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Fire Science & Technology

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Composite Fire Rubble Test Results: Implications for Models

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Background

- Modern aircraft use increasing quantities of composites in the design
  - Significant weight savings results in increased efficiency, lower fuel costs, higher payloads, etc.
  - Carbon fiber epoxy materials are heavily used in new design
  - Structural implications are well understood
  - Behavior of carbon fiber epoxy materials in a fire is not as well understood.
- Testing at Sandia has recently been aimed at developing a better understanding of the potential fire environment
  - Experiments performed at various scales
  - First test series believed to focus on the environment created by burning composites

Past Intermediate- and Large-scale Sandia Tests

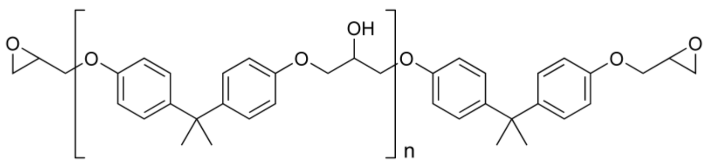
- 50-100 lbs of composite in an insulated, aspirated enclosure (with USAF-Tyndall participation)
  - Found 90-100% consumption, very long burn times (8 hours)
- Directed flux on various panels under various loading conditions
  - Confirmed the loading had a minor effect on the burn rate
- Mock fuselage fires for specific scenarios, 400-600 lbs of composite with liquid fuel
  - Achieved flux of 320 kW/m^2 in one test because of wind/fuel/panel interaction
- Final test in this series was aimed at understanding the environment created in a mix of composite rubble and jet fuel
  - 900 lbs of composite, 300 gallons of jet fuel

Background Composition Data

- 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, or similar
- Fibers around 5 μm diameter, 95% carbon

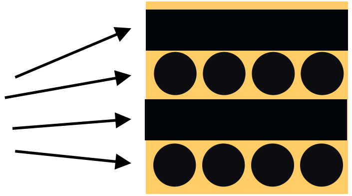
Epoxy (DEGBA) and TETA hardener (From wikipedia):

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



A four layer cross-section illustration:

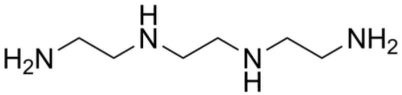
Fibers in varying orientation



Key:

Carbon Fibers

Epoxy Resin



$C_6H_{18}N_4$

Test Materials

Pre-test weight to be compared to post-test weight for mass loss

Description	Total	Total	Epoxy Fraction Estimate	Epoxy Mass Estimate
	lbs	kg		kg
Residual Bag1	135	61.2	0.0	0.0
Residual Bag2	280	127.0	0.0	0.0
Residual Bag3	180	81.6	0.0	0.0
Bags	-36.6	-16.6		
Sub-total	558.4	253.3		0.0
4 18x24	36.0	16.3	0.35	5.7
I-beams	40.5	18.4	0.35	6.4
F16 Panels	35.1	15.9	0.35	5.6
18x24	95.1	43.1	0.35	15.1
ABDR Box 5	18.3	8.3	0.35	2.9
ABDR Box 3	16.3	7.4	0.35	2.6
ABDR Pre-burnt	22.7	10.3	0.1	1.0
18x24 pre-burnt	60.1	27.3	0.1	2.7
Misc. Parts	46.9	21.3	0.35	7.4
Sub-total	371.0	168.3		49.5
Total	929.4	**421.6**		**49.5**

Instrumentation

Calorimeters

Heat Flux Gages

Thermocouple Rake in Pool

Wind

Test Arrangement

Composite Rubble Fire Test

Assembly Time Lapse

9/4/14

Test Issues

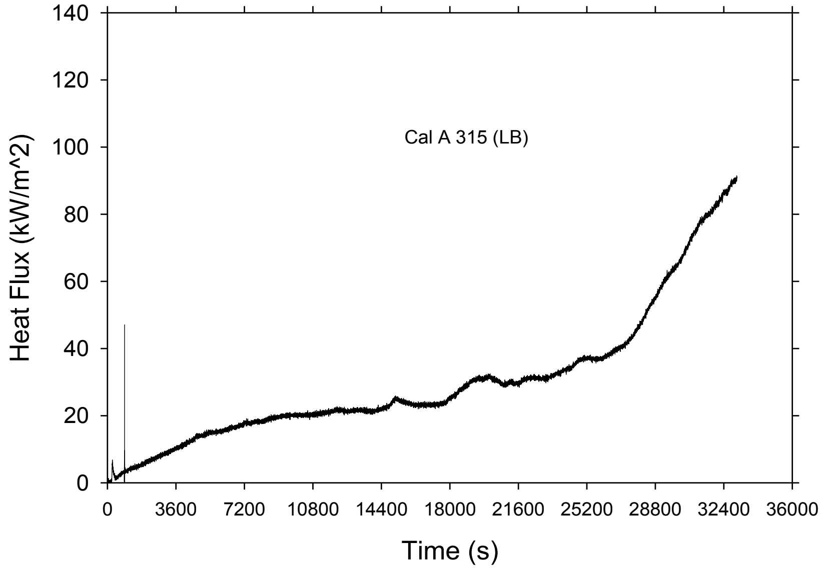
- DAQ went down 2/3 of the way through the test
- Team was unprepared for the duration of the test
  - Did not have correct procedures in place for ending the test
  - Test results did not reach the point intended
  - Dousing meant that the mass loss data were more complex than intended
- Single test (no repeats)

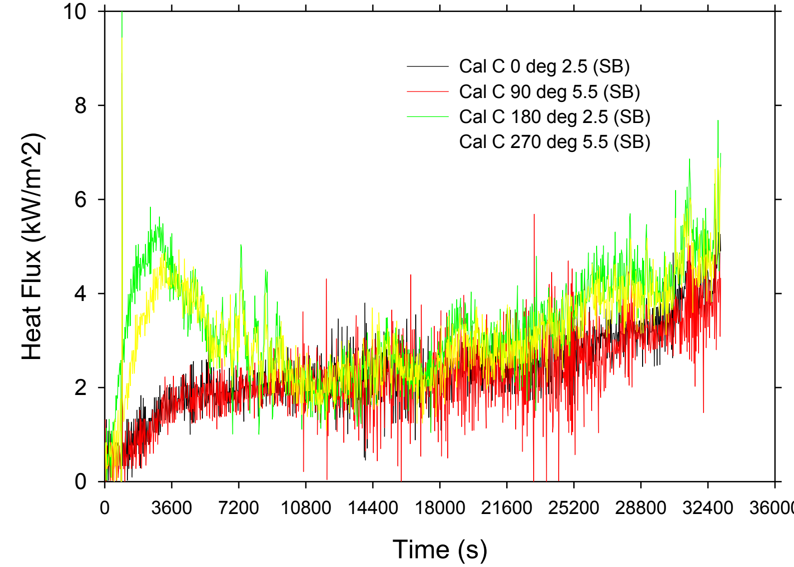
Fire Test Video

Calorimeter Data

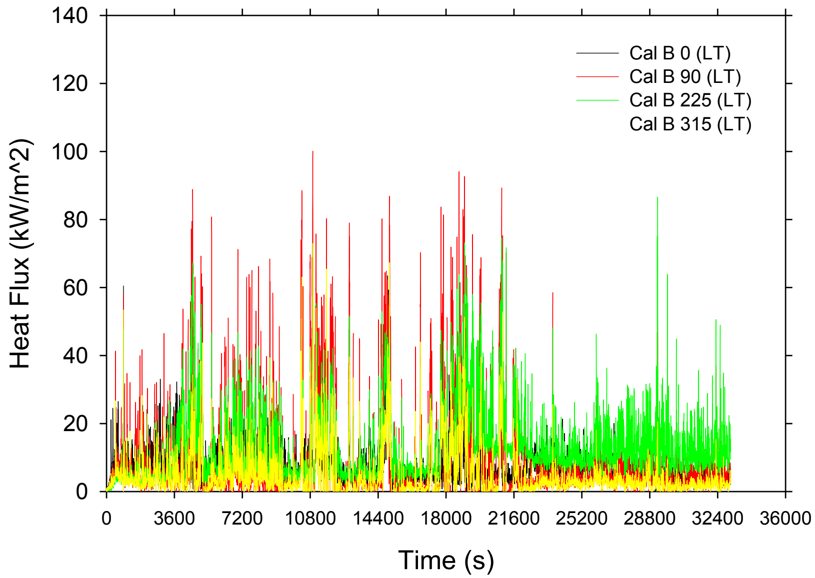
Sandia National Laboratories

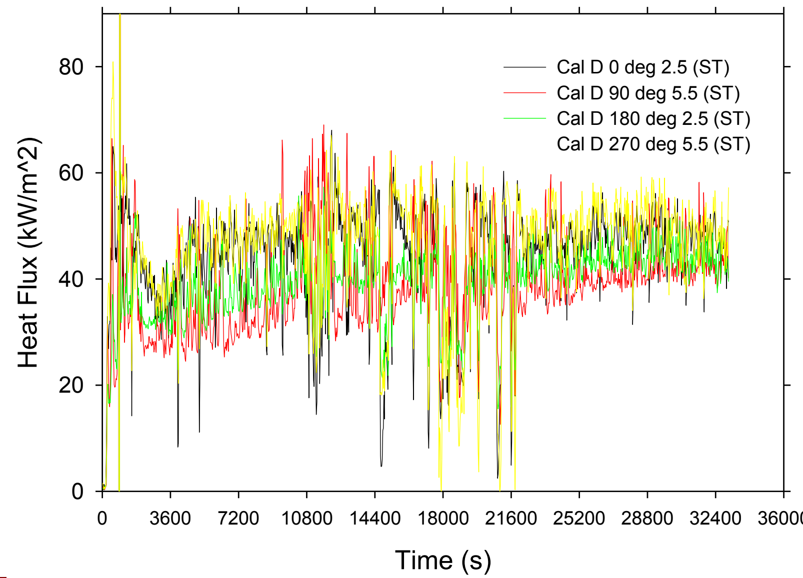
Buried Calorimeters





Top Calorimeters

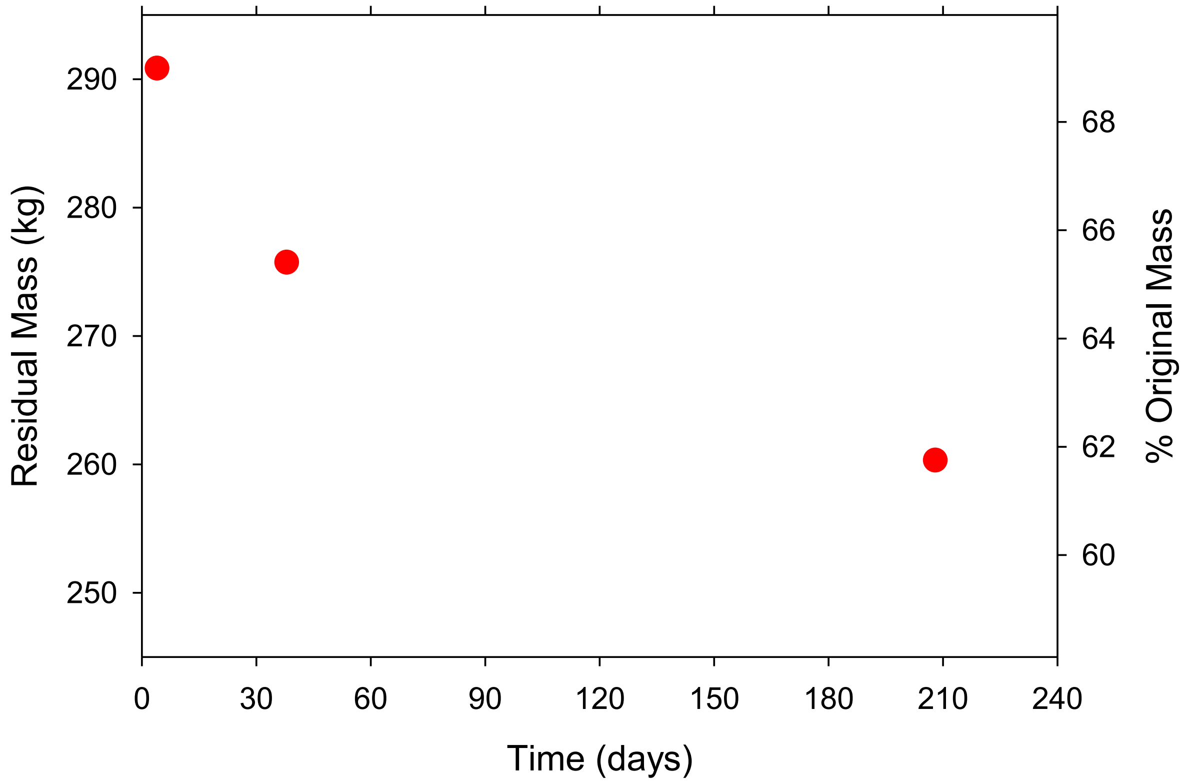




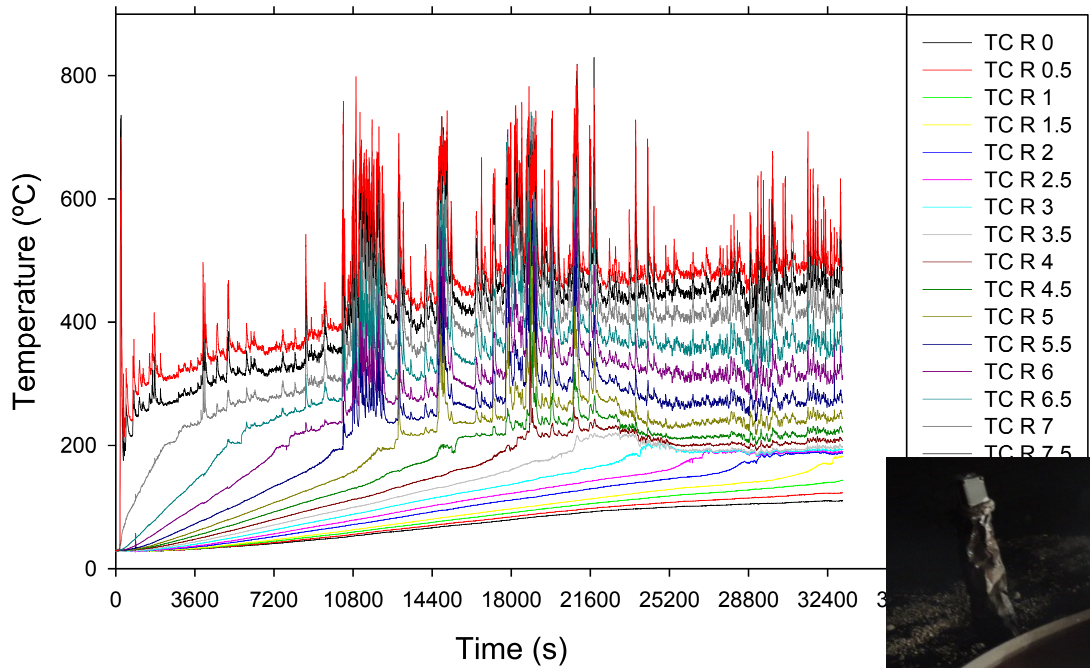
Large Calorimeters Small Calorimeters

Mass Loss Data

- Because the fire was doused, water and residual fuel are presumed to contribute to the residual mass.
- Later measurements are thought to better represent the residual mass of the composite



Other Results



Thermocouple data from the rake in the pan was used to monitor the progress of the liquid fuel burn.

Note that by the end of the test the large buried calorimeter was completely exposed.

Also, there is substantial glowing (reactions) in areas away from the active flaming.

What do the results mean?

- A fire resulting from an aircraft crash can last an extraordinary length of time (hours to days) because of the reacting rubble
- It is possible to have a low-level burn with a significant increase in temperatures at later times
- Fibers may continue to react with no flaming present if there is sufficient material (i.e. at this scale)
- The epoxy never appeared to be a significant or distinguishing factor in this test as a fuel, is thought to be mostly consumed early in the burn
- Total composite mass loss is still not resolved for an unmitigated fire scenario, longer-term data would be helpful
  - Likely to exhibit significantly higher mass loss

Modeling this Test

- Pre-test predictions were not performed because we generally lack the ability to model this scenario with existing tools
- I have not encountered a capability in any code for liquid soaked solid fuel fires
- We have performed some rubble soaked fuel tests in the past, but never had a scenario where the ‘rubble’ could also react
- Certain components exist in SIERRA/Fluid Mechanics that can be leveraged to build a capability (exhibited in next viewgraphs)

Existing Capabilities

Sandia develops the open source SIERRA mechanics. Fluid mechanics tools exist in this framework.

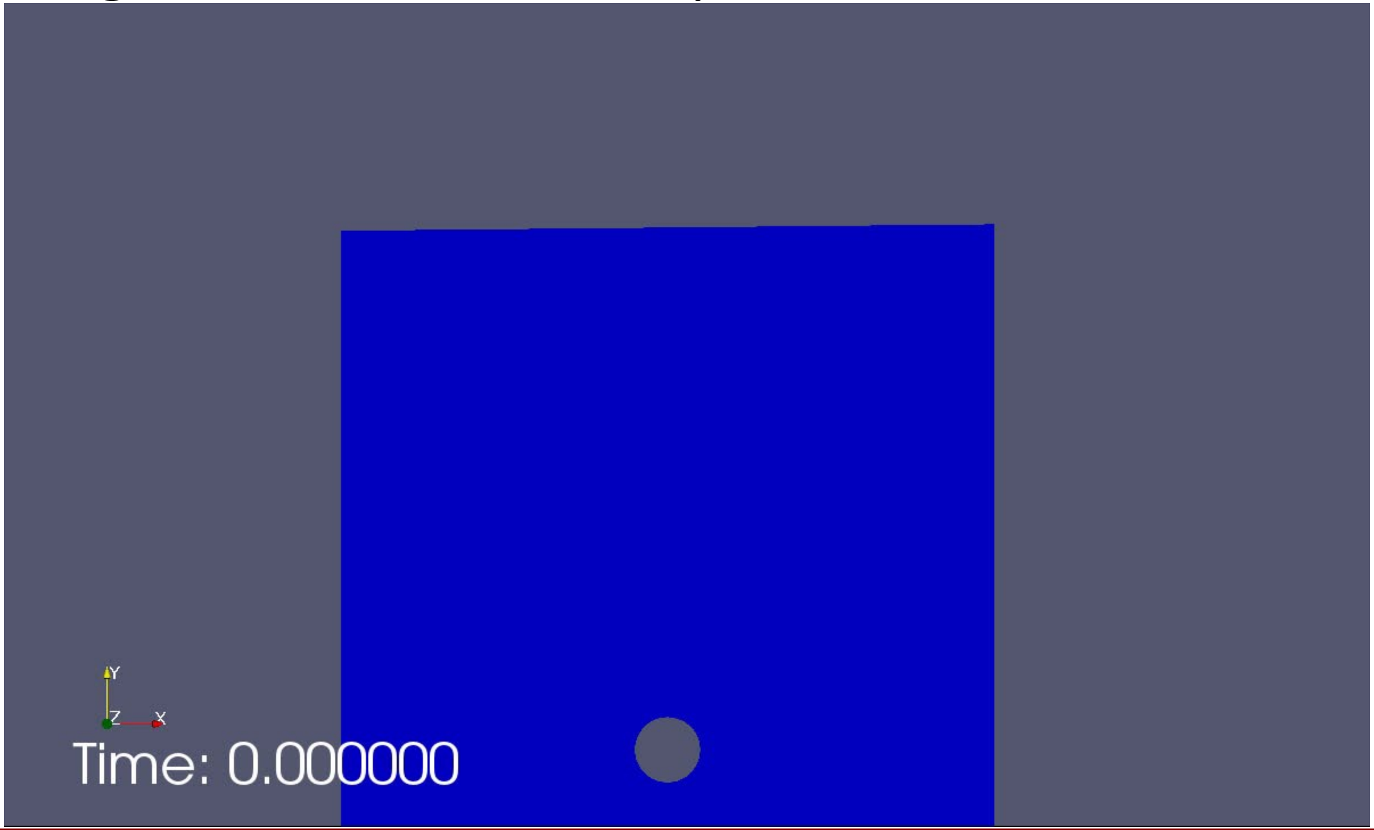
- The non-open source **Fuego** tool is primarily used for low-Mach number reacting flow problems and particle transport.
- **Aria** does heat transport and low-Reynolds number multi-phase transport and reaction
- **Aero** does shock, ablation, and high-Mach number simulations
- **Nalu** is a basic open source N-S flow code for testing new algorithms

Capabilities potentially relevant to the composite fire scenario include:

- Adaptive boundary level-set method for multiphase flows (Aria)
- Particle combustion model (Fuego)
- 1-D solid reacting boundary condition model (Fuego)
- 1-D liquid pool model (Fuego)
- 3-D solid reacting material model (Fuego/Aria)

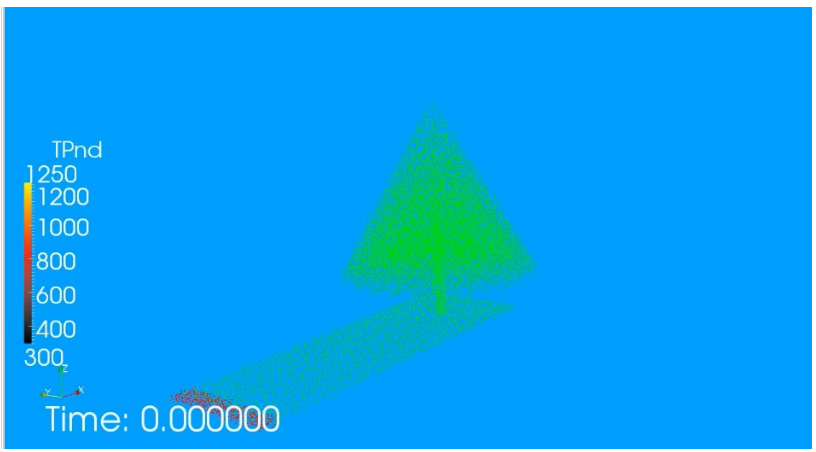
Level-set methods

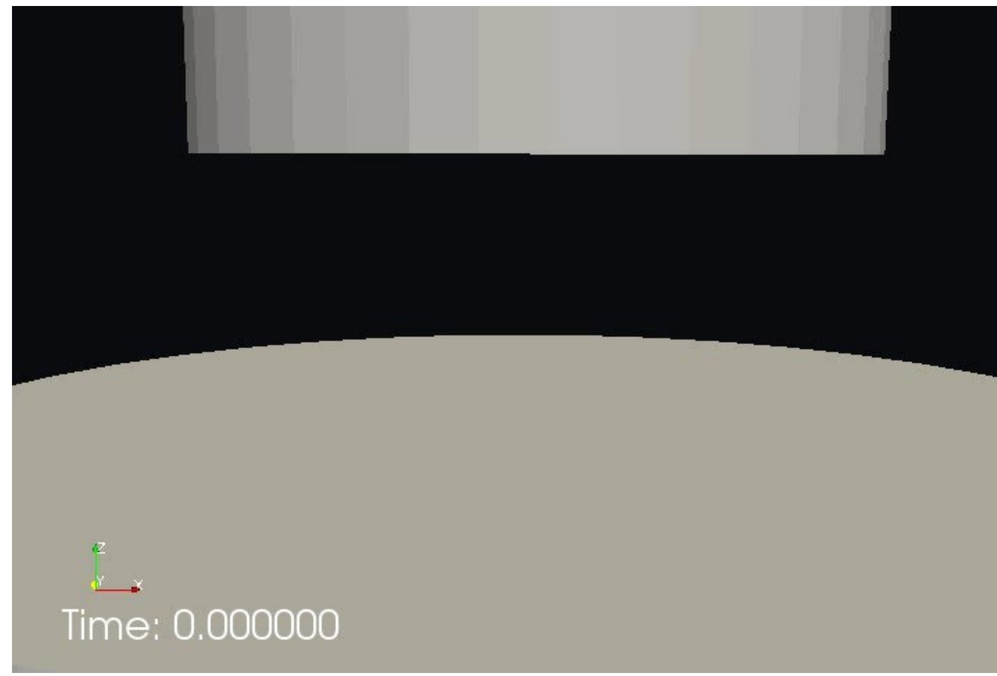
- CDFEM methods were recently implemented for resolving level-set multi-fluid interfaces
- The below video exhibits a 2-D prediction of a boiling drop rupturing on the surface of a liquid



Particle Combustion Model

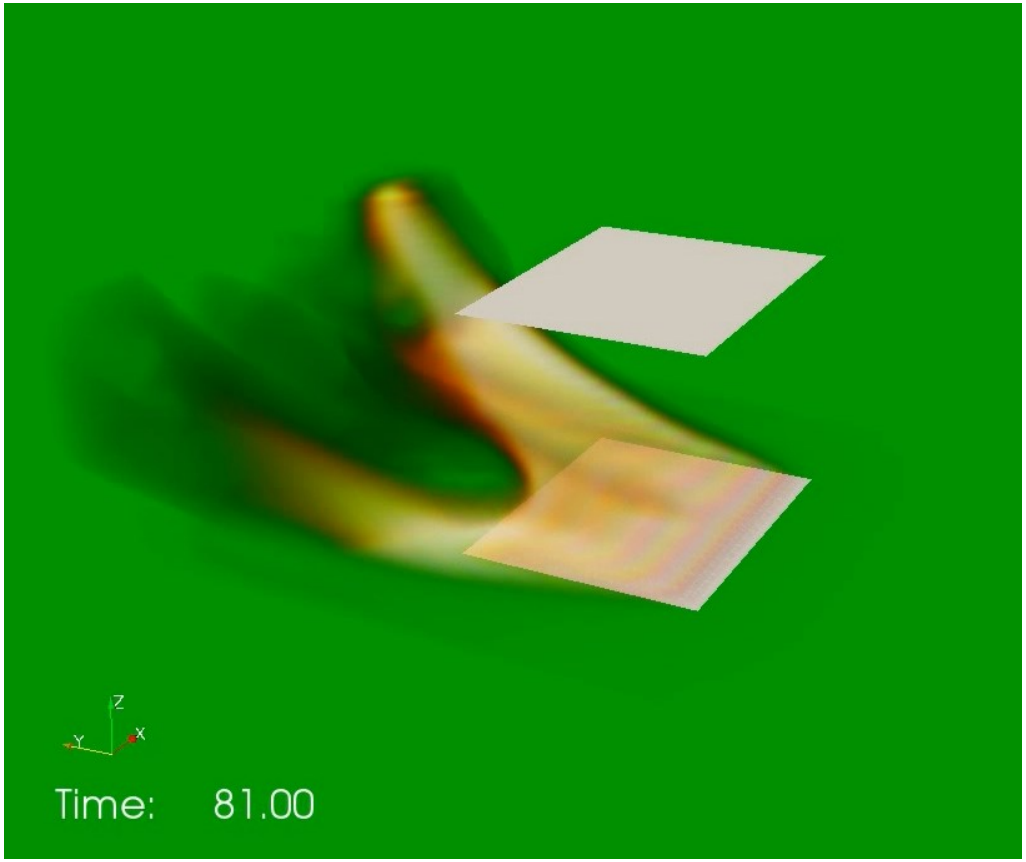
- Primarily used in the past for two projects:
  - Wildland fire predictions for idealized trees
  - Aluminized propellant reactions





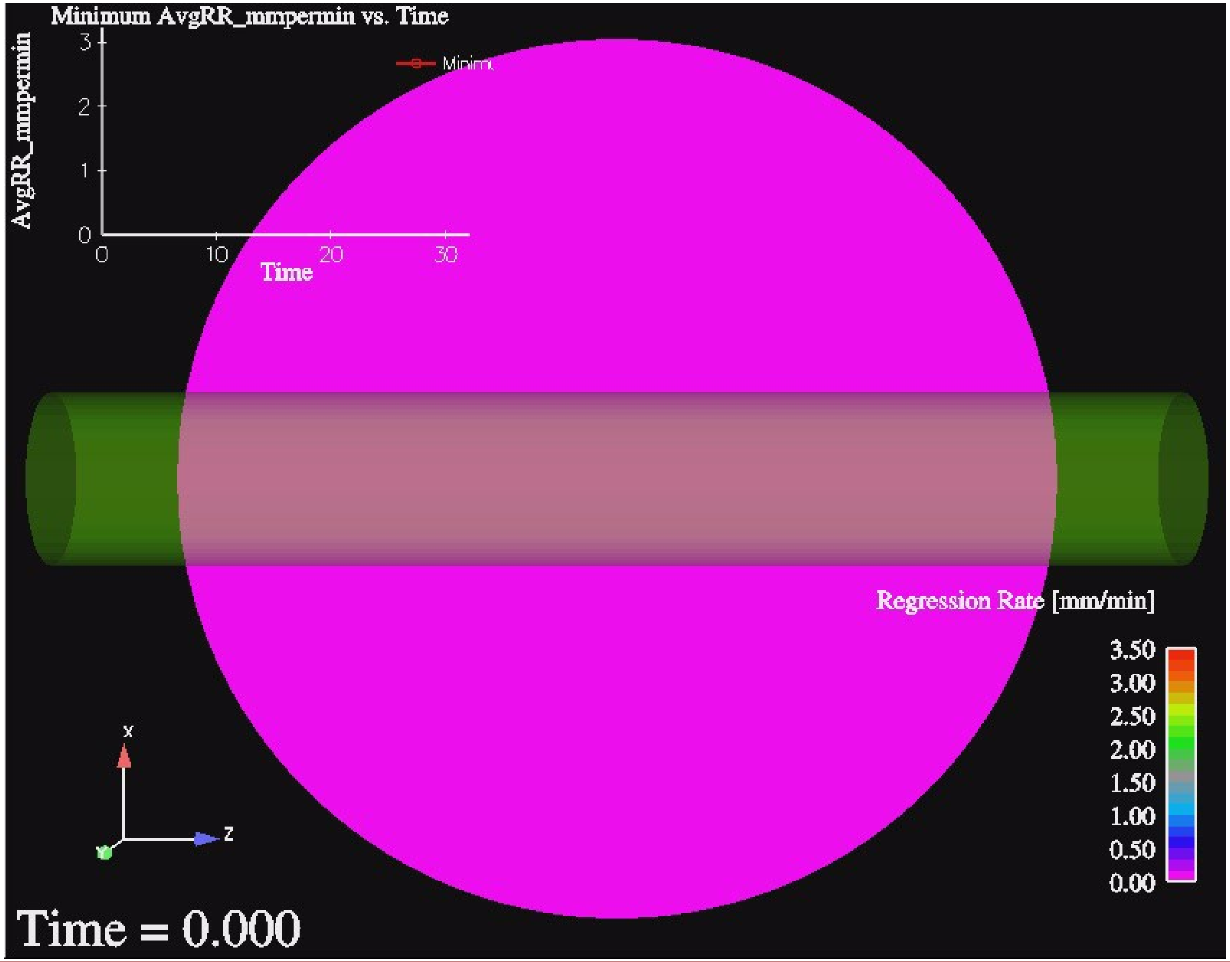
1-D Solid Reacting Boundary Condition

- Recent work demonstrates the verification of the method and compares to data in the context of a sensitivity analysis:



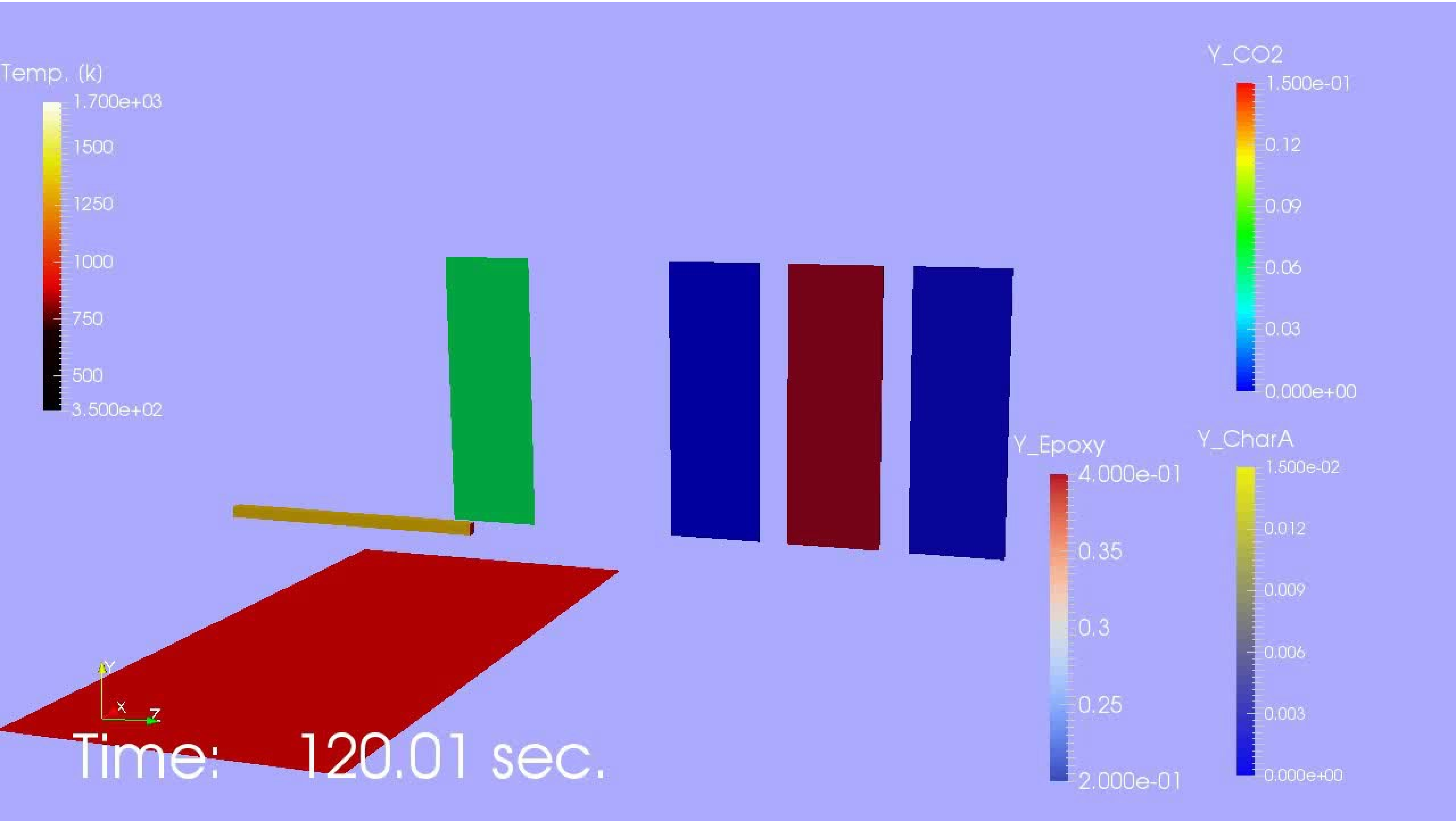
1-D Liquid Pool Model

- Historical model for predicting the burn rate for pool fires given heat transport from the flames (based on legacy SINTEF codes)



3-D Solid Reacting Material Model

- New model includes porous transport, charring reactions, oxidative reactions.



Summary

- A test was performed where rubble consisting of aviation-type composite materials was burned with jet fuel
- The duration of the test was extraordinary
  - Relatively constant flaming for 12 hours
  - Local flaming for another several hours
- Fibers outside the flaming region at the end of the test continue to glow, indicating continuing reactions
- Some calorimeter heat fluxes continually increased over the course of the test
- Modeling capabilities to simulate this environment are immature, and are in the process of being developed

Acknowledgements

- The test team including contributions from Brandon Servantes Sylvia Gomez-Vasquez, Travis Fitch, Randy Foster, Chuck Hanks, Jerry Koenig, William Dixon, Richard Simpson, Donald Mcmanaway, Deven Codding, Paul Codding, Steve Chandler, KD Pass, Craig Dickensheets, Ron Pederson, Jeff Kokos, Jim Nakos, and Randy Watkins.
- Sam Subia provided the 3-D solid reacting material video
- Major contributors to the code efforts including David Glaze, Stefan Domino, Flint Pierce, John Hewson, David Noble, Sam Subia, Amanda Dodd, Rekha Rao, Vern Nicolette, Anay Luketa, Sheldon Tieszen