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WSSCI Western States Section Combustion Institute

Solid-Dominant Ignition Thresholds for Cellulose under Extreme Irradiation

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

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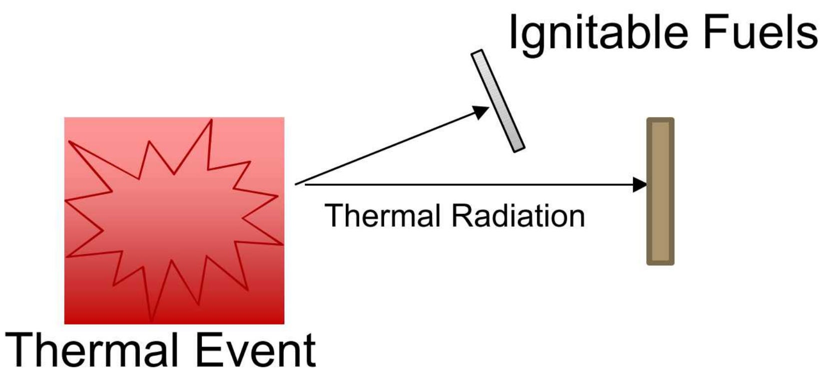
Outline

- Introduction and motivation
- The Ignition Map
- Developing Empirical Models
- Reducing Effect of Pulse Shape
- Extending the Map to Other Materials
- Conclusions

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
  - Arc Faults

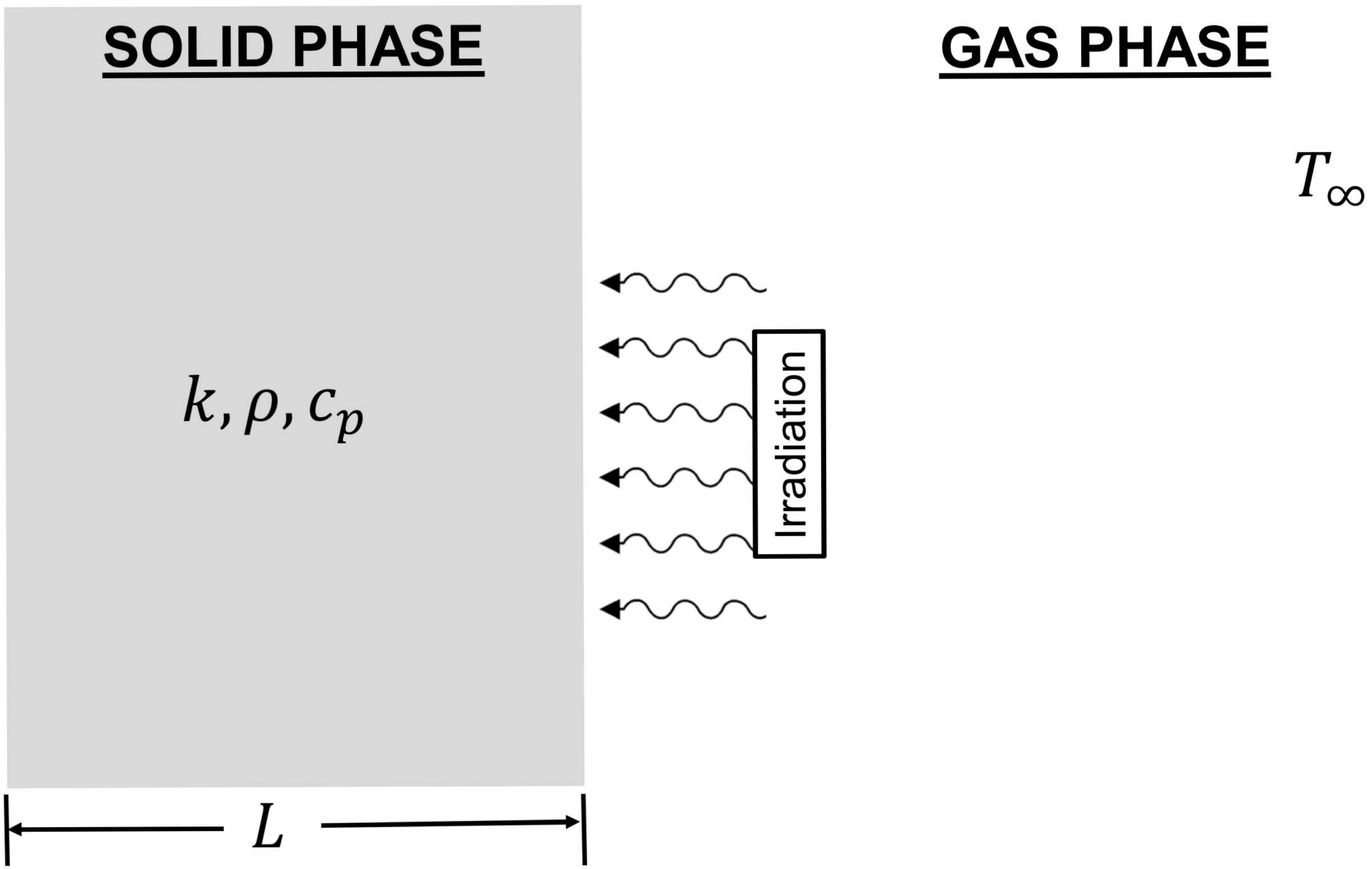


- At extreme (≫ 100 kW/m^2) heat flux, the incident energy dominates the surface energy balance
  - Radiation (~100 kW/m^2) and convection (~10 kW/m^2) are relatively small even when the surface reaches ignition temperatures (≈ 600 °C)
- **Objective:** Determine ignition and damage thresholds at extreme heat flux for a wide range of materials.

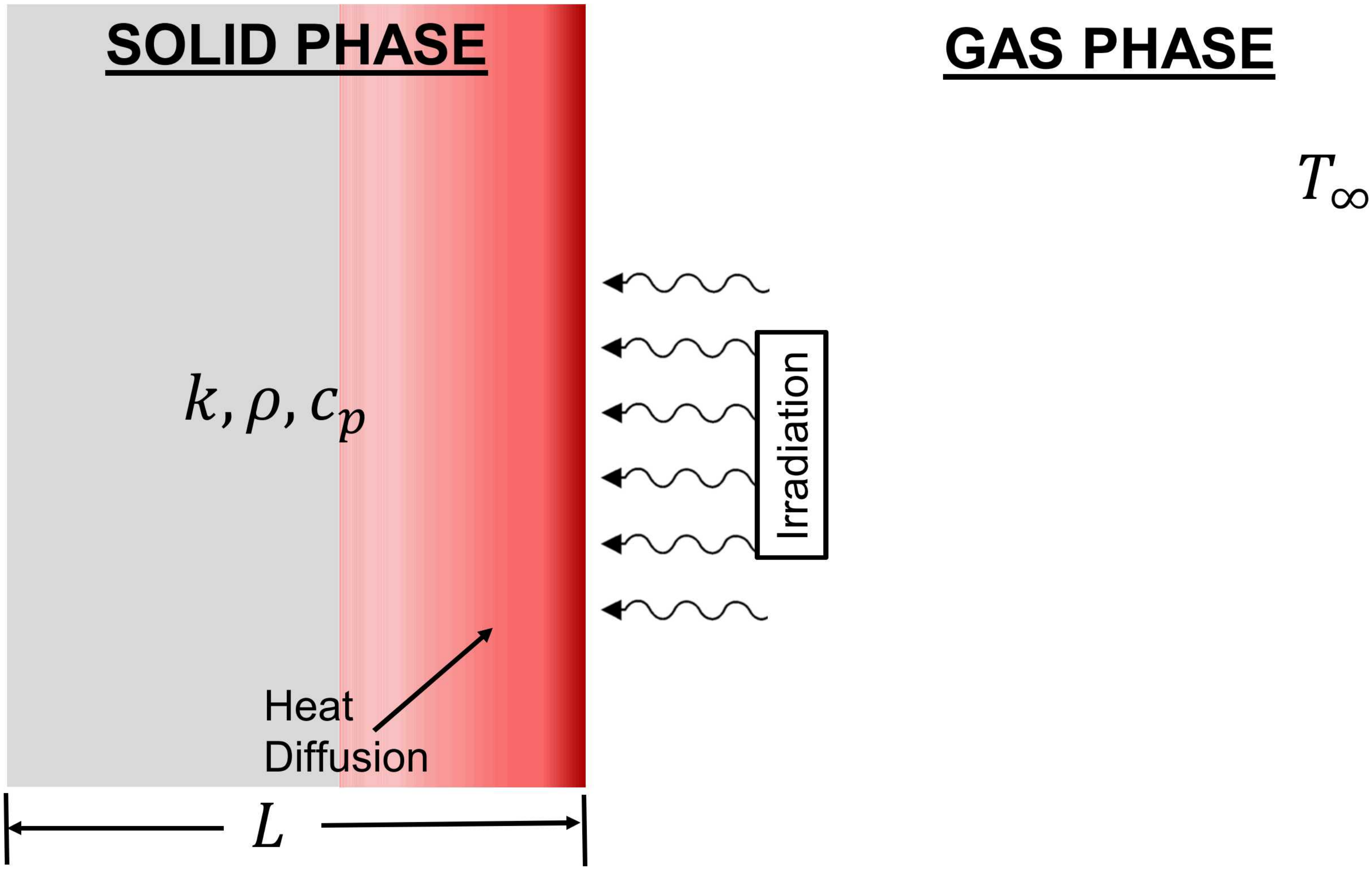
Approach

- The breadth of this problem is daunting:
  - 100's of materials (organics, polymers, composites…)
  - With varying properties:
    - Color, shape, moisture, degradation…
  - And environmental variables
    - Wind speed, humidity, orientation, rain/snow/ice…
- Models are required to collapse the problem:
  - Empirical Models
    - Simple/Easy, but neglect relevant physics (e.g., gas dynamics)
  - Computational Models
    - Complex/Difficult, but address wider range of phenomena
- Develop both types of models supported by concentrated solar power experiments

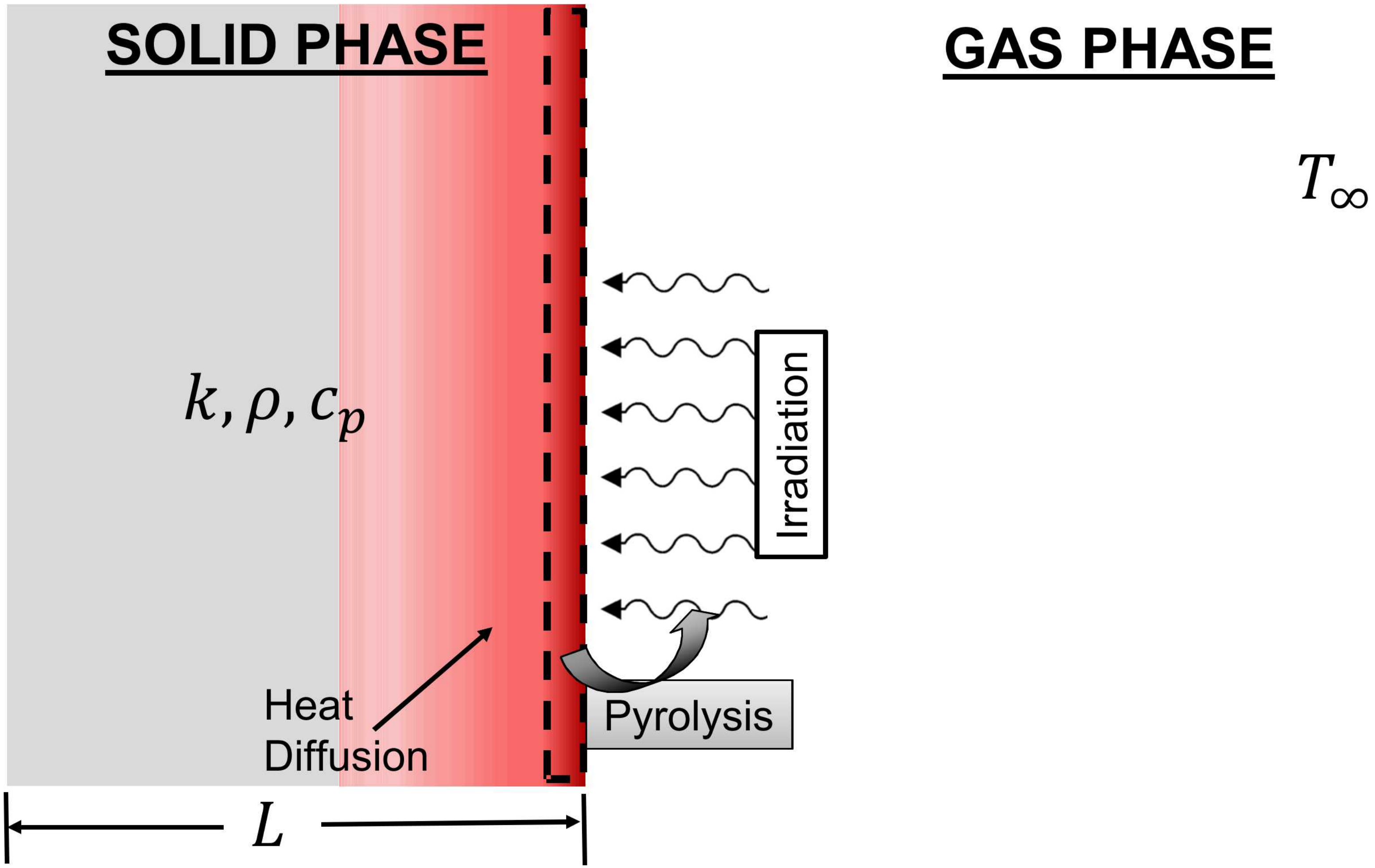
Ignition Models



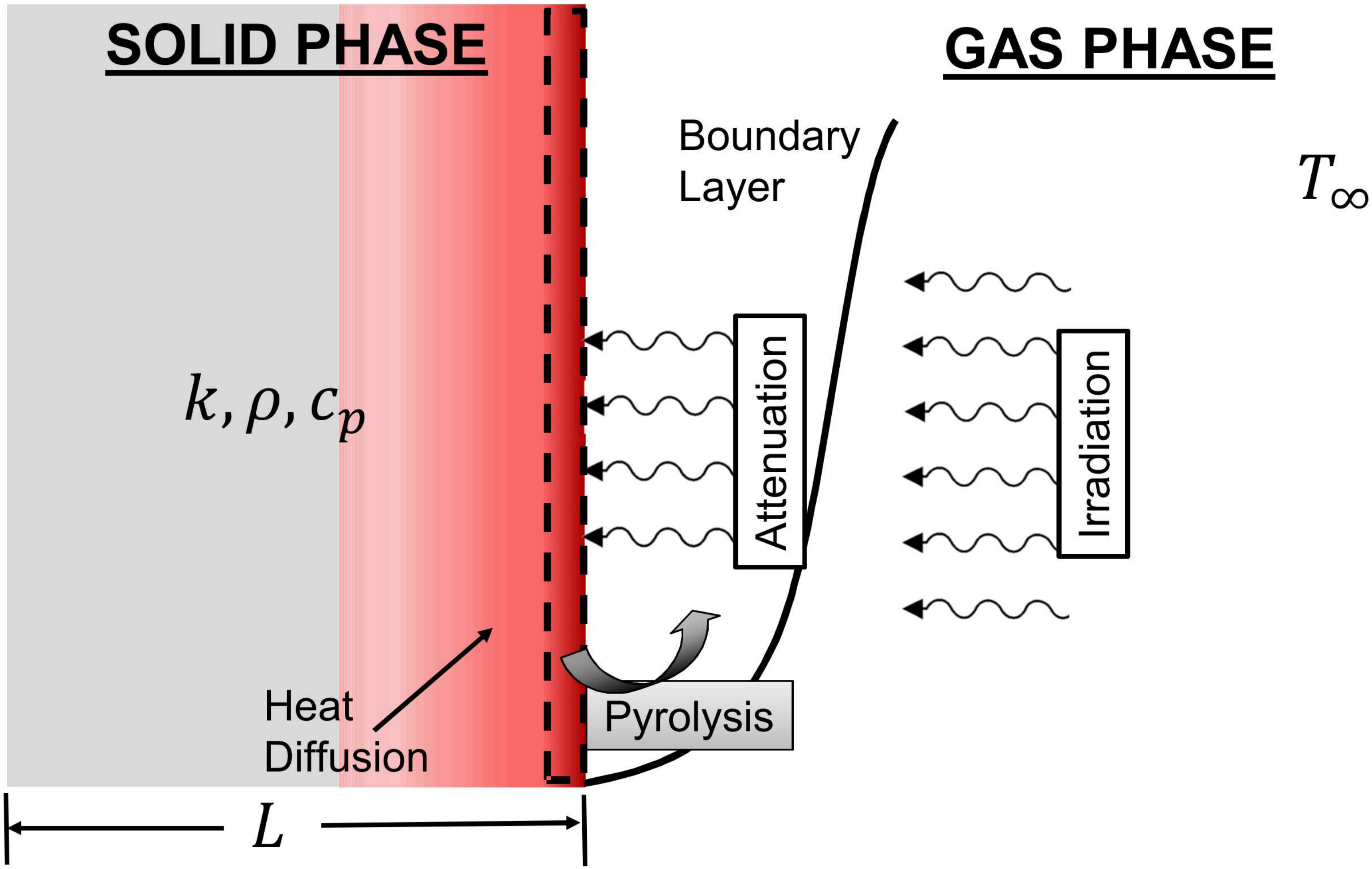
Ignition Models



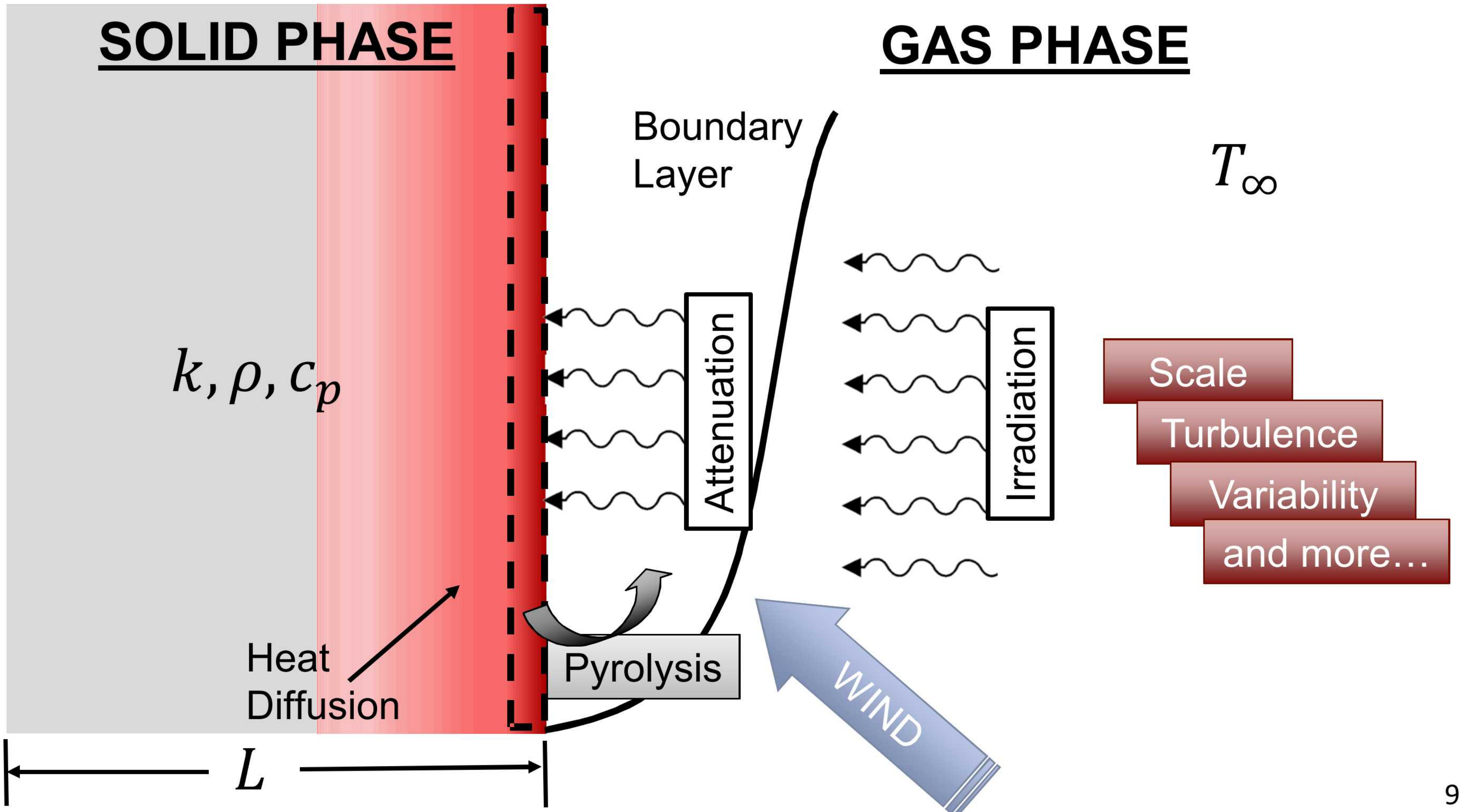
Ignition Models



Ignition Models



Ignition Models

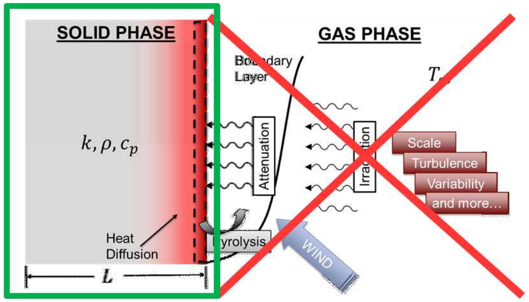


Ignition Models

- The correct approach depends on the material:

Empirical Approach (Ignition Map)

For some materials, ignition is dominated by the **solid phase**:

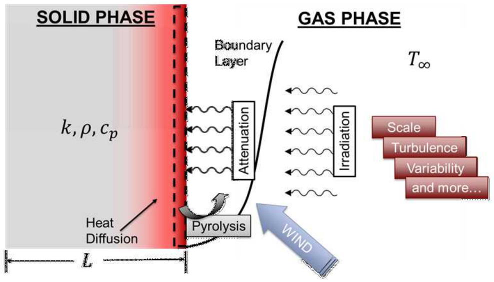


The problem is **greatly simplified.**

Ignition predicted from well-known quantities.

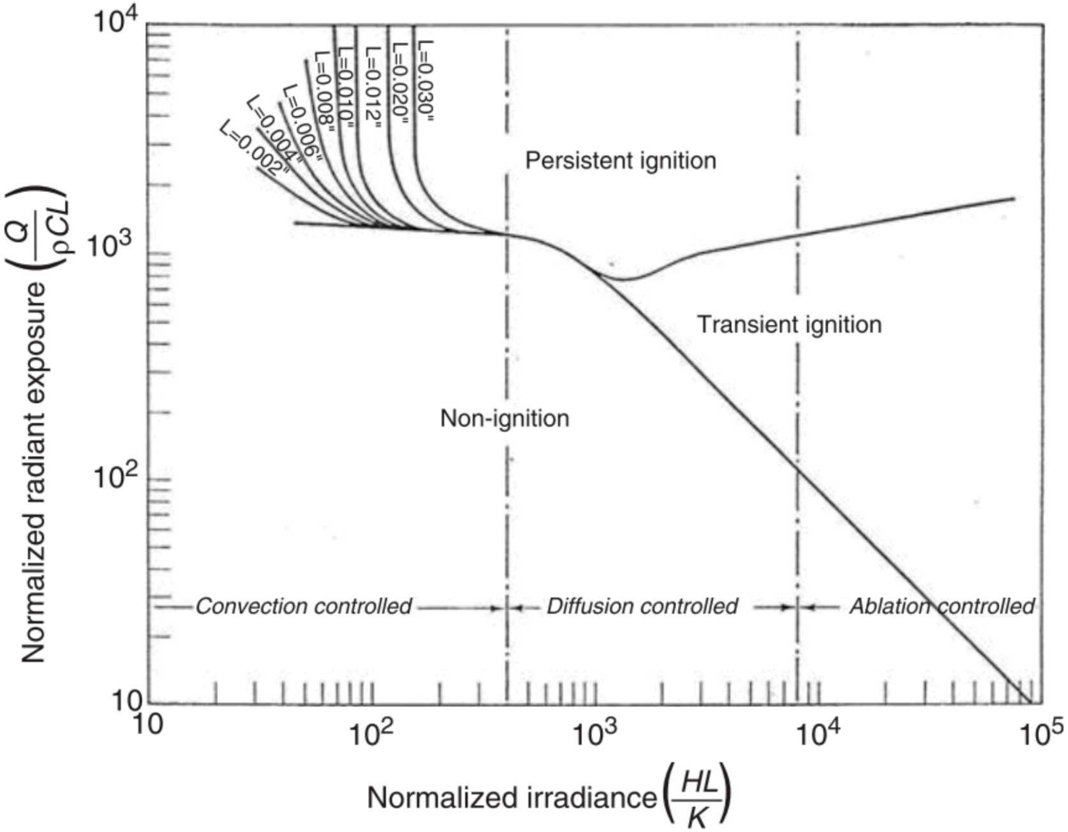
Computational Approach

For other materials, ignition is **coupled** to **both the solid and the gas:**



Full problem is **too complicated** for empirical correlations, **high-fidelity computational models** are required.

Martin's Ignition Map



Martin, S.B., 10th Sym. Comb. (1) 1965

Norm. Flux:

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

Norm. Fluence:

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

Fourier #:

$$Fo = \frac{Q^*}{q^*} = \frac{\alpha t^*}{L^2}$$

- Simple prediction variables (normalized flux and fluence).
- Intensively validated for **black, alpha cellulose papers**.
- **Limited data** for similar materials (newspaper, cotton fabric)

Empirical Ignition Models

- We believe a limited subset of the ignition problem can be addressed using **empirical ignition models**.

- The remainder of this talk demonstrates this capability by:
  - Reformulating Martin's Ignition Map into an empirical correlation.
  - Reduce ignition threshold dependence on exposure shape.

This Work

- Related work has focused on experiments:
  - Validating this theory with various cellulosic papers.
  - Extending this theory to other related materials.

Related work

Ignition Variables

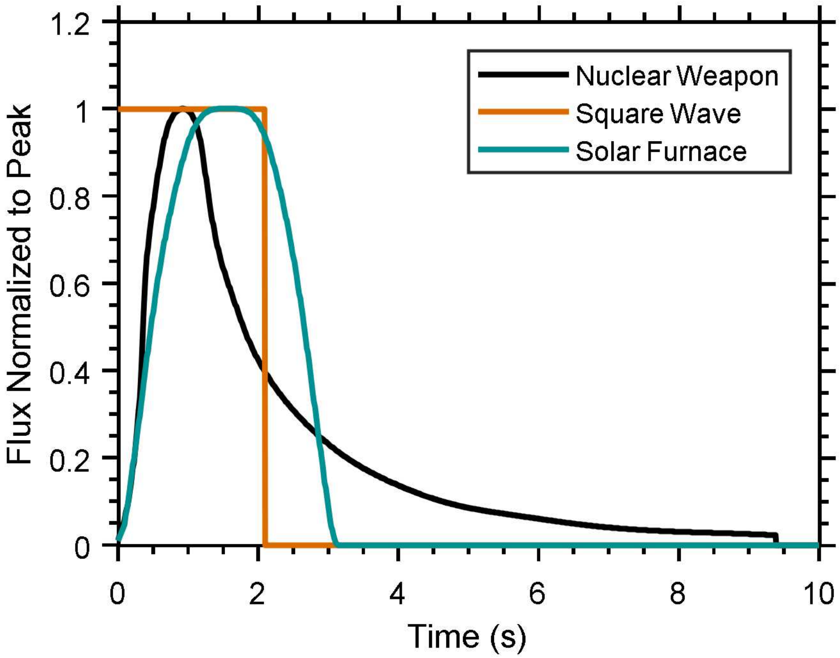
- Martin focused on four ignition variables:
  - Paper Thickness **(L)**
  - Paper Density **(ρ)**
  - Exposure Intensity **(q''_{peak})**
  - Exposure duration **(t or Q'')**
- The effects are summarized by two normalized variables.
- Studies performed for two exposure types:
  - Nuclear Weapon (NW)
  - Square Wave (SW)

Norm. Flux:

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

Norm. Fluence:

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



Ignition Types

- By **normalizing** the ignition variables, Martin's **empirical** model predicts the **ignition type**.

Ignition Variables:

$$L, \rho, q''_{peak}, Q''$$

Normalize

Normalized Variables:

$$q^*, Q^*$$

Predict

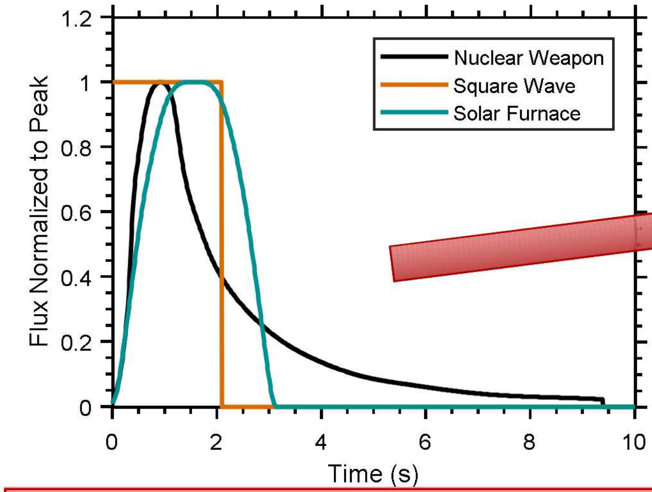
Ignition Types:

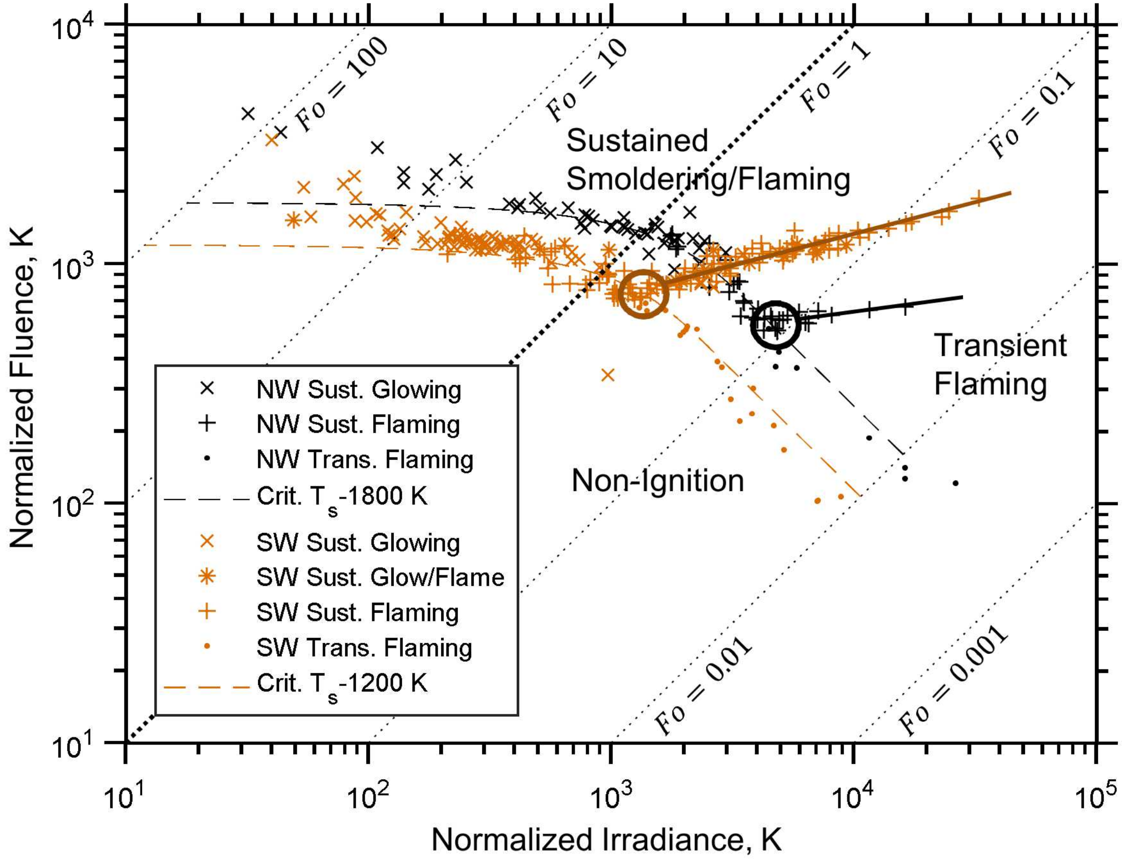
1) **Transient Flaming**
   - **Flames** during exposure
   - **Nothing** after exposure
2) **Sustained Smoldering/Glowing**
   - **Smoldering** after exposure
3) **Sustained Flaming**
   - **Flaming** after exposure

Generating the Ignition Map

$$\frac{Q^*}{q^*} = \frac{a\,Q''/\rho\, c_p L}{a q''_{peak}\, L/k} = \frac{\alpha t^*}{L^2} = Fo^*$$

- Martin generated a **separate** ignition map for each exposure type.



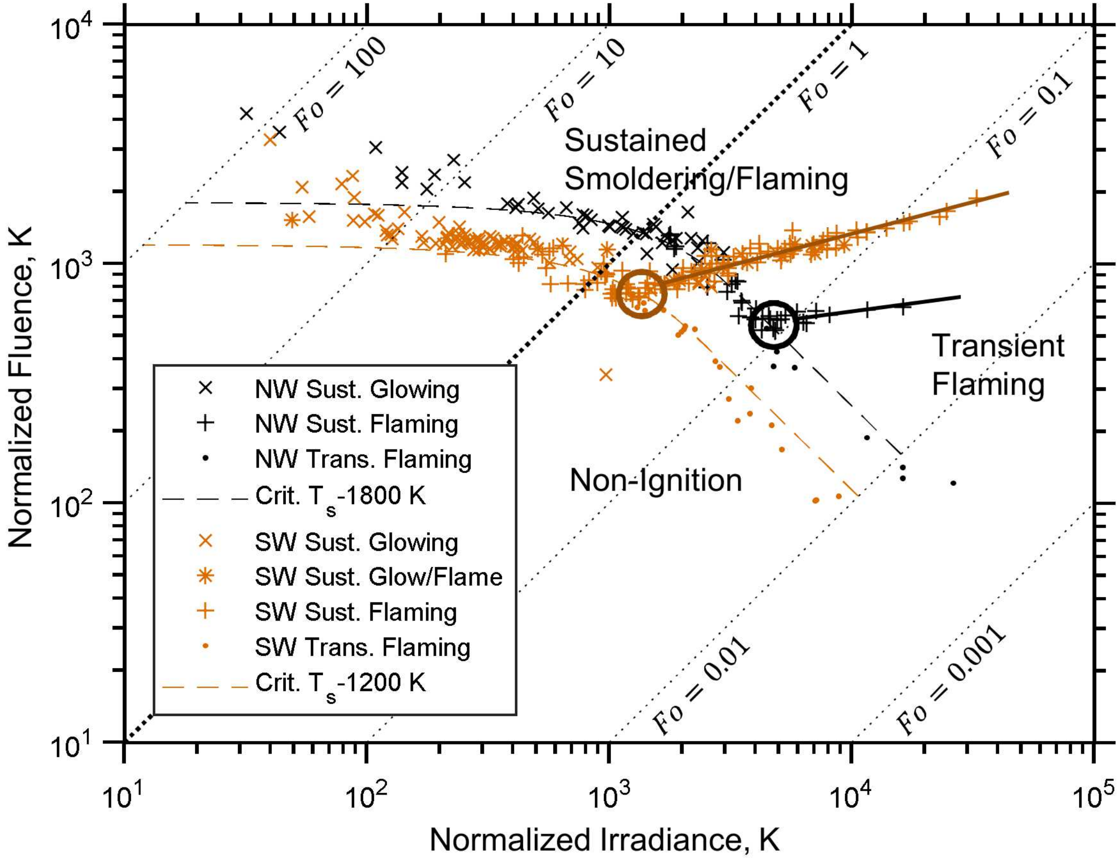


Each point on the map is based on over **20 experiments**.

The map is formulated from **1000's of tests**!

Theoretical Development

- Martin's Map is useful for **visual inspection** in current form
- How do we transform into **empirical model w/ uncertainty**?

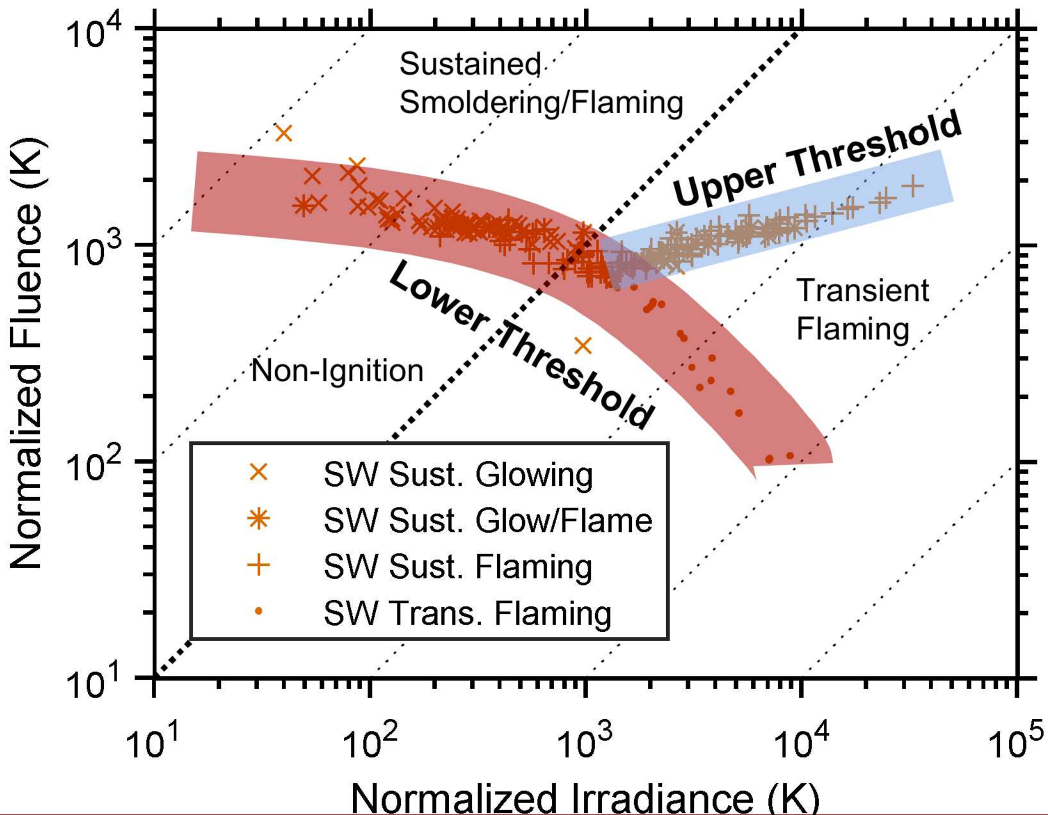


Three-Step Approach:

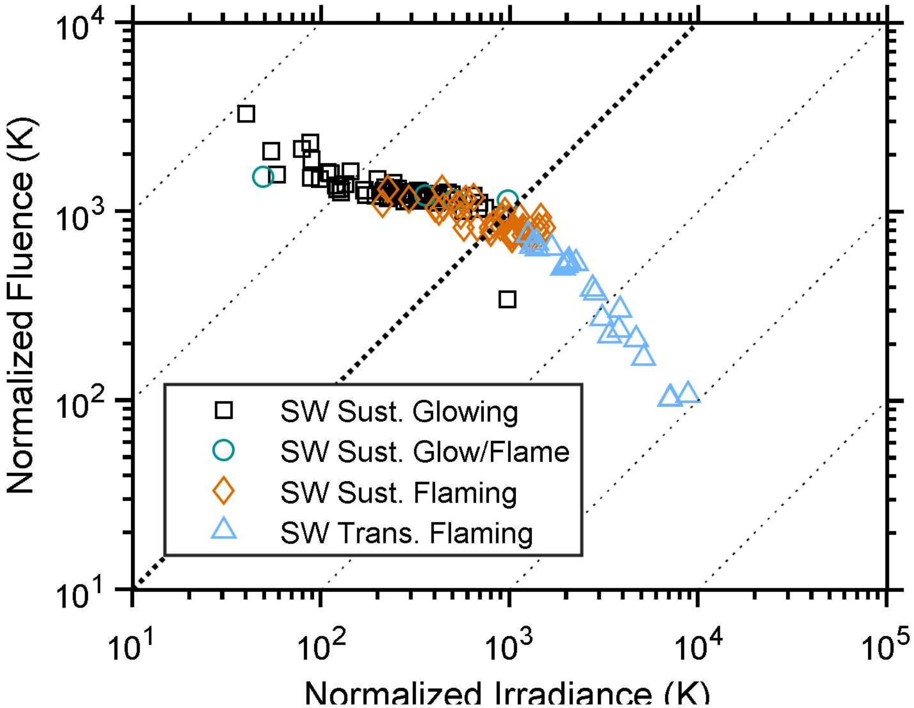
1. Divide into 'upper' and 'lower' thresholds.
2. Develop correlations for each threshold.
3. Evaluate the impact of exposure shape.

Ignition Map: Lower/Upper Thresh.

- Ignition map consists of upper and lower threshold.
  - Exceeding **lower** threshold yields ignition of **any type**.
  - Exceeding **upper** threshold yields **sustained** ignition (Glow. or Flam.).



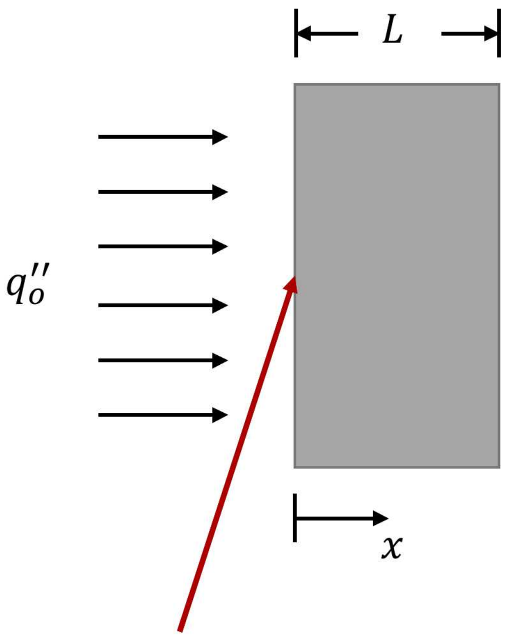
Ignition Map: Lower Threshold



- Examine Lower Threshold for square-wave data.
  - Does not have a simple form for an empirical correlation.
  - The shape matches theoretical predictions for a **critical ignition temperature**.
    - Martin was an advocate for critical surface temp.
  - Early versions of the ignition map were based on **Fourier number**.

Following the approach/mindset of Martin, quantify lower threshold using a **'critical surface temperature rise'**

Ignition Map: Crit. Surface Temp.



- Thermal diffusion into a radiantly heated slab.
  - Ignore other effects (pyrolysis, losses, etc.)
  - Solid temperature has well-defined sol'n:

$$\frac{k[T(x,Fo)-T_i]}{aq_o''L} = Fo + \frac{2}{\pi^2}\sum_{m=1}^{\infty}\frac{1}{m^2}\cos\left(\frac{m\pi x}{L}\right)\left[1-\exp(-m^2\pi^2 Fo)\right]$$

$\Delta T_s = \Delta T_{th}$

When does surface reach critical temp?

$$\frac{\Delta T_{th}}{q_{th}^*} = Fo_{th} + \frac{2}{\pi^2}\sum_{m=1}^{\infty}\frac{1}{m^2}\left[1-\exp(-m^2\pi^2 Fo_{th})\right]$$

Ignition Map: Crit. Surface Temp.

- Can predict ignition using critical surface temperature rise:

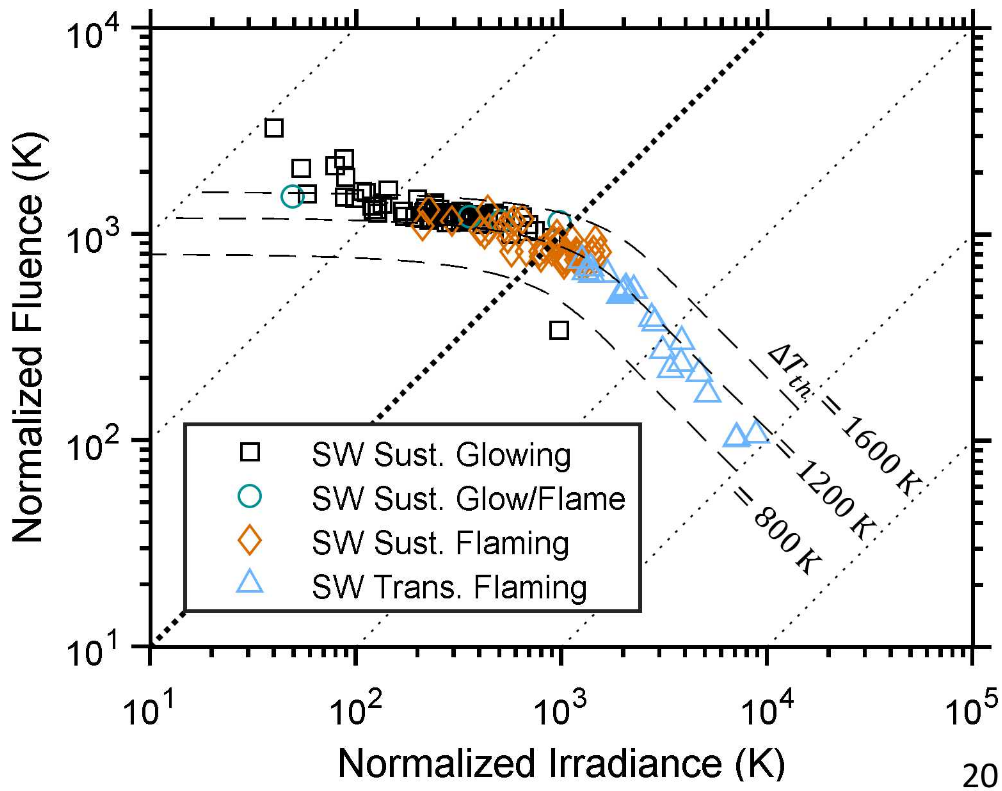
$$Q_{th}^* = q_{th}^* Fo_{th} = \Delta T_{th} \frac{Fo_{th}}{Fo_{th} + \frac{2}{\pi^2} \sum_{m=1}^{\infty} \frac{1}{m^2} \left[1 - \exp(-m^2 \pi^2 Fo_{th})\right]}$$

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

Norm. Fluence @ Ign.

Crit. Surf. Temp. Rise

Function of Fo **only**



Produce a **correlation for ΔT_{th}** and use it as the basis for the predictive model.

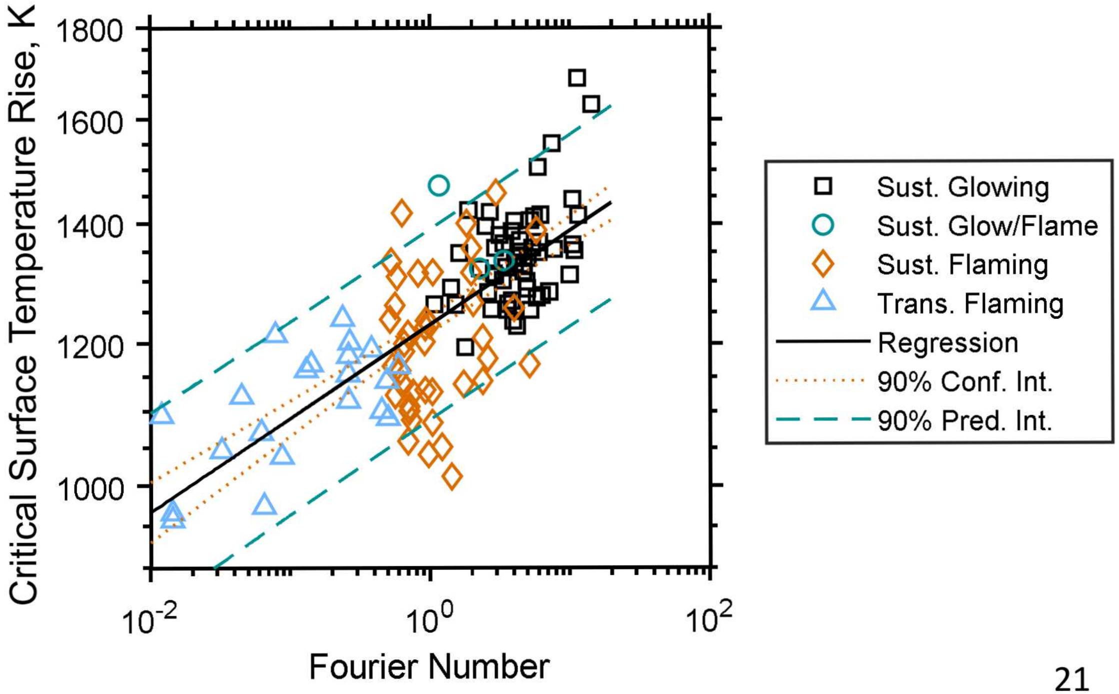
Correlating Crit. Surf. Temp. Rise

- Using Martin's SW data, generate correlation (w/ UQ) that describes lower threshold:
  - Critical Surf. Temp. Rise varies linearly with Fourier number
  - Data scatter were not (significantly) correlated to other variables

$$\log Q^*_{th} = \log \Delta T_{th} + \log f(Fo_{th})$$

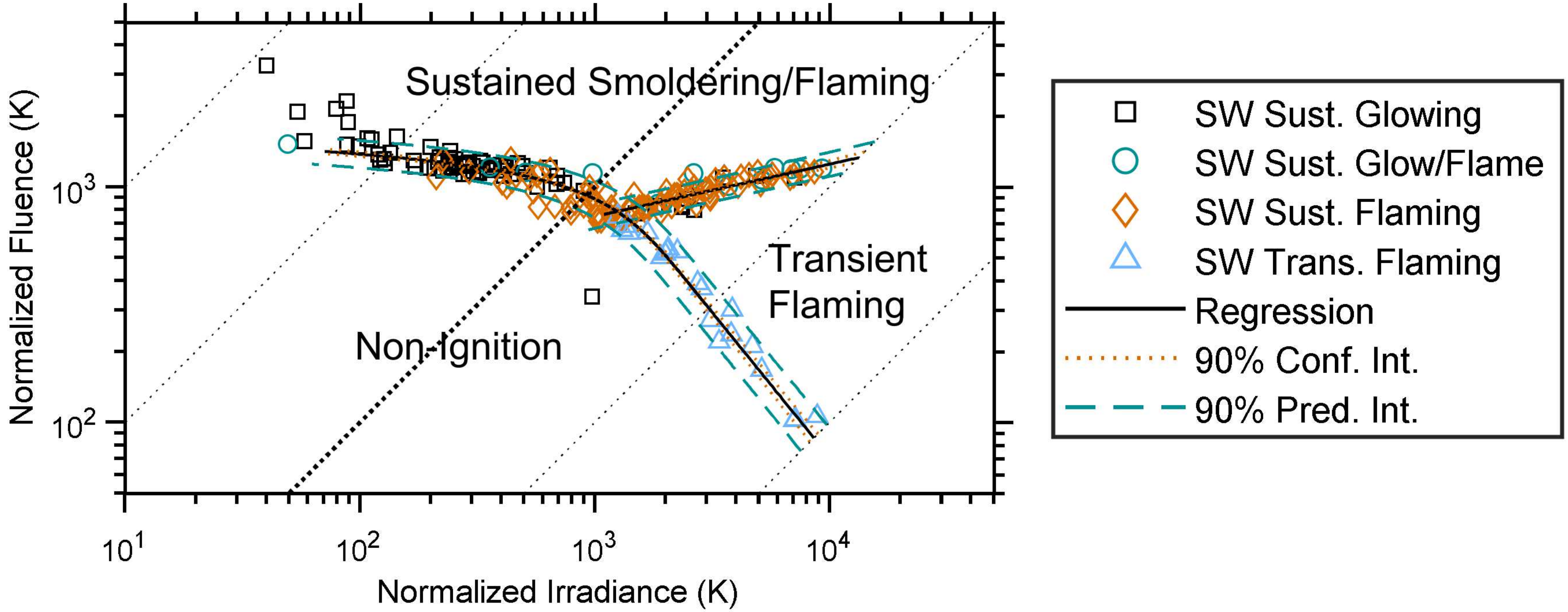
$$\log \Delta T_{th} = A_0 + A_1 \log Fo_{th}$$

$$A_0 = 3.090 \pm 0.16\%$$
$$A_1 = 0.052 \pm 14.3\%$$
$$R^2_{pred} = 0.517$$



Adding Correlations to the Ign. Map

- Returning to the ignition map, the correlation is transposed on the data.



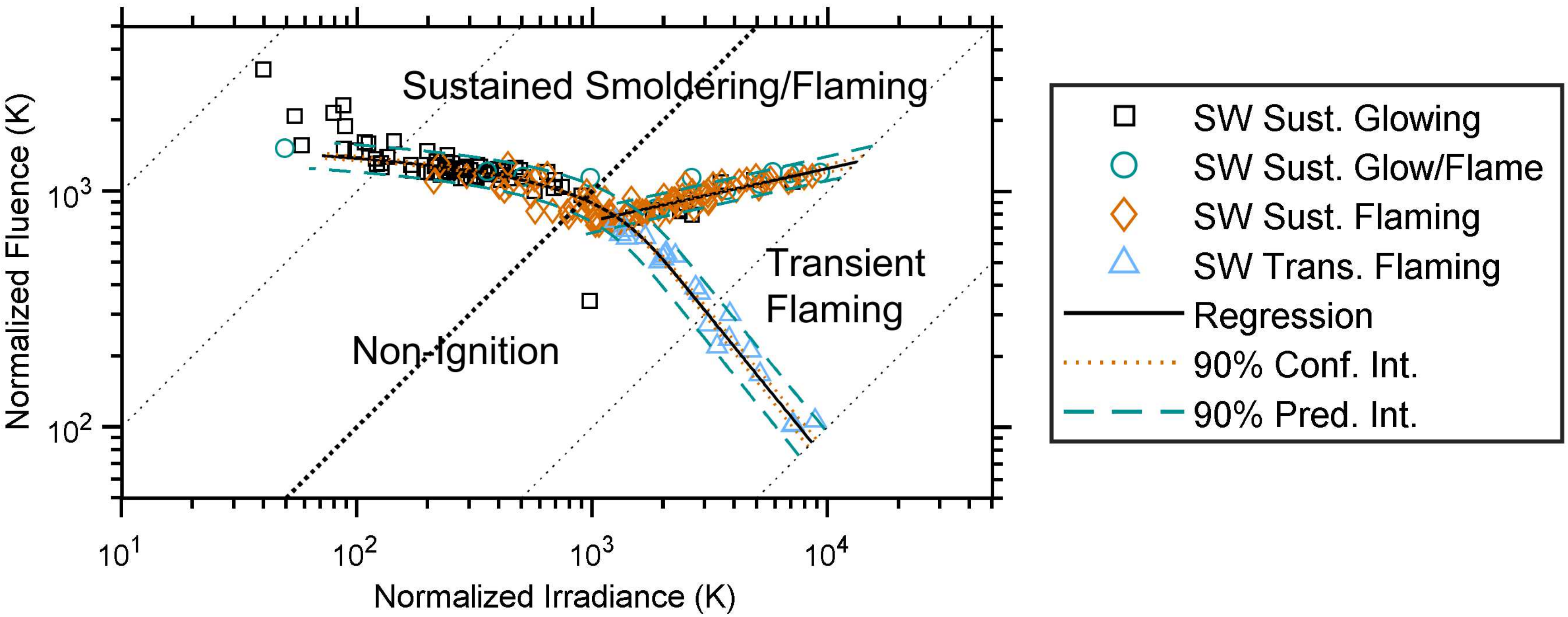
- The upper threshold is captured by a simple correlation:

$$\log Q^*_{th} = B_0 + B_1 \log Fo_{th}$$

$$B_0 = 2.84 \pm 1.1\%$$
$$B_1 = -0.286 \pm 20\%$$

Why Correlations?

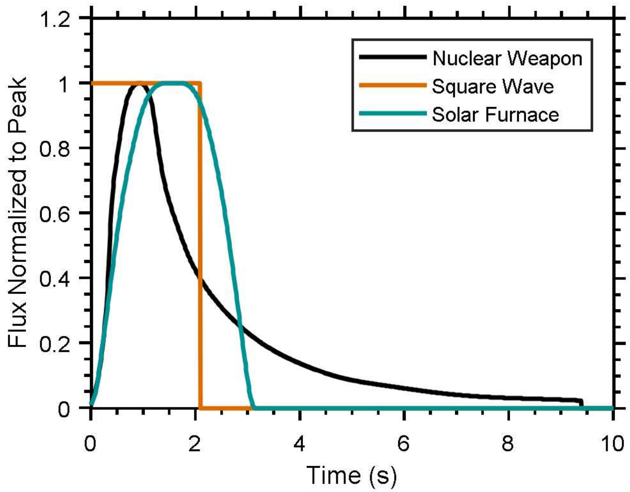
- These correlations are useful because:
  - **Predict** ignition mode (none, transient, or sustained).
  - Include **uncertainty quantification**.
  - Doesn't require 'visual inspection.'

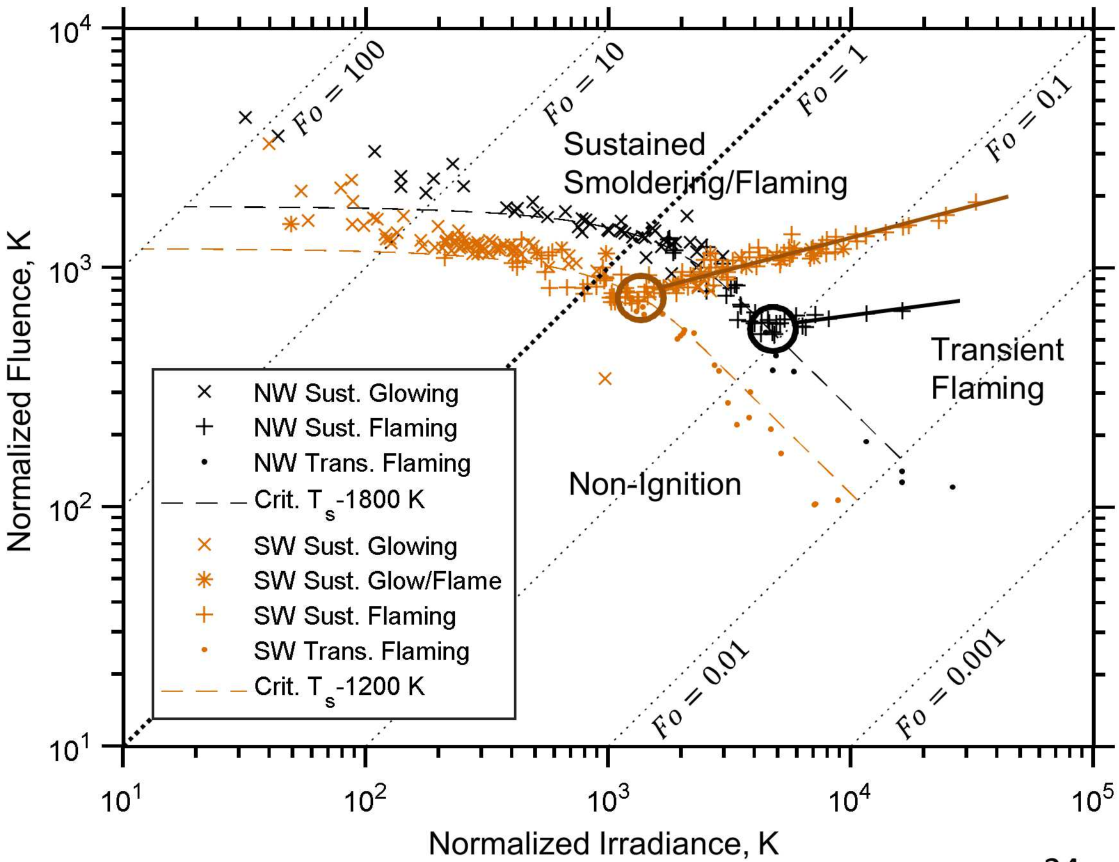


Effect of Exposure Shape

- Based on Martin's work, a **new ignition map** is required for every possible exposure shape.

How can we generate a 'unified' map?





Reducing Exposure Shape

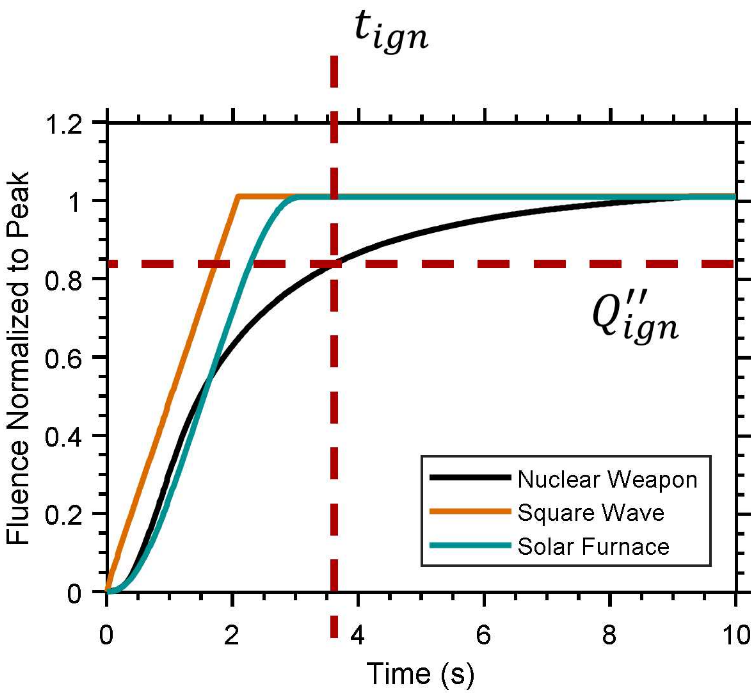
- Effect of exposure shape can be **reduced/eliminated** by:
  - Evaluate fluence at the **time of ignition**.

$$Q''_{ign} = \int_{t=0}^{t_{ign}} q''(t)dt$$

  - Fourier number at Ignition
    - Equivalent to **average flux**

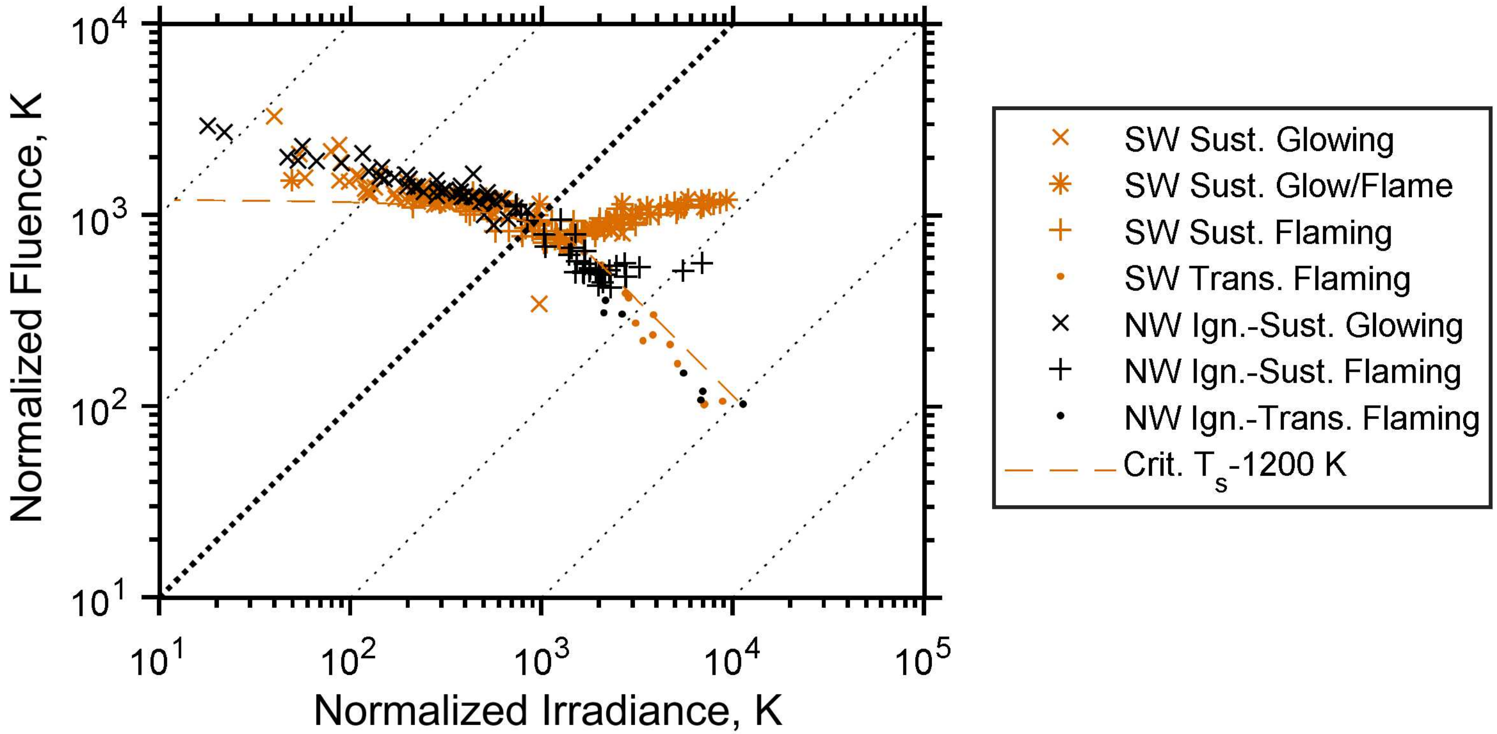
$$q^*_{ign} = Q^*_{ign}/Fo_{ign}$$

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



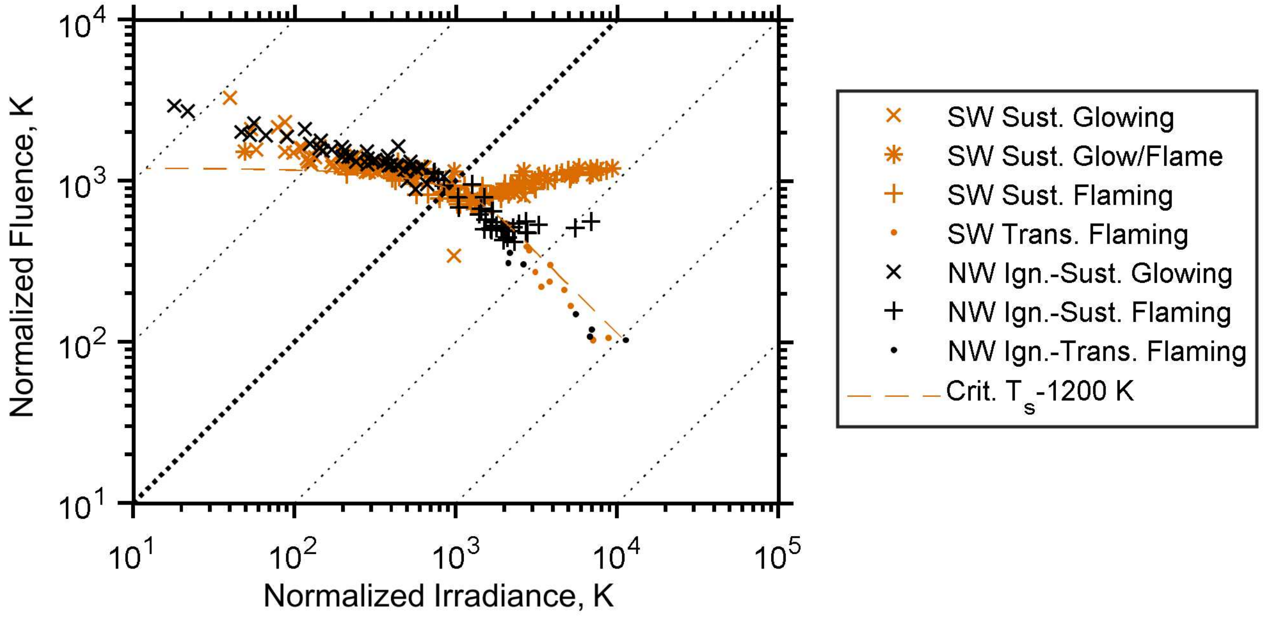
Reducing Exposure Shape

- Using the time-of-ignition quantities, the SW and NW data have reasonable agreement.
  - Lower thresholds align, but **upper threshold varies**.
  - Based on above, we can compare **lower thresh.** to **Solar Furnace** data.



Why Time of Ignition?

- The **time-of-ignition data** are incredibly useful because:
  - **Single ignition map** describes any radiation source (NW, SW, etc.)
    - Only lower threshold is the same. Upper threshold varies.
  - The map does NOT require **threshold** exposures!
    - Much more efficient then **staircase method** used in historical work.
  - We can use the developed correlation (SW) for any exposure shape.



Ignition Map: Other Materials

- Variables for **Empirical Models**:
  - **Every material** will have a **different ignition threshold!!**
    - For example, ignition of a **plastic** will (probably) **not align with cellulose**.
    - For the empirical model, **a new ignition map** must be generated for **every** material of interest.
  - Might be able to **tune parameters** in critical surface temp. rise model

$$\log Q_{th}^{*} = A_0 + A_1 \log Fo_{th} + \log f(Fo_{th})$$

    - However, the **validity of this model must be demonstrated** as the coefficients are generated.
    - For relevant materials, we can **generate a look-up table.**

Material	A_0	A_1
Cellulose (black)	3.09 ± 0.16%	0.0523 ± 14.3%
Polystyrene	?	?
Wood	?	?

Conclusions

- Ignition map neglects a variety of physics, with reasonable success.
- The lower and upper thresholds can be described by **simple correlations**, with uncertainty quantification.
- The effect of **exposure shape** can be reduced by basing the ignition maps on **time-of-ignition data**.
- Data from related work indicate ignition map is perhaps extensible to other materials.

Acknowledgements

- 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.
- Tests were conducted with the help of the team of technologists at the National Solar Thermal Test Facility.
- Student support from Jeff LaRocco, Noah Siegel, and Bobby Thomas was also key to the success of the test programs.
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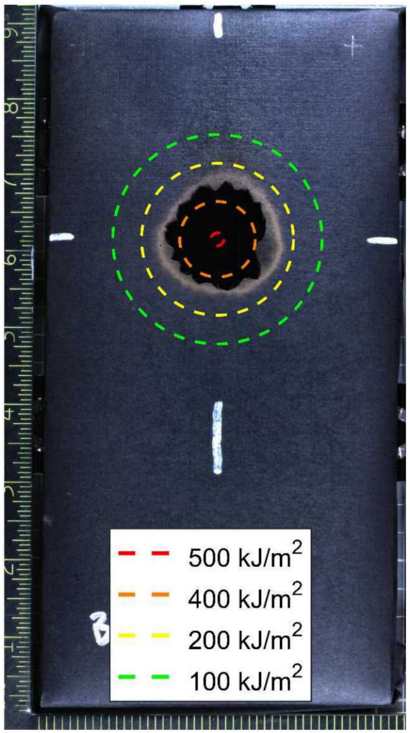
- Graphite papers and cellulose pulp provided by Alan Rudie (Forest Products Laboratories)
- Programmatic support from Jon Rogers (SNL), and the Defense Threat Reduction Agency (DTRA) is appreciated.

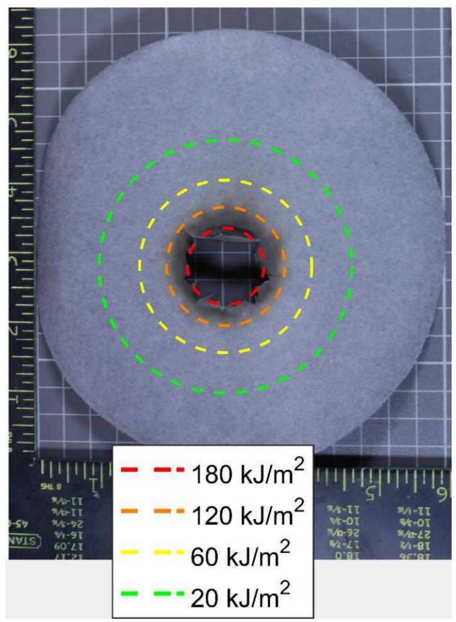
Ignition Map: Papers

- Four types of paper were tested at the Solar Furnace

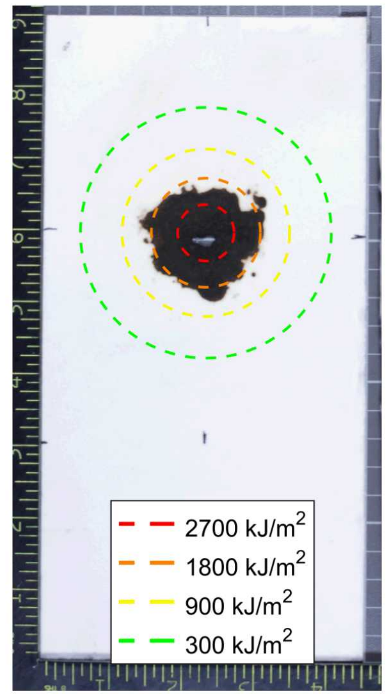
Black Poster Board



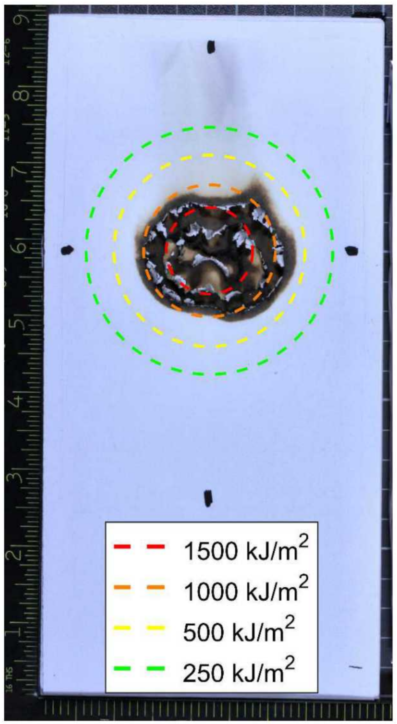
α-Cellulose Paper w/ Graph. Powder



α-Cellulose Pulp

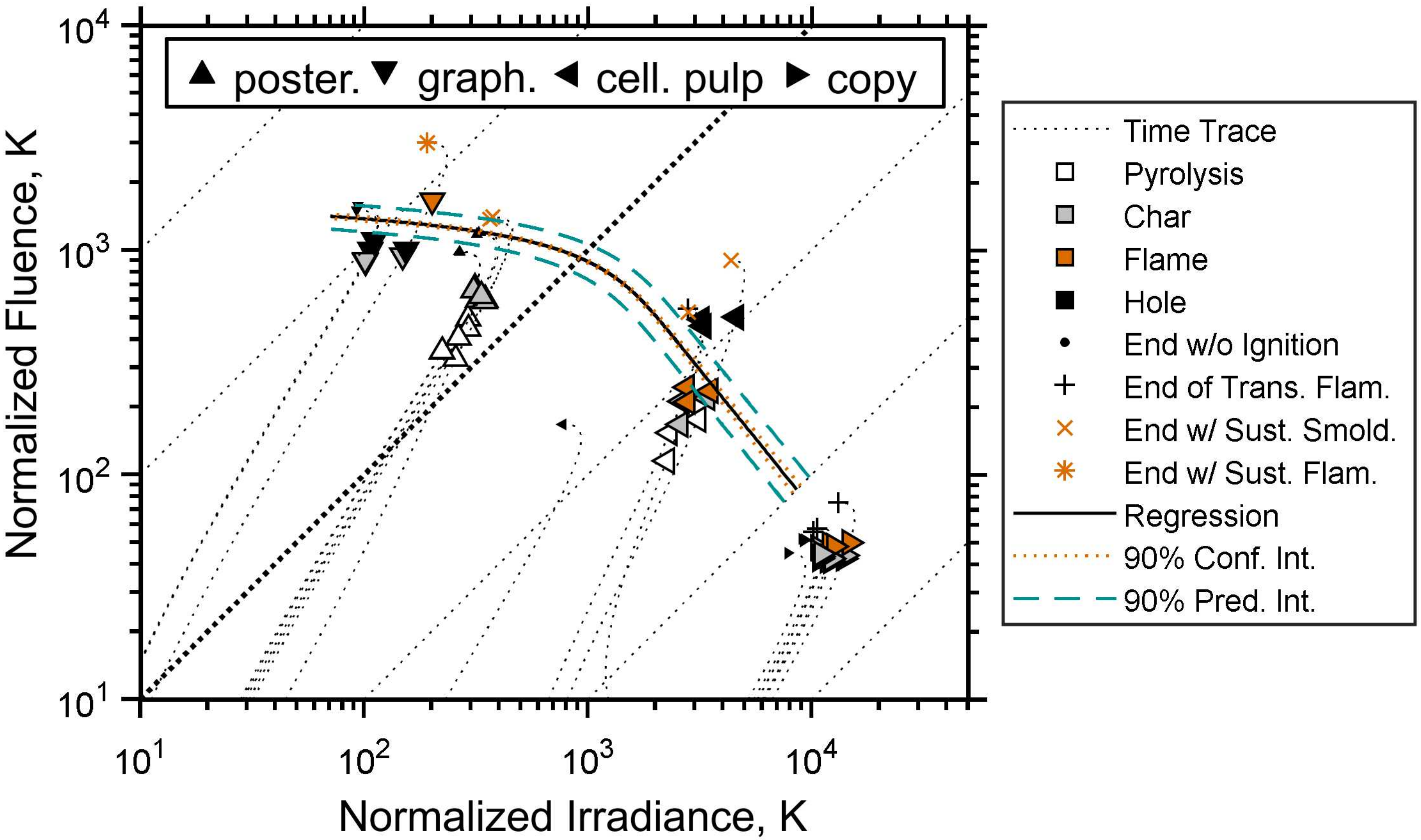


Copy Paper



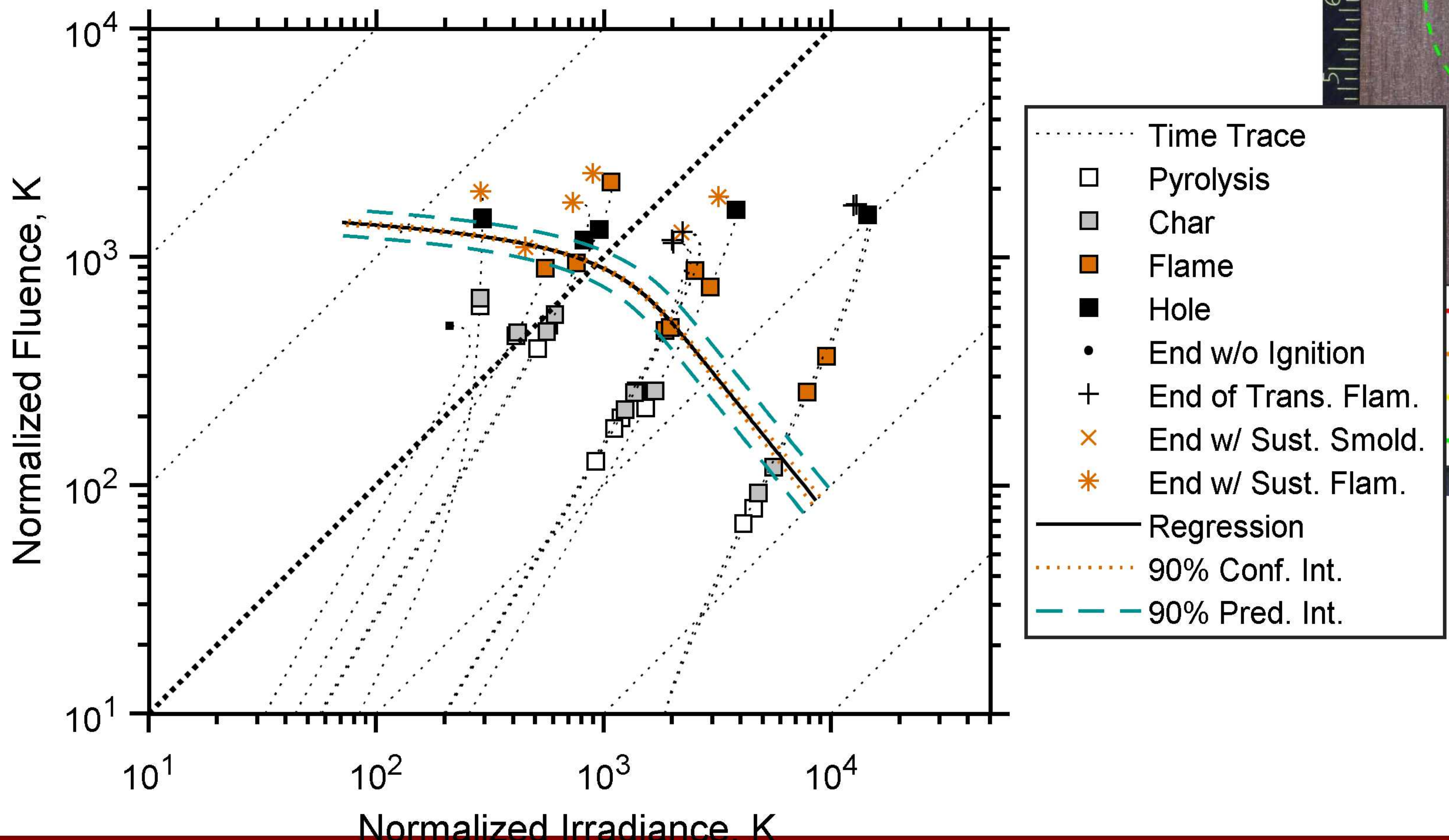
Ignition Map: Papers

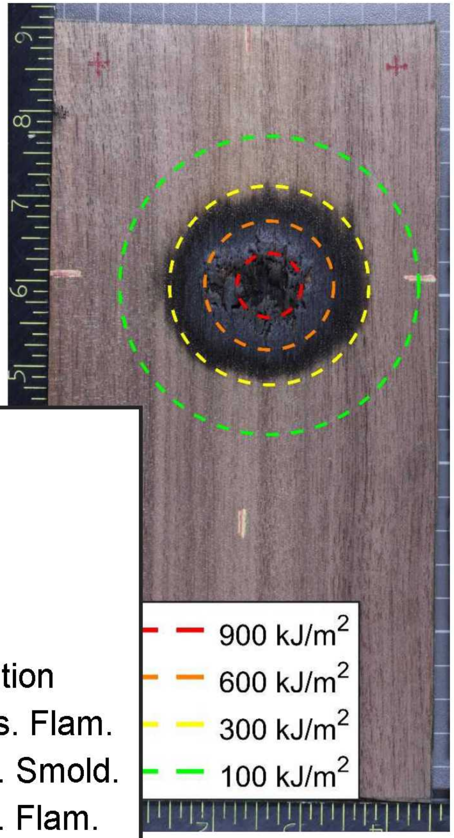
- All papers align reasonably well with ignition map
- Data are insufficient for examining upper threshold.



Ignition Map: Walnut Veneer

- Map extends reasonably well to wood?





Ignition Map: High-Impact Polystyrene

- Polystyrene has similar trend, but higher threshold