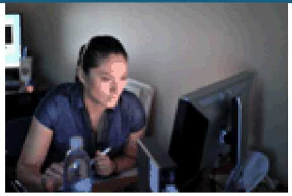
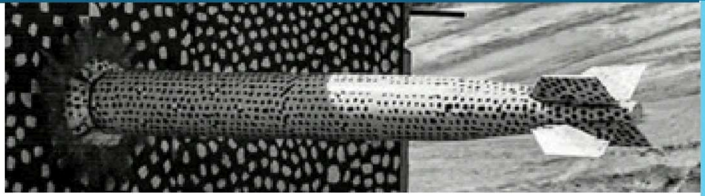
Oct 14-15 Fall 2019
Technical Meeting
Albuquerque, NM, USA

WSSCI
Western States Section Combustion Institute

SAND2019-12310C

Initiation of Pyrolysis from High Flux Exposures





Alexander L. Brown; albrown@sandia.gov; (505)844-1008
Jeffrey D. Engerer, Allen J. Ricks, Joshua Christian
Fire Science and Technology Department

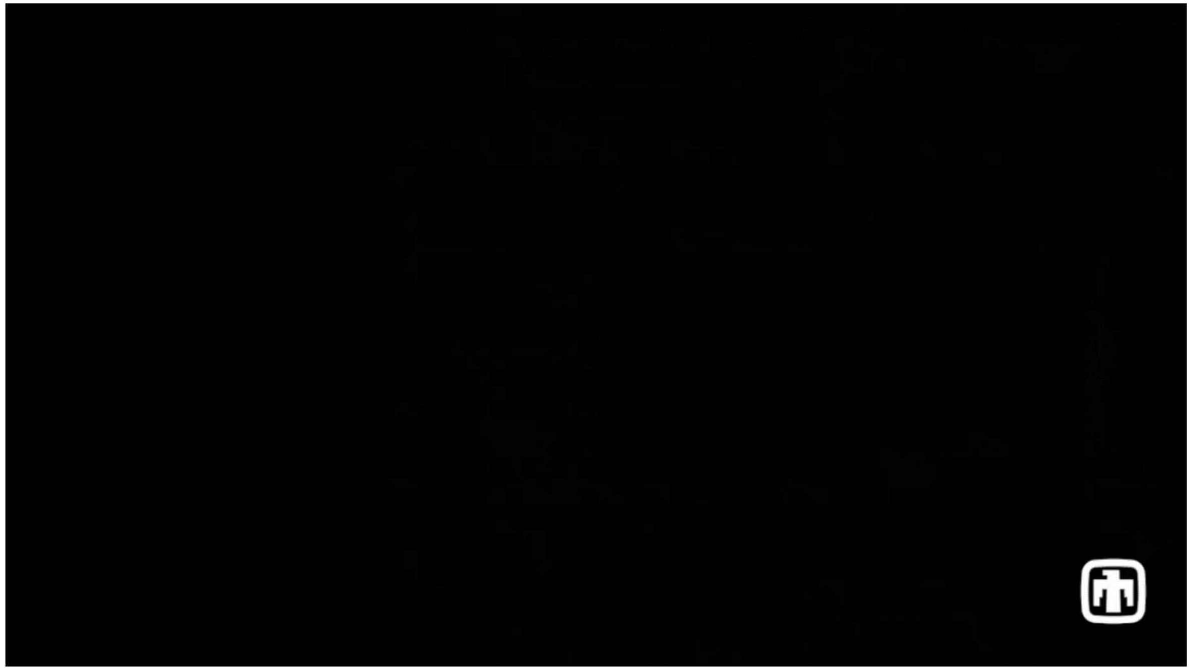
Fire Science & Technology

SAND2019-?????

Outline

1. About the High Heat Flux Ignition Regime
2. Sandia's Test Program (methods)
3. Objectives
4. Ignition and Pyrolysis Maps (current data results)
5. Assessment of Contributing Factors
6. Summary

High Heat Flux Ignition (>200 kW/m^2)



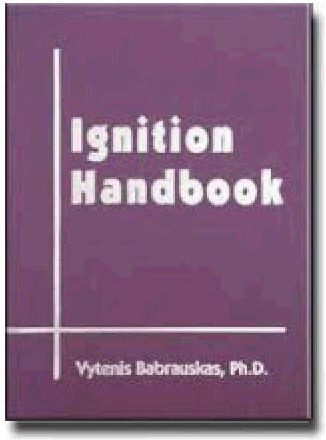
Why we care?

- Fires from above ground nuclear detonations
- Directed energy weapons
- Lightning strikes
- Ablation
- Propellant and metal fires
- Processing of solids to liquids

Differentiating features from common ignition

- Short pulses, comparatively fast ignition
- Ignition and mass loss might not collapse to the more traditional environment variables (by temperature, flux, energy, etc.)
- Ignition behavior might be different (sustained flaming, char formation, opacity, etc.)
- Reaction kinetics may not be linear through the regime change

Current High Flux Ignition Literature

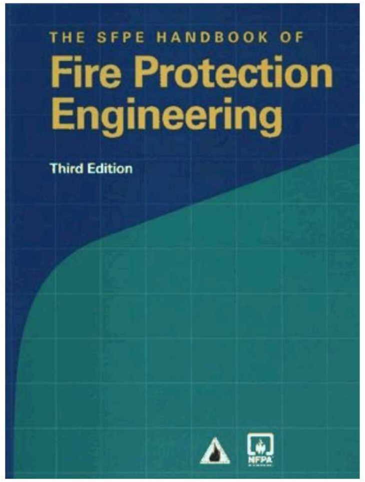


Ignition Handbook (Babruskas, 2003)

- Cites Glasstone and Dolan (1977) as main source
- We believe their ignition data are based on the historical data from the 50's-60's.

SFPE Handbook

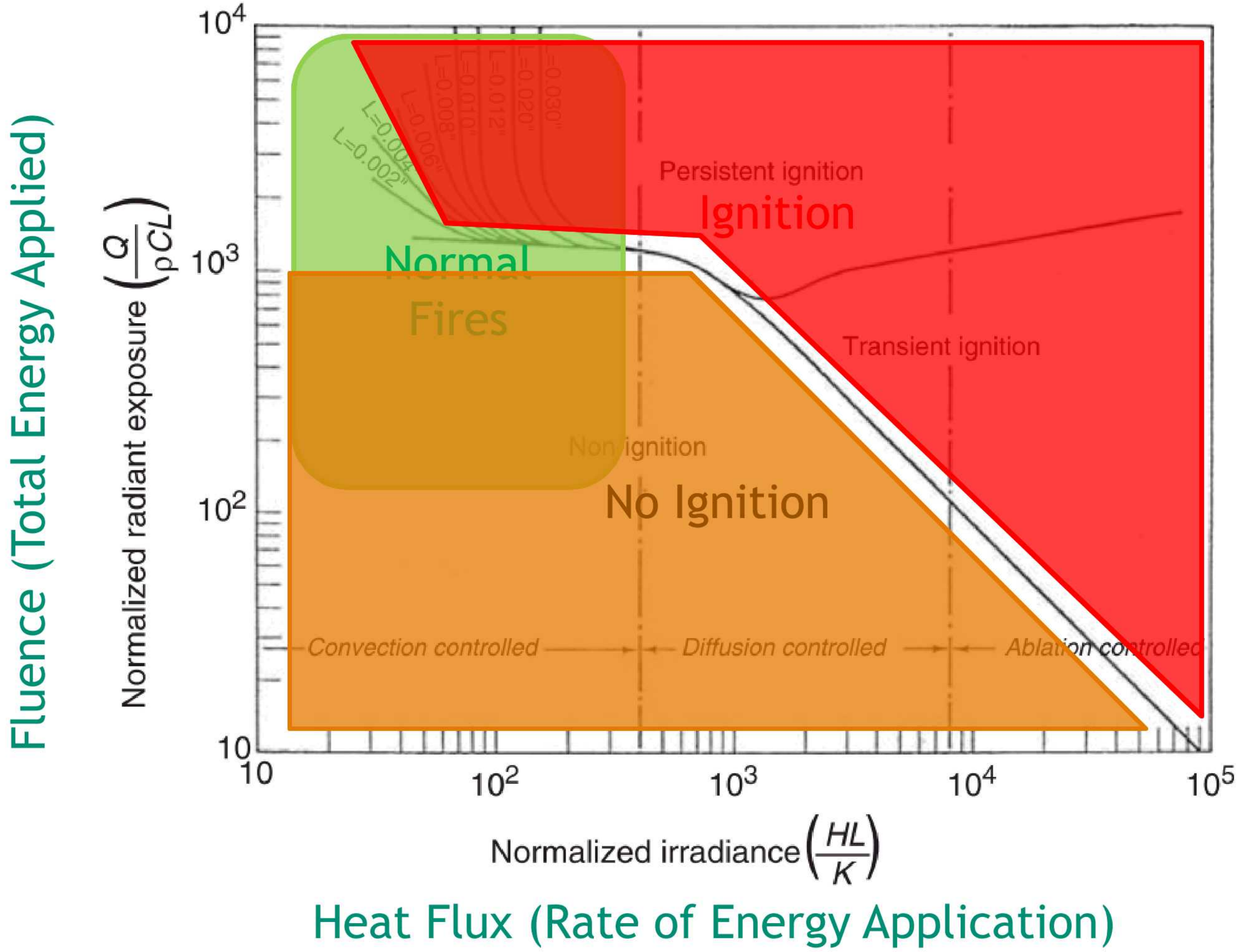
- Ignition section written by Kanury, heavily references Martin's work
- "Martin and his collaborators had honed the technique of ignition measurement to such a fine art that their measured ignition thresholds of drapes, typing paper, dry rotted wood and leaves were included in the newer printing of Glasstone's Effects of Nuclear Weapons"—Kanury, A. M. (2009). SFPE Classic Paper Review: Diffusion-Controlled Ignition of Cellulosic Materials by Intense Radiant Energy by Stanley B. Martin. Journal of Fire Protection Engineering, 19(2), 125-131.



Most current recommendations for high flux ignition go back to the same dated sources

Martin et al. (1965) Ignition Regimes

Martin et al. summarized their ignition data for blackened cellulose in terms of flux/fluence regimes



Martin's test apparatus involved a carbon arc, two parabolic mirrors, and an attenuator

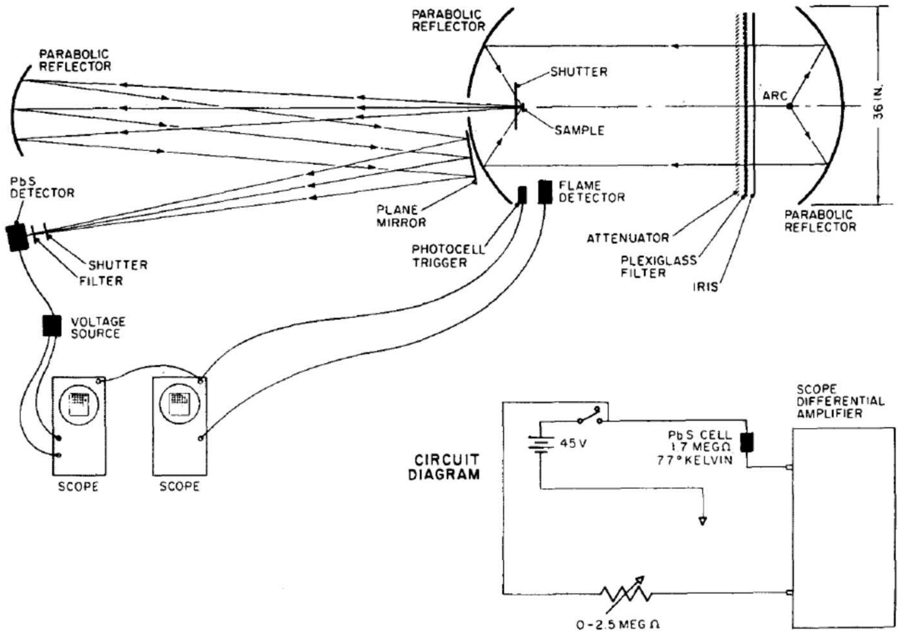


FIG. 4. Apparatus for the measurement of temperatures of the irradiated surface of cellulose.

Martin et al.'s Threshold Data

Martin et al. produced a detailed ignition threshold map for darkened cellulose

- Three regimes, four types of ignition

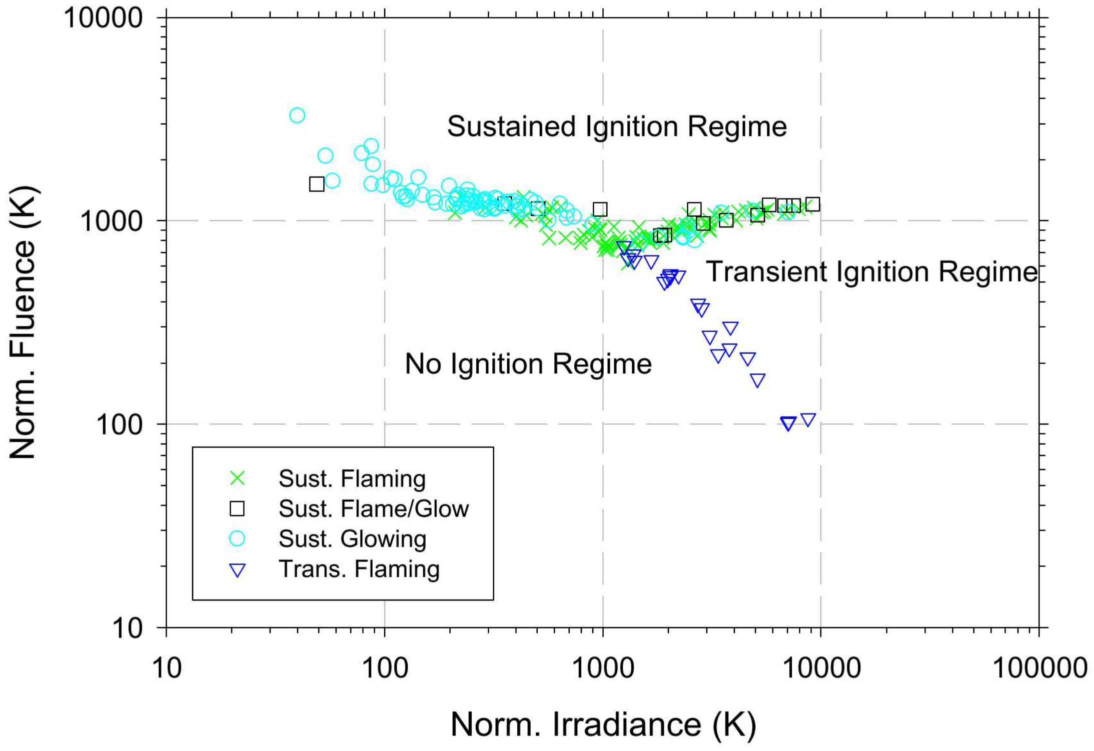
Figure on left shows square wave data

- Rapid rise, hold, then drop in flux
- These best conform to our test data

This normalization construct is useful because it incorporates Fourier number

- Diagonal lines are constant Fourier number ($Fo = kt/\rho C p L^2$) lines in the plot
- Historical cellulose ignition thresholds collapsed to lines using this construct

Martin et al.'s Square Wave Ignition Thresholds for Cellulose



Each datapoint represents many repeat tests to identify the threshold

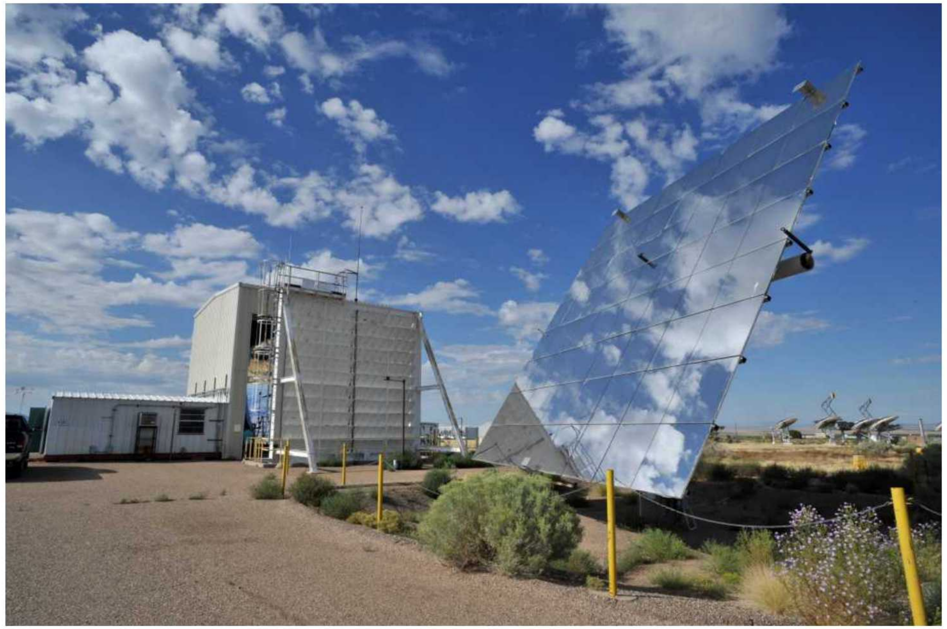
Program Fire Test Facilities

SNL Solar Furnace

- Relevant fluxes at 10 cm-scale spot
- Relatively agile for testing
- Three phases (50 tests each) completed

Solar Tower (SNL)

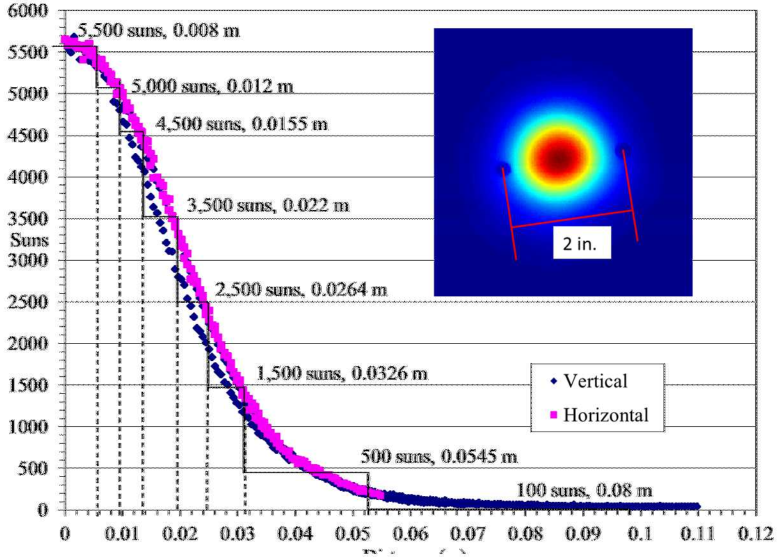
- Relevant fluxes at meter-scale spot
- Field of heliostat mirrors
- Moderately agile for testing
- One phase (30 tests) completed

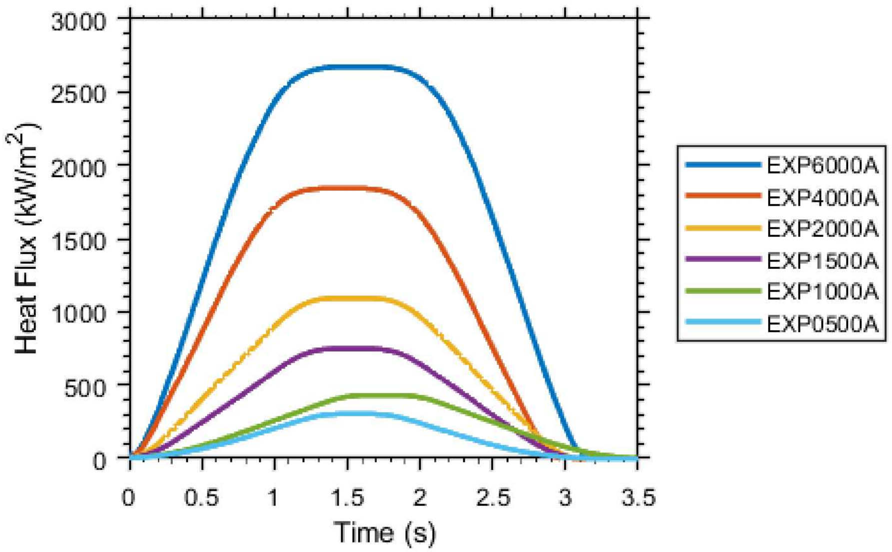


Exposure Characteristics

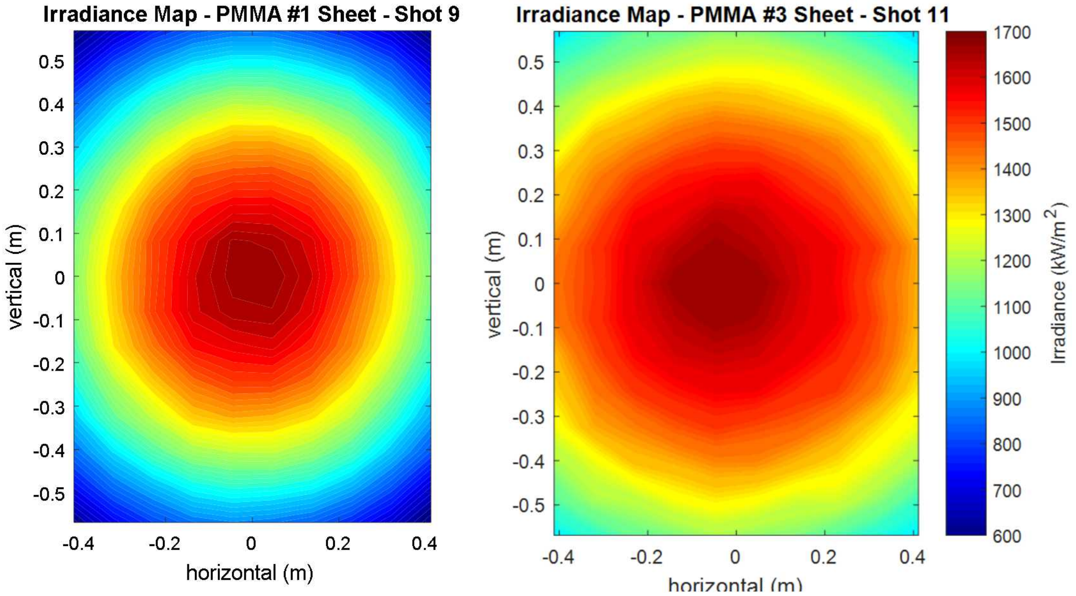
Spatial and temporal variations of flux were characterized for the tests

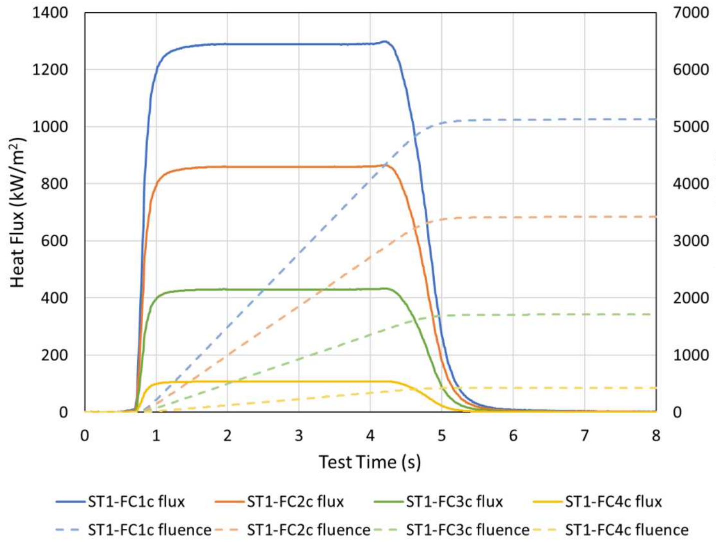
Solar Furnace





Solar Tower





Test Details

Wide range of materials tested enumerated below with categorization described

Category	Sub-category	Details
Cellulosic	Biomass	Green pine needles, dry pine needles, wheat (dry), dry tumbleweed, 100% moisture tumbleweed, green tumbleweed, pinon pine tree
	Paper	Posterboard, bundled paper, cellulose
	Fabric	Olive canvas fabric, flame retardant and rain retardant
	Wood	Walnut veneer
Synthetic polymer	PMMA	Poly-methyl methacrylate (Plexiglas), blackened
	HIPS	High impact polystyrene, black
	Mixed Polymers	Vinyl siding, black; polypropylene chair; polyethylene trash can; synthetic rubber tires and seats

Tests were performed in phases

- 3 Solar Furnace phases, 1 Solar tower phase
- Allowed for data collection, assessment, adapting
- Variations included materials, ambient environments, imposed environments (flux/fluence)

Diagnostics included:

- Visible and IR videography
- Mass loss (pre- and post-test)
- Environment characterization (flux, weather)
- Emissivity measurements, 3D scanning and photography of post-test samples

Objectives

Three main objective areas of the test program:

1. Produce data to validate simulation capabilities
2. Reach-back testing for comparing to historical results and constructs
3. Testing of new or novel ideas, materials, environments, concepts

Objective of this presentation:

- Historically there is no mention of the threshold of pyrolysis, only ignition
- Our data provide this new detail, and we want to explore the utility of it
  - Potentially a cleaner metric than ignition, which is influenced by plume absorption
  - Below this threshold, zero probability of ignition
  - Toxic inhalation and material damage threshold
- Does it follow similar trends in the normalized flux/fluence map?
- Do material variations result in significant threshold variations?

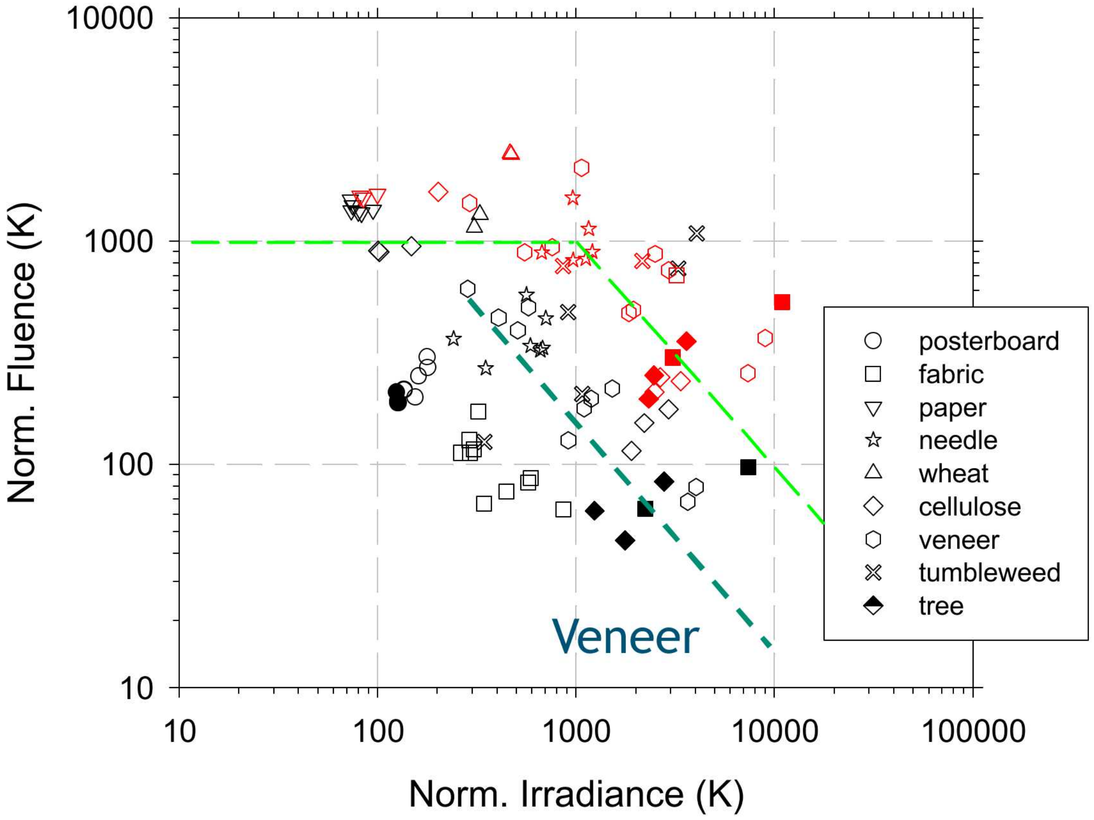
Cellulosic Material Results

- Plot on left summarizes cellulosic test results
- More data exist for pyrolysis initiation (black) than for ignition (red)
- Some of the spread due to material variations (water content, suppressant, color of object, etc.)
  - Surprised still by data variability
- Wood veneer tests exhibited the largest range variance on the map
  - Suggest diagonal trends similar to ignition

Red marks for ignition suggest general agreement with Martin's construct (green)

Pyrolysis initiation (black) exhibits wider spread

Solid markers are for solar tower tests



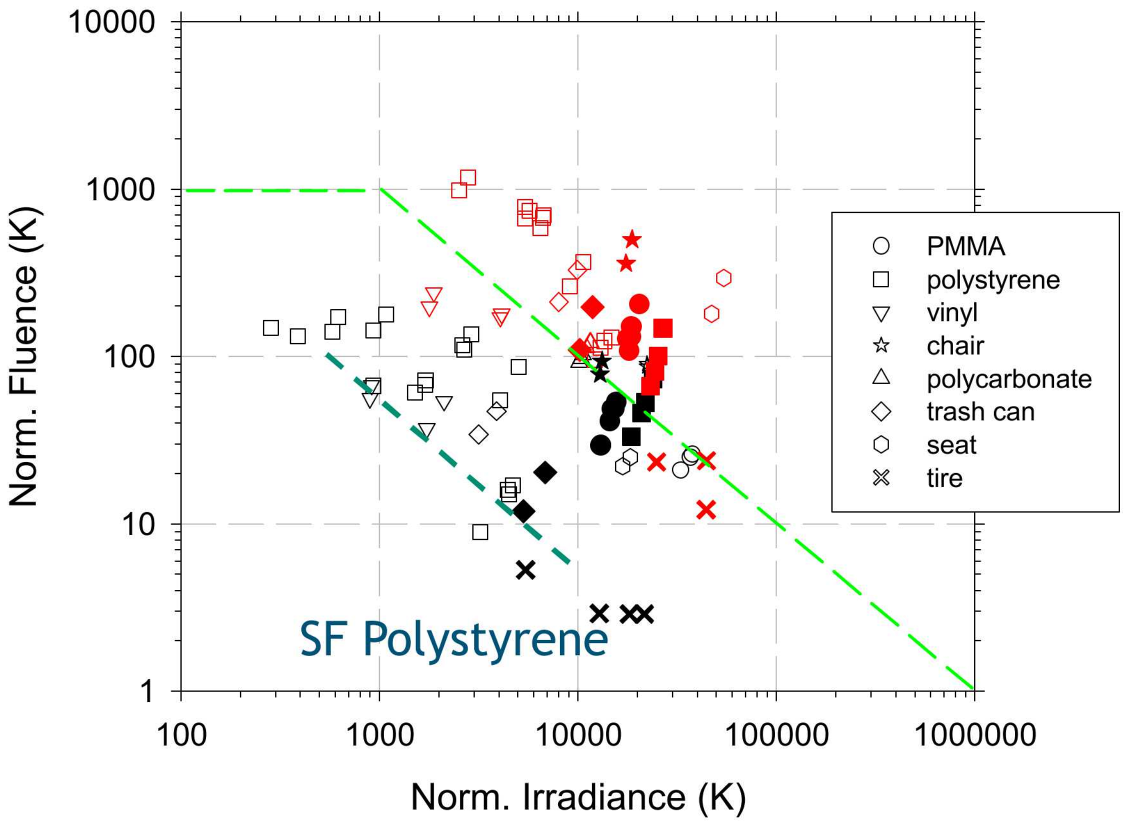
Synthetic Polymer Material Results

- Plot on left summarizes polymeric test results
- More data exist for pyrolysis initiation (black) than for ignition (red)
- Wide material variations
- Most tests to the right of *Fo*=1 inflection point on the map
- Polystyrene tests exhibited the largest range variance on the map
  - Suggest diagonal trends for Solar Furnace (open markers)
  - Solar tower polystyrene tests diverge from trend, an indicator of scale effects

Red marks for ignition suggest general agreement with Martin's construct for cellulose (green)

Pyrolysis initiation (black) exhibits wider spread

Solid markers are for solar tower tests (larger scale)



Synthetic Polymer Material Results

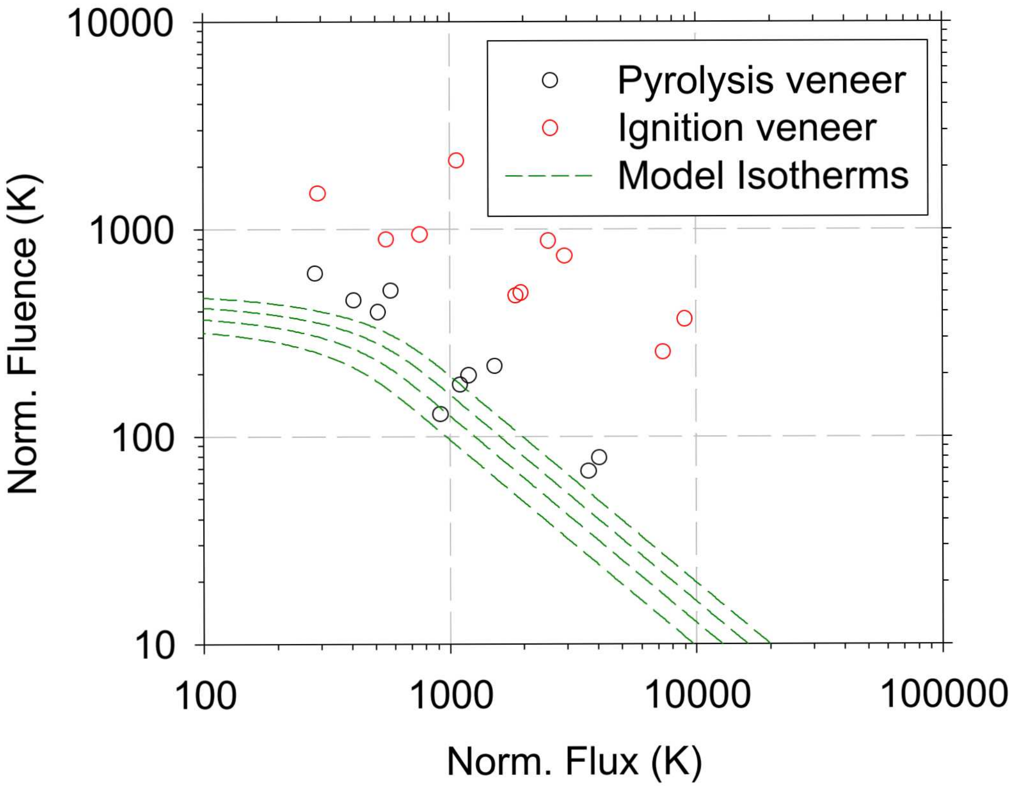
We have derived a model that fits the cellulose ignition data from Martin et al.:

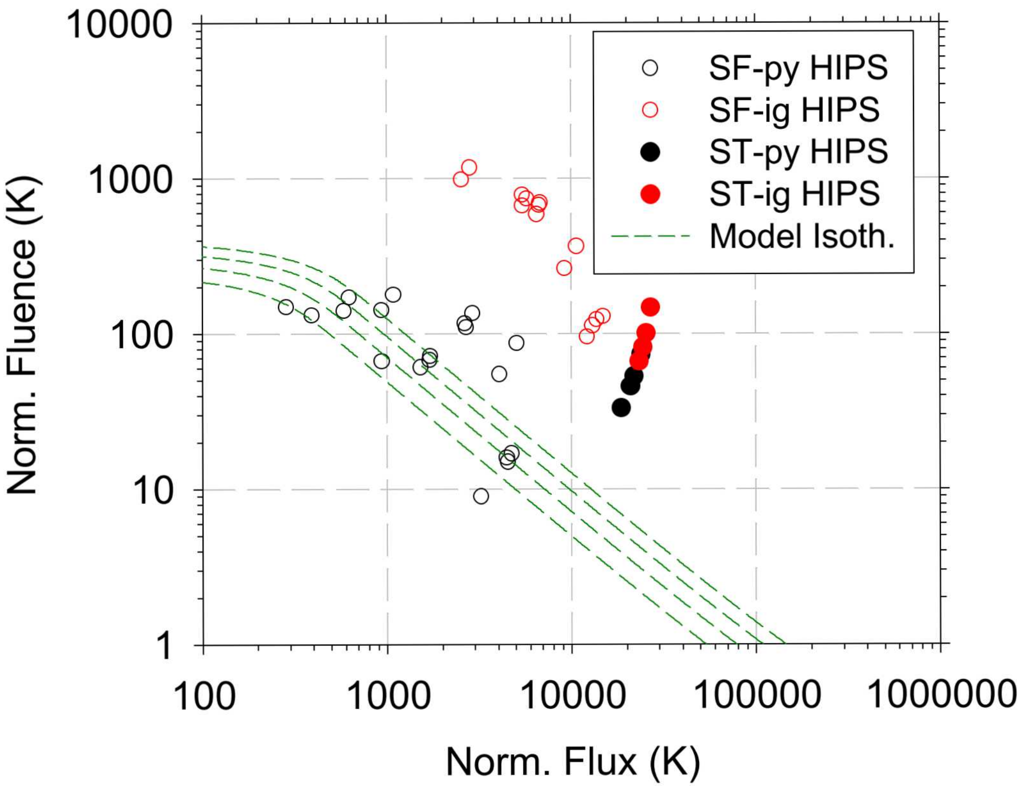
$$Q_{th}^{*} = q_{th}^{*} Fo_{th} = \Delta T_{th} f(Fo_{th})$$

$$f(Fo_{th}) = \frac{Fo_{th}}{Fo_{th} + \frac{2}{\pi^2}\sum_{m=1}^{\infty}\frac{1}{m^2}\left(1 - e^{-m^2\pi^2 Fo_{th}}\right)}$$

Plotting isotherm curves from 250-500ºC gives potential model fits for ignition thresholds for veneer and HIPS data in the two below plots

More data are needed to complete the fits





Parameter Sensitivity

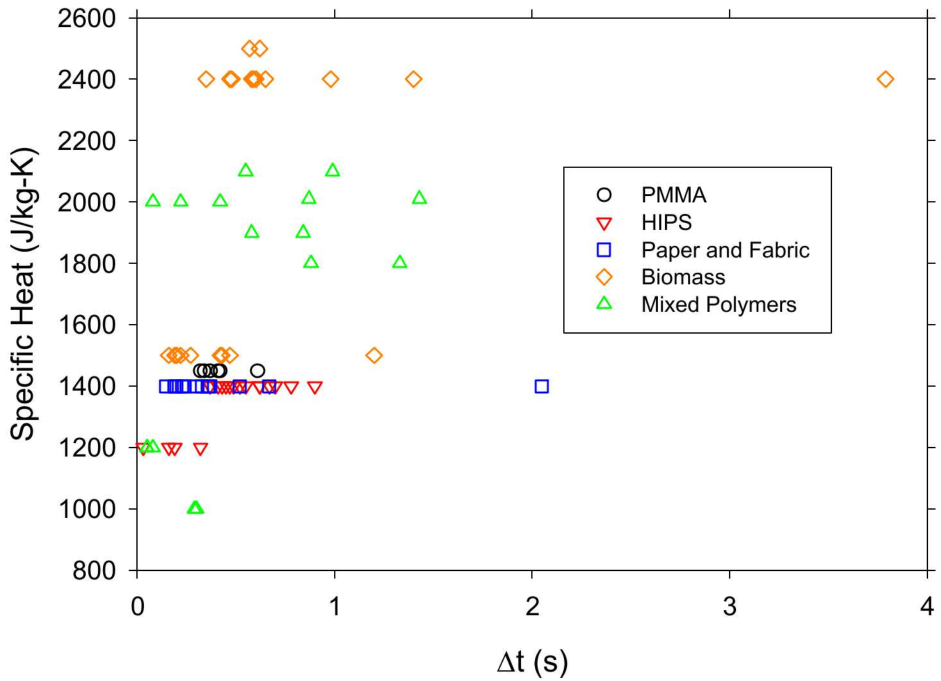
There appears to be a repeatable feature that closes the gap between the ignition time and the initiation of pyrolysis time

Correlation analysis helps identify relationships

Parameter	Correlation Coefficient
Total Fluence	**-0.3365**
Absorptivity α	**0.1806**
Thickness L	-0.0038
Density ρ	-0.0968
Conductivity k	-0.0187
Specific Heat Cp	**0.4053**
ρCp	0.0362
ρCp/k	0.1195

Time between initiation of pyrolysis and ignition was best correlated to specific heat

- Numeric correlation suggests total fluence, absorptivity, specific heat are biggest factors
- Specific heat was not expected, details below



Summary

- New test data provide pyrolysis initiation data for a variety of materials under high flux exposure conditions
  - Prior data in the literature does not include pyrolysis initiation
  - This is significant because this threshold is basically a response threshold
- Pyrolysis initiation appears to follow similar trends when mapped using the same construct as Martin et al. used for ignition of cellulose
  - Diagonal trends for high flux apparent in veneer and polystyrene data (ignoring scale data)
  - Threshold approximately 1 order of magnitude lower (large variability)
  - Material variables exist, with response variations not captured by the largest categorization (cellulosic versus synthetic polymer)
- Specific heat relationship identified to relate to ignition delay
  - Absorptivity and fluence also factors, as expected
- Difficult to formulate credible conclusion regarding material variations
  - Suggests a need for additional testing

Extras