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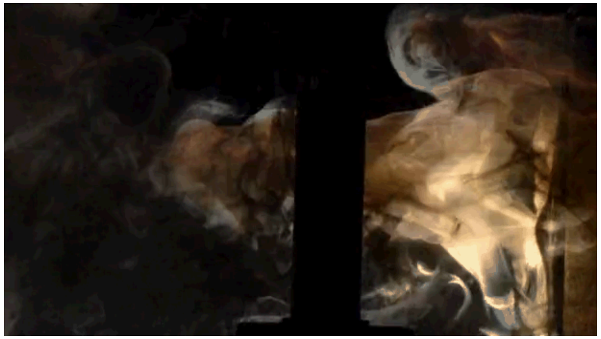

Mass-Loss Measurements on Solid Materials after Pulsed Radiant Heating at High Heat Flux

Jeffrey D. Engerer, Alexander L. Brown, Joshua M. Christian

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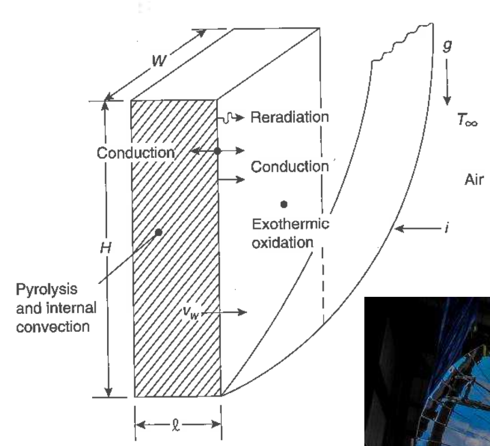
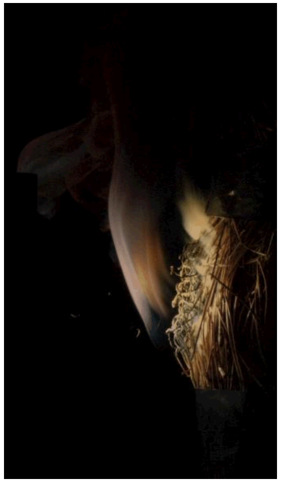
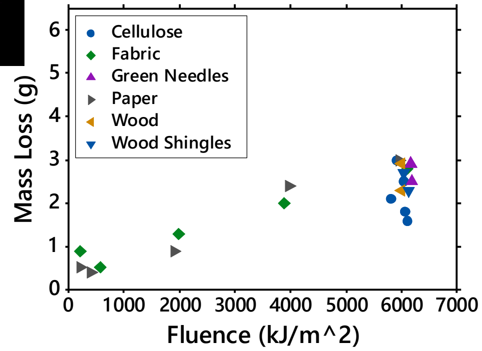
Outline

- Introduction and motivation
- Solar Furnace at the National Solar Thermal Test Facility
- Materials tested and overview of results
- Mass-loss data
- Conclusions







Introduction and Motivation

- Nuclear weapon airburst produces intense radiant energy (>1000 kW/m^2)
- Materials exposed to this radiant energy may be damaged and/or ignite
- Data available in this range are limited
  - Glasstone and Dolan
  - Martin et al. -- black α-cellulose
- Validation of fire simulations (Fuego) requires more detail on the material response and combustion characteristics
- Mass-loss data obtained from a larger data set

Martin et al. -- Mass-Loss Data

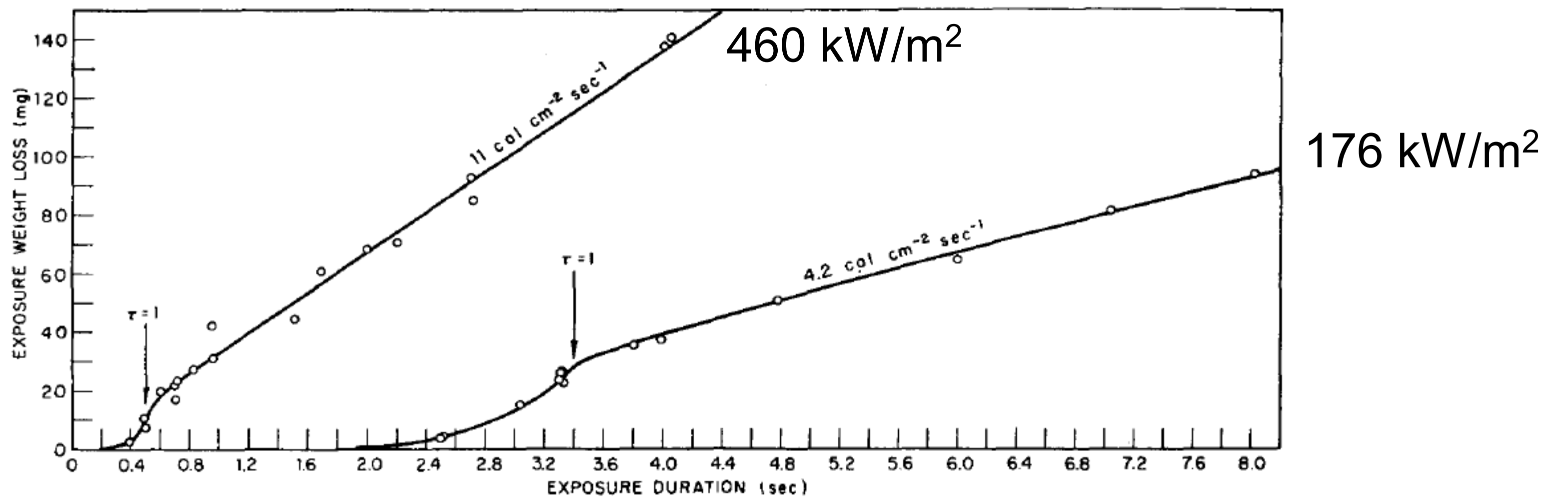


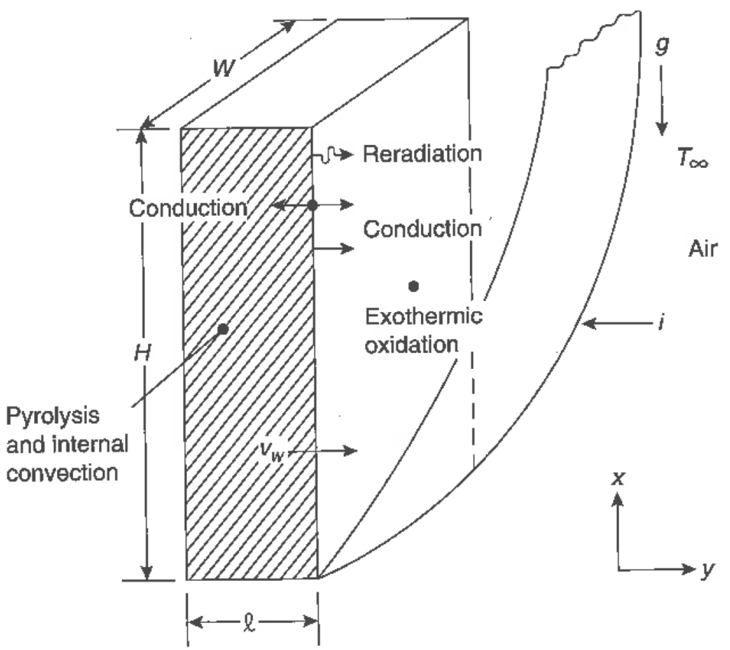
FIG. 5. Weight loss of cellulose as a function of time of exposure to two different irradiance levels.

- Experiments on thermally thick, black α-cellulose
- After ignition (τ=1), mass-loss is linear with time (linear with fluence)
- Does this trend extend to other materials?

Martin, S., Symp. (Int.) Combust., 10 (1965) 877-896.

Parameters for Fire Modeling

- Pyrolysis gas:
  - Mass flux from surface
  - Variation over time/space
- Important/negligible terms in energy balance
  - Incident radiation dominant?
- Conduction of energy into solid



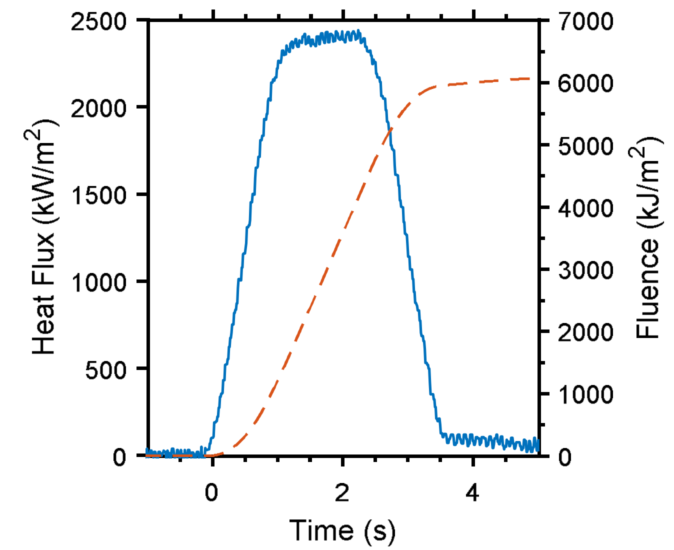
Kanury, A. M., SFPE Handbook of Fire Prot. Eng., 11 (2002) 2-269–2-296

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

Instrumentation

- Radiometer and heat-flux gauge quantify flux/fluence



- Cameras capture material response
- Images taken before and after
- Mass recorded before and after

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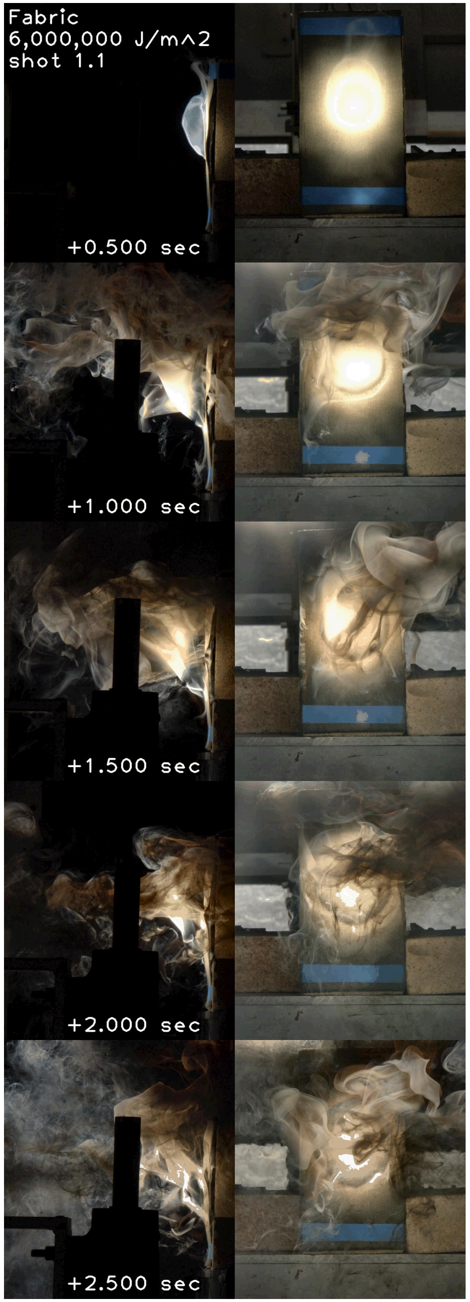

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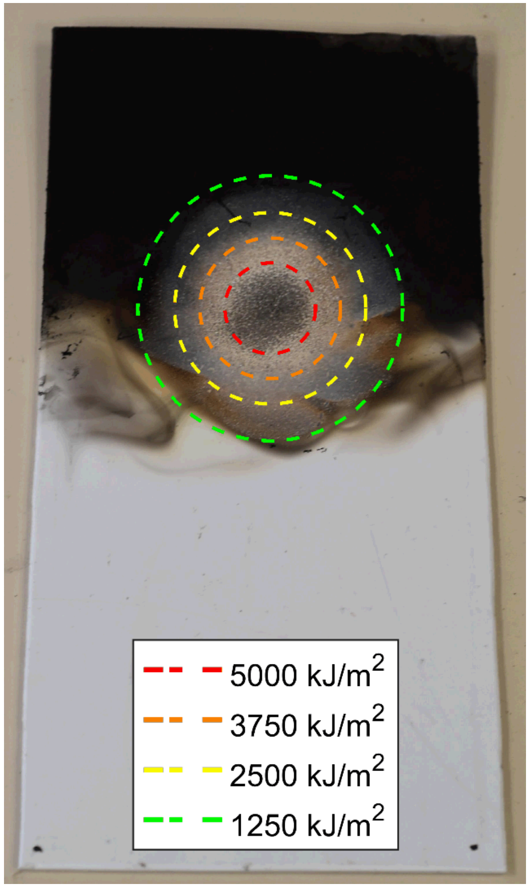

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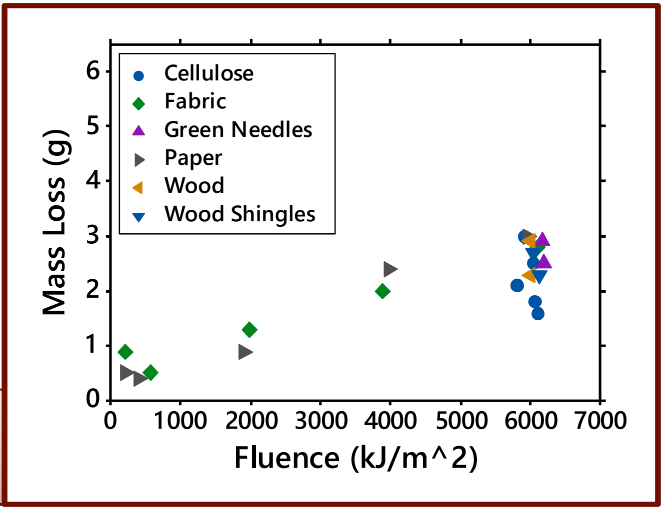
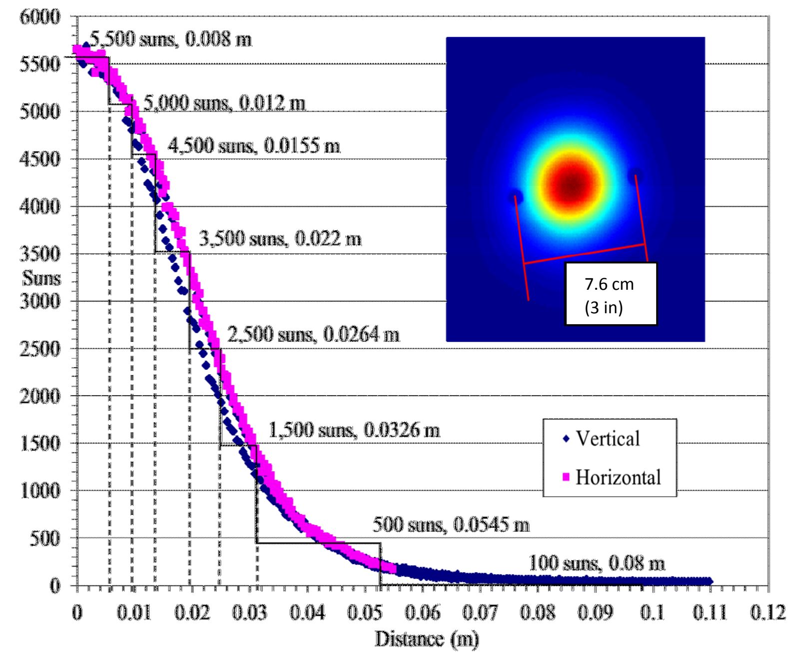


Heat Flux: Spatial Profile

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

$B = 6.662$
$C = 27.7$
$D = 0.401$
$R_0/R_1 = 1.34$
r is radius in meters

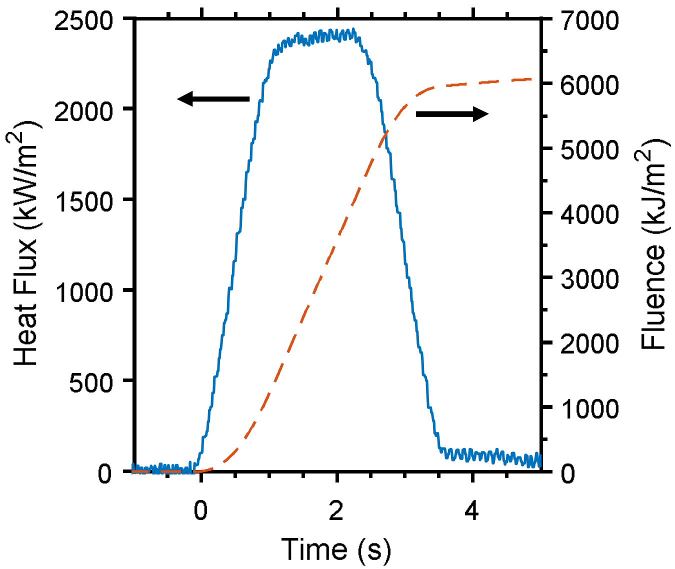


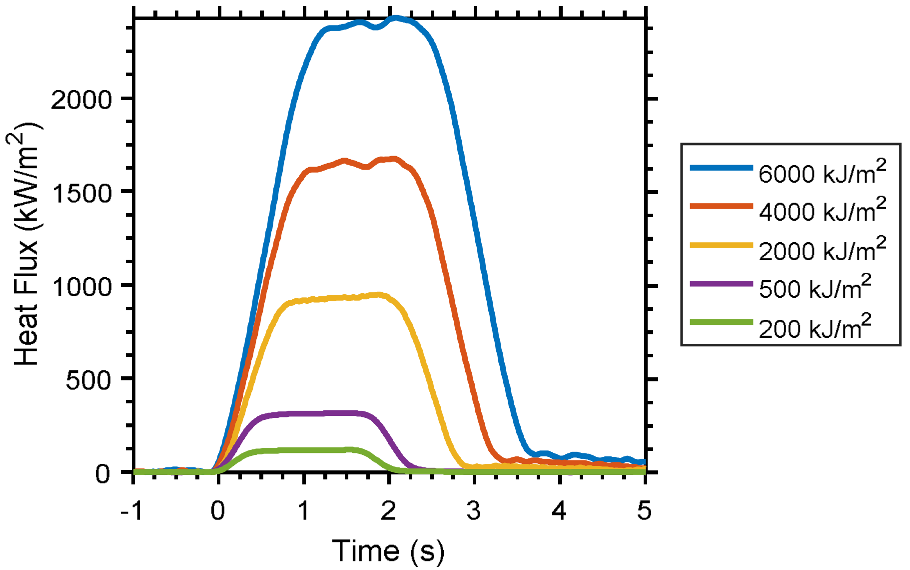
- Spatial distribution of beam has been characterized:

  Ho, C. K. et.al., Proc. Int. Conf. on Energy Sustain. 4 (2010) 1-9.

- Spot diameter is roughly 8 cm

Heat Flux: Temporal Profile





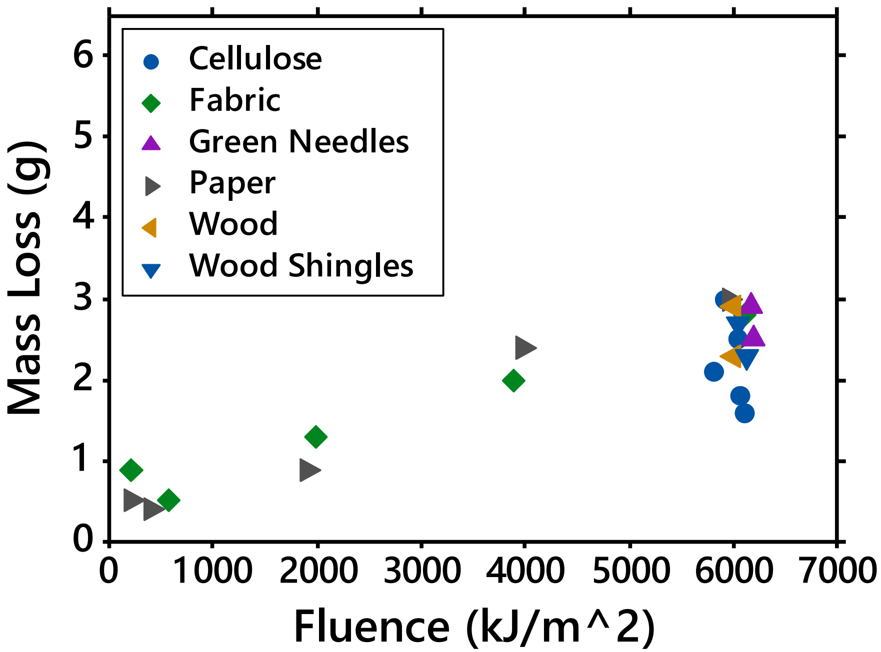
- 5 fluence conditions (200 kJ/m² to 6,000 kJ/m²)
- Higher fluence conditions are longer
  - Peak flux does not scale linearly with fluence
- Pulse resembles a nuclear weapon

Material Selection

- A variety of polymeric and lignocellulosic materials tested:

	Material	Samples	Nom. Fluence (MJ/m^2)
Organic Materials (Lignocellulosic)	**Cellulose**	5	6
	Paper	5	0.2–6
	Fabric	5	0.2–6
	Wood Shingles	2	6
	Dry Needles	3	6
	Green Needles	3	6
	Wood	2	6
Engineered Polymers	**PMMA**	5	6
	Polystyrene	5	6
	Rubber/Tire	5	0.5–6
	Polycarbonate Roofing	2	6
	Epoxy/Fiber Composite	2	6

Mass Loss: Organic Materials



Material	Intercept (A)	Slope (B)
Fabric	5.7×10^{-1} ($\pm 61\%$)	3.6×10^{-4} ($\pm 29\%$)
Paper	N/A	5.3×10^{-4} ($\pm 15\%$)

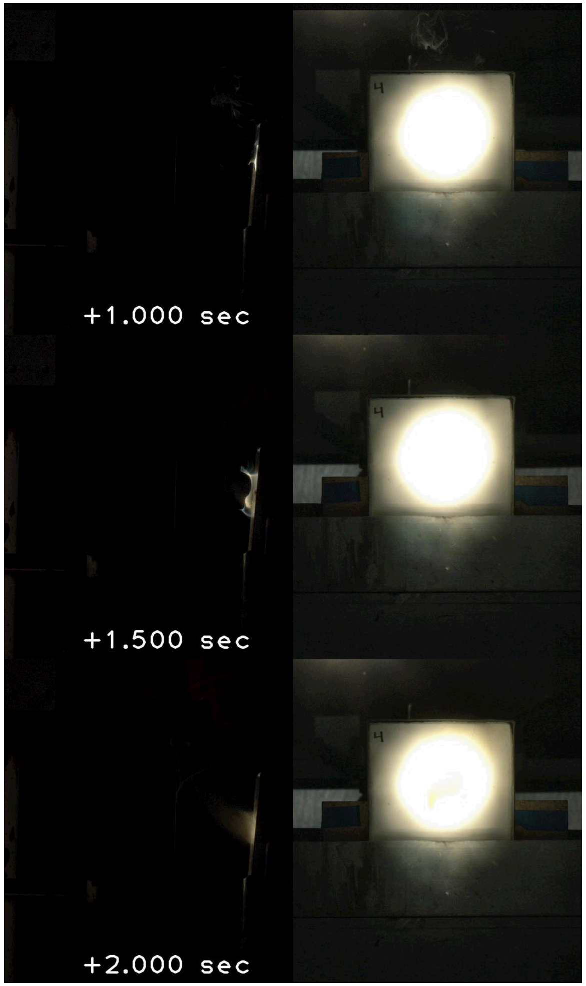
$$\Delta m = A + B Q_0''$$

- Mass-loss data similar for most organics
  - Dry pine needles sustained ignition until entirely consumed
- Cellulose data scattered (1.6 – 3.0 g)
- Linear correlations found for fabric and paper
  - Mass-loss (g) with Fluence (kJ/m^2)

Video Data: Organic Materials

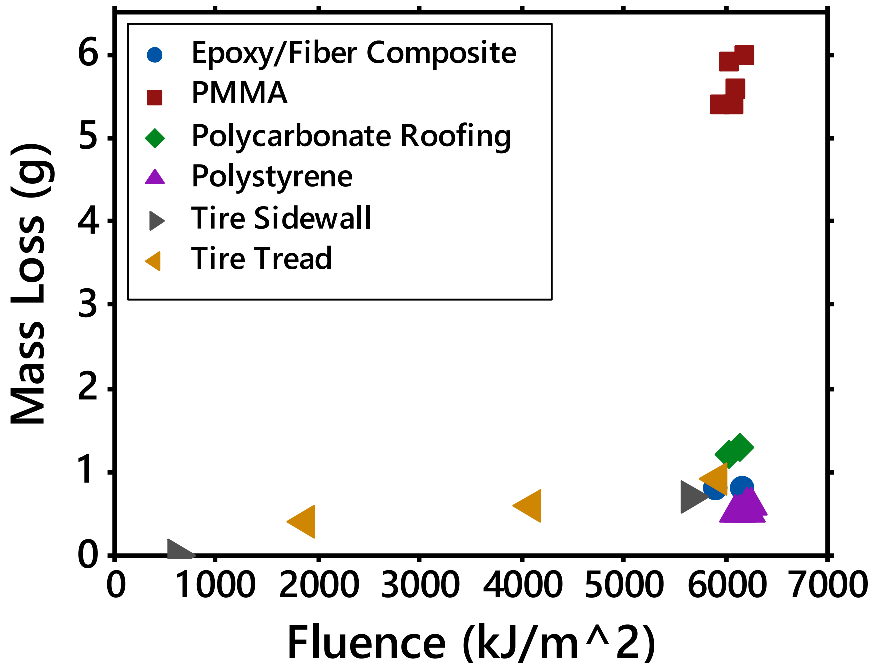
- White/light smoke with flame
  - Some materials exhibit a distinct moment of ignition
    - Example: Cellulose
- Materials quickly blacken
  - Initial emissivity may only be valid for a short time
  - May explain similar mass loss despite differing emissivity

Cellulose at 6 MJ/m^2



Video Data: Cellulose at 6 MJ/m^2

Mass Loss: Engineered Polymers



Material	Intercept (A)	Slope (B)
Tire	N/A	1.4×10^{-4} ($\pm 15\%$)

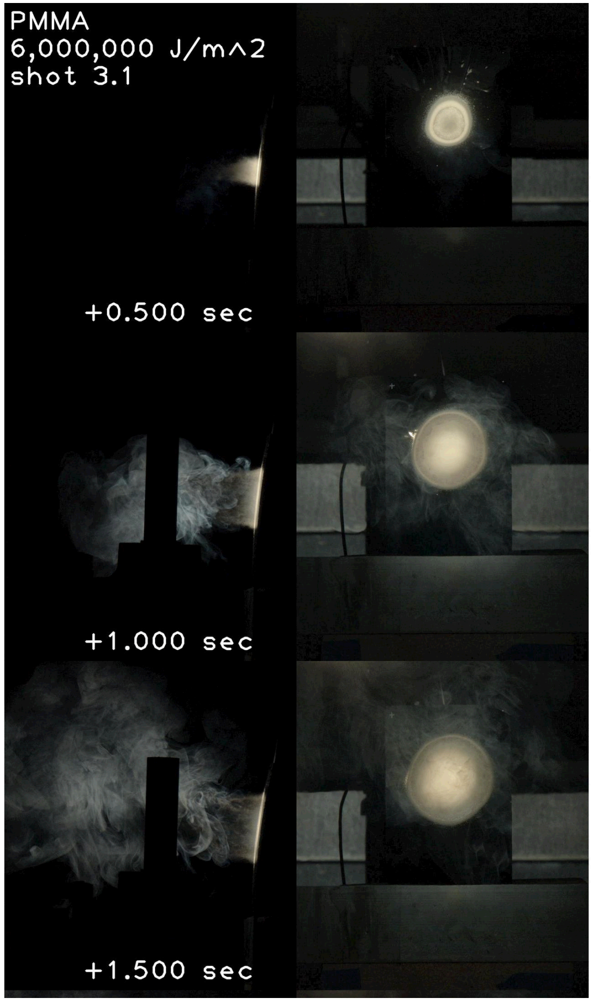
$$\Delta m = A + BQ_0''$$

- PMMA lost the most mass
- Other polymers behaved similarly (mass-loss and video)
- Linear correlation found for tire sidewall/tread
  - Mass-loss (g) with Fluence (kJ/m^2)

Video Data: Engineered Polymers

- Begins pyrolysis as white/light smoke
- After sudden ignition event (≈1 s), flames and dark smoke
  - Example: Polystrene (next slide)
- PMMA does not ignite, despite high mass loss
  - Material ablates through to the back of the 5 mm sample in 3 of 5 cases

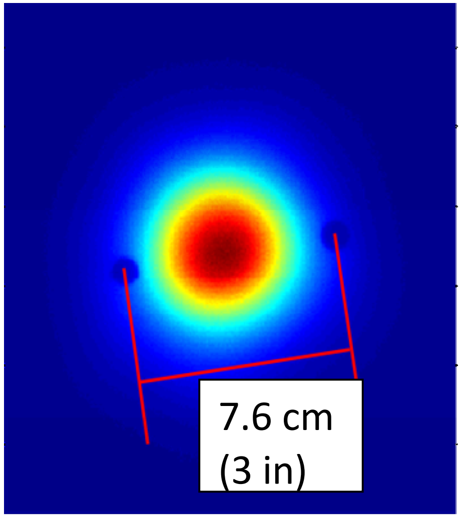
PMMA at 6 MJ/m²



Video: Polystyrene at 6 MJ/m^2

Effective Spot Size

- Mass-loss data are not spatially resolved
  - Effectively an averaged measurement
- Reported fluence values are at the center of the spot



- To compare to 1-D, define effective area:

$$A_{eff} = \frac{\int_{t=0}^{t_f} \int_{r=0}^{\infty} q''(r,t)drdt}{\int_{t=0}^{t_f} q_0''(t)\,dt} = \frac{\text{Net Incident Energy}}{\text{Incident Energy-Density at Center}}$$

- Effective area: 26.7 cm^2 (5.8 cm diameter)
  - Spot-size at peak fluence that delivers same total energy to sample

Ongoing Progress

- 3-D scanning for spatially resolved mass loss (crater depth)
- Ignition thresholds (Martin’s Map)
- Larger scale experiments (Solar Tower)
- Video analysis of pyrolysis gasses/combustion
- Detailed model-validation study

Conclusions

- Mass-loss data are linear at very high heat flux (~1 MJ/m^2)
  - Linear correlations found with uncertainty data
- Mass-loss from organic materials were similar
  - Exception: Dry pine needles sustained ignition
- Mass-loss from engineered polymers were similar
  - Exception: PMMA lost significantly more mass
- Effective spot size defined for comparison to 1-D models/exp.
  - Spatially resolved quantity (3D scan) would be more appropriate

Acknowledgments

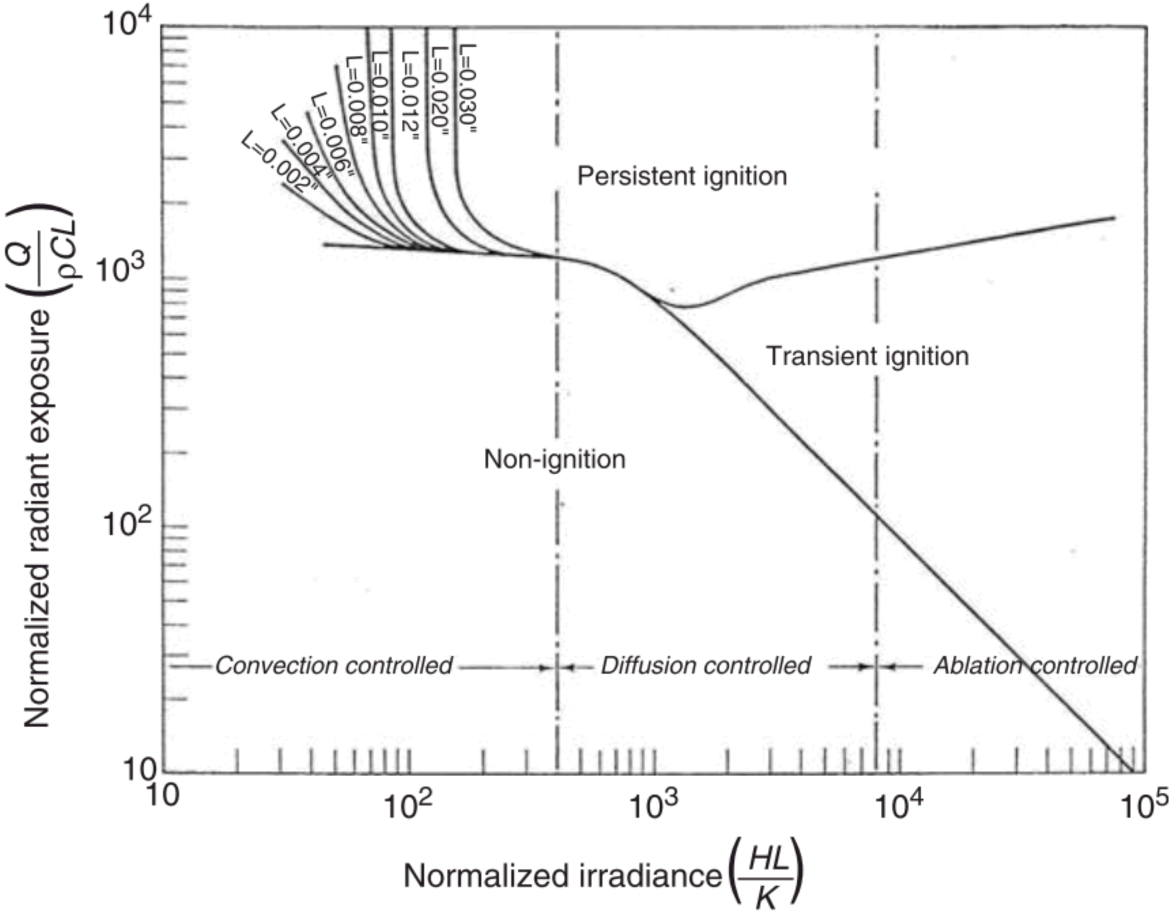
- Funding for this project provide by the Defense Threat Reduction Agency

- Undergraduate Interns: Bobby Thomas and Noah Siegel
- Solar Furnace Technician: Doug Robb

Backup Slides

PMMA at 6 MJ/m^2

Ignition Thresholds



- Maps ignition regimes for cellulose
- Has units of temperature (K)
- Based on black α-cellulose paper using square flux waves
- Recommended in the SFPE handbook

Martin S.B., Diffusion-controlled ignition of cellulosic materials by intense radiant energy. In Symposium (International) on Combustion 1965 Jan 1 (Vol. 10, No. 1, pp. 877-896). Elsevier.