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Pyrolysis Under Extreme Heat Flux Characterized by Mass Loss and Three-Dimensional Scans

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SAND2019-####C

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

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Outline

- Introduction and motivation
- Literature Review
- Solar Furnace & Experimental Methods
- Mass loss, crater size, & 3D scans.
- Discussion
- Conclusions

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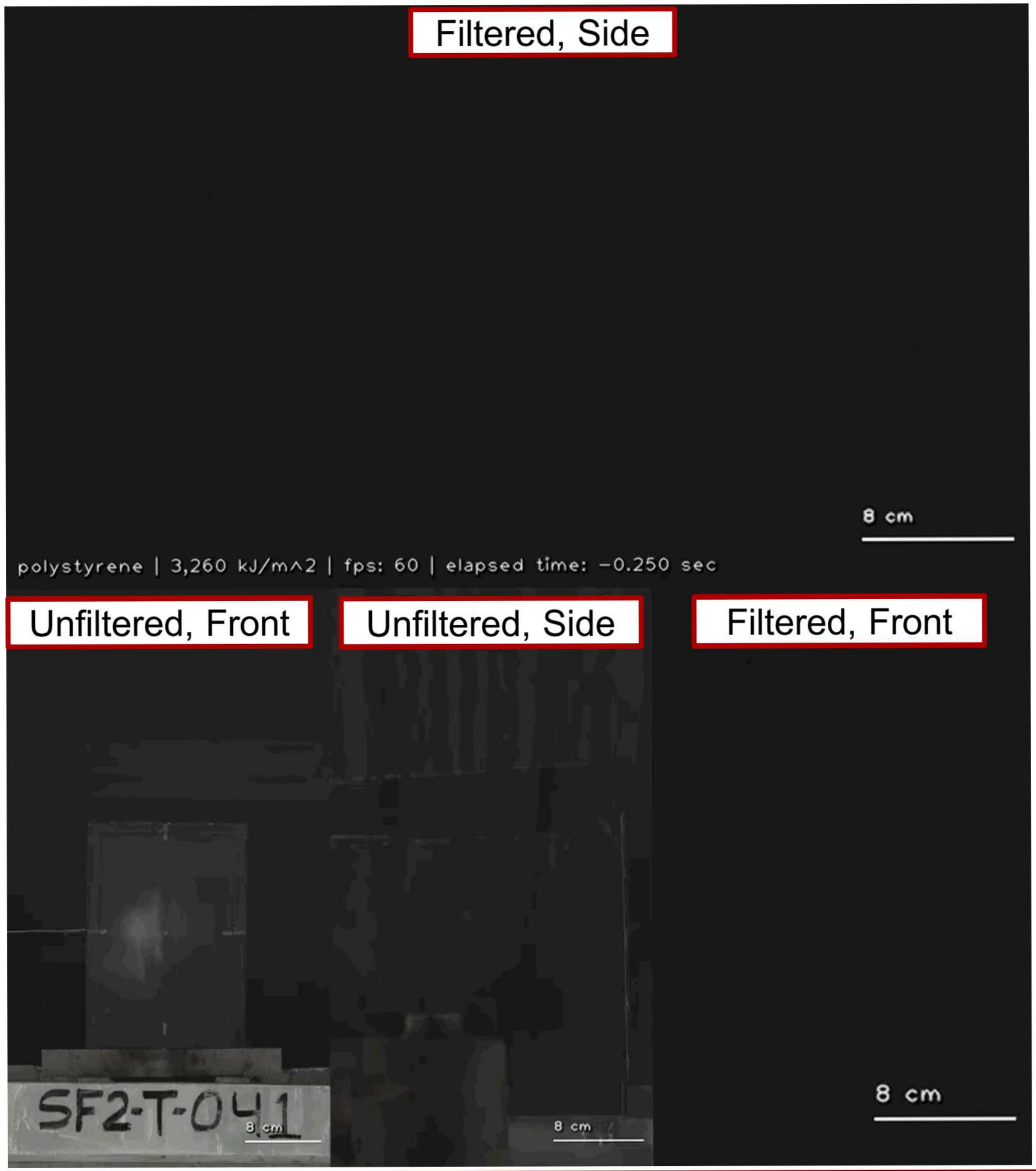
Introduction and Motivation

- A variety of sources can produce heat flux well beyond those typical of fire environments:
  - Directed Energy Weapons
  - Nuclear Weapons
  - Explosives
  - Propellants
- At extreme (~1 MW/m^2) heat flux, the incident energy dominates the surface energy balance
  - Radiation (~100 kW/m^2) and convection (~10 kW/m^2) are relatively small even when the surface reaches ignition temperatures (≈ 600 °C)
- **Objective:** Improve experimental characterization through **quantitative image analysis** and **surface topology** of samples after exposure to intense thermal irradiation.

Response to Extreme Irradiation

- Under extreme irradiation (~0.1 – 1 MW/m^2), a material can:
  - Pyrolyze strongly as the surface chars and/or recedes.
    - The material chemically decomposes, producing combustible gases.
  - Ignite by a variety of mechanisms:
    - Transient Flaming
    - Sustained Flaming
    - Sustained Smoldering
  - As well as other responses:
    - Melt, spall, char, exfoliate, etc.

Example: Polystyrene



Material:
High-Impact Polystyrene
3.2 mm thick

Exposure:
3.26 MJ/m^2

Ignition Data:
Sustained Flaming
Ign. time: 0.85 s
Pyr. time: 0.38 s

Programmatic Objectives

- This study is part of a wider program, **focusing on pyrolysis and ignition** at extreme radiative heat flux.
  - **Experimental** data at small and large scale
    - Solar Furnace (≈10 cm spot)
    - Solar Tower (≈1 m spot)
  - **Simple ignition models** (e.g., empirical correlations) that can predict material response to a given environment.
  - **High-fidelity computational models** that capture the complex physics and accurately predict pyrolysis and ignition.
- These advancements will produce **ignition models** spanning a wide range of **environments** and **materials**.

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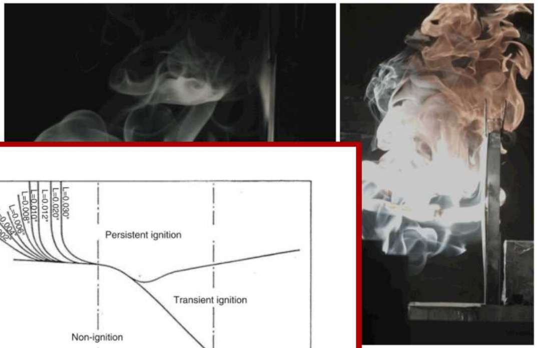

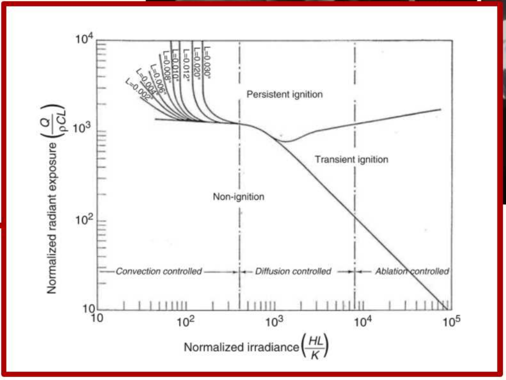

Literature Review

- Most data at extreme heat flux from three sources:
  - Nuclear Testing
    - Real environment, large scale
    - Poorly Characterized
  - Glasstone
    - Expansive reference table
    - Citations not listed, qualitative information
  - Martin
    - Rigorously characterized
    - Narrow focus (black alpha-cellulose papers)
- Previous research focuses on **categorical data** (*ignition*).
  - Supports underlying objective: **simple empirical ignition models**.
  - **Categorical data is inferior for high-fidelity computational models!**

Sample Analysis in Prev. Literature

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Glasstone & Dolan:

- Minimal sample characterization
- Broad range of materials.
- **Qualitative** response
- *Only ign. threshold is quantitative.*

APPROXIMATE RADIANT EXPOSURES FOR IGNITION OF FABRICS FOR LOW AIR BURSTS

Material	Weight (oz/yd^2)	Color	Effect on Material	Radiant Exposure* (cal/cm^2) 35 kilotons	1.4 megatons	20 megatons
CLOTHING FABRICS						
Cotton	8	White	Ignites	32	48	85
		Khaki	Tears on flexing	17	27	34
		Khaki	Ignites	20	30	39
		Olive	Tears on flexing	9	14	21
		Olive	Ignites	14	19	21
		Dark blue	Tears on flexing	11	14	17
		Dark blue	Ignites	14	19	21
Cotton corduroy	8	Brown	Ignites	11	16	22
Cotton denim, new	10	Blue	Ignites	12	27	44

Martin et. al.:

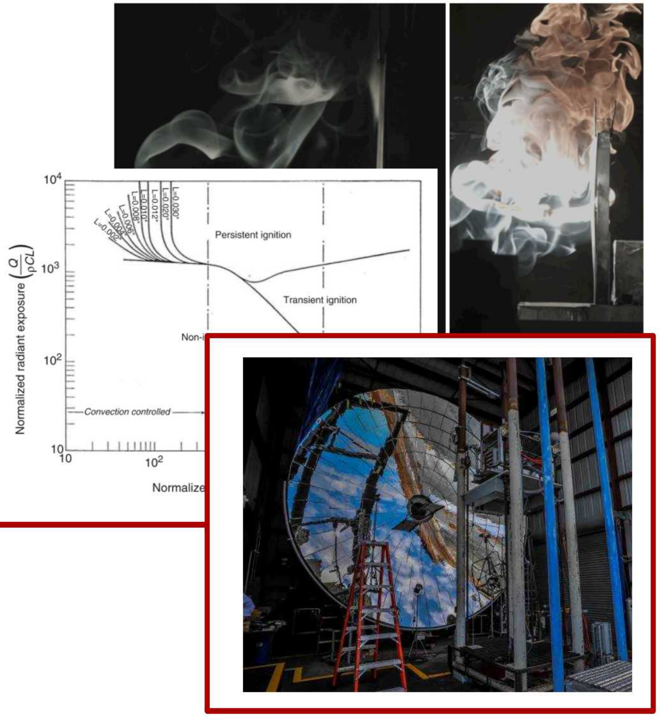
- Well-characterized samples.
- Mostly black cellulose.
- **Categorical** response.
- *Only ign. threshold is quantitative.*

Ignition Data for 0.7 g cm^{-3} Nominal Density Material

Thickness and Physical Properties	Effect	Peak Irradiance	Time to Peak (±s.d.)	Radiant Exposure
		$cal\ cm^{-2}\ sec^{-1}$	sec	$cal\ cm^{-2}$
Manufactrs No. 4096	Flame	21.9	0.30	13.5
$L = 31$ mil		18.3	0.35	13.4
$= 0.0795$ cm		16.4	0.38	12.9
$\rho = 0.69\ g\ cm^{-3}$		15.1	0.40	12.4
$c = 0.35\ cal\ deg^{-1}\ g^{-1}$		14.6	0.38	11.4
$K = 2.2 \times 10^{-4}$		13.1	0.41	11.2
$cal\ cm^{-1}\ deg^{-1}\ sec^{-1}$		10.4	0.83(±0.02)	17.9
		10.2	0.85	18.0
	Transient Flame	15.1	0.29	9.1
		14.6	0.26	7.9
		13.7	0.40	11.4
	Glow	7.1	1.45	21.3

Simple data is appropriate for simple models. Need better data for high-fidelity models (gas-phase dominant ignition).

Outline



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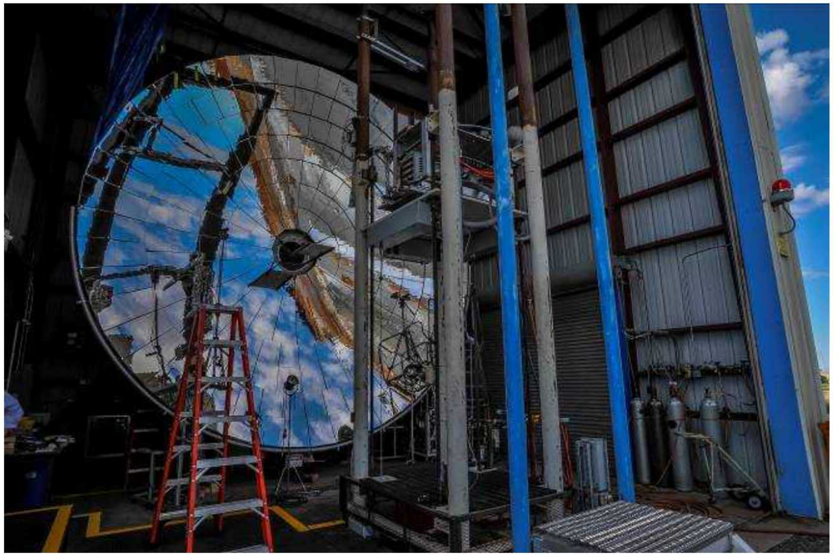
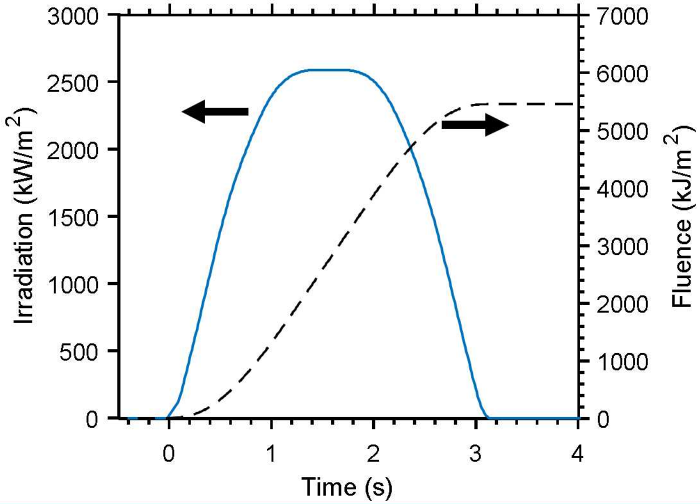
Solar Furnace



- Heliostat tracks sun
- Parabolic dish focuses light
- Attenuator controls temporal flux profile
- 3-axis table positions sample/instrumentation
- Generates heat flux of up to 6 MW/m^2 on a ≈8 cm spot

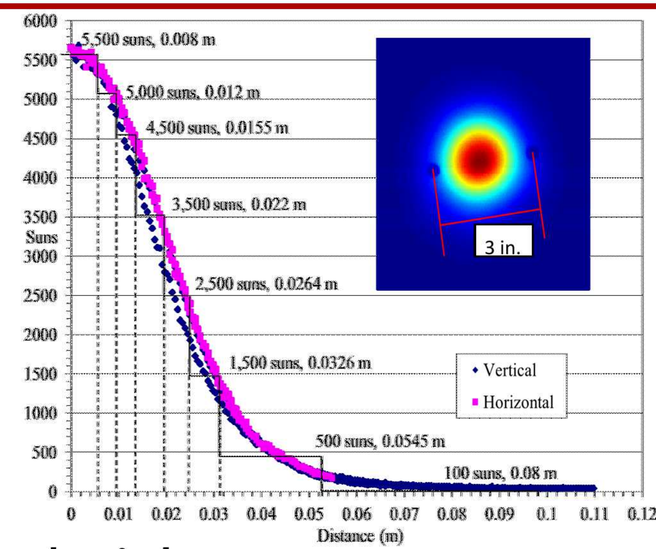
Solar Furnace Environment

- Temporal Profile
  - Ramp up/down.
  - Limited by attenuator speed.



- Spatial Profile
  - Characterized in previous paper.
    - Ho, C. K. et.al., Proc. Int. Conf. on Energy Sustain. 4 (2010) 1-9.

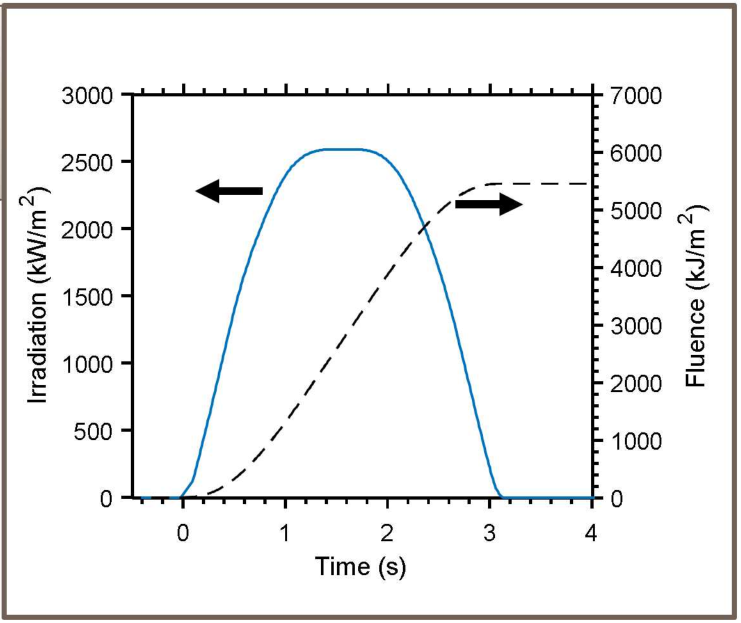
$$q''(t,r) = \frac{q''_o(t)}{1 + \exp\left(C\left(\frac{R_0}{R_1}r\right)^D - B\right)}$$



- Both distributions complicate data analysis!

Instrumentation

- Radiometer and heat-flux gauge quantify flux/fluence
- Cameras capture material response
- Photographs taken before and after
- Mass recorded before and after
- 3D Scans after



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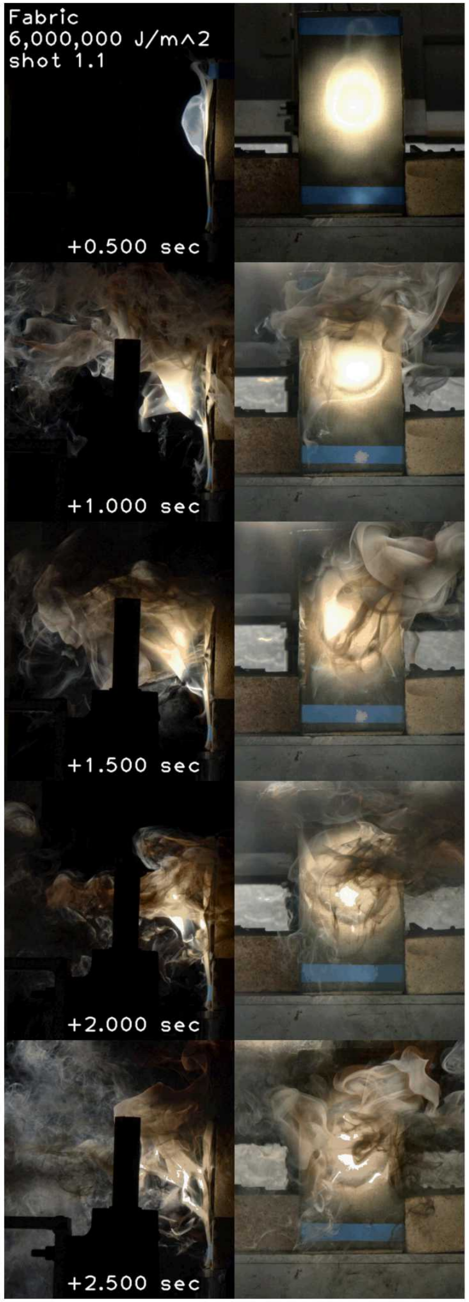

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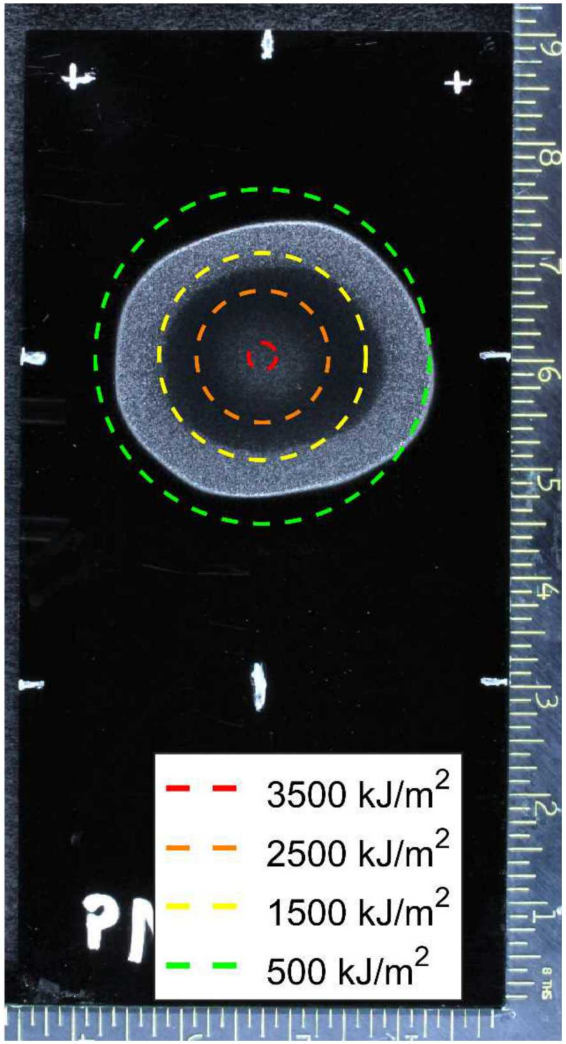

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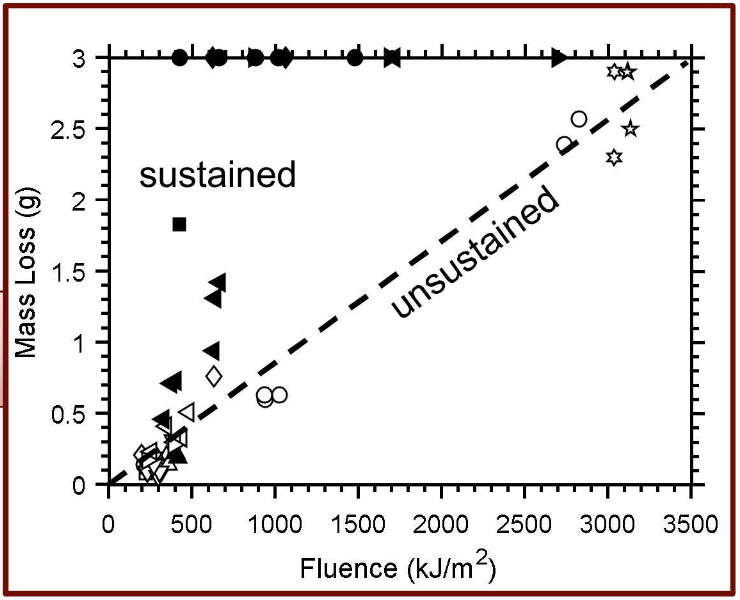

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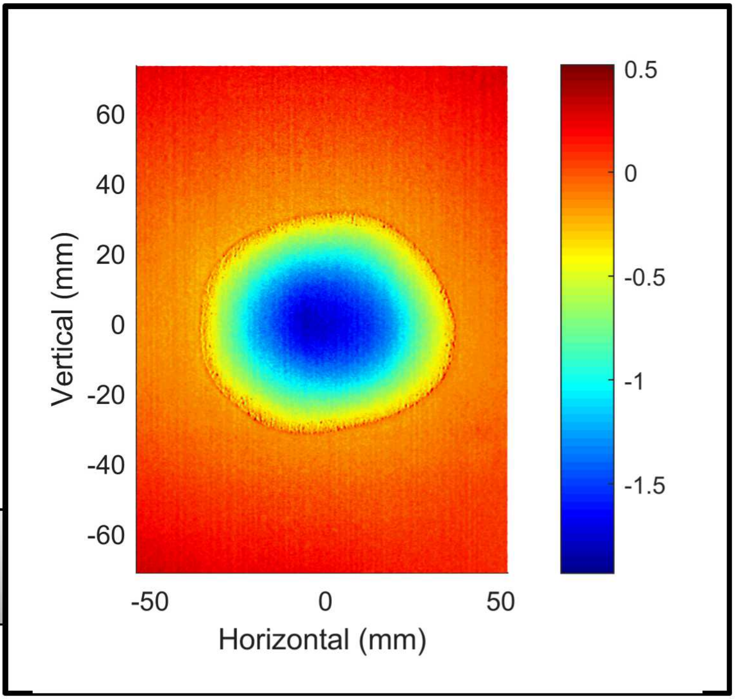
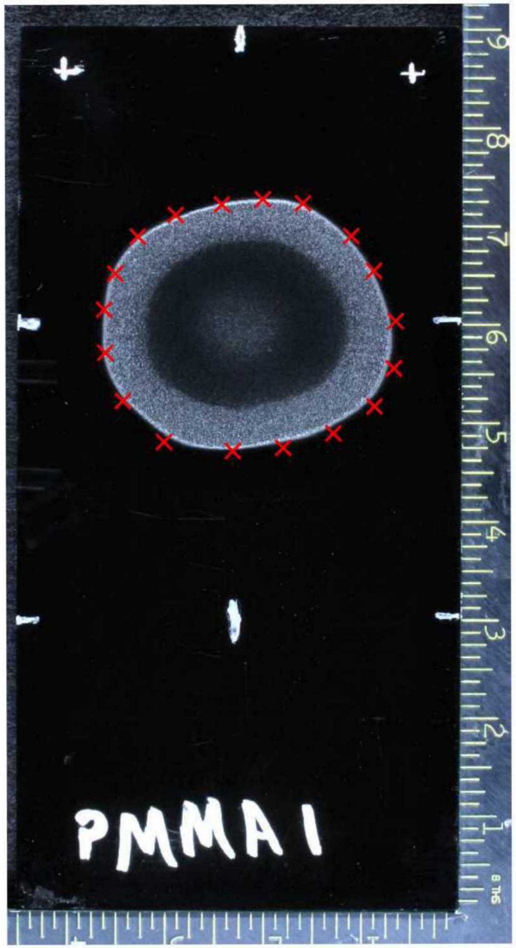


Enhanced Post-Test Analysis

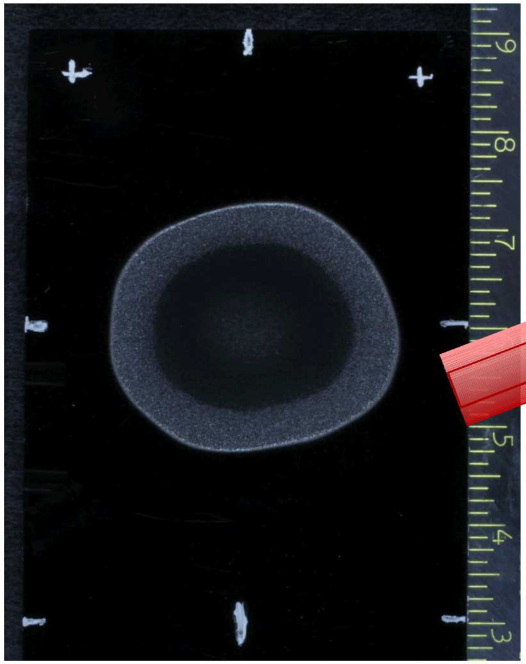
- Better, quantitative empirical data through:
  - Ignition thresholds (see our previous papers)
    - Similar to past data.
  - Mass-loss data
  - Photographic data
    - Quantitative analyses including:
      - Char area.
      - Heat flux at crater rim.
      - Net energy delivered to crater.
  - 3D Scanner data
    - Quantitative analyses, similar to above.
    - Spatially resolves surface recession.
      - Resolves 2D mass-loss map (non-charring materials)
      - Maps mass loss to heat flux.

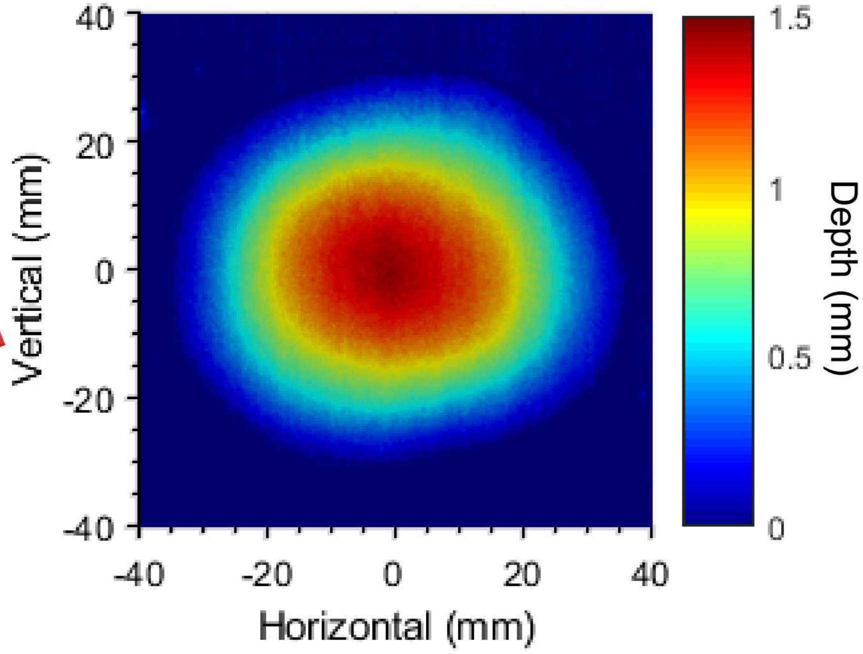
Newly Implemented Analysis



3D Scanner Technique

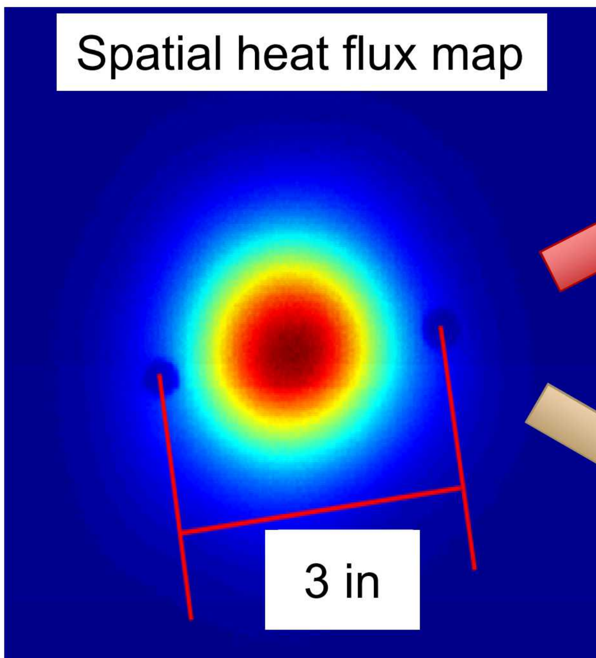
- 3D Scanner most valuable if surface receded (unstable char)
  - Technique presented in previous paper. (Engerer & Brown, AIAA 2018-3761)
  - Scanner spatially resolves surface recession.
  - Localized mass loss calculated from surface recession
    - Assumption: Residual material density unchanged.

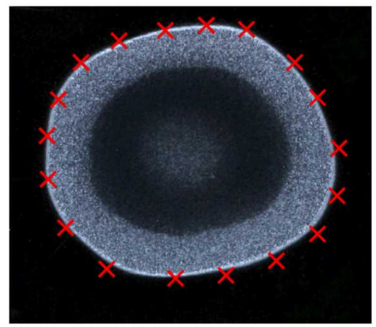




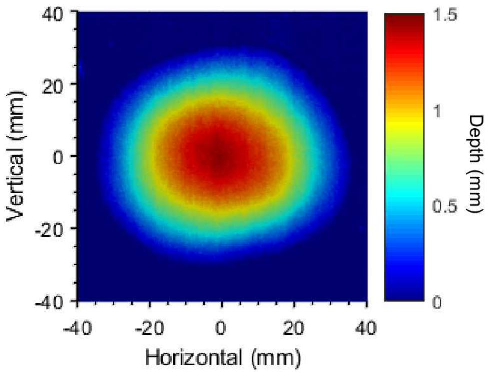
Mapping Data to Heat Flux

- Spatially distributed heat flux complicates analysis.
- However, sample exposed to a variety of heat flux conditions.
  - If deconvolve the problem, more data than in uniform heating case.





Minimum heat flux/fluence to degrade material



Mass efflux at variable heat flux

These enhanced techniques turn a non-ideality into a feature!

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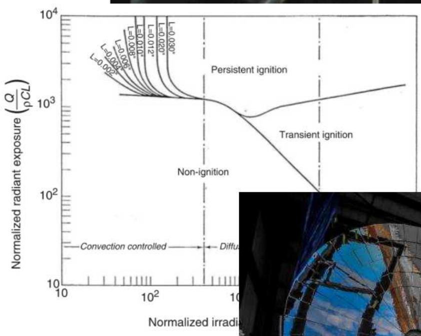
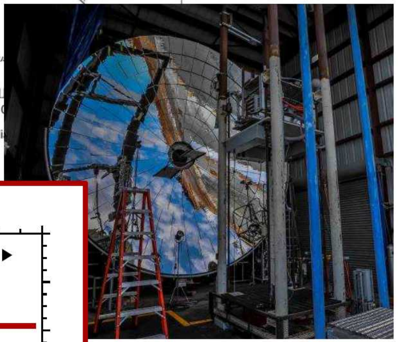
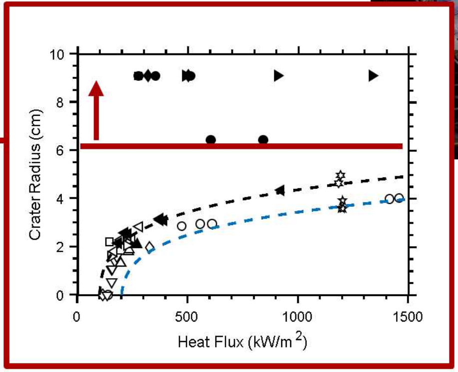
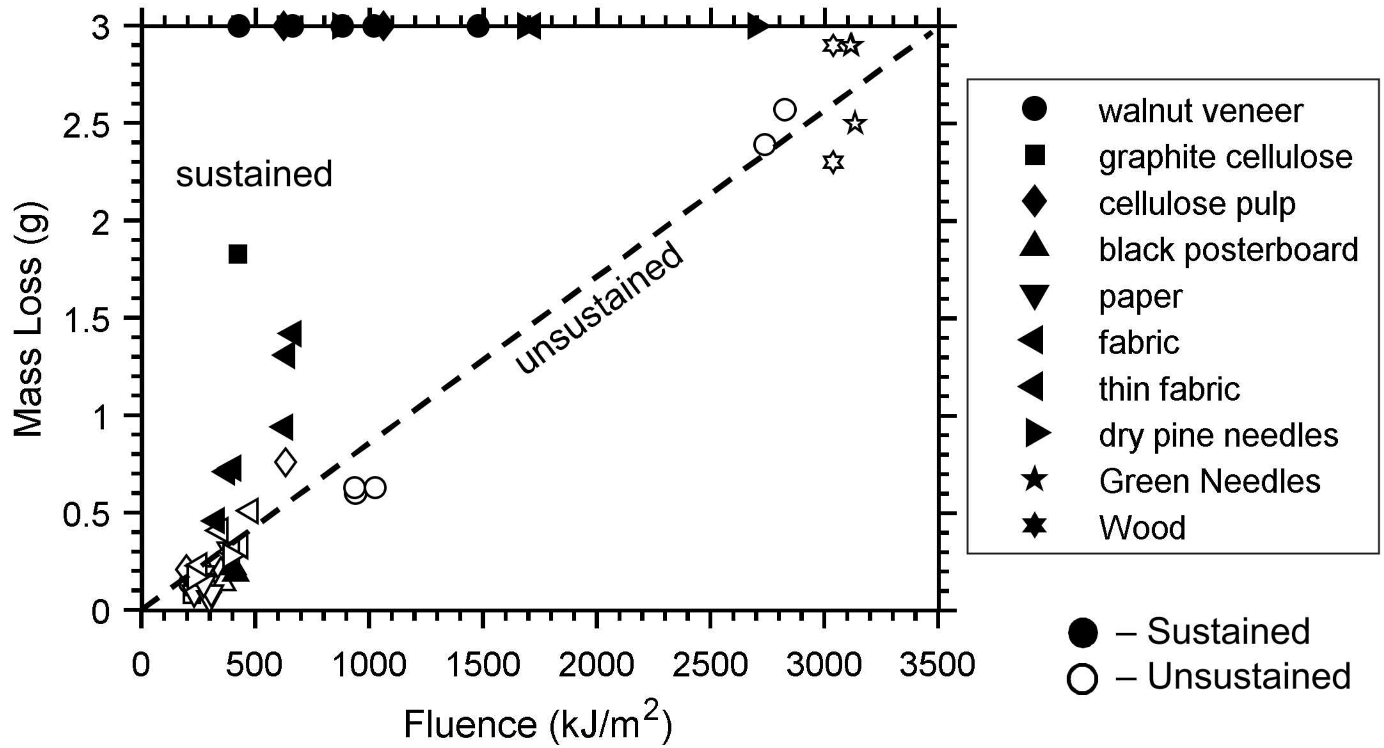






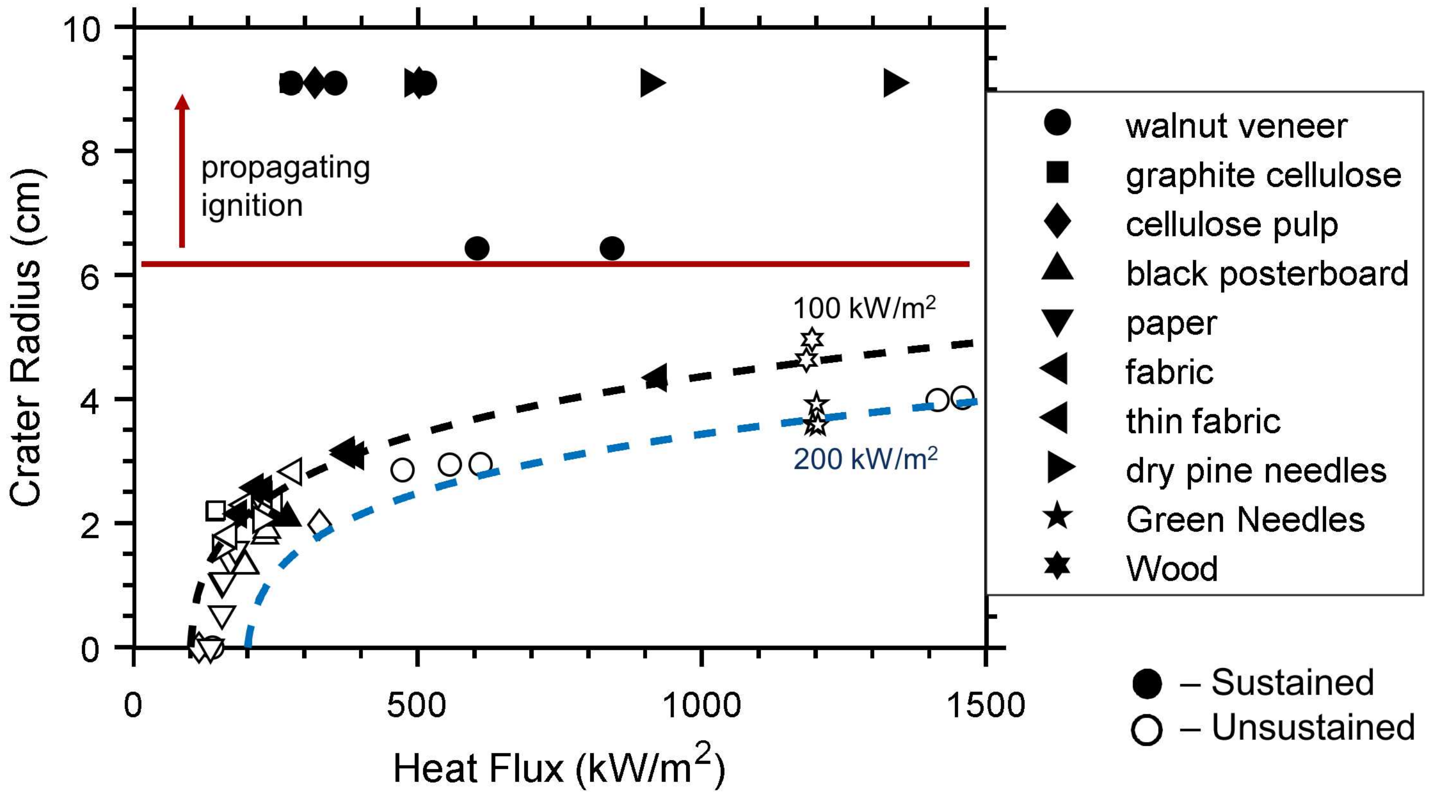
Cellulosic Materials

- Mass loss for cellulosic materials are consistent.
  - Mass loss linear with fluence for unsustained ignition.
  - Mass loss higher for sustained ignition cases.
  - Data are coupled with other effects (e.g., increasing degraded area).



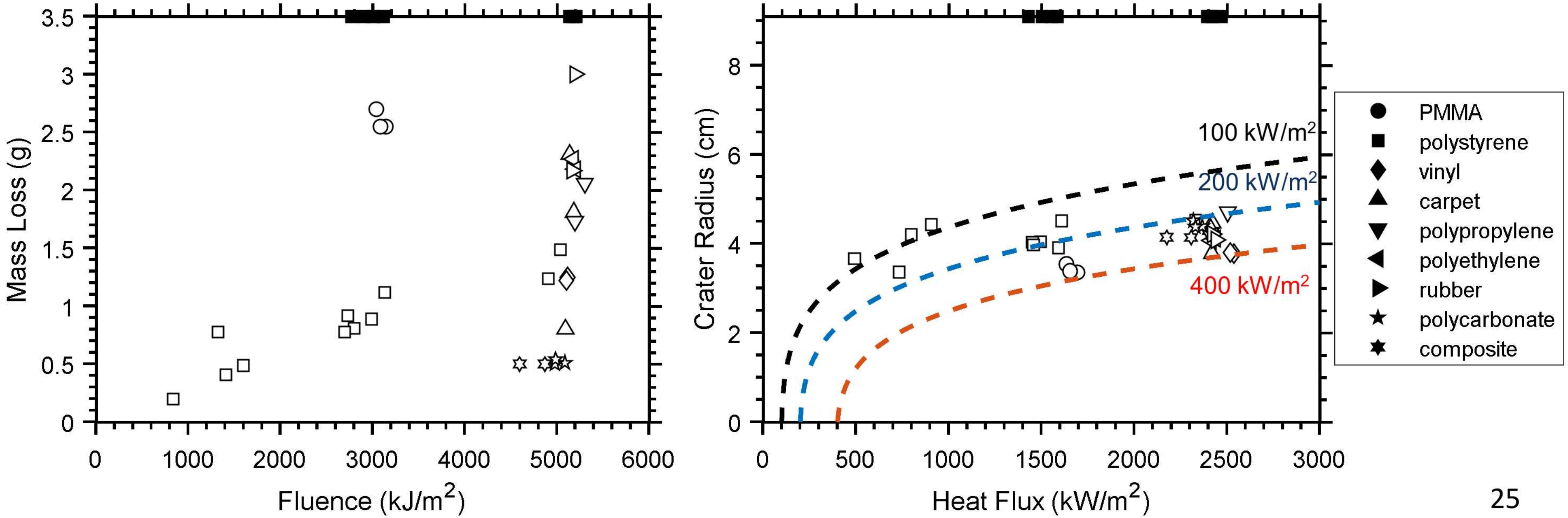
Cellulosic Materials

- Crater radius determined from post-test images.
  - Char extent predicted by heat flux at perimeter.
  - Propagating ignitions consume upper-half or all of the sample.



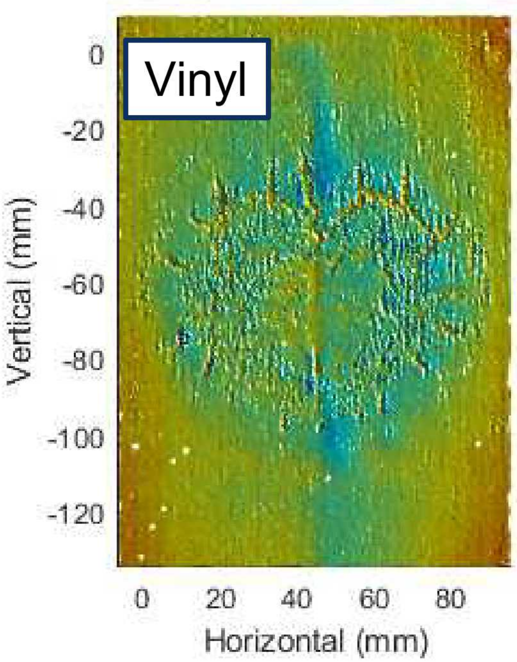
Synthetic Polymers

- Mass loss for synthetic polymers are less consistent.
  - Chemical composition varies
  - Heat flux was varied only for polystyrene experiments.
    - Mass loss fairly linear.
    - Crater radius consistent across various exposure magnitudes.
      - Physics more complex? (e.g., screening of radiant energy?)

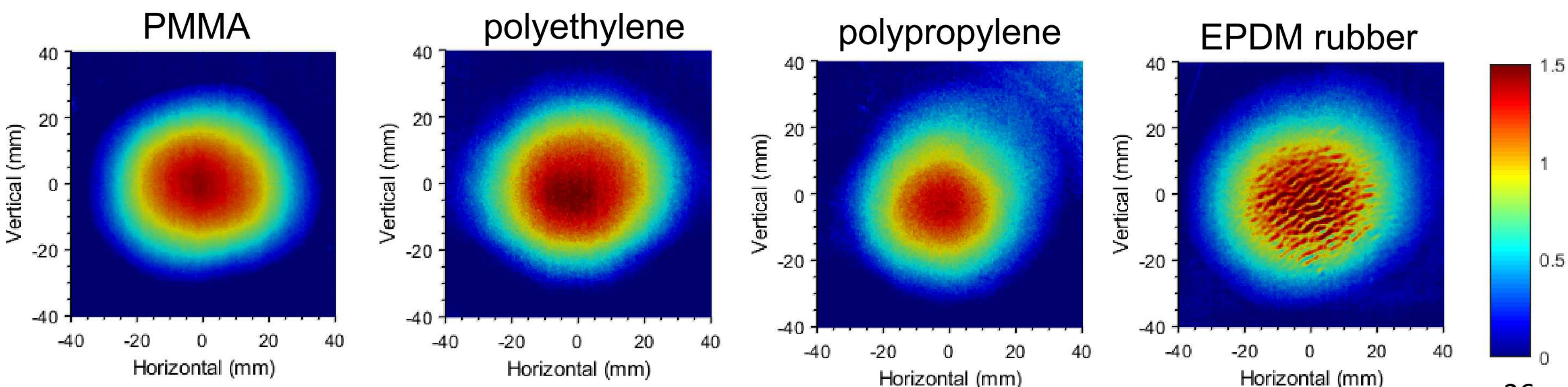


3D Scanner Results

- Among materials with significant thickness:
  - Stable Chars inhibited surface recession.
    - Data at/near resolution of scanner; lacking trends.
    - Examples:
      - walnut veneer
      - epoxy/fiber composite
      - polycarbonate
      - vinyl



  - Without stable char, significant surface recession.



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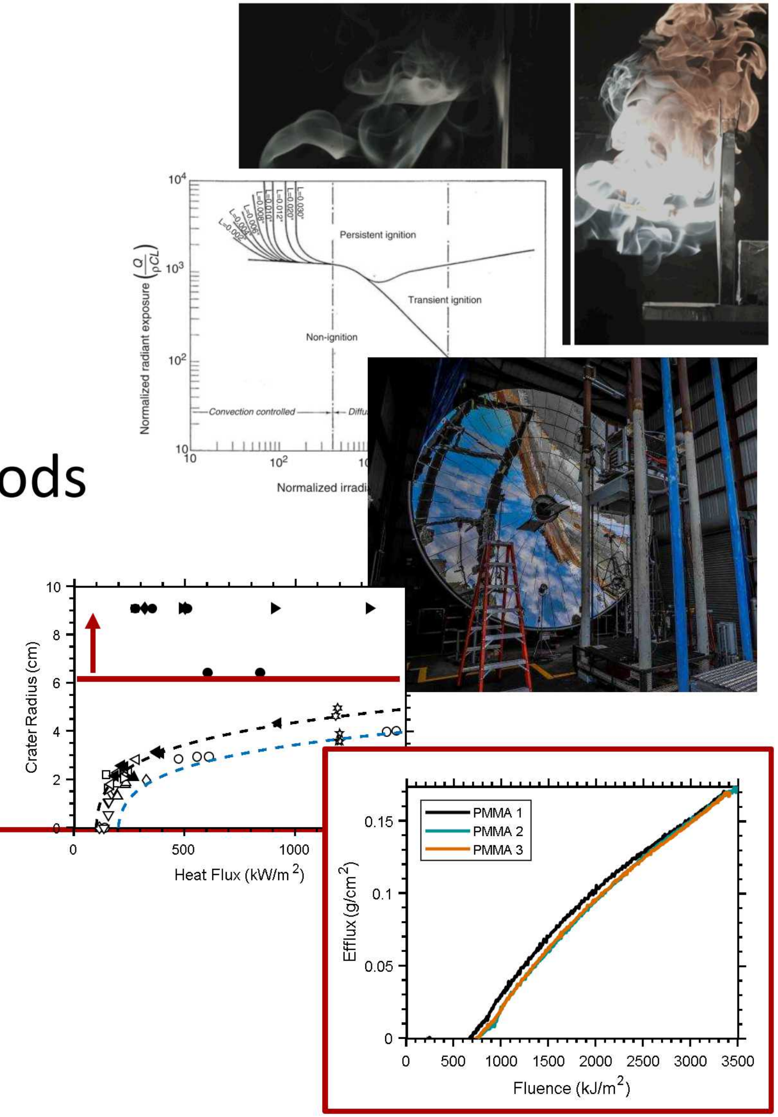
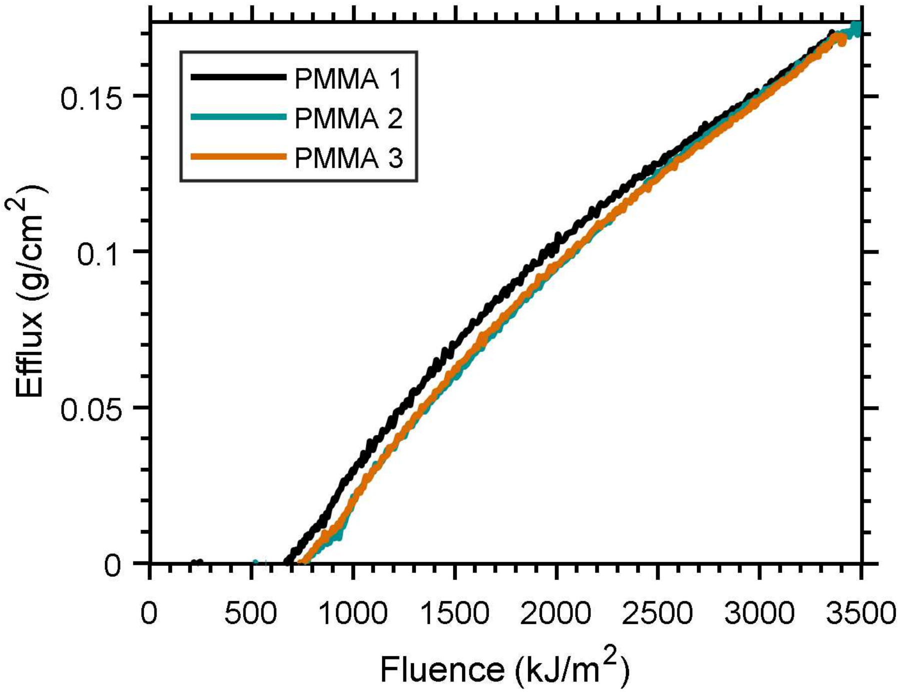
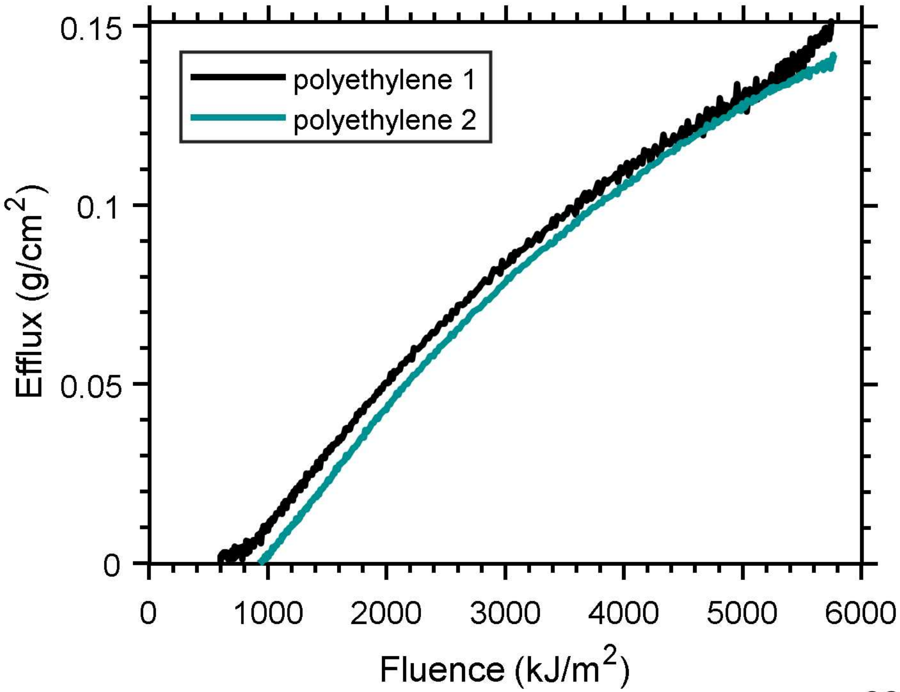


Spatially Resolved Mass Loss

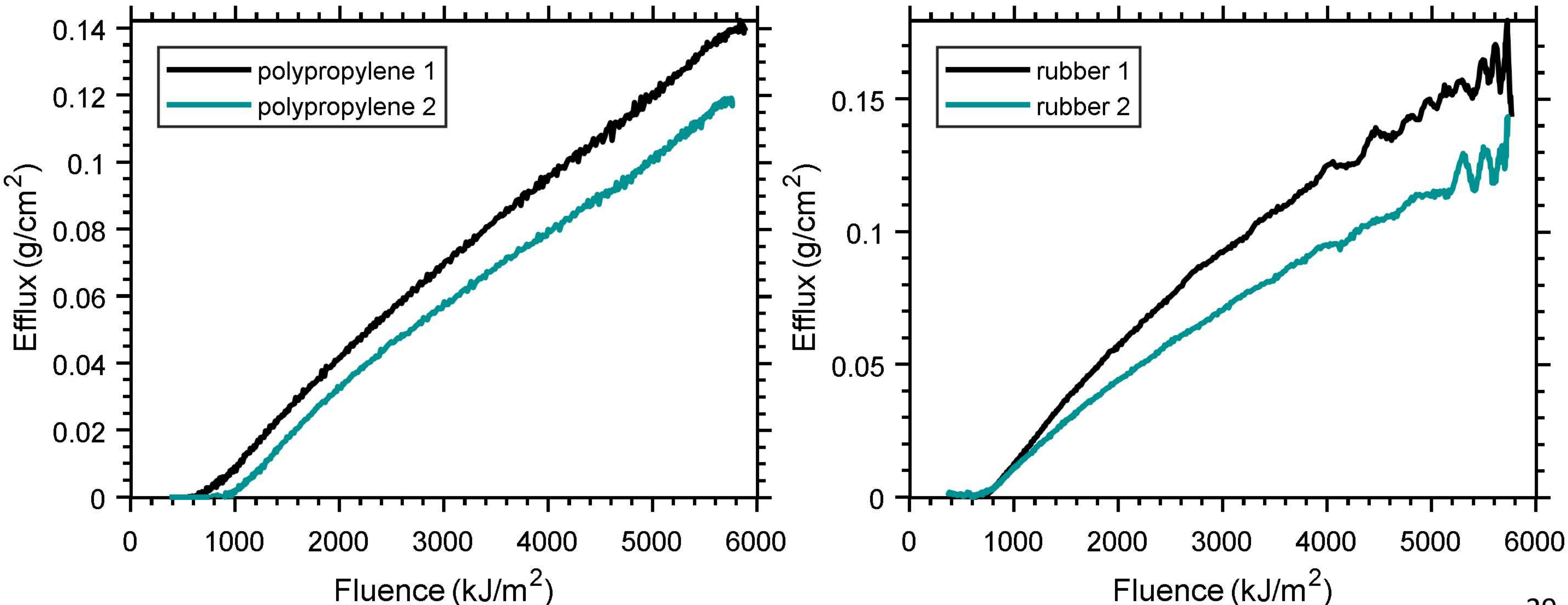
- Mass loss calculated from crater depth.
  - Assumption: Density unchanged by exposure (no residual char/swelling)
- Localized efflux approximately linear with fluence.





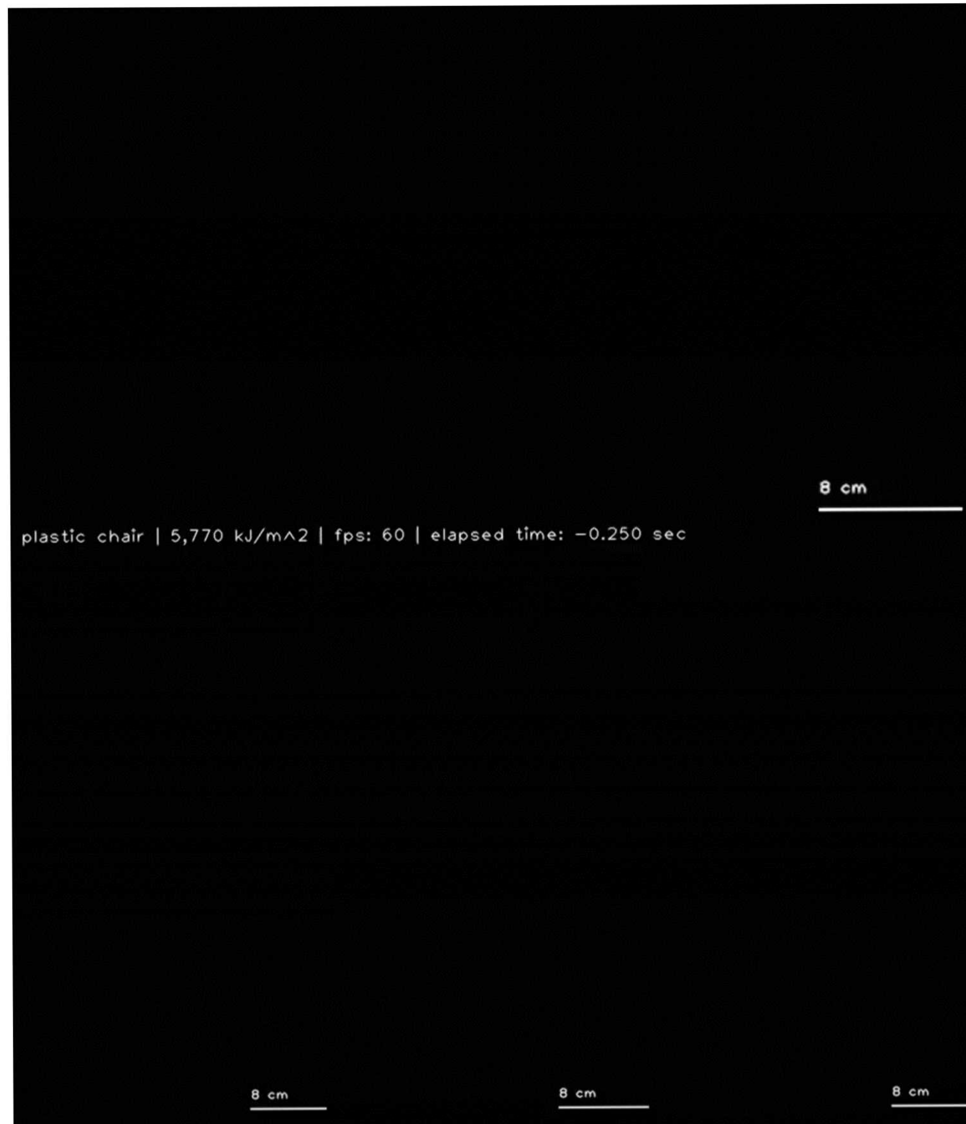
Spatially Resolved Mass Loss

- Polypropylene and rubber samples show variations, despite having same nominal exposure level.
  - Perhaps, radiation screening from pyrolyzate.



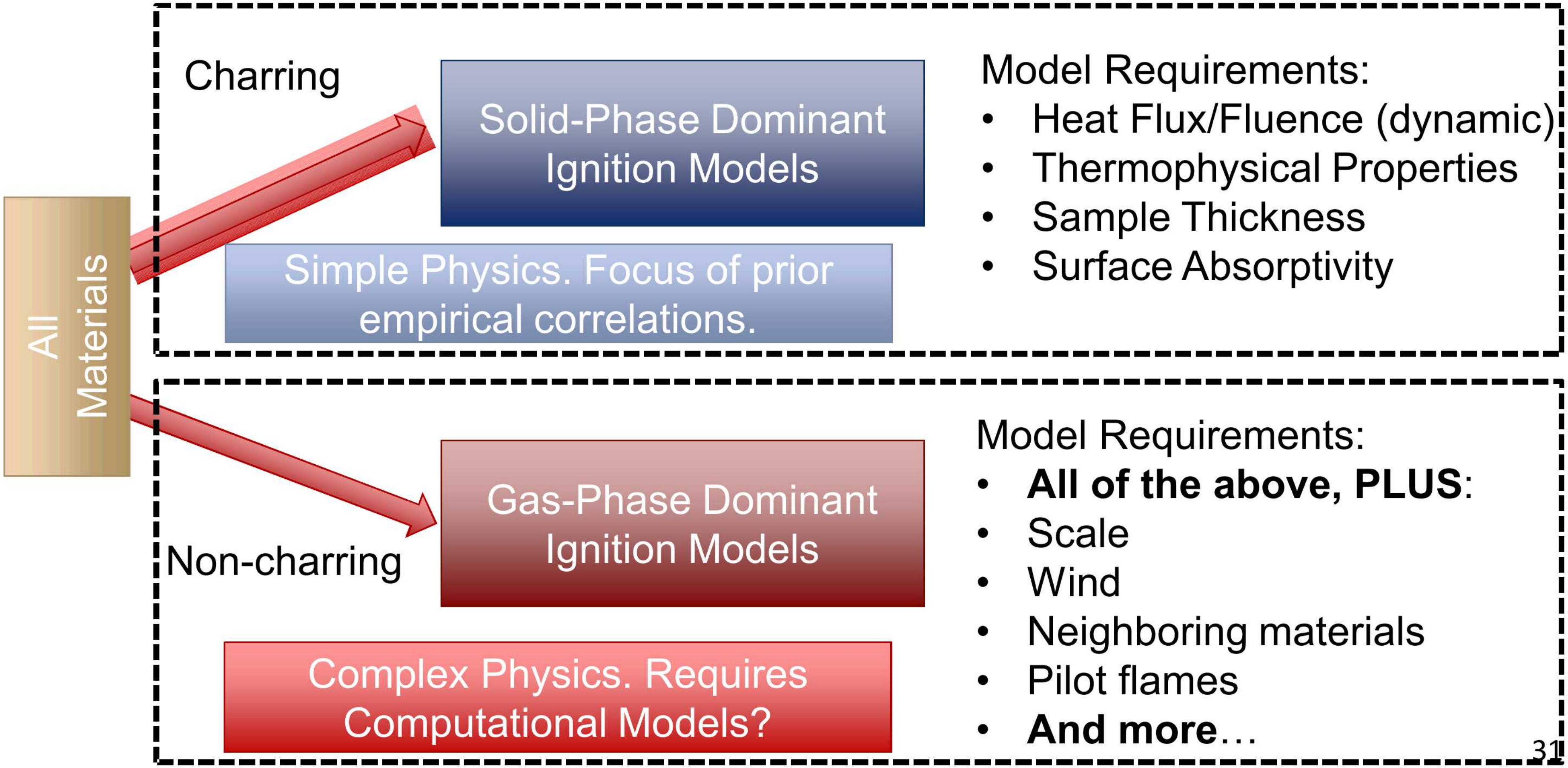
Radiation Screening

- Many polymers produced large pyrolyzate clouds.
- Example:
  - Polyproylene



Extreme Heat Flux Models

- We theorize ignition models determined from the presence or absence of a char (exceptions likely exist).



Conclusions

- Radially distributed heat flux complicates data analysis, but in many cases enhances the end data.
- Quantitative image analysis provides estimates:
  - Heat flux required to degrade sample.
  - Area / total energy contributing to pyrolysis reaction.
- 3D Scans better characterize sample response:
  - Recession depths.
  - Mapping localized efflux to heat flux.
- Data will contribute to model development for gas-phase dominant ignition.
  - Solid-phase dominant ignition typically well-predicted by empirical models (Engerer, et al., AIAA 2018-3764).
  - Gas-phase dominant ignition requires further development.

Acknowledgements

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