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INTERMEDIATE-SCALE FIRE PERFORMANCE OF COMPOSITE PANELS UNDER VARYING LOADS

Sandia National Laboratories
Albuquerque, NM, USA

Alexander L. Brown, Ph.D.
(505) 844-1008
albrown@sandia.gov

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Broad Objectives

1. Gain an understanding of the importance of structural loading to burn rates for composite materials*
2. Evaluate composite burning at a practical scale during glowing combustion
3. Develop model validation data

Methods:

- A test rig was designed to actively weigh composite panels under fire-like conditions
- Tension, compression, and torsional forces could be imposed on the panels during decomposition
- Three types of panels were used varying in weight from 0.5 - 4.5 kg

*Prior work suggests some relationship between reaction rates and loading for small samples at early times:

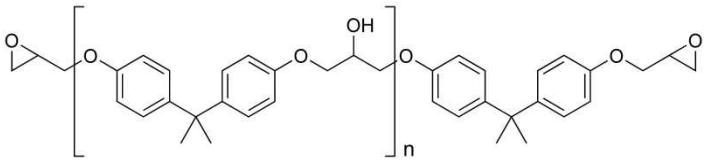
Elmughrabi, A.E., M. Robinson, and A.G. Gibson, "Effect of stress on the fire reaction properties of polymer composite laminates," Polymer Degradation and Stability, 93, 1877-1883, 2008.

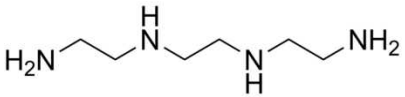
Background: About Carbon Fiber Epoxy Aircraft Composites

- Around ~35% epoxy, ~65% carbon fiber
- Fabric (woven) or uni-tape sheets, usually multiple layers thick
- Possibly sandwich material with high void fraction material between two composite sheets
- Pressed and cured in an autoclave
- Fibers around 5 μm diameter, 95% carbon

Epoxy and TETA hardener (From wikipedia):

$[C_{18}H_{20}O_3]_n$

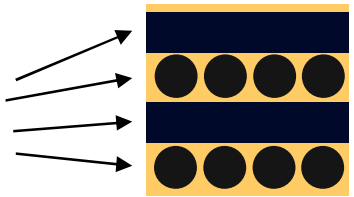




$C_6H_{18}N_4$

A four layer cross-section illustration:

Fibers in varying orientation



Key:

- Carbon Fibers
- Epoxy Resin

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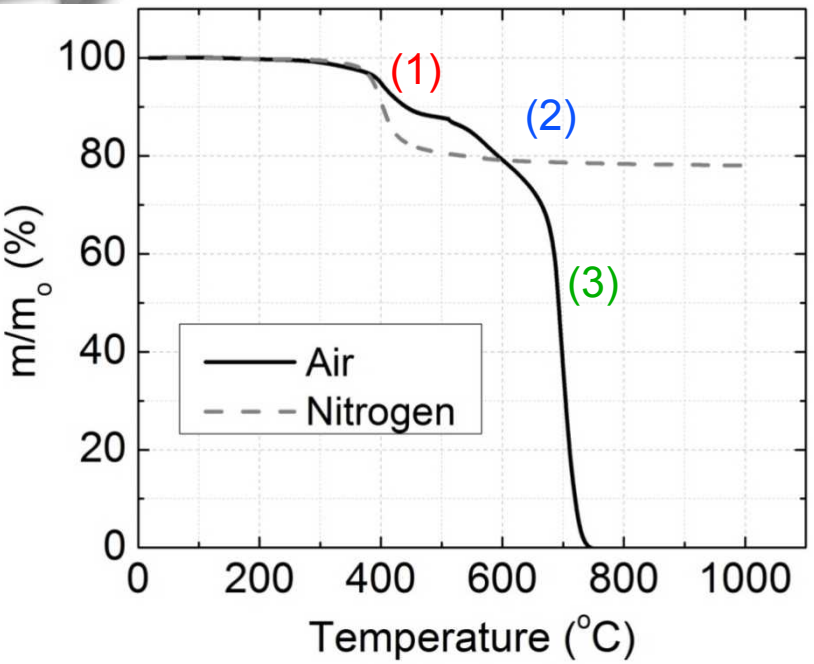
Background: Full Testing Plan

	Characteristic Length Scales	*Characteristic Mass*	*Experiments*	*Purpose of Testing*
Very small	0.1 mm to 1 mm	Milligrams (initial mass)	TGA, DSC	Fundamental kinetic, chemistry, decomposition behavior, and property measurements
Small	mm to 10 cm	Hundreds of grams	Cone calorimetry, radiant heat	Burn rate and scaled dynamics determination, simple validation testing
Intermediate	10-100 cm	0.1-100 kg	Radiant heat and environmental chamber tests	Bridge the gap between small and very small scale and large scale testing to discover dynamics not exposed at the smaller scales that will be present at larger scales
Large	Meters and above	Hundreds of kg and above	Full-scale fire testing	Full-scale with all physics represented in appropriate scale range

This presentation is focusing on a series of intermediate scale tests.

Background: TGA Results, 3 Regimes



(1) Epoxy Decomposition (both Thermal and Oxidative Pyrolysis) and Char Formation
(2) Slow Char Oxidation
(3) Carbon Fiber Oxidation

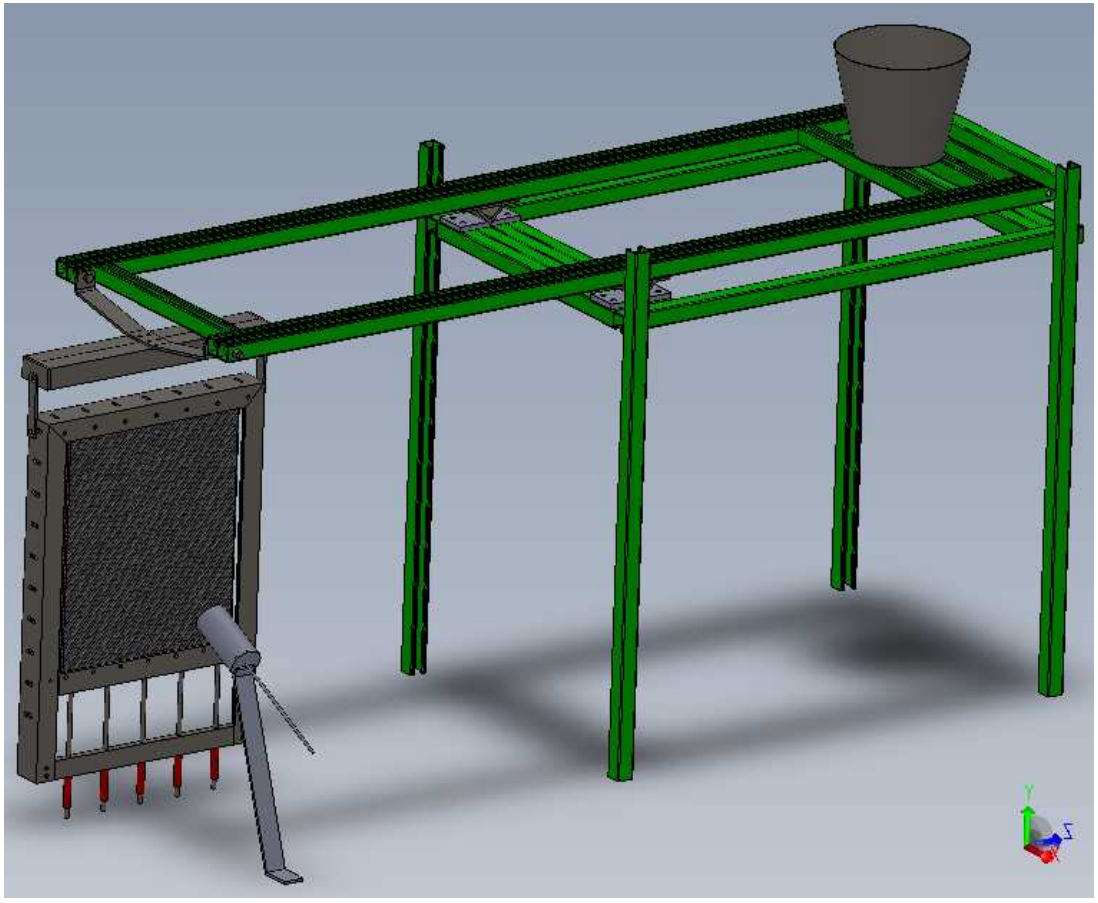
TGA Details:

- 1-2 mg samples
- 20°C/min
- Cytec 977-3 resin
- IM7 Fibers
- Single sheet cured in 1 atm oven

- In N_2, pyrolysis reaction generate organic vapors/fuel and char
- In air, O_2 interacts with the epoxy and changes rate at which organic vapors are generated
- Char formation inhibits combustion of carbon fibers
- Char oxidation occurs BEFORE carbon fiber oxidation

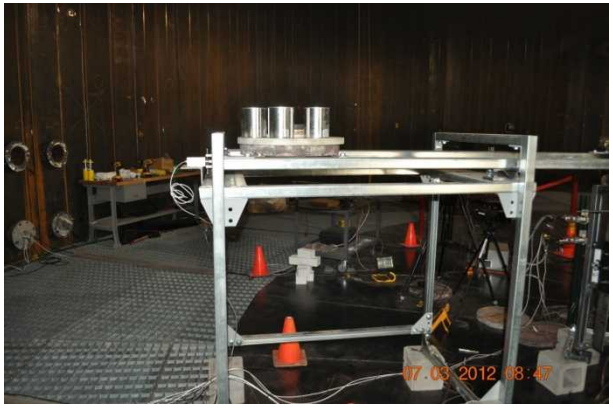
Test Rig

- **Test rig designed to impose various forces on a decomposing panel**



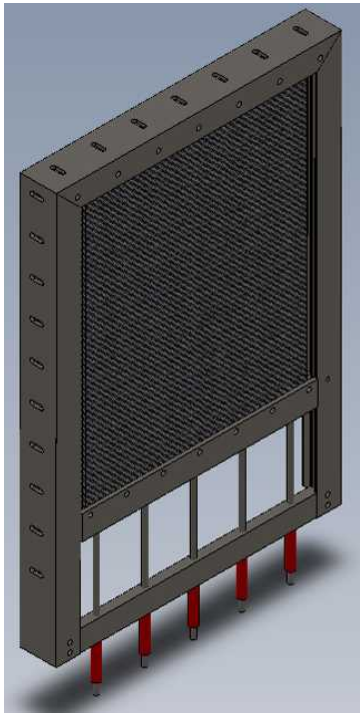
Instrumentation

- IR cameras
- Visible cameras
- Radiometers
- Thermocouples
- Mass loss
- Deformation and force
- Synchronization

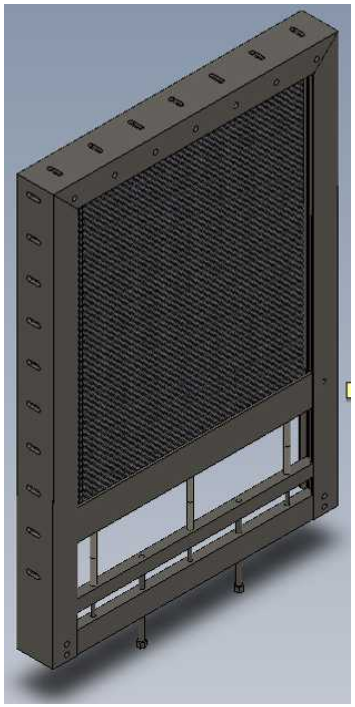


Structural Loading

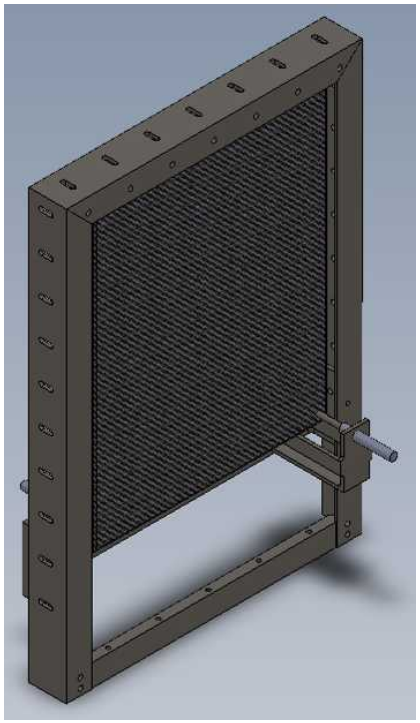
No-force option also available by not applying force from the springs



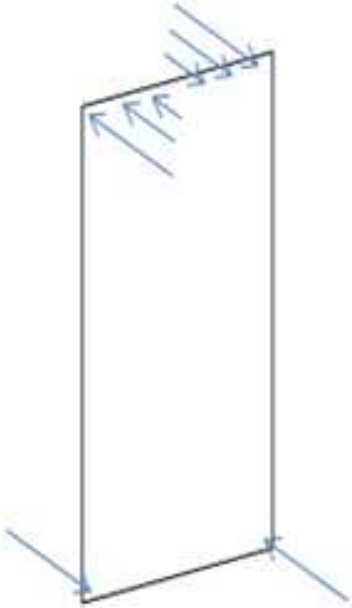
Tension



Compression



Torsion



Composite Materials

- ABDR sandwich panels
  - Cytec 5208 uni on front
  - Kevlar epoxy on back
  - 1” HRP-3/16 NOMEX honeycomb
- 18x24” thick
  - 8 mm thick
  - Cytec 5208 woven throughout
- 19x24” thin
  - Hercules IM7G/8551-7A
  - Cut from the same sheet

Panel	Average Mass *[kg]*	Standard Deviation *[kg]*
ABDR sandwich	0.753	.0325
18x24 thick	4.070	.00377
19x24 thin	1.354	.00835

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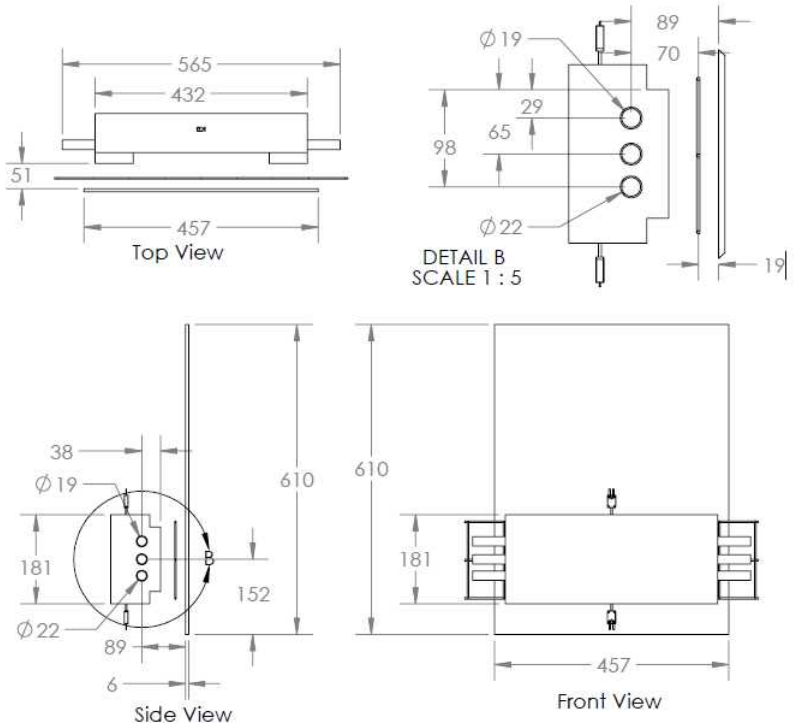
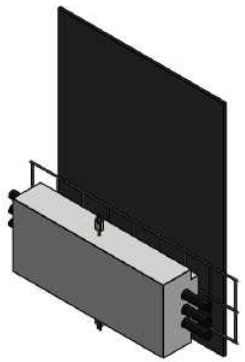
Heat Source

- 6,700 Watts of power to three Starbar brand 10 inch heater rods in a Pyrotherm I-14 insulation board box
- Wire cage mounted in tension to structural frame protects mass loss signal during distortions
- Thermocouples actively monitor oven environment





Units in mm

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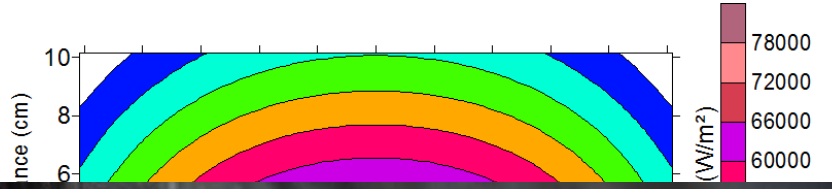
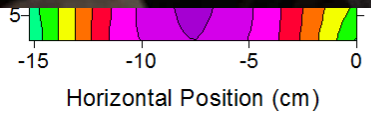
Heat Source Characterization

- View-factor model used to estimate radiative flux to the composites f oven
  - Under-represen geometry
- Pyromarked stee with thermocoup to measure total
  - Plate was oxidiz distorted
- Model contours r believable, experimental magnitudes believed to be more accurate

Core Model





Horizontal Position (cm)

Experiment

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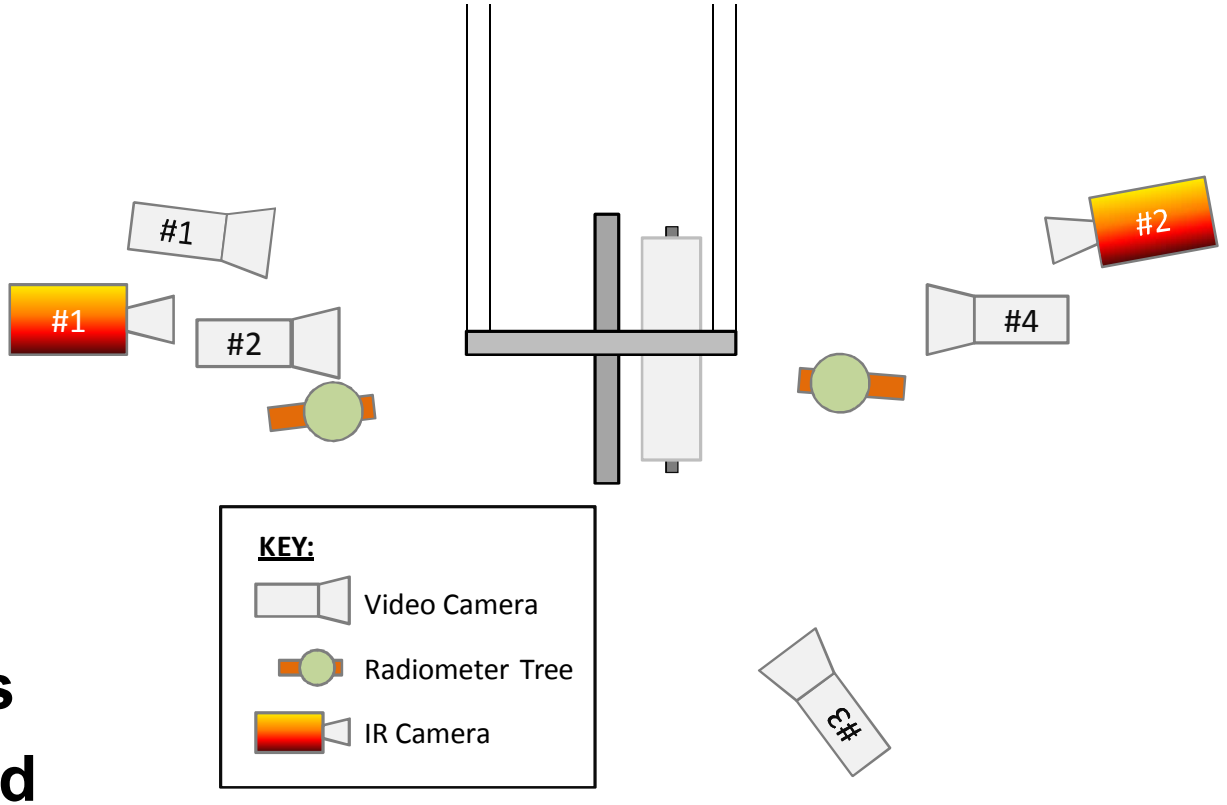
Videography

- Videos captured significant detail of motion and decomposition dynamics
- Radiometers provide good validation metrics
- IR cameras helped with real-time assessments, provided redundancy to radiometers



Instrument	Distance (cm)	Elevation	Target
Video Camera #1	123	Level	Back side center
Video Camera #2	104	Low	Back side springs
IR Camera #1	178	High	Back side center
Back side radiometer tree	76	Level	Back side
Video Camera #3	170	High	Oblique view
Front side radiometer tree	76	Level	Front side
Video Camera #4	118	Level	Front side center
IR Camera #2	170	High	Front side center

Test Matrix

PANEL TYPE	COMPRESSION	TENSION	NO FORCE	TORSION
WOOD ABDR MOCK	23	28	22	
ABDR SANDWICH COMPOSITE	24,27	31,32	25,33	43
WOOD 18x24 MOCK				36
18x24 THICK COMPOSTE	26,34	29,35	30	
19x24 THIN COMPOSITE	(38) 39,45	41	37,40	42
DAMAGED 19x24 COMPOSITE			44	
DFT			46	

- **Test ordering was not pre-determined (randomly sampled)**
- **19x24 tests were added later**
- **Some repeats to understand variability, others to confirm aberrant findings**
- **One 19x24 panel was pre-damaged structurally**
- **Consistent colors, symbols, lines used to report results, making analysis easier**

Visual Observations

1 min 30 sec:

2 min 30 sec:

4 min:

ABDR Sandwich Panels

Test	First Flaming	End Front Side Flaming	End Flaming
Comp-24	2 min 25 sec	3 min 6 sec	10 min 41 sec
NoForce-25	1 min 5 sec	3 min 0 sec	16 min 20 sec
Comp-27	1 min 24 sec	3 min 2 sec	10 min 1 sec
Tens-31	1 min 24 sec	3 min 3 sec	14 min 40 sec
Tens-32	1 min 25 sec	2 min 50 sec	15 min 17 sec
NoForce-33	1 min 29 sec	2 min 43 sec	15 min 49 sec
Tors-43	1 min 11 sec	2 min 50 sec	15 min 3 sec

18x24 Thick Panels

Test	First Smoking	First Flaming	End Flaming
Comp-26	0 min 57 sec	3 min 50 sec	19 min 46 sec
Tens-29	1 min 0 sec*	5 min 19 sec	15 min 26 sec
NoForce-30	1 min 11 sec	8 min 46 sec	14 min 27 sec
Comp-34	0 min 38 sec	3 min 59 sec	19 min 59 sec
Tens-35	1 min 2 sec	6 min 7 sec	18 min 44 sec

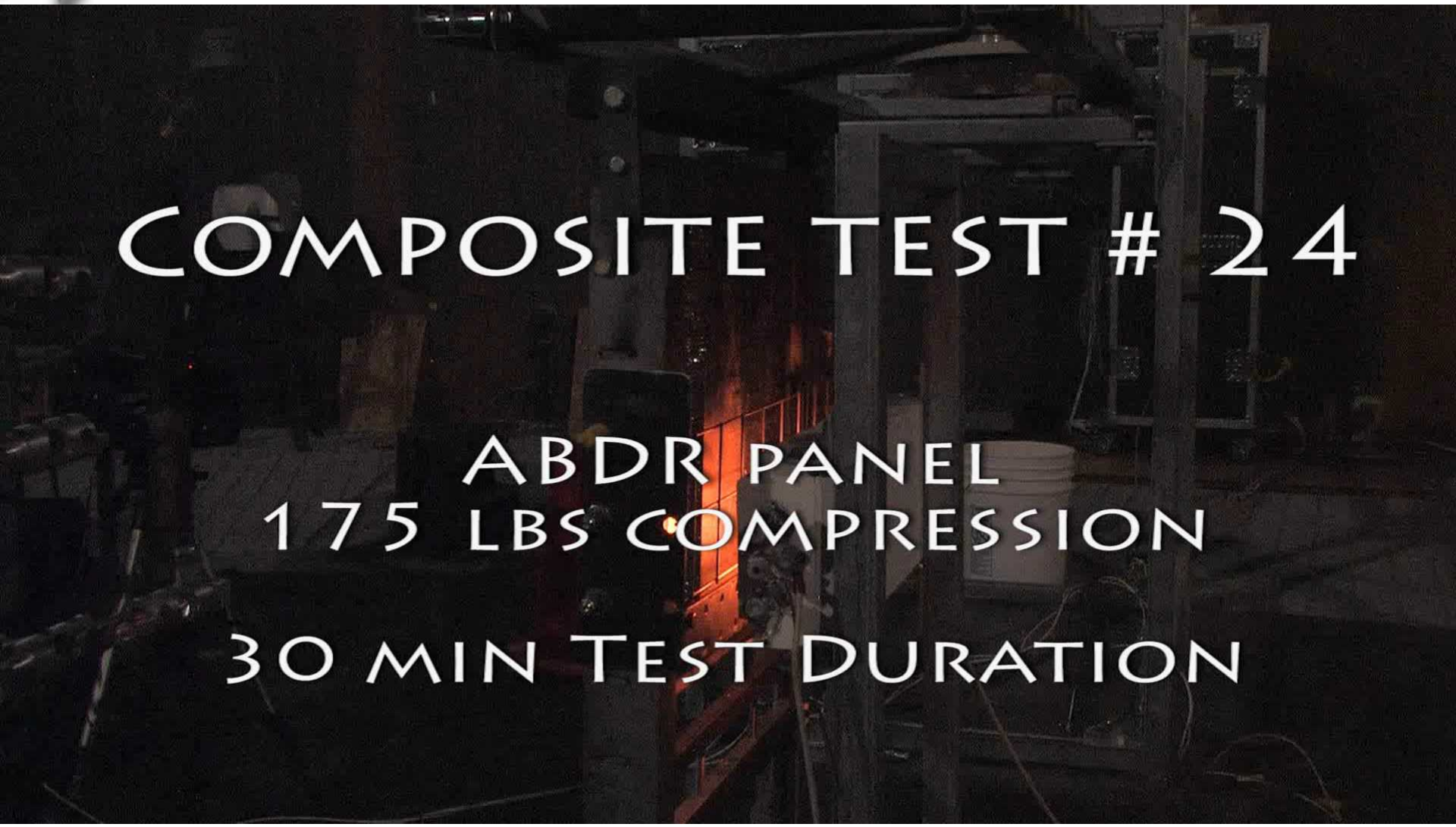
*This value by assumption, subsequent values referenced from this time

- **ABDR tests were substantially different**
  - **Most flaming on sides**
  - **Believed to be internal material**
- **Panels with more mass generally flamed on face for a longer time**
- **No apparent relationship between force and flaming**

19x24 Thin Panels

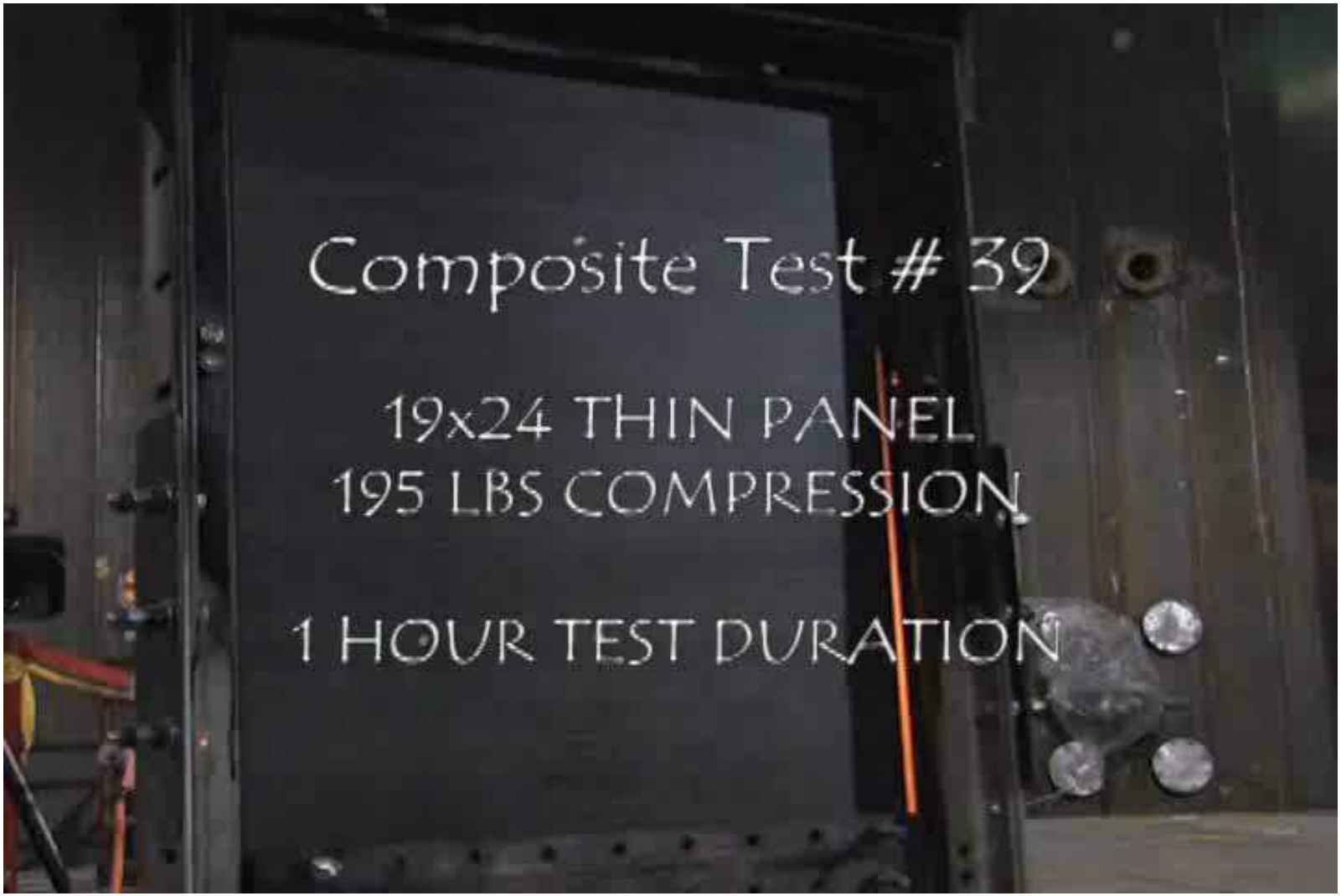
Test	First Smoking	First Flaming	End Flaming
NoForce-37	1 min 26 sec	1 min 43 sec	8 min 1 sec
Comp-39	1 min 12 sec	1 min 29 sec	6 min 54 sec
NoForce-40	1 min 15 sec	1 min 23 sec	6 min 45 sec
Tens-41	1 min 11 sec	1 min 20 sec	6 min 46 sec
Tors-42	1 min 21 sec	1 min 45 sec	6 min 54 sec
Broken-44	1 min 7 sec	1 min 52 sec	5 min 58 sec
Comp-45	1 min 7 sec	1 min 24 sec	6 min 45 sec

ABDR Test 24 Video



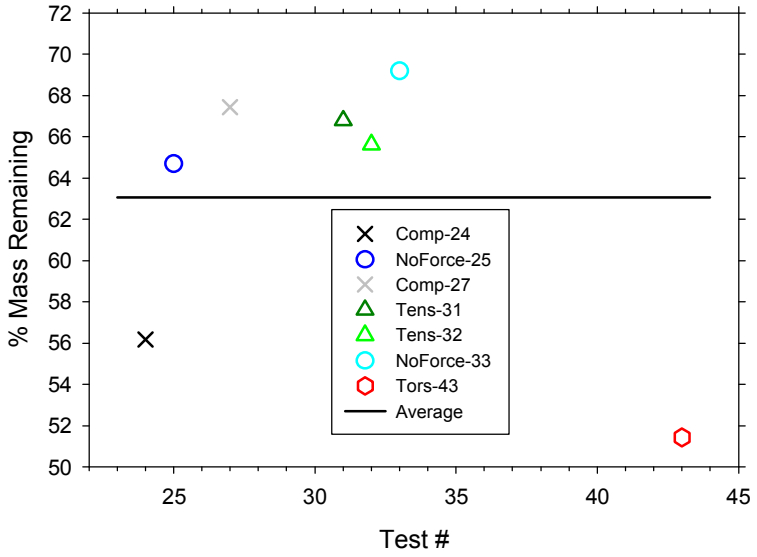
18x24 Thick Test 35 Video

19x24 Thin Test 39 Video

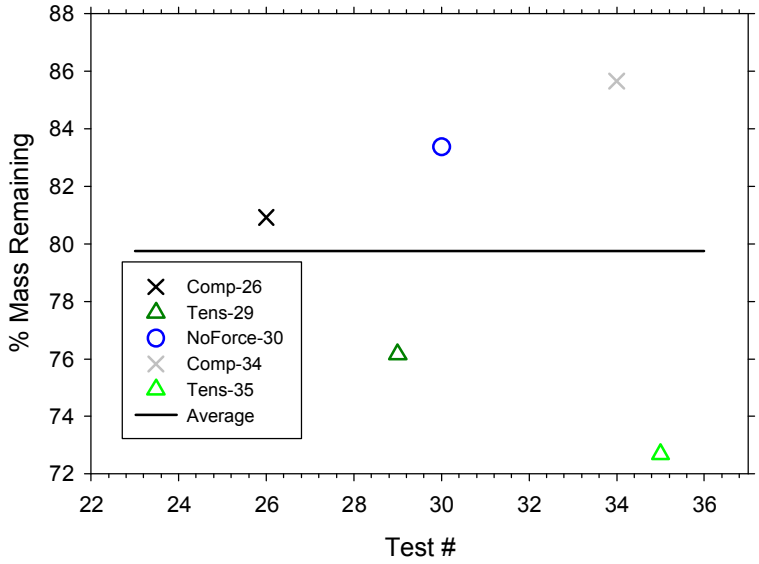


Residual Mass

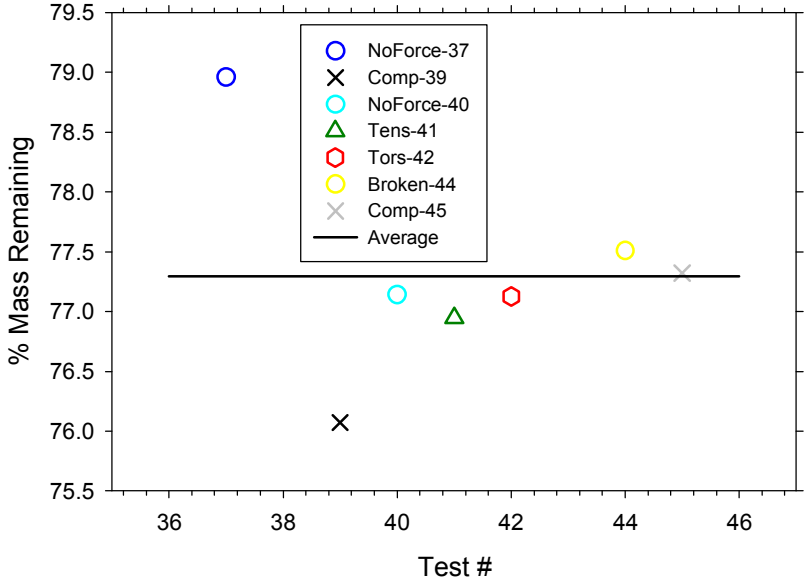
ABDR Sandwich Panels



18x24 Thick Panels



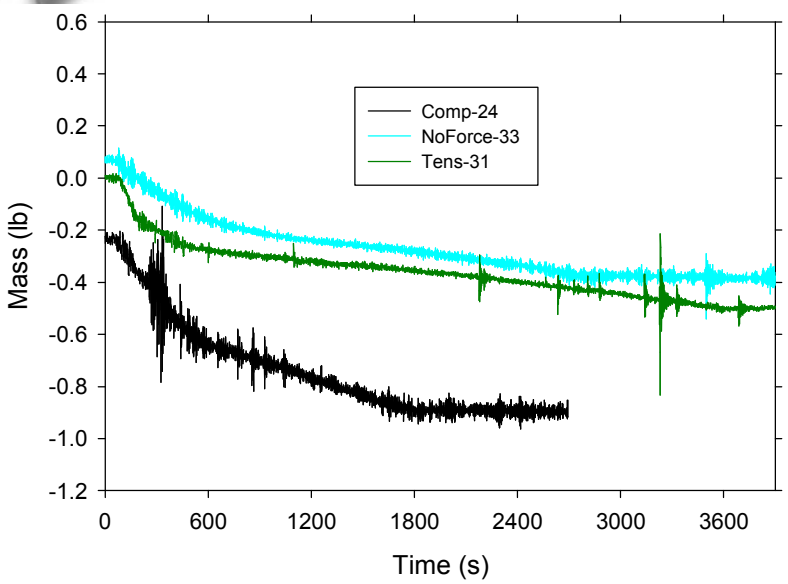
19x24 Thin Panels



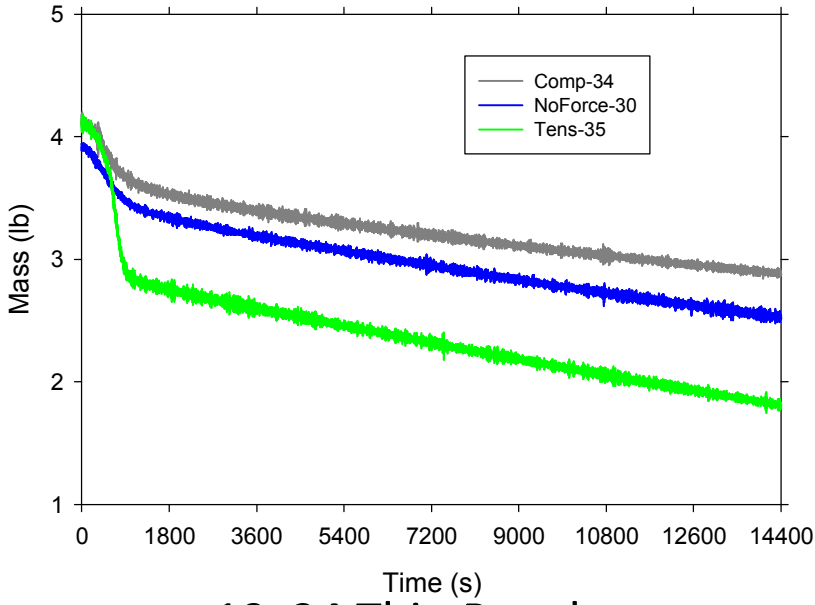
- **ABDR tests were substantially different**
  - **Lost 63% of mass compared to 80%, 77%**
- **Much better repeatability for 19x24 thin panels**
- **No apparent relationship between force and residual mass except for 18x24 thick panel**

Mass Loss

ABDR Sandwich Panels

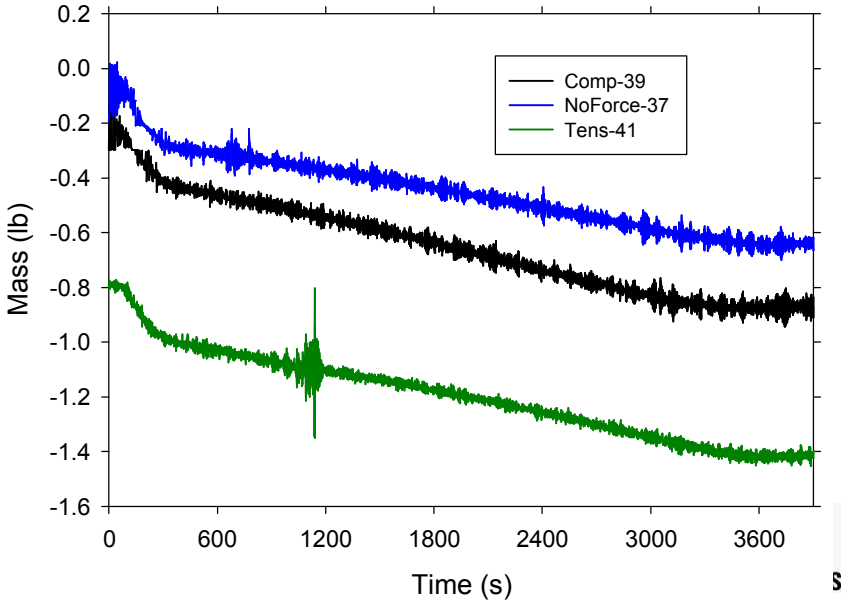


18x24 Thick Panels



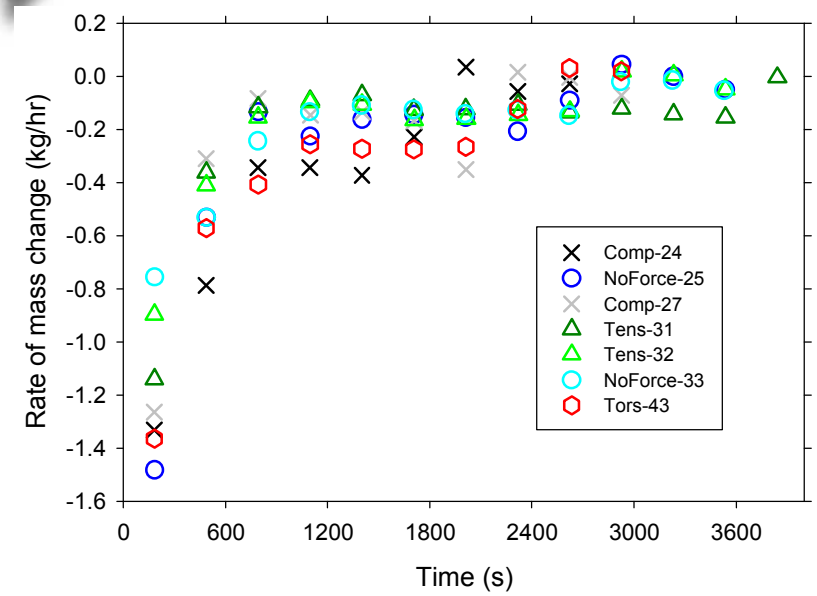
- **18x24 thick panel tests in tension had much larger flaming loss.**
  - **Caused by back-side flaming**
- **Tests with force (tension and compression) were more prone to 'ringing' signals**
- **ABDR compression Test 24 significantly faster than the other tests**

19x24 Thin Panels

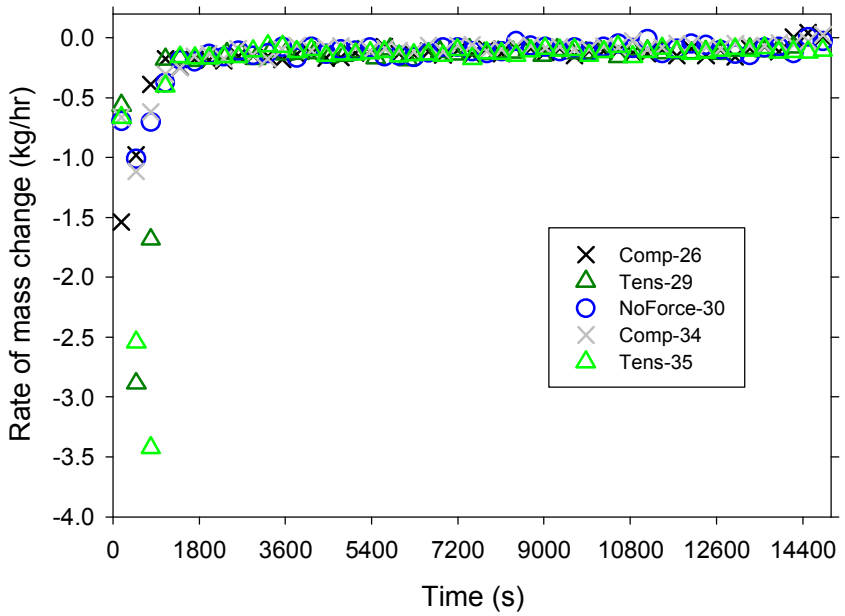


Mass Change Rate

ABDR Sandwich Panels

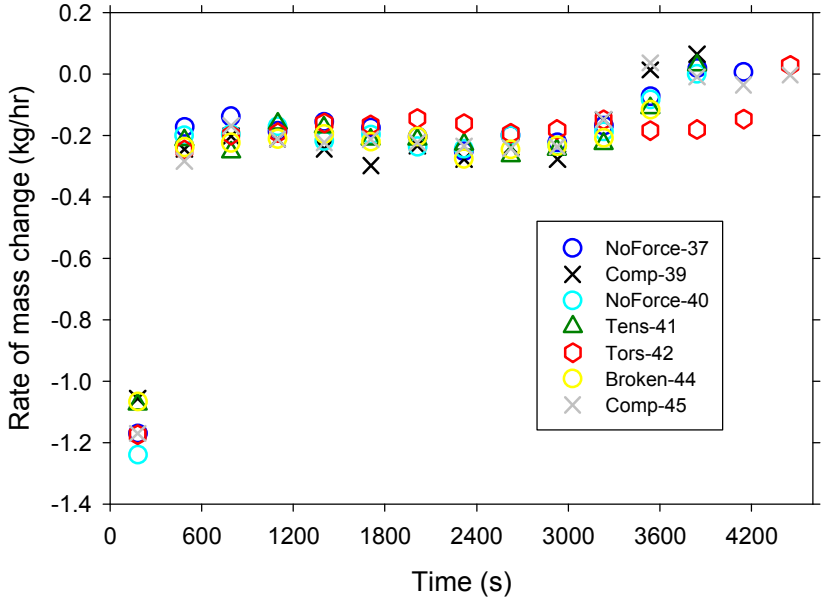


18x24 Thick Panels



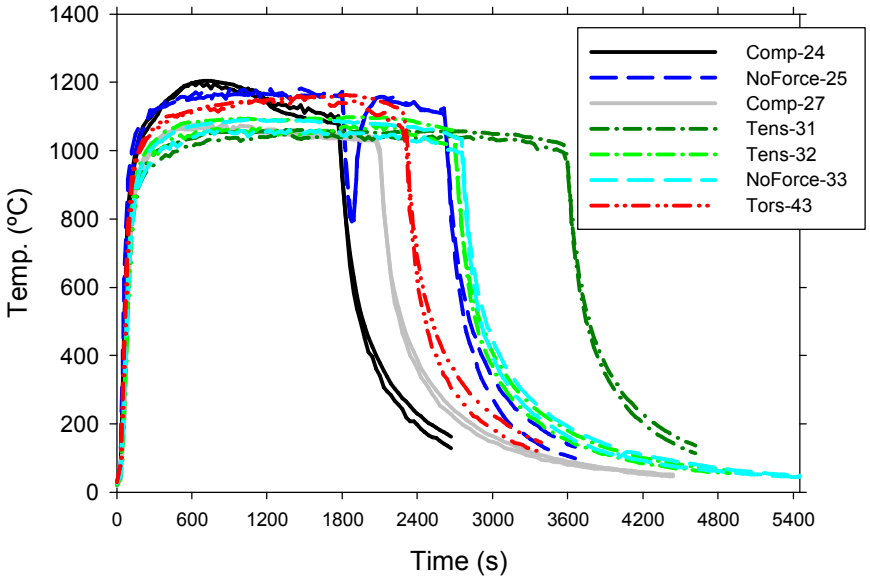
- **Five minute interval average mass change rate assessed for each test**
- **Rapid mass loss early, followed by a fairly steady low rate during glowing combustion**
- **Note that the early rate is about ten times that at later times**

19x24 Thin Panels

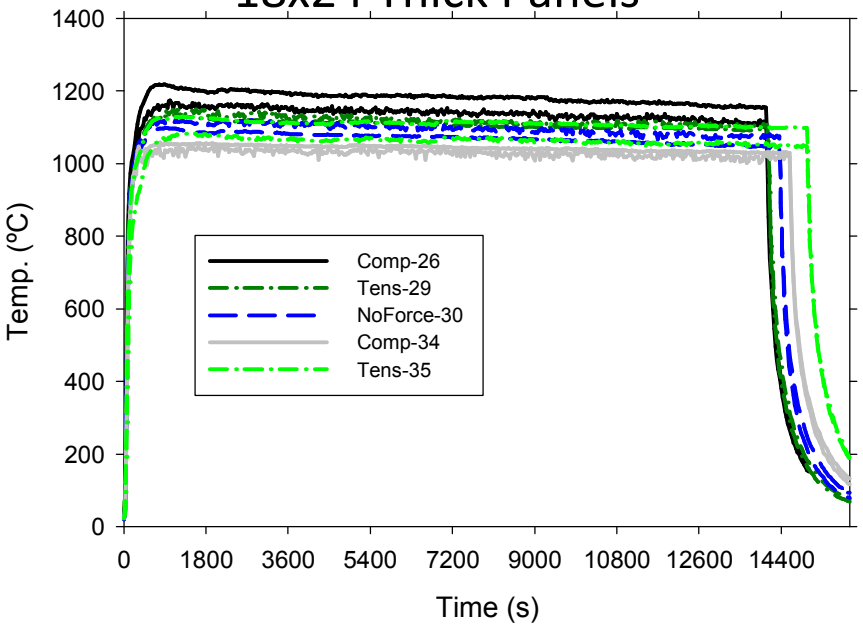


Oven Temperatures

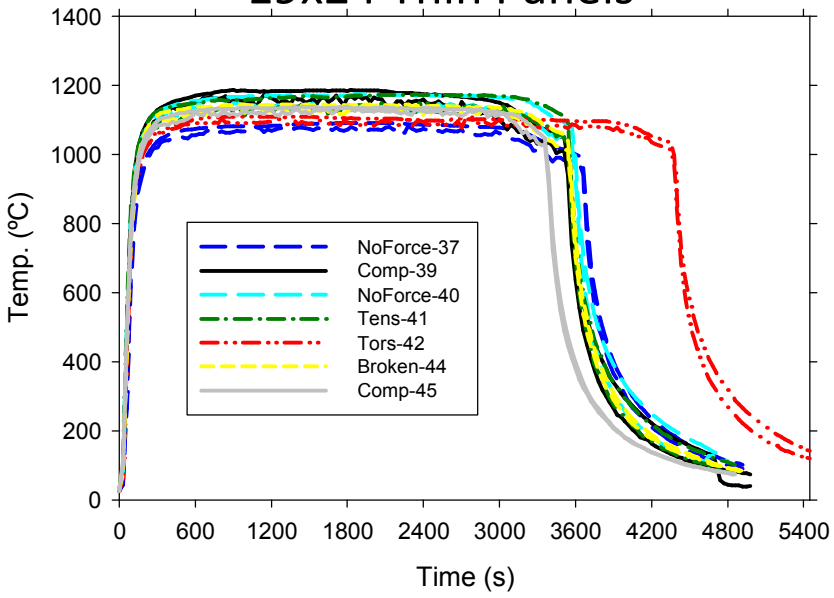
ABDR Sandwich Panels



18x24 Thick Panels



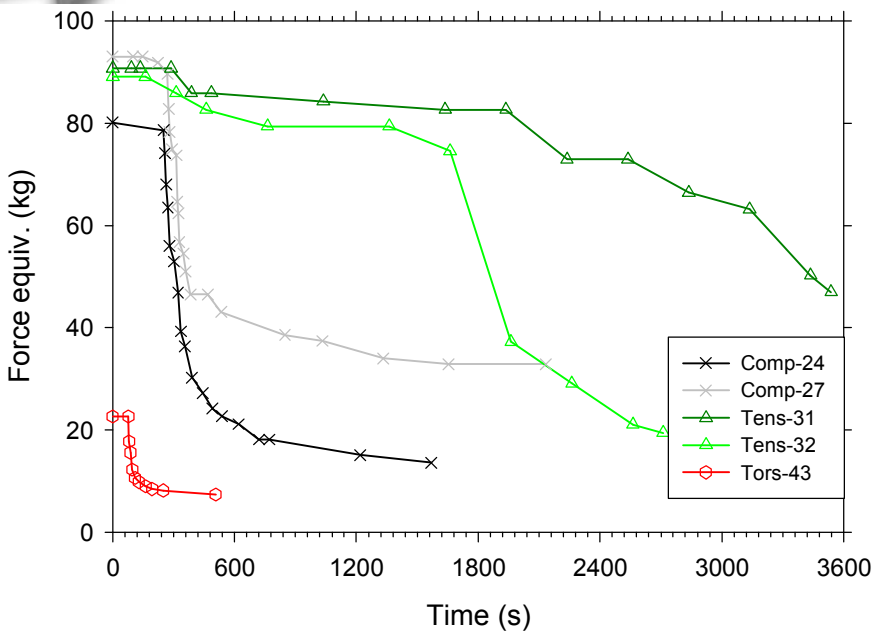
19x24 Thin Panels



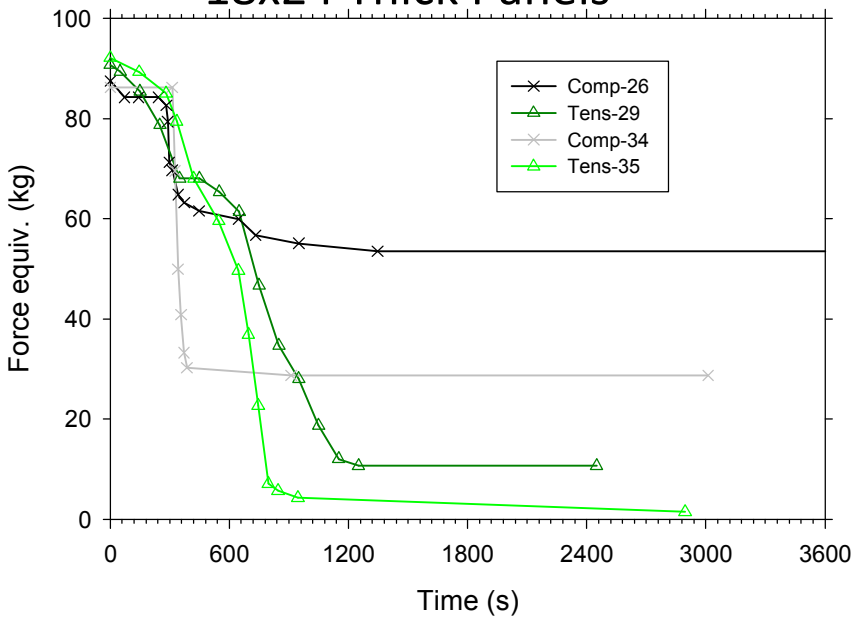
- **Steady-state oven temperatures varied between 1000-1200 ºC**
  - **Partly due to panel distortions**
  - **Partly due to aleatoric variation**
- **Oven temperatures dipped at the end of tests as holes were formed in the panels**

Force On Panels

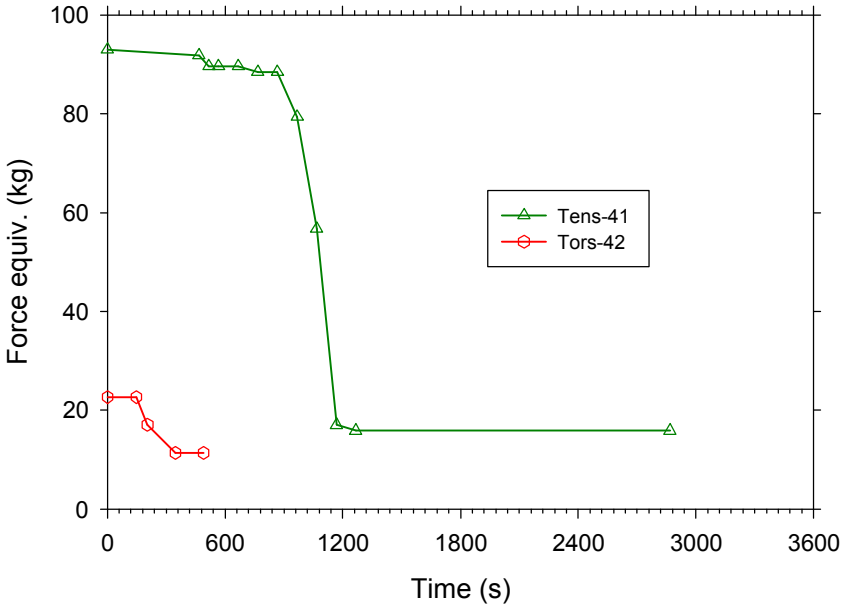
ABDR Sandwich Panels



18x24 Thick Panels

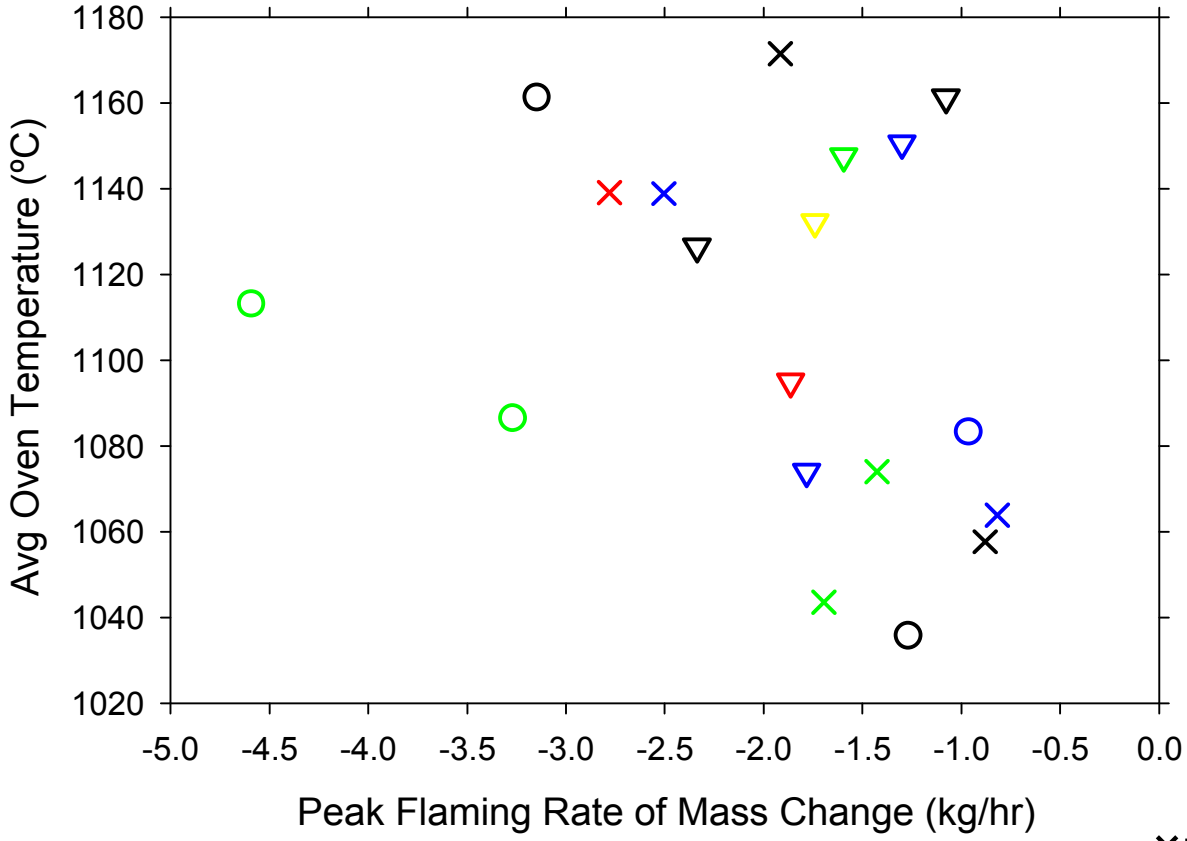


19x24 Thin Panels



- **Panels were weak to the torsional forces**
- **Panels appear most robust to the tensile forces**
- **No data illustrated for 19x24 thin panels in compression because they did not ever move**
- **19x24 and 18x24 panels sheared from bolts in tension**

Flaming Reaction Rate



×=ABDR

○=18x24 thick

▼=19x24 thin

- **18x24 tension tests had highest rates, only panels to exhibit back-side flaming**
- **No other clear trends apparent**

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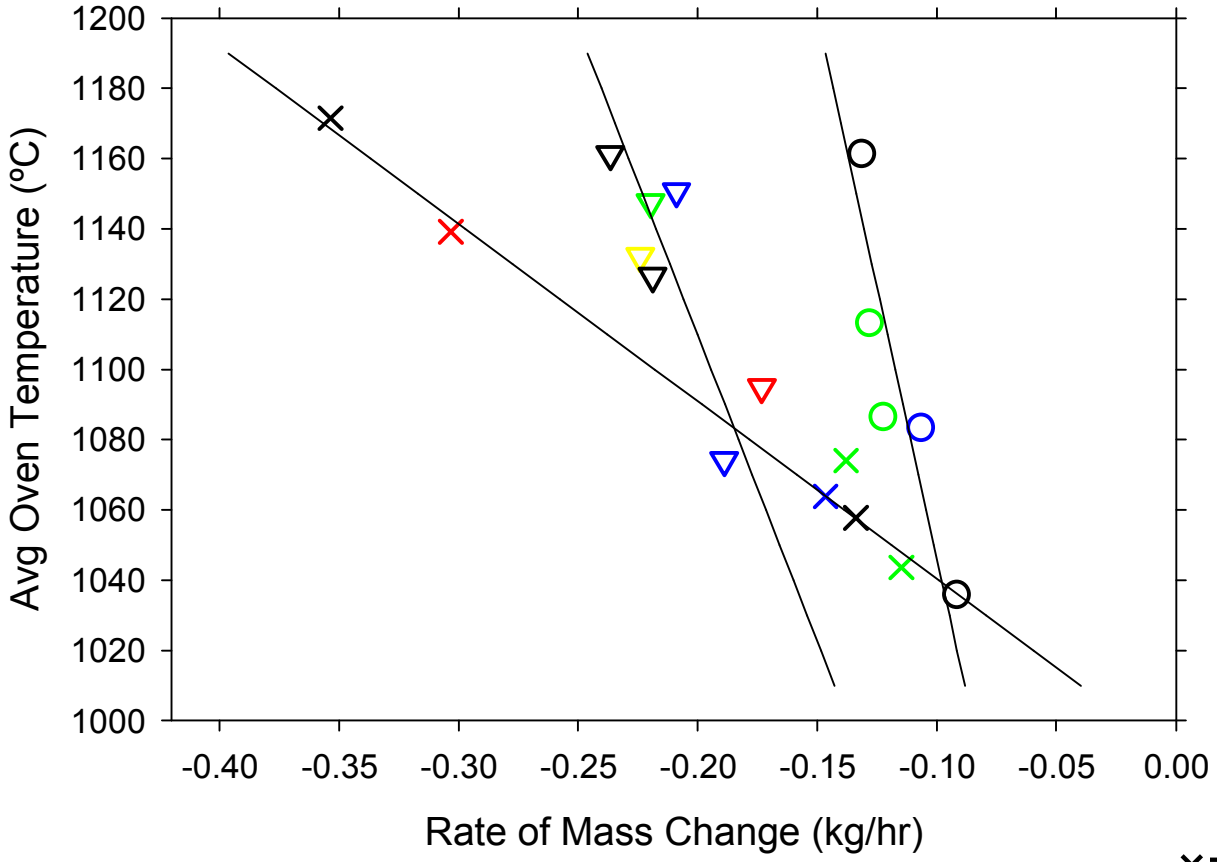
Glowing Reaction Rate



- **Very apparent relationship between oven temperature and glowing reaction rate**
- **Force on the panel had little effect on the reaction rate in this phase of decomposition**

×=ABDR

○=18x24 thick

▼=19x24 thin

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Compression Induced Deformations

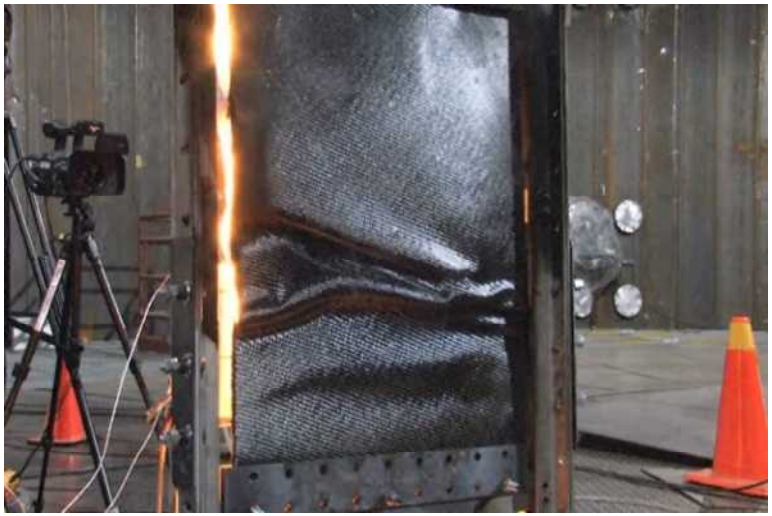
ABDR Sandwich

Test 24 at 10 min. 41 sec.:

Test 27 at 5 min. 24 sec.:

18x24 Thick

Test 26 at 16 min. 31 sec.:



Test 34 at 17 min. 17 sec.:

Summary

- During early phases of combustion that included flaming, some relationship was seen between the type of force imposed on the panels and the decomposition rate. This was most apparent in the 18x24 thick panels, as the tension tests were the only ones to exhibit back-side flaming that resulted in significantly higher decomposition rates.
- Panels deform differently depending on how they are loaded. The morphology of the deformation may play a role in how they react, although these tests did not find quantitative evidence in this regard.
- Two parameters governed post-flaming reaction rates. These were panel type and oven temperature. Structural loading had no discernable effect in this phase of the tests, despite the variations in deformation morphology.
- In the fire environment, a panel resists early deformation due to tension better than compression. Torsional forces imposed in these tests resulted in the earliest deformations due to the thermal environment, despite the fact that the torsional force imposed was a quarter that of the other two types of force.
- As a rule of thumb, the glowing reaction rate was about a tenth of that of the flaming reaction rate for these tests.
- Our sandwich panels exhibited significant flaming compared mass proportionally to the other panels, presumed to be due to the exposed edges and the flammable internal materials. The fact that the edges were not closed is an issue with these data, as most aircraft do not have exposed sandwich material edges.

Acknowledgements

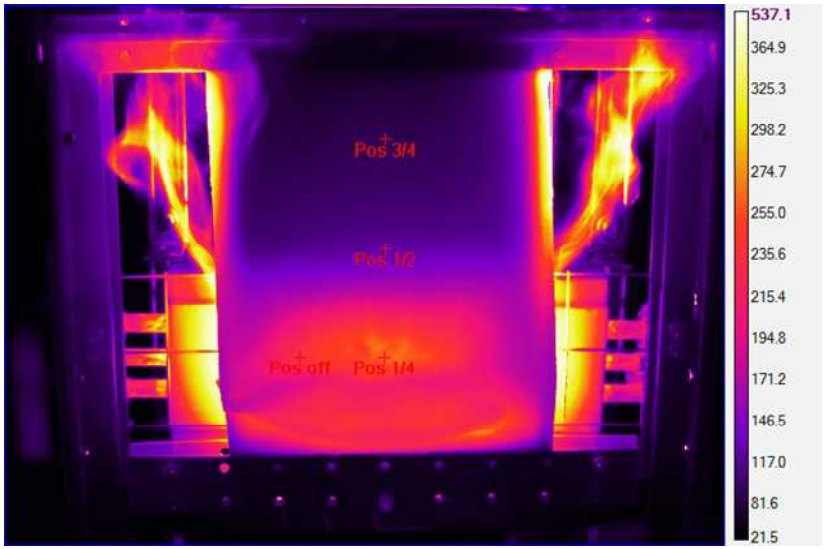
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

The technologists who conducted the tests, included Jerry Koening, and Jesse Fowler. Shea Loges and Richard Simpson provided video editing services. The design and construction of the test structure was overseen by Pat Brady. Bennie Belone and Randy Foster helped with test rig assembly.

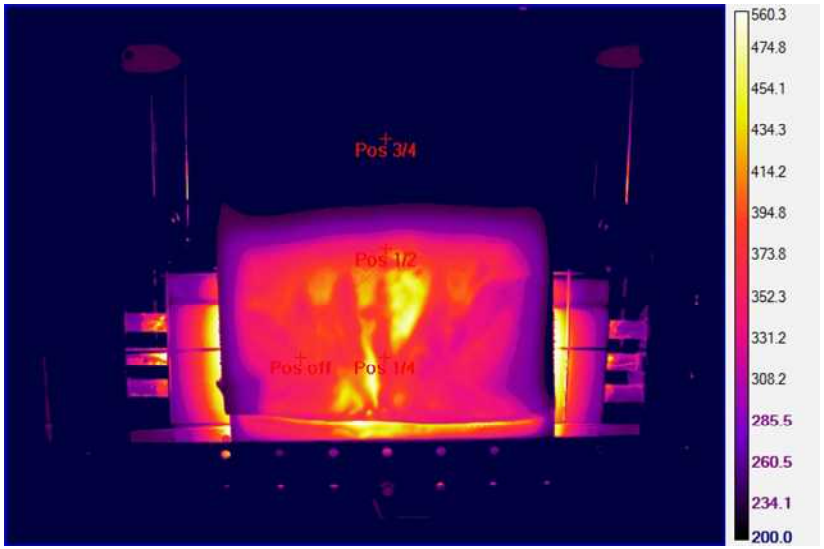
ABDR and 18x24 thick panels were donated by the Air Force Advanced Composite Office, Hill AFB. Their contributions to this testing were invaluable. The remaining materials were acquired at a discount from Composite Tooling Corporation.

ABDR Comp Test 24 IR Camera Results

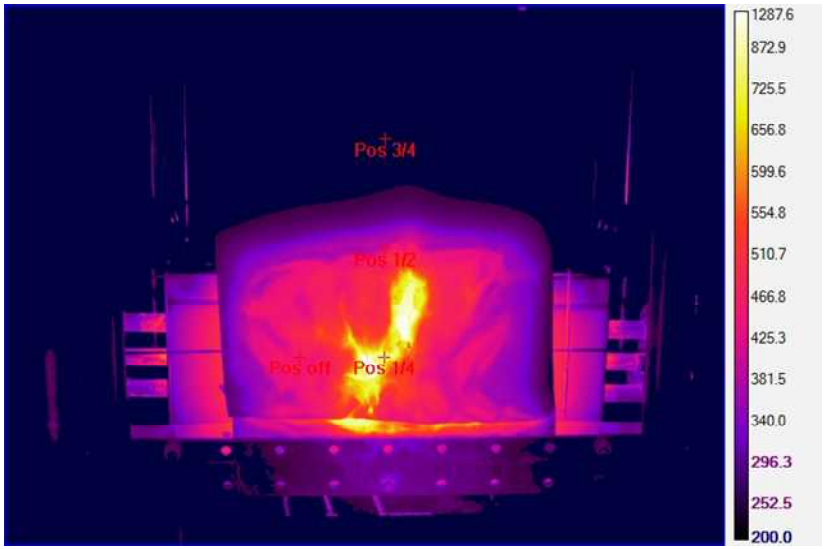
5 min:



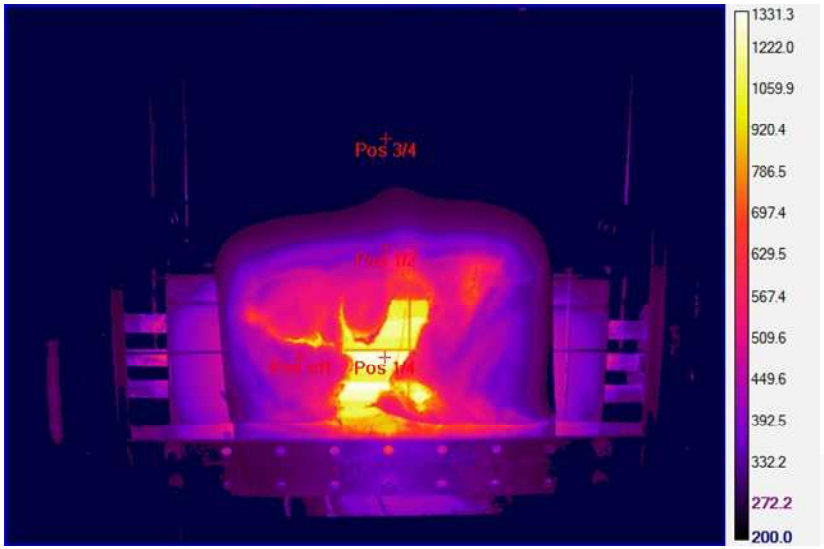
10 min:



20 min:



27 min 30 sec:



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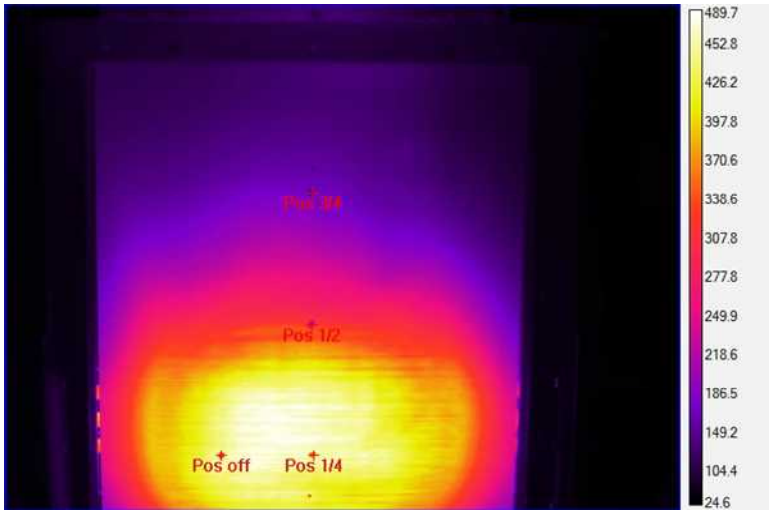
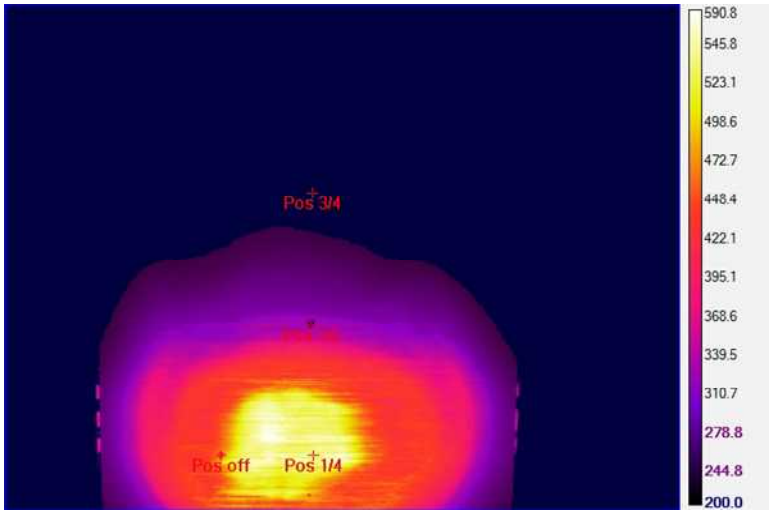
19x24 Thin Comp Test 45 IR Camera Results

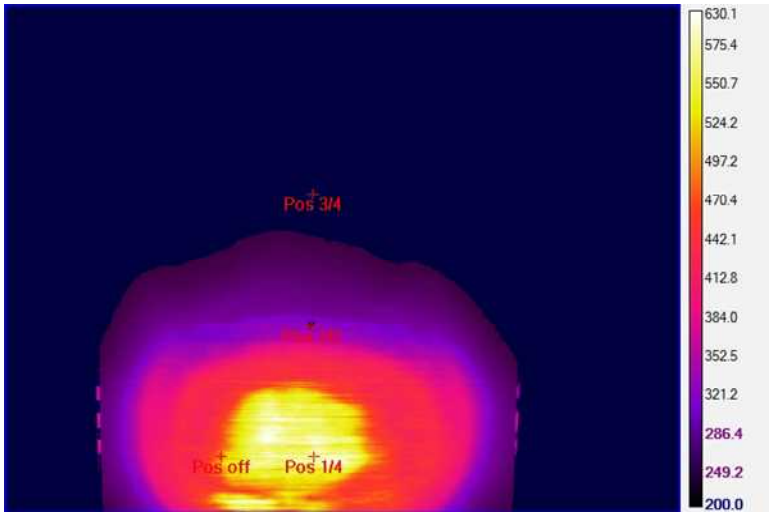
13 min 20 sec:



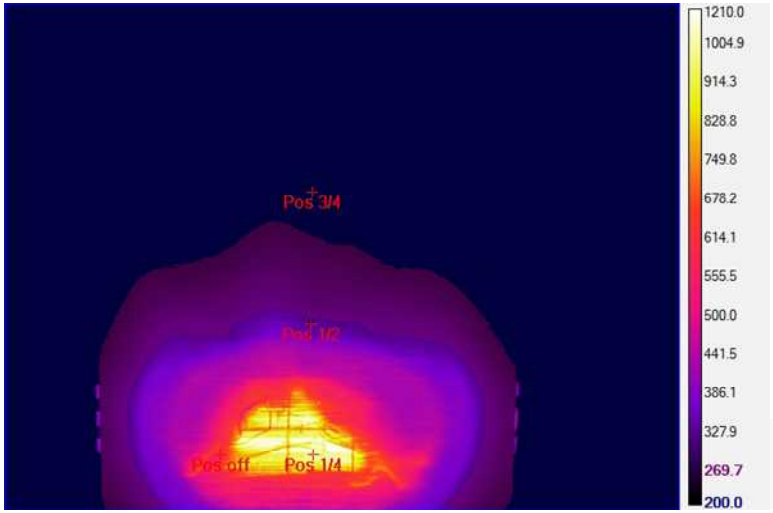
40 min:



45 min 7 sec:



55 min 7 sec:



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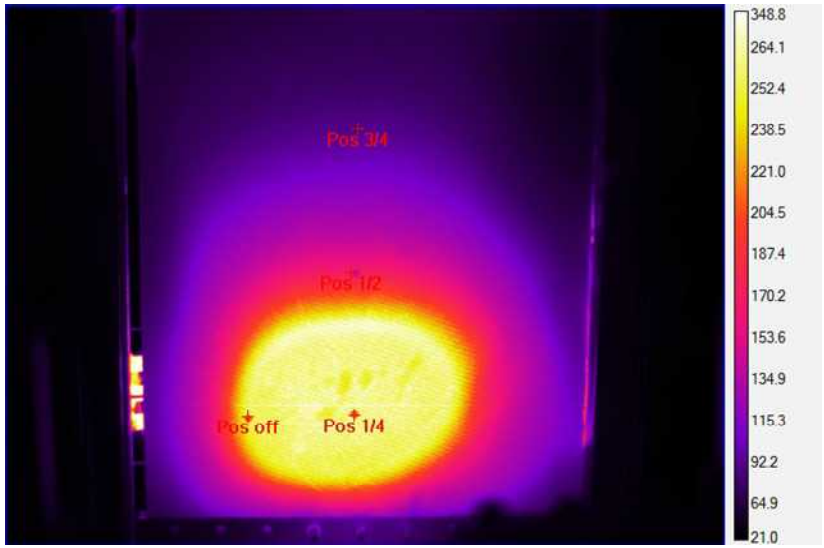
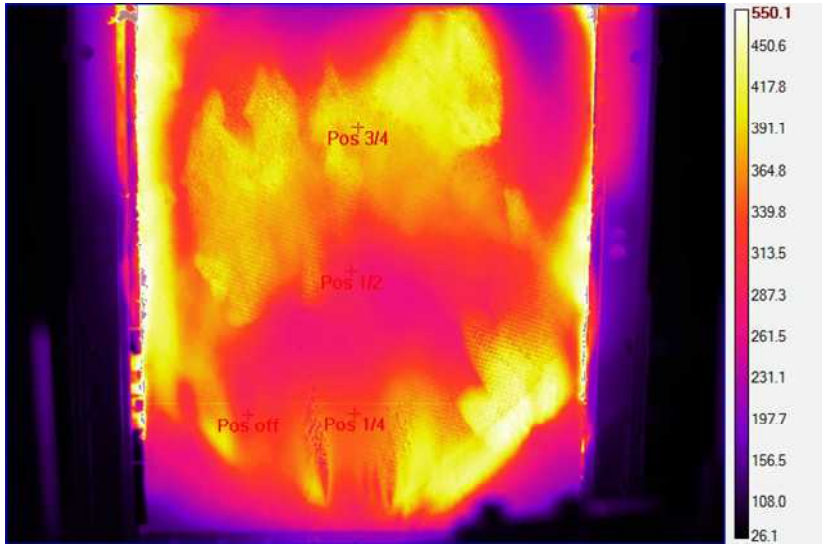
18x24 Thick Tens Test 35 IR Camera Results

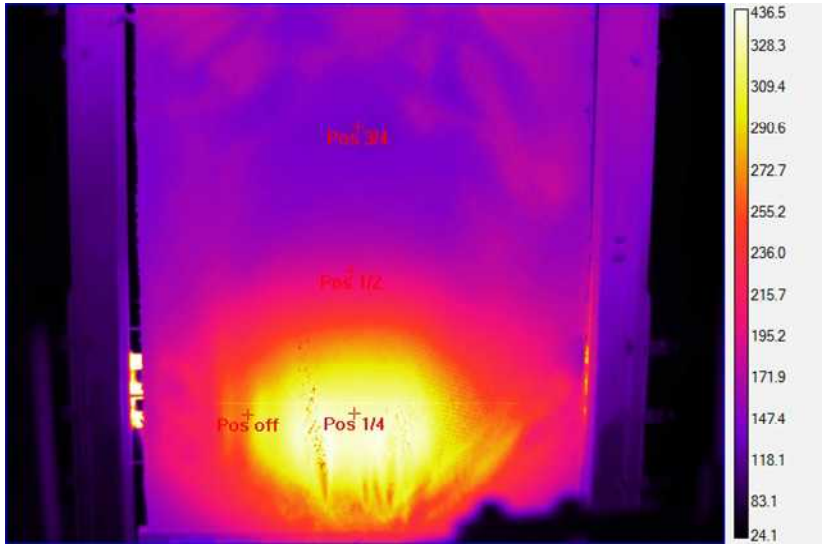
6 min 15 sec:



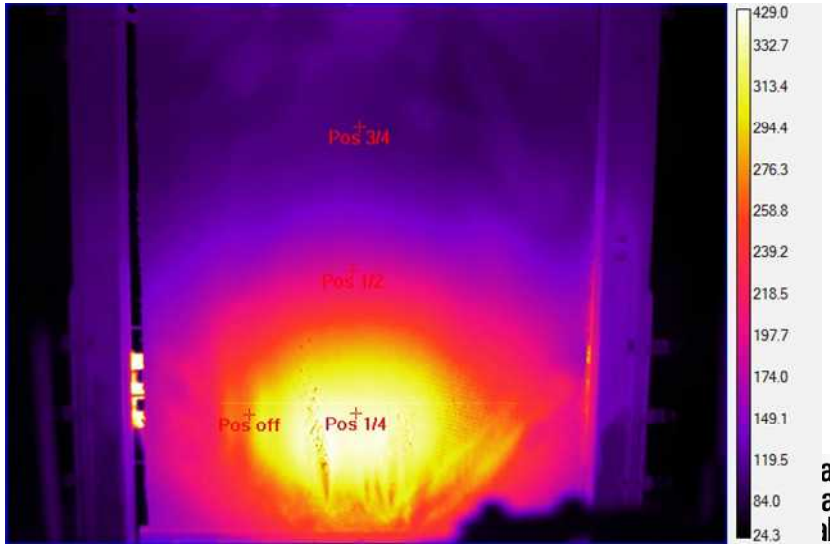
12 min 42 sec:



22 min 55 sec:

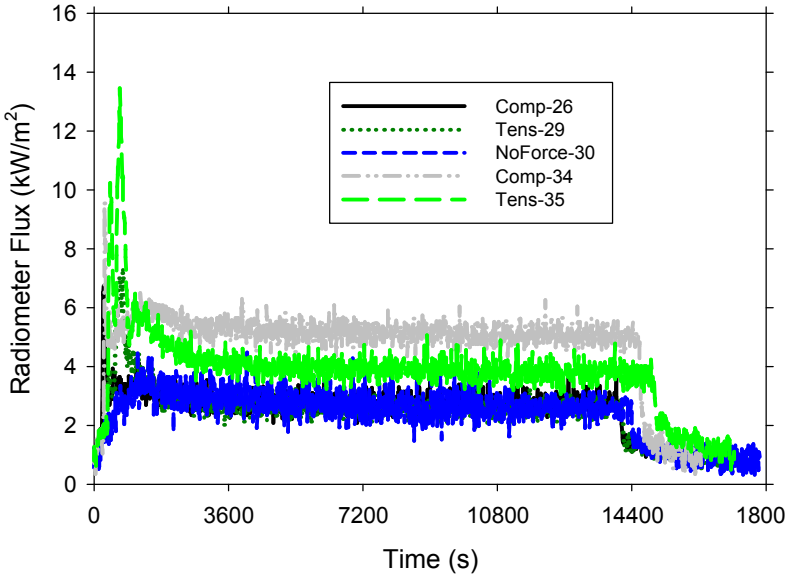


60 min:

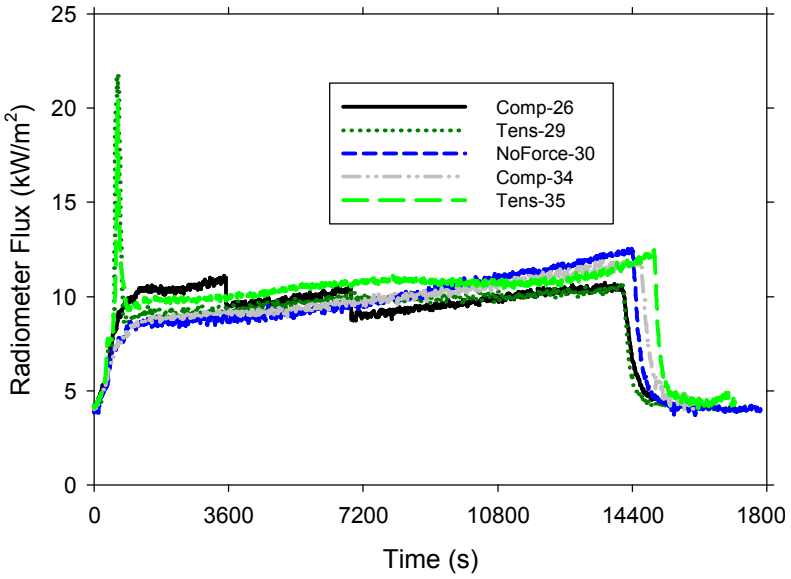


18x24 Thick Radiometer Data

Front, 75% up from bottom

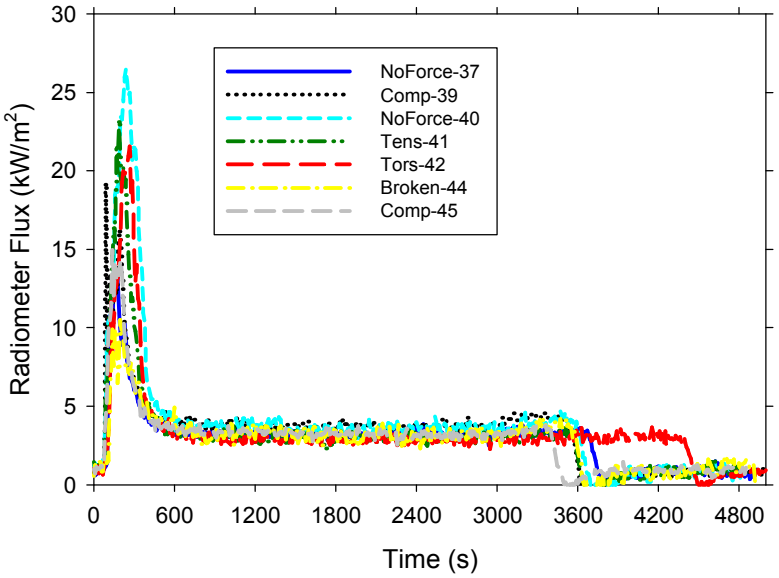


Back, 25% up from bottom



19x24 Thin Radiometer Data

Front, 75% up from bottom



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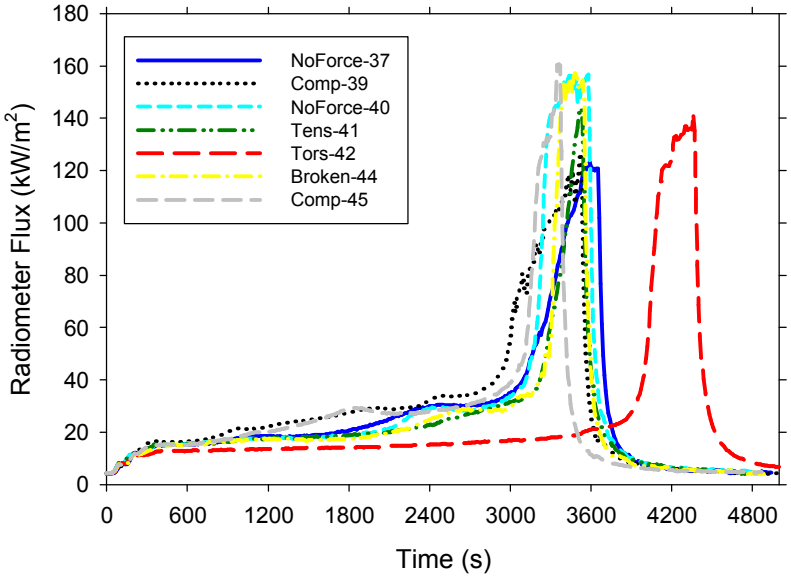

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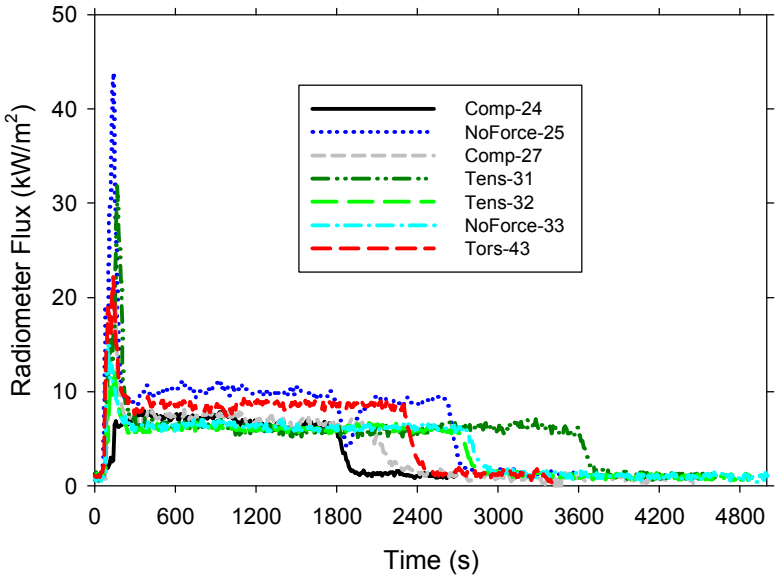
ABDR Sandwich Radiometer Data

Front, 75% up from bottom



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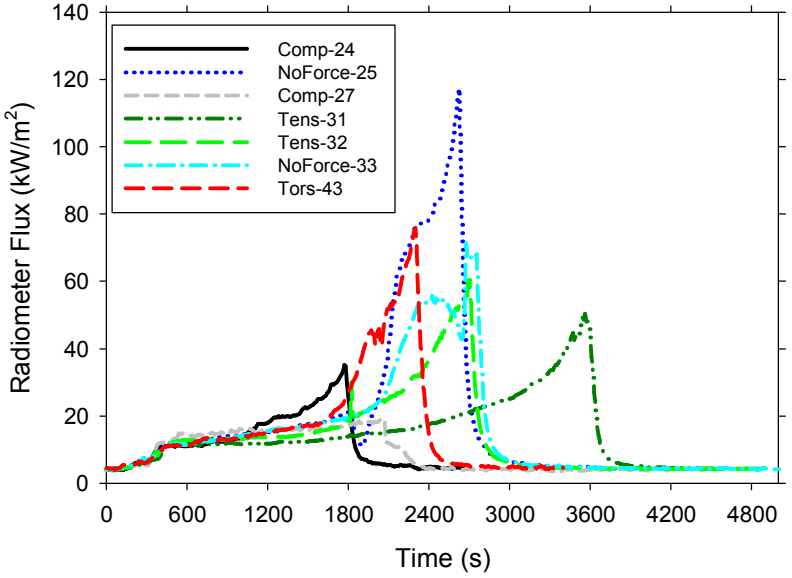

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