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# Ignition and Damage Thresholds of Materials at Extreme Incident Radiative Heat Flux

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## Abstract

Upon detonation, a nuclear weapon irradiates the surroundings with intense thermal energy for a short (~1 s) duration. The Solar Furnace at the National Solar Test Facility simulated this environment for an extensive experimental study on the response of many natural and engineered materials. Solar energy was focused onto a spot (~10 $cm^2$ area) in the center of the tested materials, resulting in an intense radiant load (~100–1000 $kW/m^2$) for approximately 3 seconds. Using video photography, the response of the material to the extreme heat flux was carefully monitored. The initiation time of various events was monitored, including charring, spalling, ignition, and melting. These ignition and damage thresholds are compared to historical results predominantly for black, alpha-cellulose papers. When normalized by the thickness and the thermal properties, ignition and damage thresholds are comparable across a wide range of materials.

## Preliminary Results

Martin and his collaborators[2] extensively studied thresholds for ignition upon high-intensity irradiation, focusing predominantly on black α-cellulose. Multiple modes of ignition were identified including sustained-glowing, sustained-flaming, and transient-flaming ignition. Sustained-glowing ignition is a smoldering surface oxidation that persists beyond the exposure. Sustained-flaming ignition features gas-phase combustion of pyrolysis gasses that again persists beyond the exposure. Similarly, transient-flaming ignition features combustion of pyrolysis gasses; however, the reaction terminates with the exposure. Whether an ignition is sustained or transient is determined by whether the heat returning to the surface from the flame exceeds the diffusion of heat into the bulk material.

Normalizing the results with the sample properties, they found ignition thresholds for α-cellulose could be predicted using the flux (irradiance) and fluence (irradiant exposure). While much of their data focuses on square-wave exposures, they also studied exposures simulating the irradiation

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[1] Sandia National Laboratories is a multimission laboratory operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc. for the United States Department of Energy's National Nuclear Security Administration under Contract No. DE-NE0003525.

[2] Martin, S. "Diffusion-controlled ignition of cellulosic materials by intense radiant energy." Symposium (International) on Combustion. Vol. 10. No. 1. Elsevier, 1965

from a nuclear-weapon airburst[3]. These ignition data for nuclear-weapon exposures are displayed in Figure 1, a diagram referred to as "Martin's Map". Here, the irradiance (flux) is normalized as:

$$q^* = \frac{a q''_{peak} L}{k}$$

where $q''_{peak}$ is the peak flux of the nuclear-weapon-shaped pulse, and sample properties $a$, $L$, and $k$ are the surface absorptivity, thickness, and thermal conductivity, respectively. The fluence is normalized as:

$$Q^* = \frac{a Q''}{\rho c_p L}$$

where $Q''$ is the fluence, $\rho$ is the density, and $c_p$ is the specific heat.

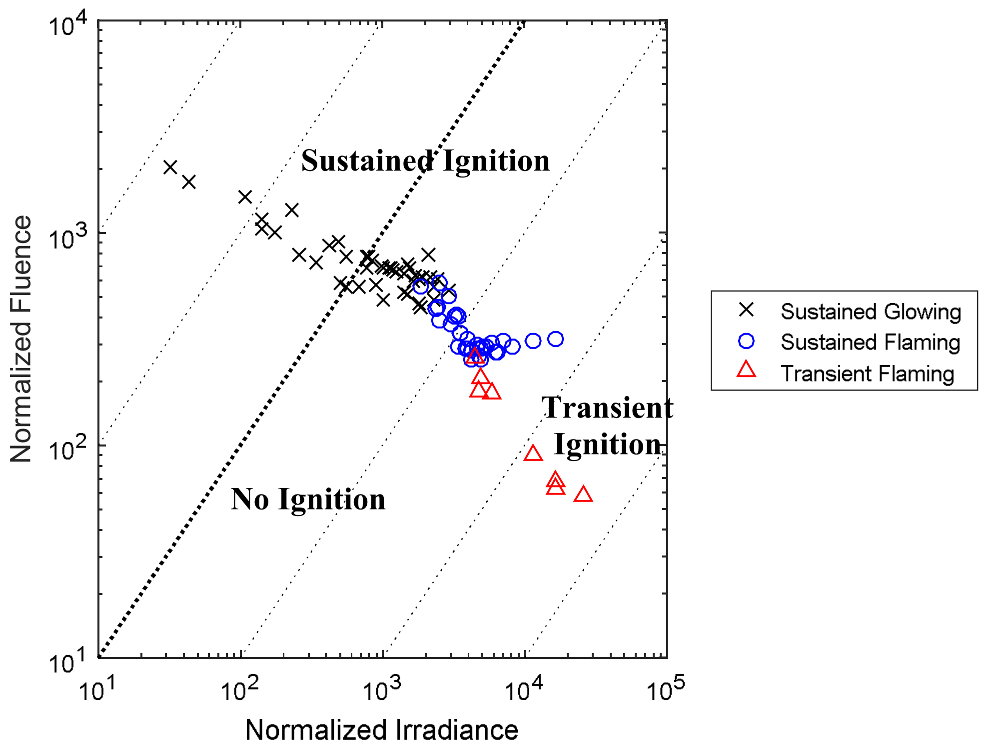


Figure 1. Ignition thresholds obtained by Martin et. al. (2004) for black α-cellulose exposed to radiant energy pulses simulating that of a nuclear weapon. Dotted lines are at constant Fourier number. The line in bold represents unity.

The occurrence of ignition is determined by the region where the point falls. In the lower left, no ignition is expected; however, as flux and fluence increase, the point moves into the sustained- or

[3] Martin S.B. Fire setting by nuclear explosion: A revisit and use in nonnuclear applications. Journal of Fire Protection Engineering. 2004 Nov;14(4):283-97.

transient-ignition domains to the upper right. The ignition thresholds were generated using cellulose samples of differing density, conductivity, and thickness and presumably extend to any black α-cellulose sample; however, the utility of the map for other materials has not been demonstrated extensively.

The ignition data from our Phase 1 experiments are compared to the ignition thresholds obtained by Martin et al. in **Error! Reference source not found.**. Normalized fluence is calculated using the total fluence delivered to the sample; likewise, normalized irradiance is calculated using the peak flux. For laminate materials, the thickness of a single layer is used. Martin's data for nuclear-weapon exposures is replicated in red, indicating the thresholds for sustained-glowing, sustained-flaming, and transient-flaming ignition. The dashed lines are added as guides to the eye and roughly match the ignition conditions reported by Martin.

There is a general agreement between our data and the thresholds reported by Martin. The paper samples transition from non-ignition to ignition at the appropriate threshold. The threshold found experimentally for fabric is higher, likely due to the presence of coatings including fire-retardants and waterproofing. However, for each of these we noted transient flaming ignition rather than sustained smoldering; this disagreement could be because our samples were layered. We may wish to retest some of these samples as single sheets to verify our data agree with that of Martin.

Dry and green needles are also notable because they respond differently despite being at the same point on the map. Dry needles sustain ignition, as expected, but green needles do not ignite. The disparity demonstrates that other factors, such as moisture content and maturity, need to be accounted for to extend Martin's Map to other materials.

The rest of the materials (cellulose, wood, and wood shingles) fall within the transient ignition regime, which aligns with the experiments. The cellulose is very close to the transition from transient- to sustained-flaming ignition.

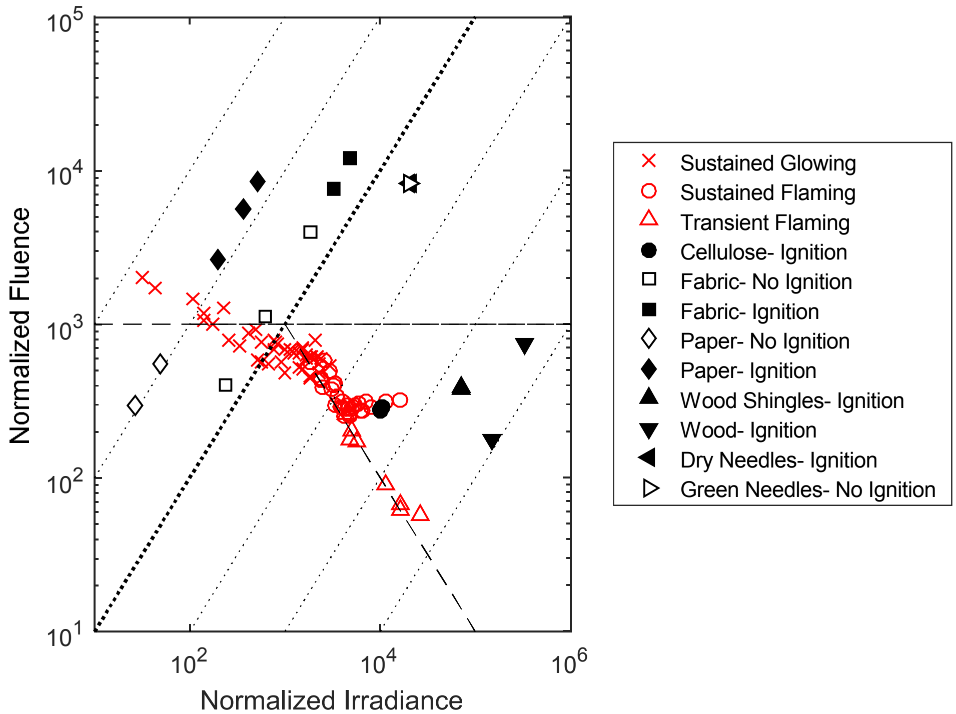


Figure 2. Ignition conditions for lignocellulosic materials.

To produce their ignition thresholds, Martin et. al. conducted an extensive set of experiments (at least 20 experiments per data point) searching for the conditions where the sample ignited at the very end of the exposure. Replicating this approach is certainly not feasible for the broad scope of this project. Instead we opt to approximate the transient-ignition thresholds using the flux and fluence at the time of ignition. The same data adjusted for time-of-ignition quantities instead of total quantities for normalized flux and fluence are shown in Figure 2.

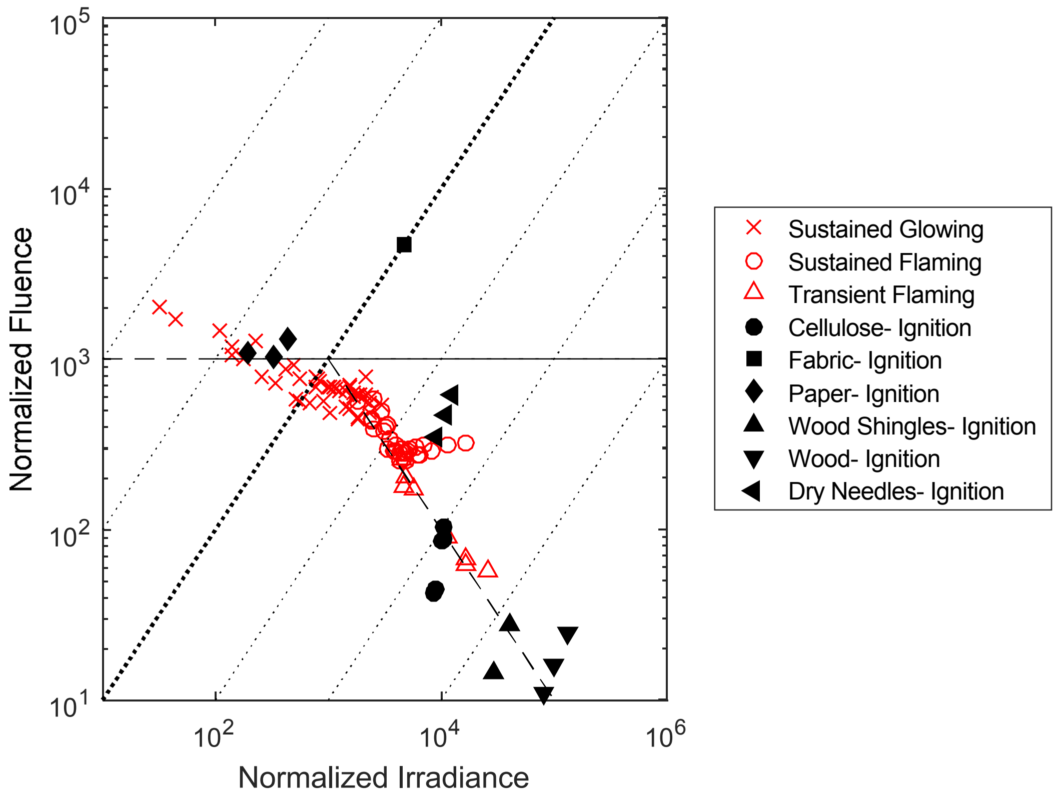


Figure 3. Ignition conditions for lignocellulosic materials. Normalized fluence and irradiance are calculated using at the time of ignition.

The thresholds obtained experimentally using the time-of-ignition data align with Martin's data well. The thresholds for cellulose, wood, and wood shingles are along the lower edge of the transient ignition regime (the dotted diagonal). Transient flames are seen from paper at the conditions corresponding to smoldering ignition (our paper was layered, whereas Martin's was not). Fabric is the largest outlier, and the points overlay on each other, suggesting confidence that the data are not in error. Dry needles ignite a little later than predicted, but do exhibit the appropriate behavior (sustained flaming).