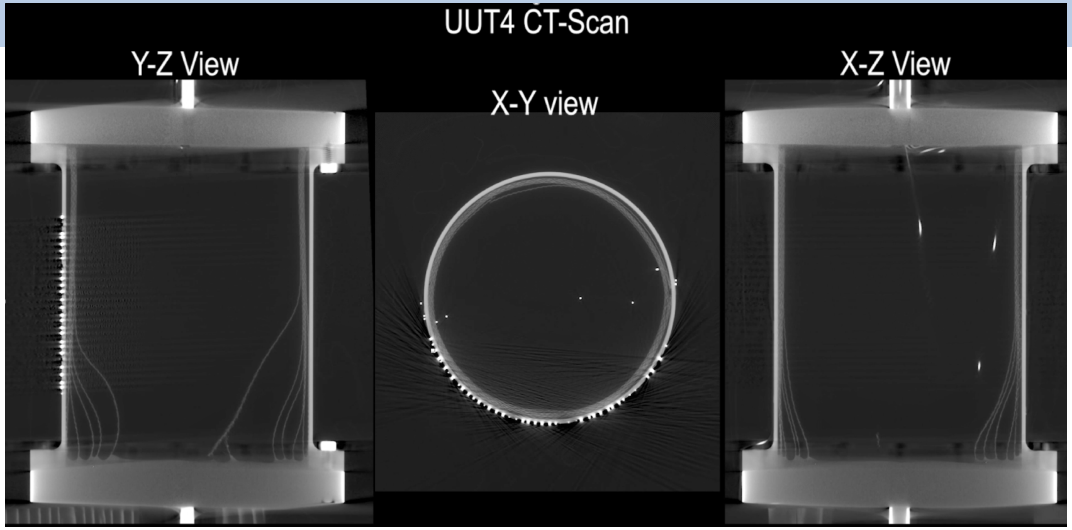


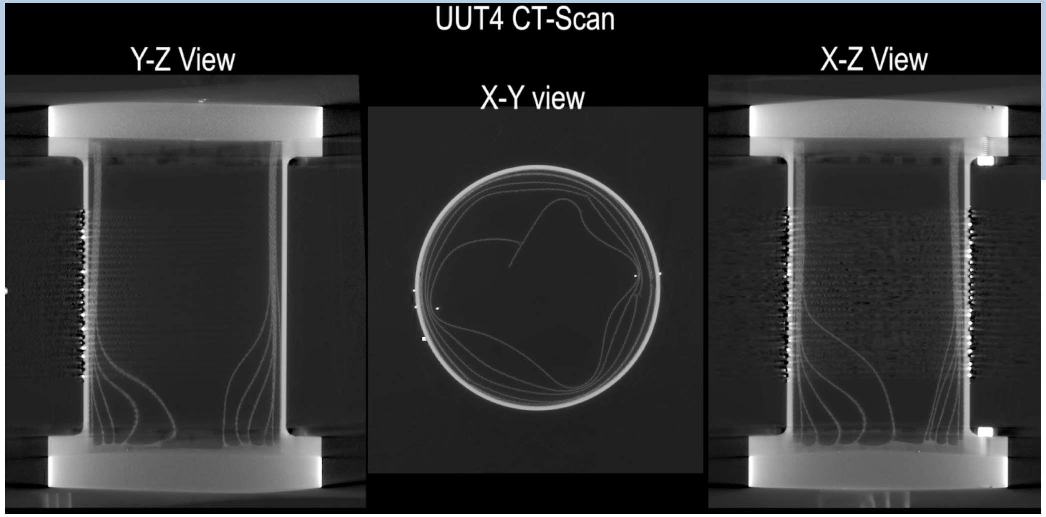
video compilation, courtesy Alvaro Cruz-Cabrera

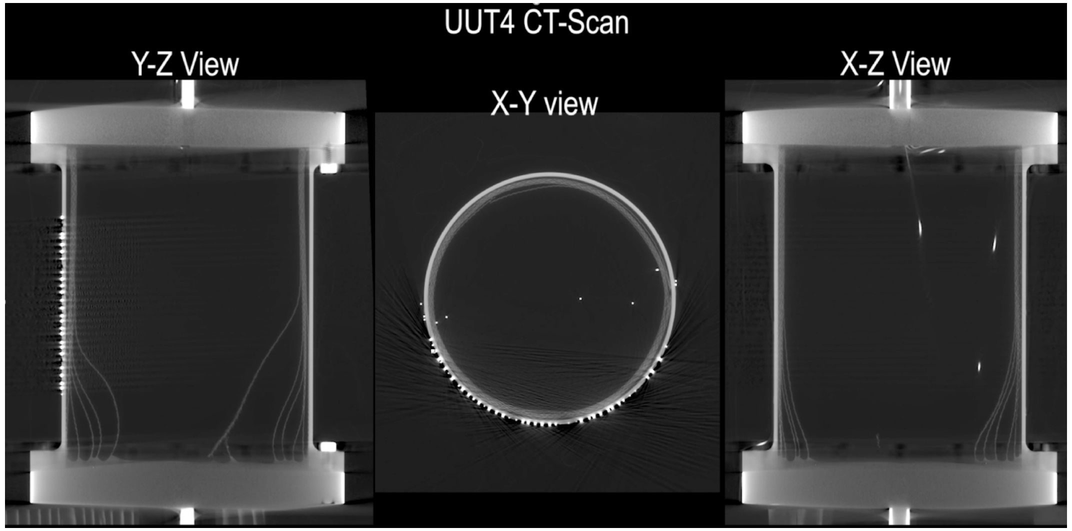
- Generated nearly 200 psia at peak
  - some gas observed leaking from pressure line
    - max pressure likely higher with better seal
- Bulging occurred just after start of fire
  - case still partially pressurized
  - external case temperature spikes w fire
  - seal leaks in vicinity of bulge
    - shroud biased ~1/8” toward rods on same side as bulge
    - reflected in high shroud temps on that side
- External case maximum temperature ~410 °C at onset of seal leak

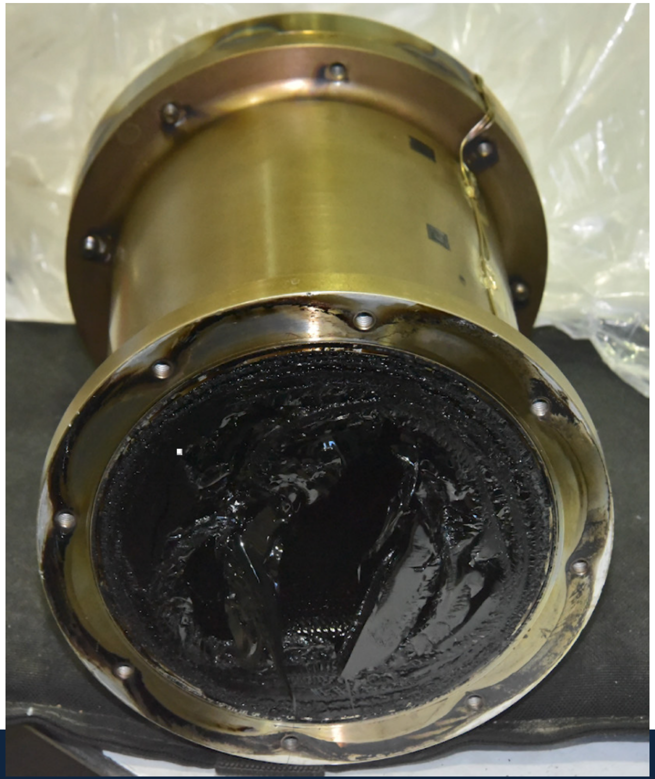
x-ray DIC, courtesy Elizabeth Jones

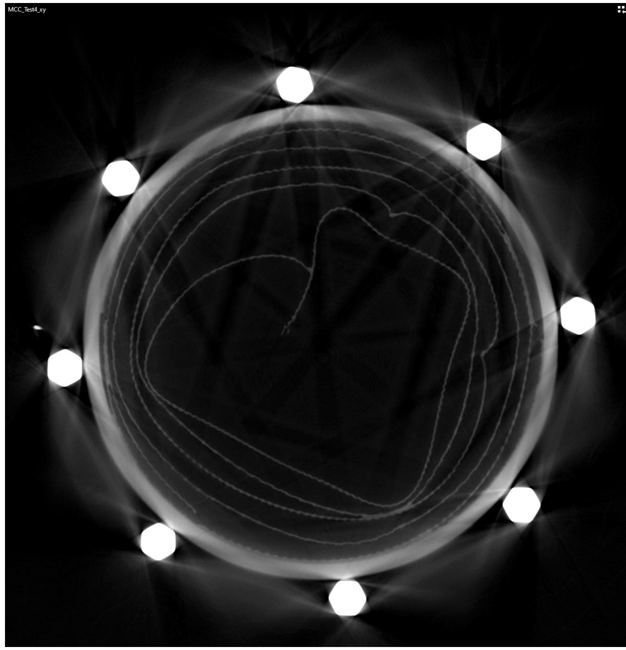
Unit 4 Post-test Scans











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  - two visible light video cameras
- x-ray
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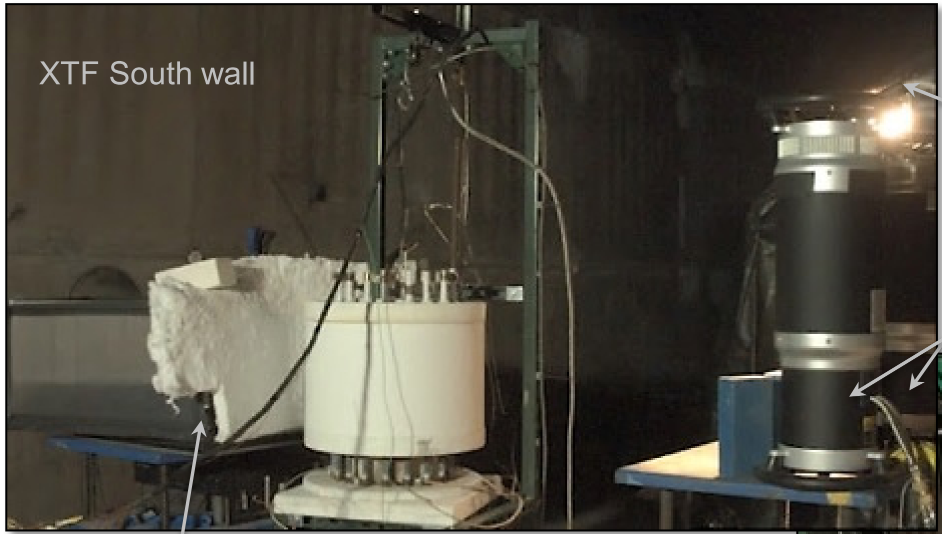
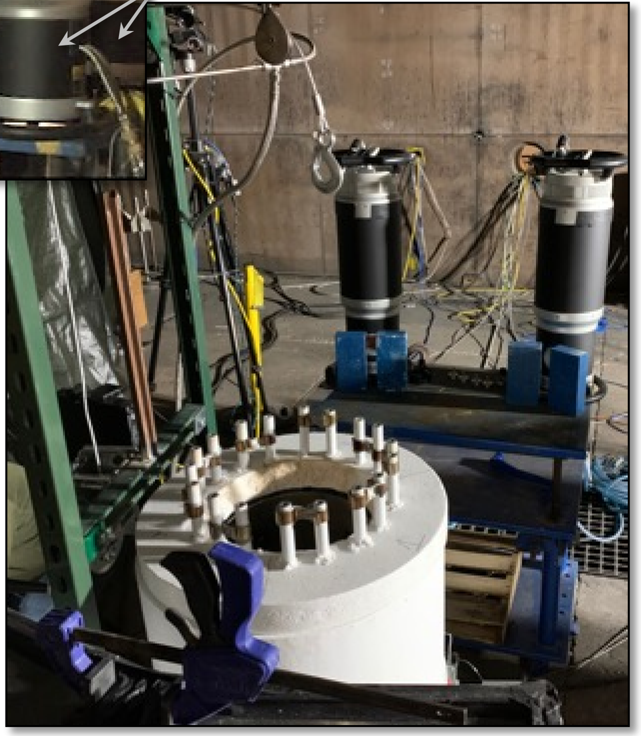
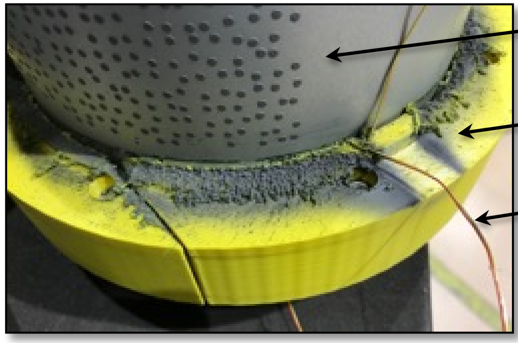
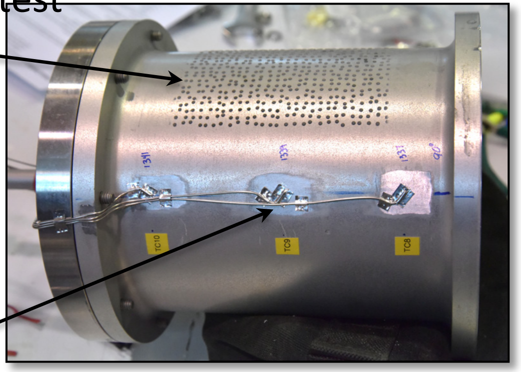
- Stereo x-ray DIC used in one test
  - real-time visualization of surface deformation due to thermal expansion and/or pressurization
    - Tantalum (Ta) pattern
  - test suite represents first application of x-ray DIC technique to a material characterization test









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  - Governing equation:

$$\rho c_P \frac{\partial T}{\partial t} = k\nabla^2 T + \dot{Q}$$

- Conduction in all solid bodies and internal air voids
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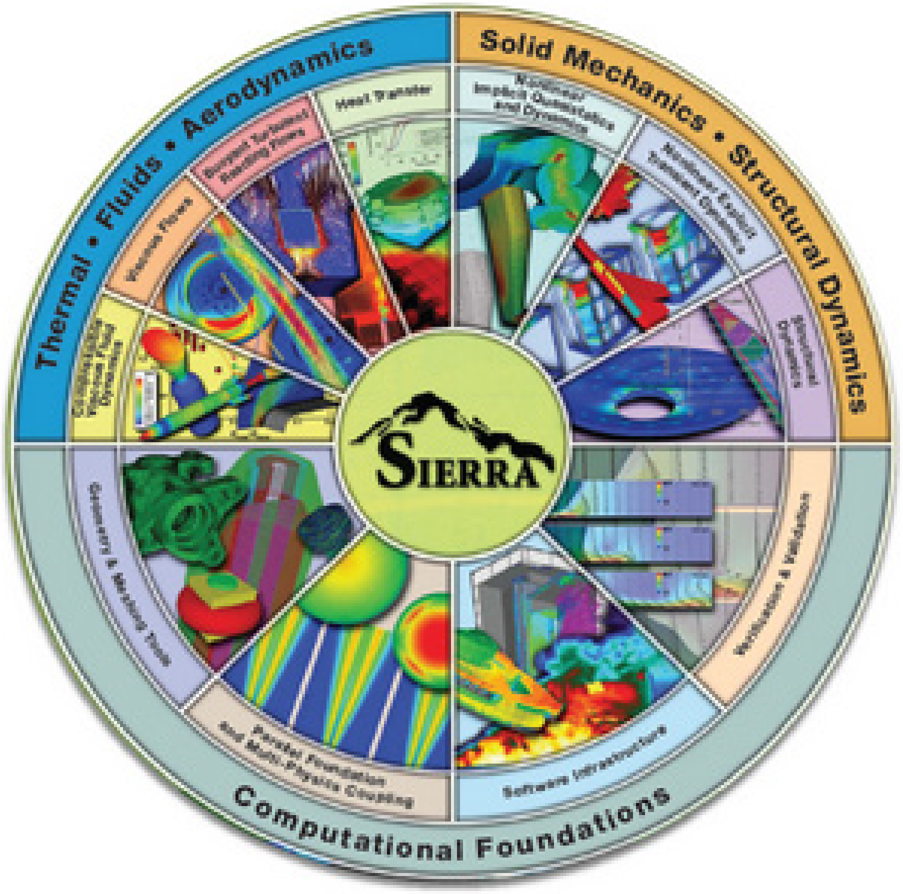
  - $q = h(T)(T_s - T_b)$
- Radiation on all internal surfaces
  - $q_n = \sigma\epsilon T^4 - \alpha G$
- Average element size = 2mm
- Adaptive timestep control with maximum timestep = 15s



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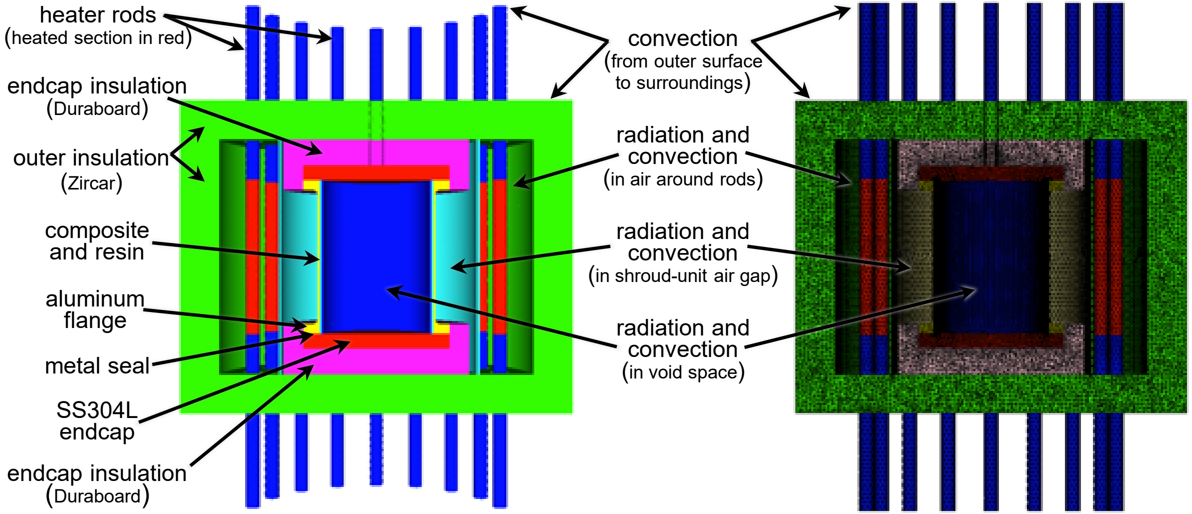
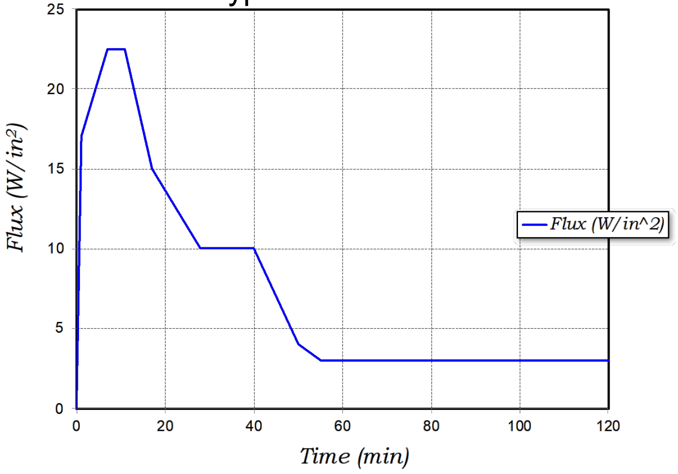
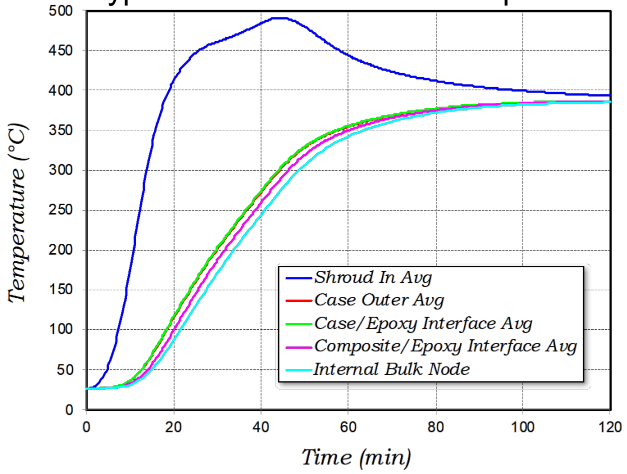


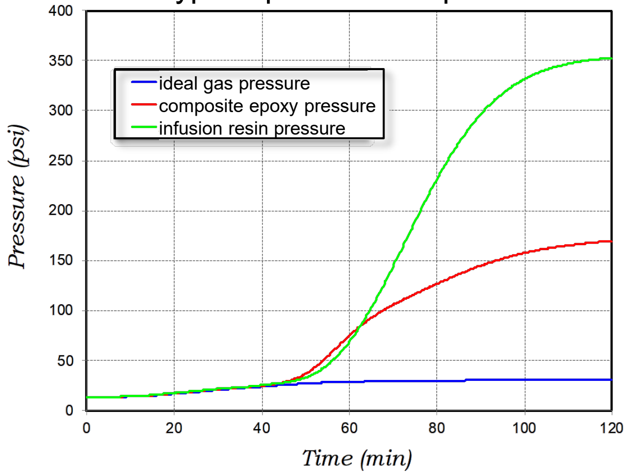
typical heater flux



typical slow-heat thermal response



typical pressure response



sum of pressures (minus 2 x atm) gives total response