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Fire Science & Technology

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JANNAF INTERAGENCY PROPULSION COMMITTEE

Fire Environment Tests for Carbon-Fiber/Epoxy Composite Materials

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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Outline

- Introduce the notion of fast/slow cookoff
- Describe carbon-fiber/epoxy test program
- Overview of three test program results
  - Enclosure fire tests (2013)
  - Mock fuselage composite tests (2015)
  - Rubble fire test (2014)
- Results in relation to fast/slow cookoff
- Synopsis

Test Requirements

- Munitions and fires don't mix well, can be very hazardous
- It is impossible to eliminate the potential for fire environments
- Standards exist, and numerous documents (below) describe requirements
- Fast and slow heating scenarios are typically required

Document	Title/Description	Relevance
MIL-STD-2105C	Hazard Assessment Tests for Non-Nuclear Munitions	Section 5.2, Insensitive Munitions Tests
STANAG 4240	Liquid Fuel/External Fire, Munition Test Procedures	Section 20, Test Requirements for Engulfing Munitions in a Fire
STANAG 4382	Slow Heating, Munitions Test Procedures	Section 11, Test Requirement for Slow Heating Tests
STANAG 4439	Policy for Introduction and Assessment of Insensitive Munitions (IM)	Definition of what qualifies as an "Insensitive Munition"
AOP-39E(3)	Guidance on the Assessment and Development of Insensitive Munitions (IM)	Page C-1 #2, simplified categories for thermal environment tests
TB 700-2	Department of Defense Ammunition and Explosives Hazard Classification Procedures	Section 5-7, UN test series 6, External Fire section

Fast versus Slow Heat

- Fast heat scenarios postulate fires of maximum realistic severity
  - Challenge response because there isn't a lot of time to react (evacuate, suppress, etc.)
  - Munitions will generally pass this test before service commissioning (IM)
- Slow heat scenarios can be mechanistically very different
  - Generally defined as 6ºF/hr (3.3ºC/hr)
  - Can result in detonation or explosion where fast heat for the same materials only deflagrates
  - May be more difficult to pass this requirement
  - Often wavers are given for munitions not passing
- Questions regarding slow heat:
  - Is it credible/realistic?
  - Is it relevant?
  - Do we keep testing slow heat because of the value in comparing to historical tests?

Sandia's Composite Testing

- Sandia is primarily responsible for design and safety of some stockpile systems
- New aircraft contain carbon-fiber/epoxy in increasing quantities
- In 2008 a B-1 bomber crashed on the runway in Guam on take-off
  - The fire was extraordinary in terms of duration
  - Suppression activities lasted several days
- We decided to perform some testing to better understand implications of the material to the fire environment.

Experimental Matrix

- Test program can be organized by scale of tests
- Fewer intermediate and large scale tests performed
- Environment Implications in this presentation come from Intermediate and Large scale testing

Scale Description	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-, 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

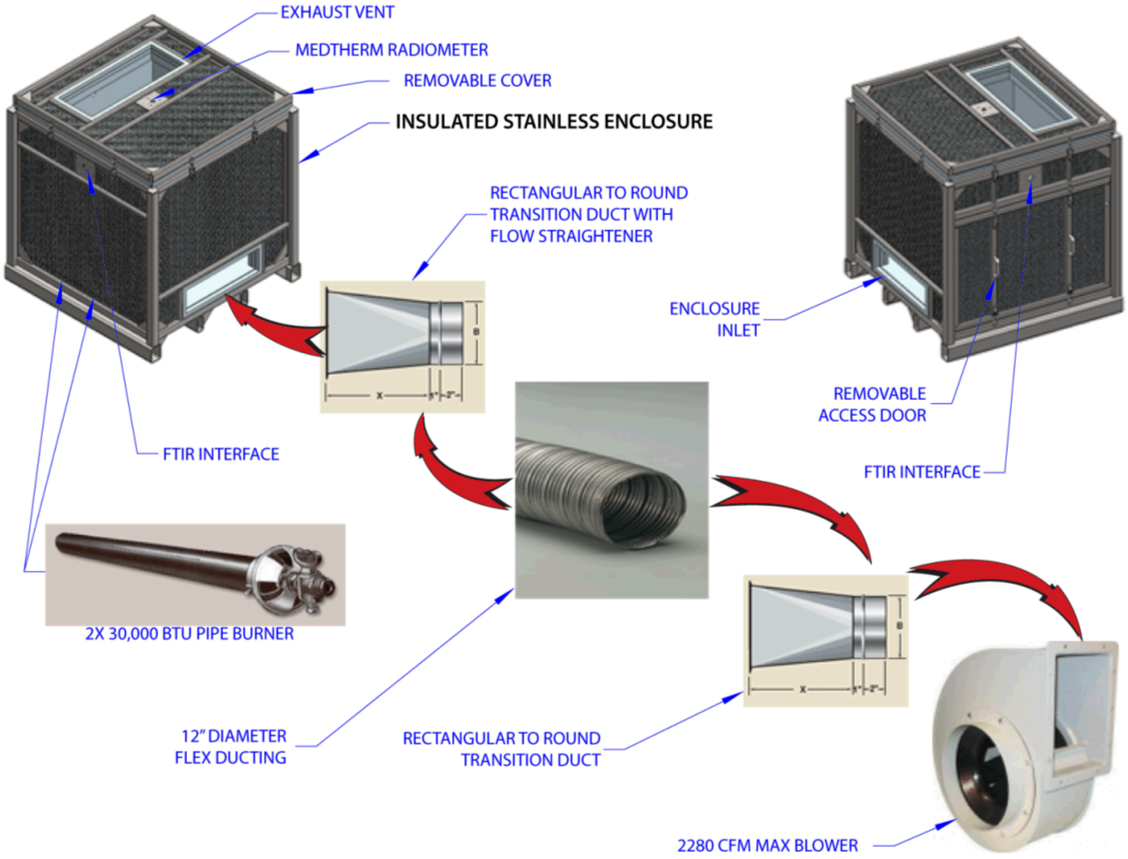
Results Focus

- In this presentation, focus is on three of the tests from the overall matrix
  - Enclosure Fire—Emulating a semi-infinite composite only fire
  - Mock B-2 Fire—Emulating a runway fire with ordinance
  - Rubble Fire—Emulating an un-suppressed crash environment (crash in remote wildland)
- Implications for the test environment are obtained from the results of these tests
- This presentation will show selected data from these tests

Test	Scale Description	Characteristic Length Scales	Characteristic Mass	Experiments
Enclosure Fire	Intermediate	10-100 cm	0.1-100 kg	Environmental chamber tests
Mock B-2	Large	Meters and above	Hundreds of kg and above	Full-scale fire testing
Rubble Fire	Large	Meters and above	Hundreds of kg and above	Full-scale fire testing

Enclosure Fire Test

- 91.0 cm aspirated internal cube designed to create an idealized semi-adiabatic environment

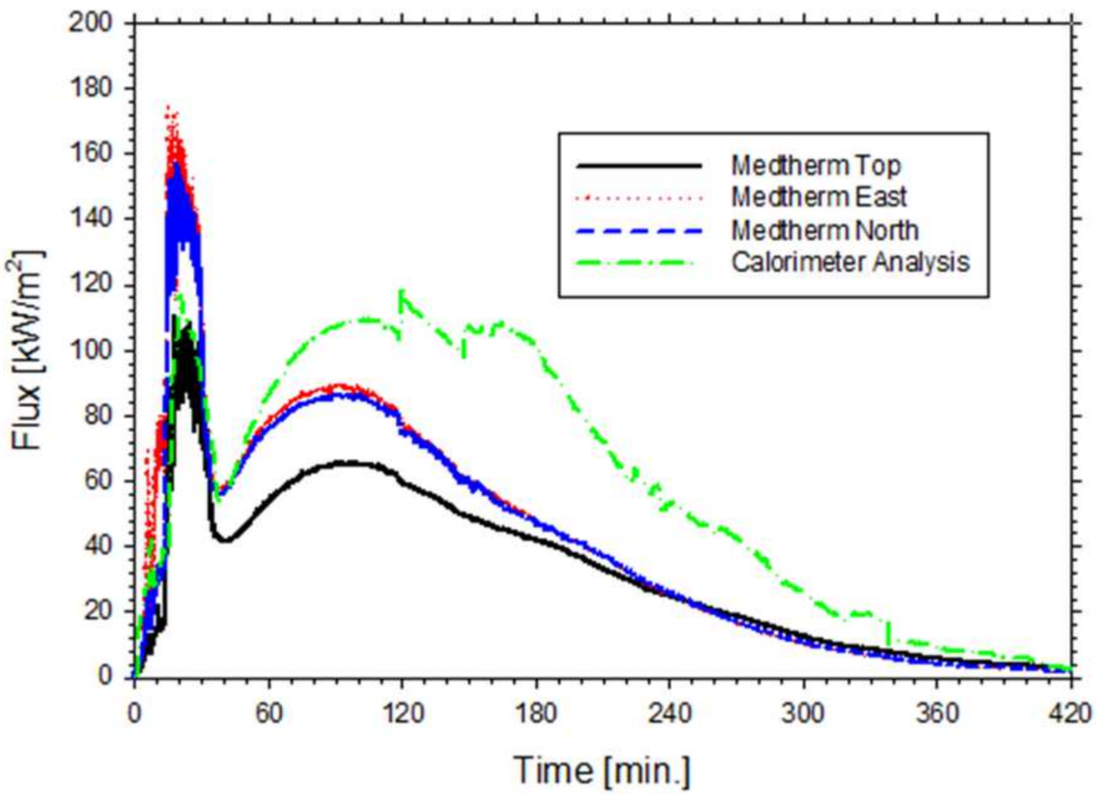


<u>Instrumentation</u>

- FTIR
- RGA/Mass Spec.
- Radiometers
- Calorimeter
- Thermocouples
- Pitot Velocity Probe
- Video

Enclosure Fire Flux

- Initial flux due to burning epoxy
- Second peak due to glowing char and fiber oxidation reactions
- Very long duration tests



Test 6 (Composite Strips) Video

Late-term burnout pattern evident in still photography
Air inlet is from the left in these photographs

Testing Summary

A summary of various results from six tests.

	Test	Initial Mass	Residual Mass	Peak Flux	Flaming Duration	Total Duration	SA/V	Mean Consumption Rate
	#	*kg*	*%*	*kW/m²*	*min*	*min*	*cm⁻¹*	*g/s*
Wood	1	40.8	-	220	-	90	2.4	7.56
	2	31.8	-	220	-	60	1.3	8.82
Composites	4	36.5	9.56	180	25	330	-	1.84
	5	38.5	2.59	175	30	420	2.0	1.53
	6	39.3	6.74	220	20	300	9.2	2.18
	7	26.5	10.34	160	10	240	6.9	1.84

Compared to wood, peak fluxes tend lower, consumption rates are much lower, thermal release duration is much longer.

Very low residual mass!

Mock B-2 Fire Test Materials

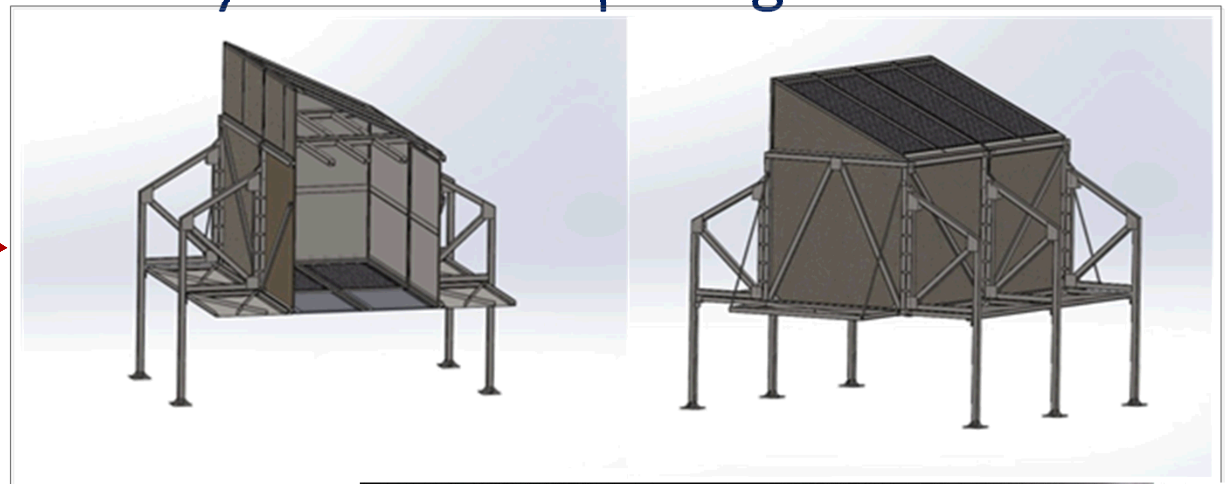
- 22 4’ x 8’ panels
  - 12 of which were sandwich panels with aluminum or paper core
  - Remainder were flat panels
- Simulation Matrix:

Scenario	Composite Mass	Wind Speed	Door Configuration
Units	*kg (lbs.)*	*km/hr*	
High-wind	205.6 (453.3)	8	One open
Low-wind	178.9 (394.4)	5	Both closed

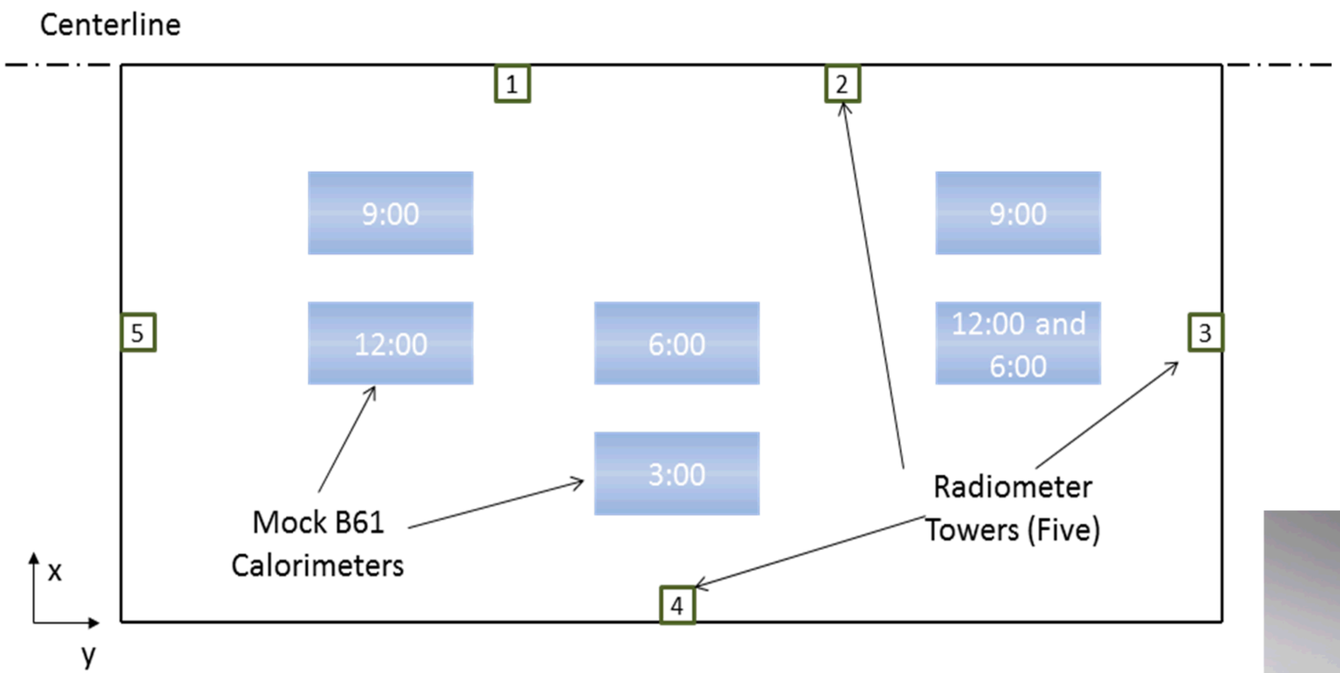
Photograph of a single panel

B-2A Mock Weapons Bay – Test Setup-Large Scale

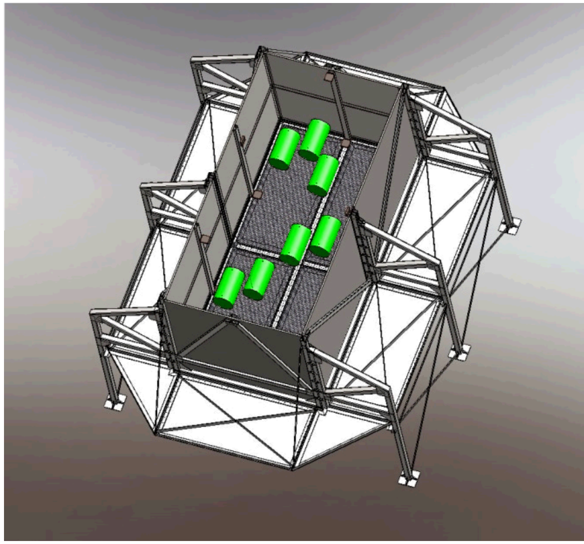
Mock weapons bay
~2/3 of full size



Instrumentation Layout

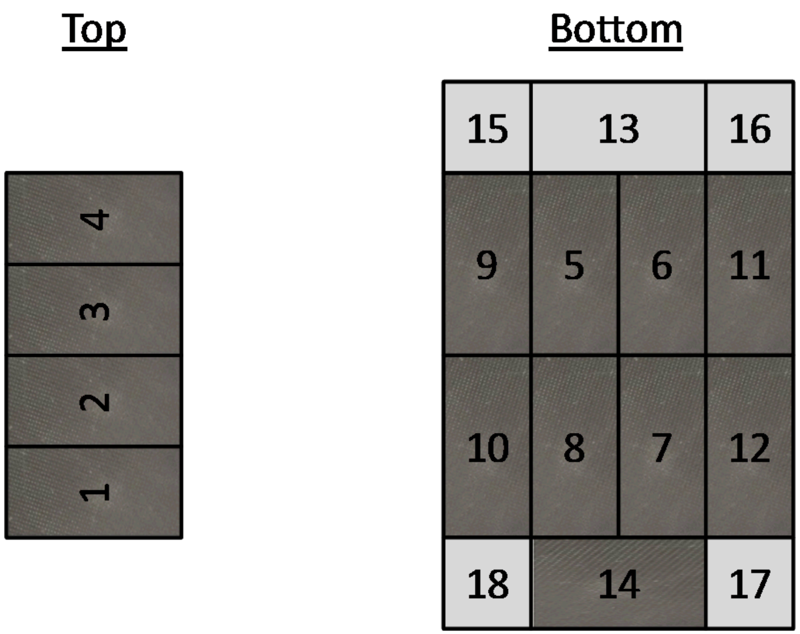


Top view of calorimeter locations with angular rotation by time analogy

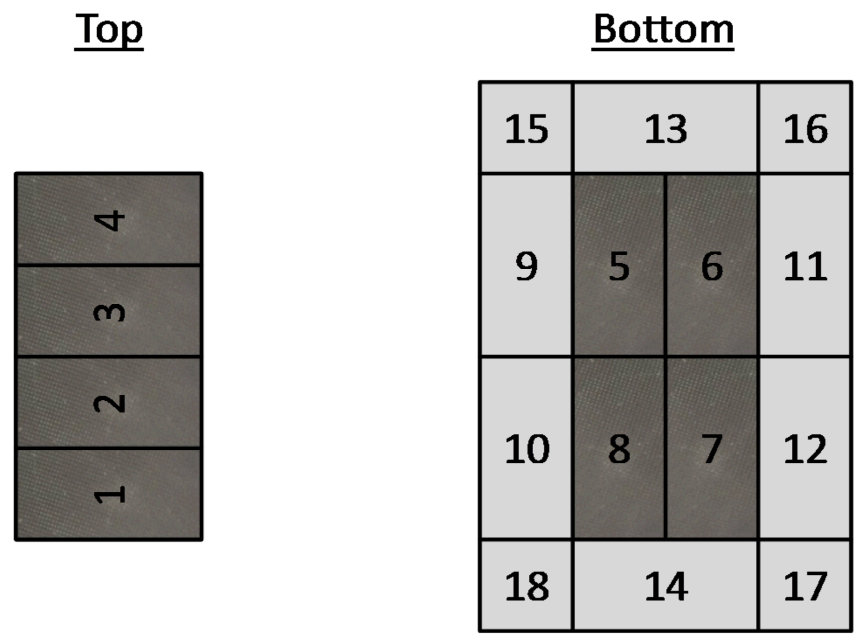


Panel Layout

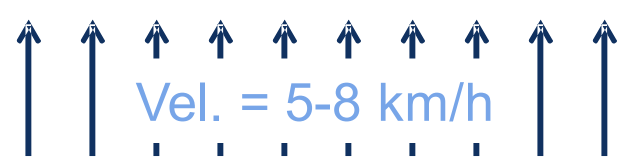
High-wind scenario



Low-wind scenario

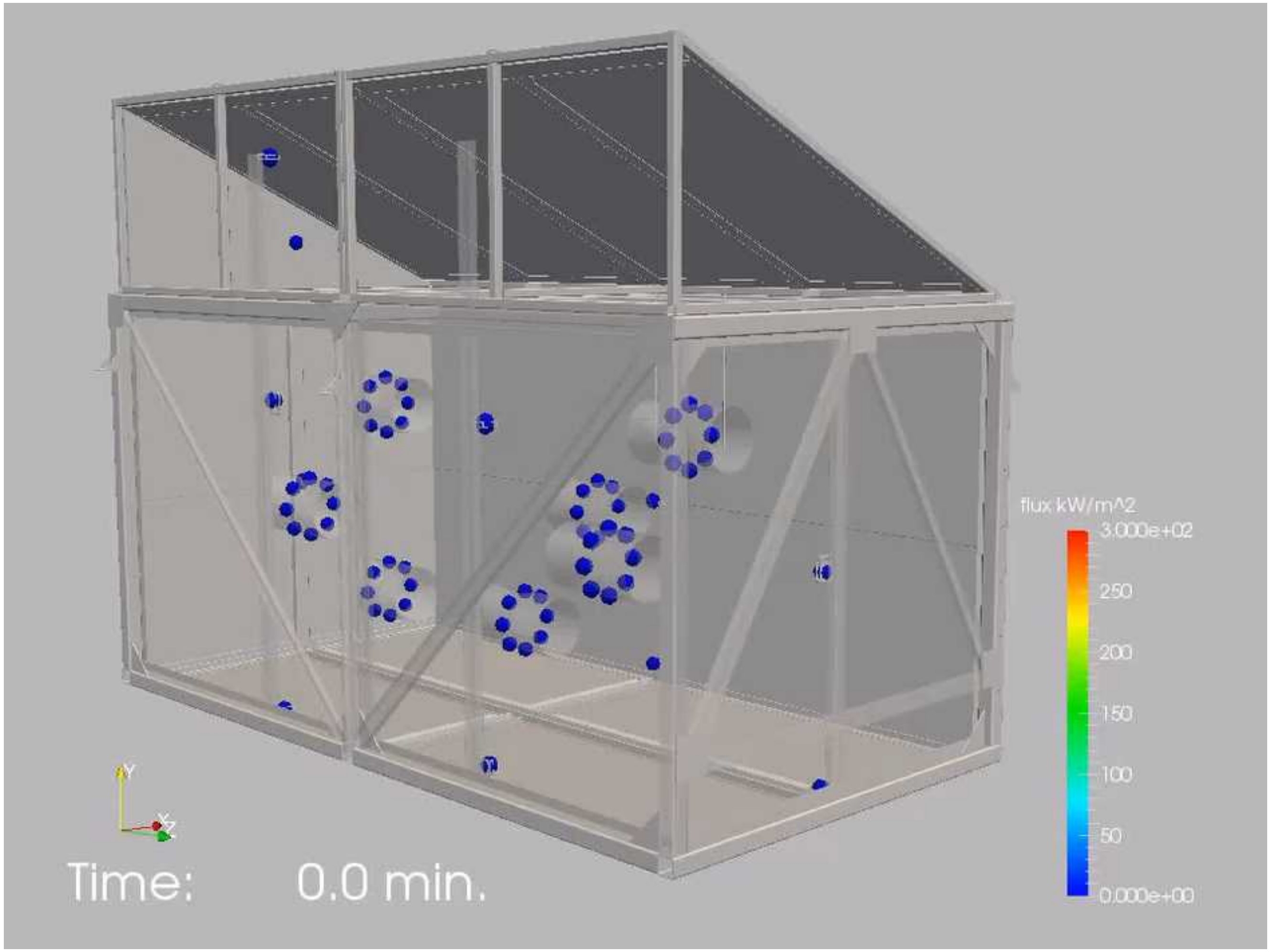


Fuel pan was located under Panel 14, 7, 8



Video Results

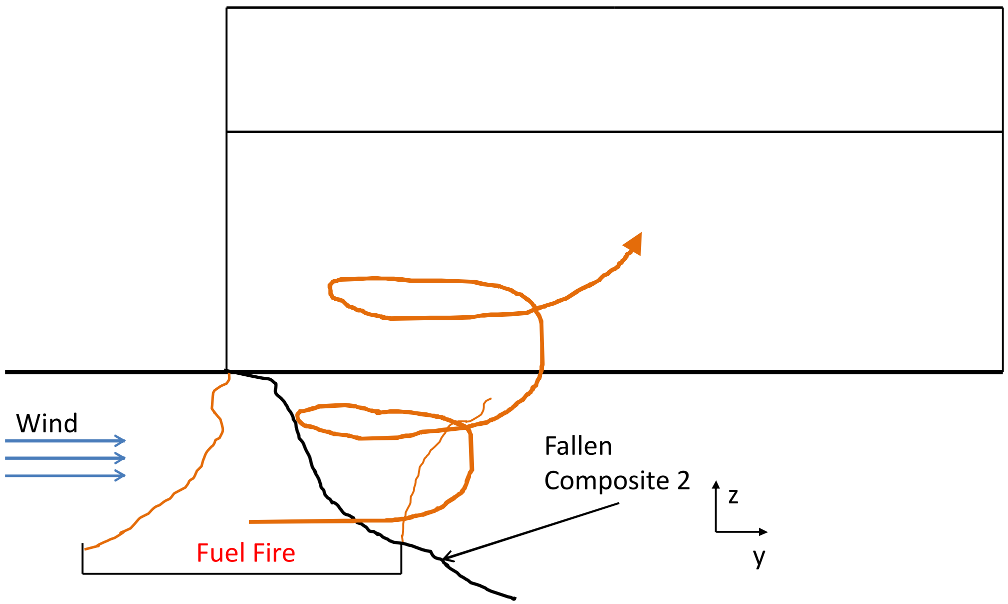
Heat Flux Measurements



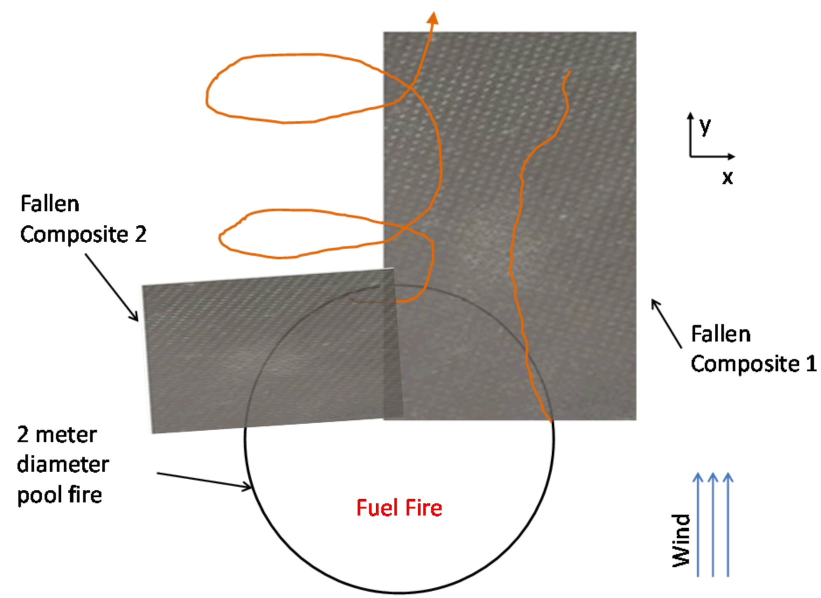
Why Were Fluxes So High?

Vortical flows generated around a fallen composite panel
High mixing and burn rate caused by fuel/flow interaction

Side View

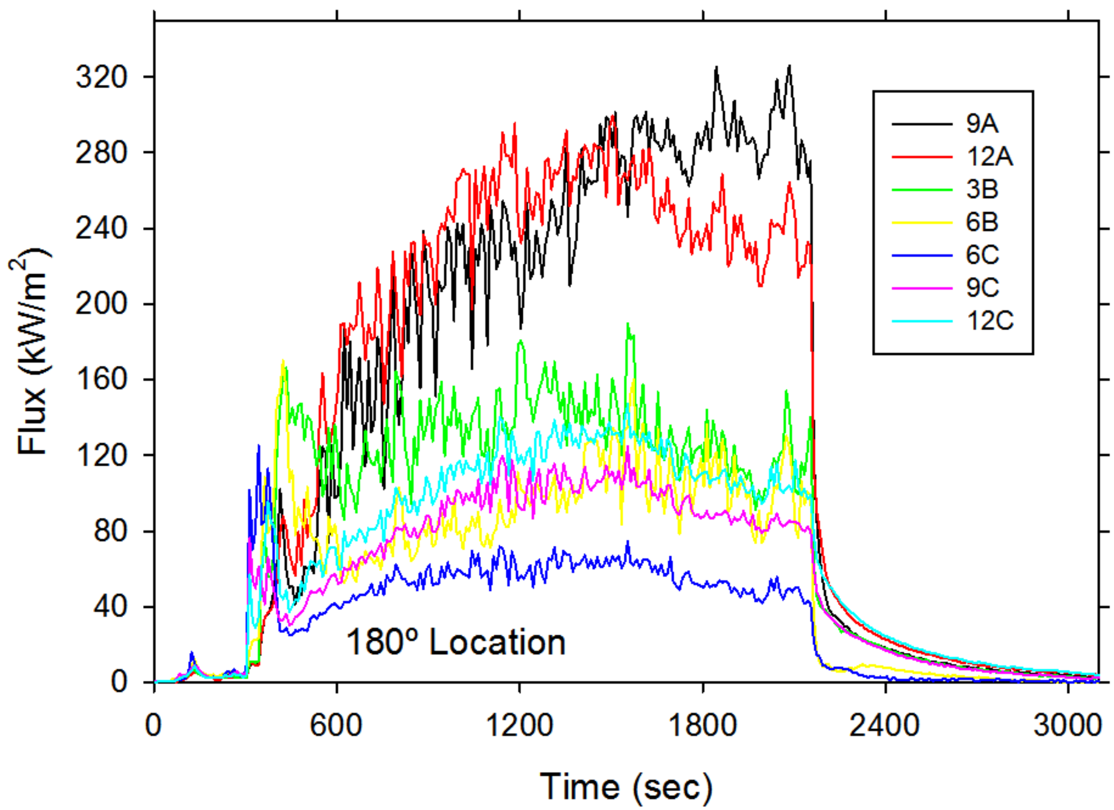


Top View



Typical Test B heat flux measurements

The 180 location was on the bottom of each calorimeter



JP-8 fuel fire in circular pan under mock bay; ~35 minute burn typical of liquid fire durations

Low flux until doors fall at 300 sec., increase to very intense fire at 1800 sec.

- Fast heat environment

Mixed JetA-Composite Fire Test-9/14

Calorimeters

Heat Flux Gages

Thermocouple Rake in Pool

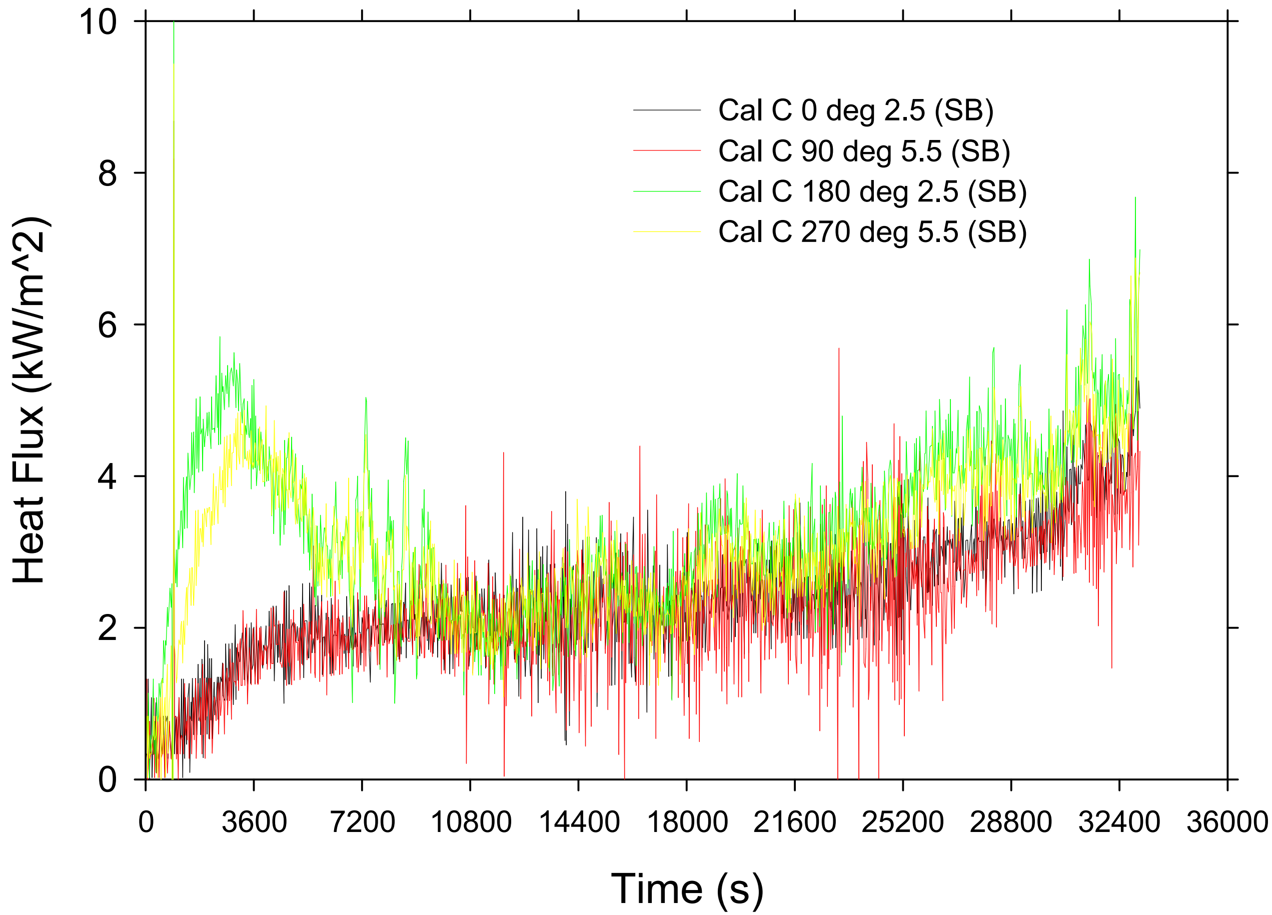
Wind

Rubble Test Arrangement

Test Video

Sample Flux from Calorimeter

- From the small buried calorimeter
- Flux was initially low, but increased hour by hour



Synopsis

- The three tests suggest environments characteristic of slow and fast heat scenarios
- The rubble fire in particular produced a relevant slow heat scenario
- Results have been taken into account in the planning process for safety analysis of cargo systems

Test	Slow Heat	Fast Heat
Enclosure Fire Tests	Yes	Yes
Mock Fuselage Fire Tests	No	Yes
Rubble Fire Test	Yes	No

Questions?

Acknowledgements

- A large number of people helped with the test programs, and are credited in the various reports
- Sandia programs for supporting this work

Composite Aircraft in Fires

Sandia National Laboratories

- Composite materials behave differently from conventional fuel sources and have the potential to smolder and burn for extended time periods

- B-2 crash on take-off February 2008*:
  - 30 minutes JP8 burning
  - 4-6 hours of aircraft structure flaming with transition to intermittent flare-up at random locations
  - followed by 24-48 hours of smoldering
  - all with active fire suppression (83,000 gallons of water containing 2,500 gallons of aqueous film-forming foam (AFFF))

*Baker, D., “Impact Analysis,” http://leehamnews.files.wordpress.com/2009/03/b2fire.pdf

Test Setup and Pre-test

Test Setup and Pre-test