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Measuring the Fire Growth Potential of a Combustible Solid in the Cone Calorimeter*

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Objective

Determine the Full-Scale Fire Hazard of a Combustible Material From a Single Cone Calorimeter Experiment

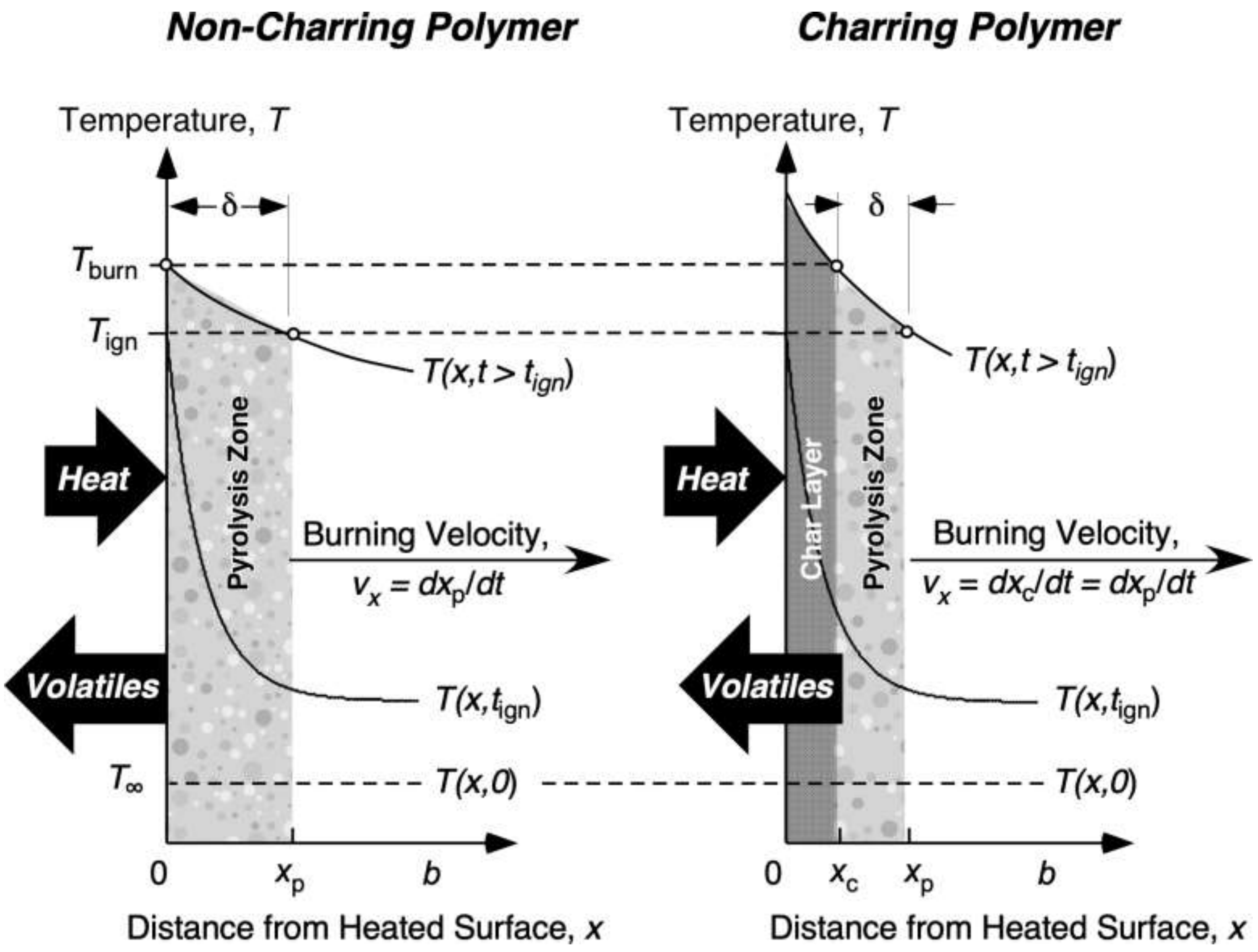
Hypothesis

Fire Growth of a Combustible Solid is a Continuous and Coupled Process of Ignition and Burning

Approach

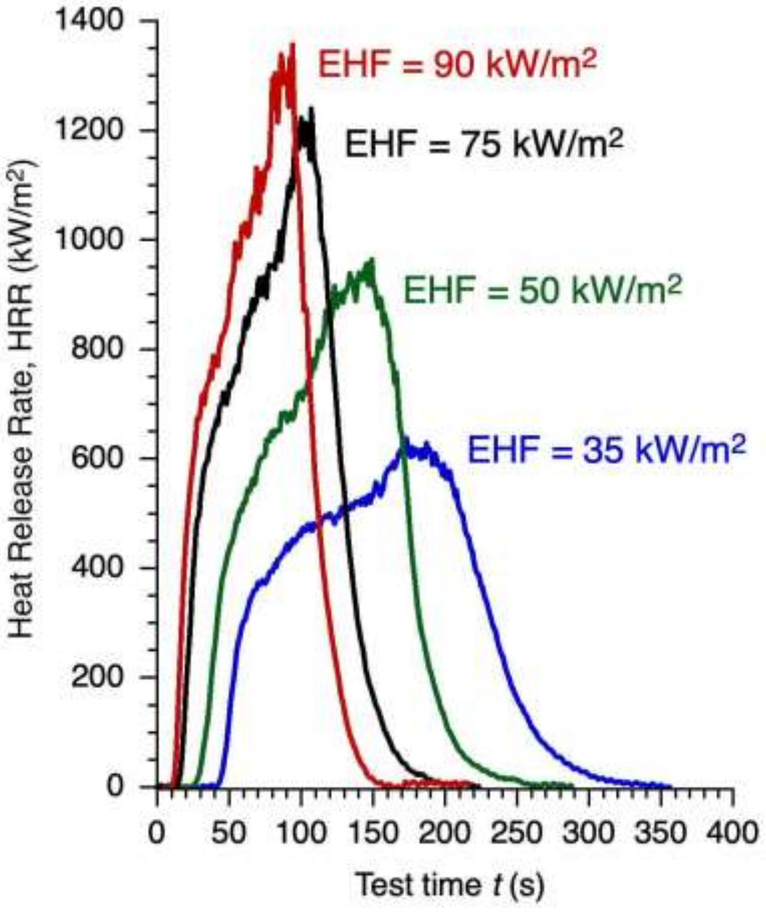
- Parameterize Cone Test Data
- Define Physically-Based Fire Growth Parameters
- Compare Fire Growth Parameters to Fire Test Results

The 1-D Burning Process (e.g., in the Cone Calorimeter)



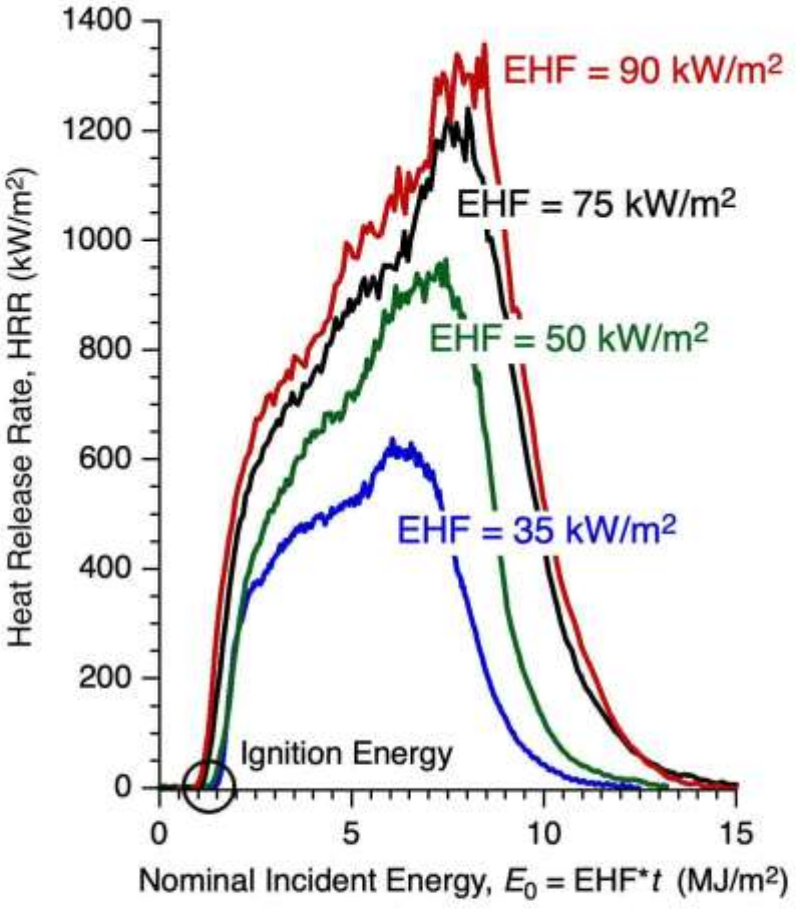
Metrology

Heat Release Rate History
(3 mm black PMMA)



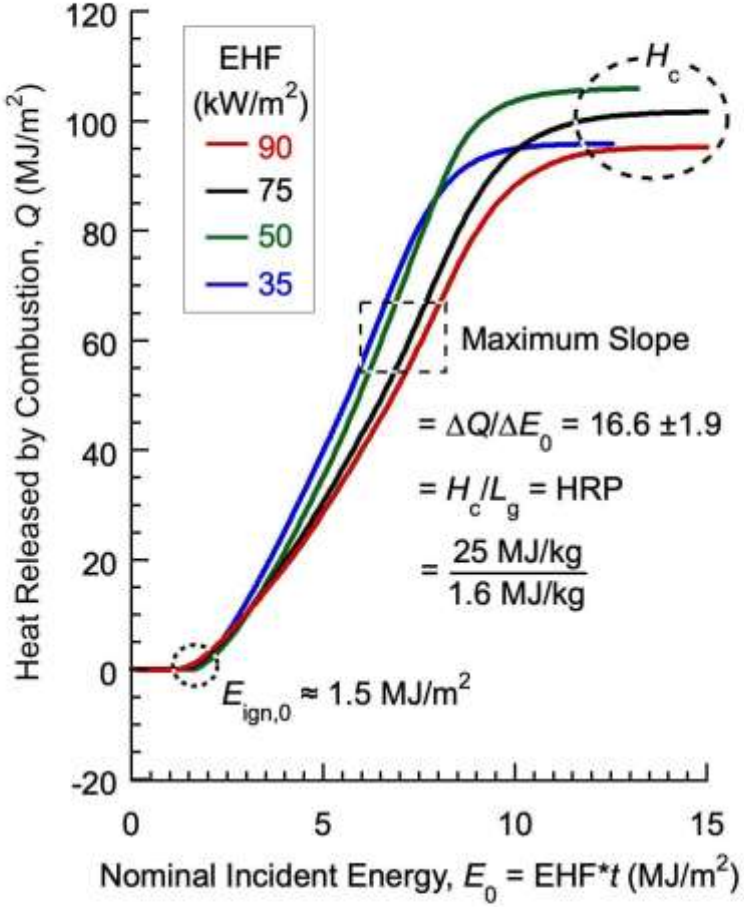
Peak HRR (PHRR)

Synchronize HRR to Incident Energy



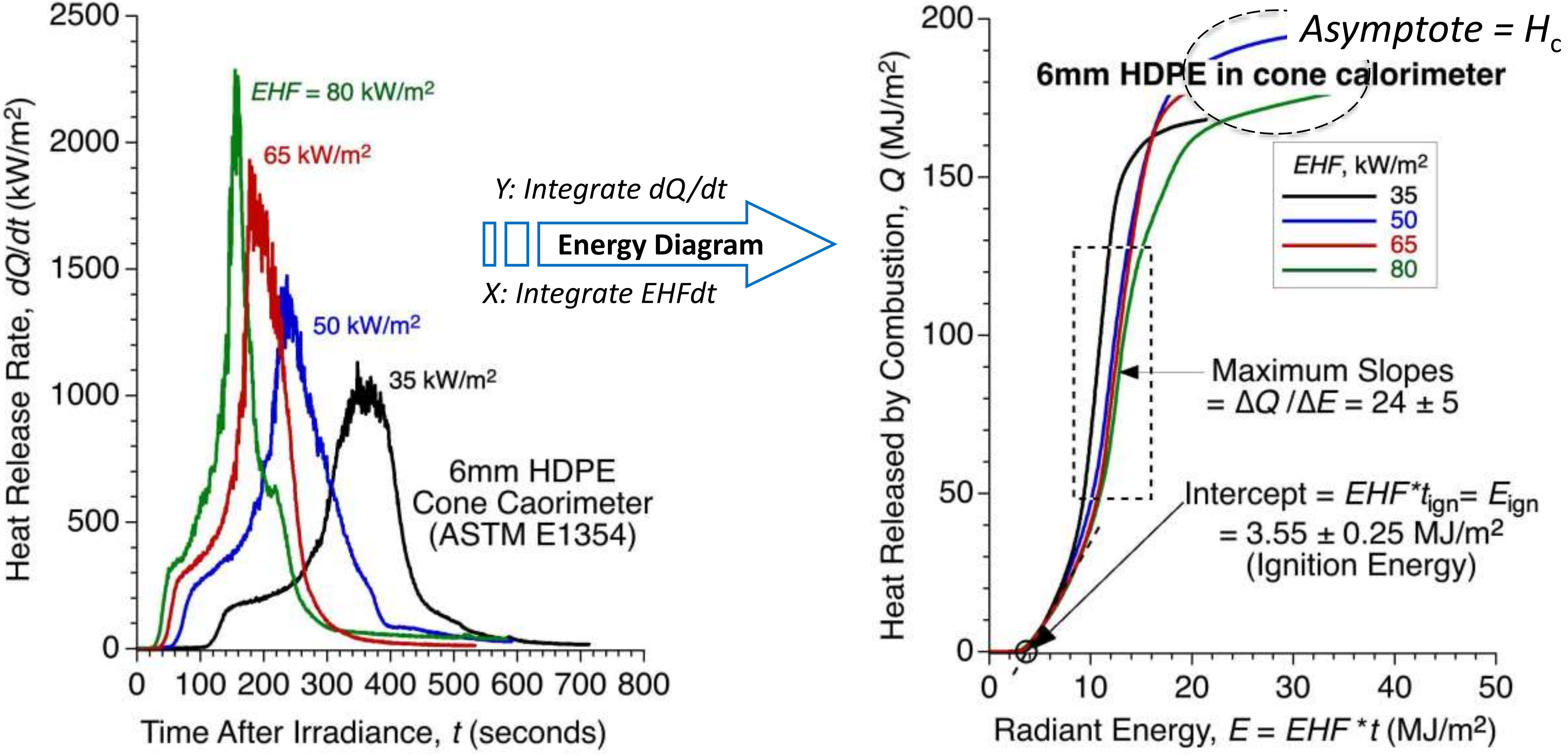
Nominal Ignition Energy ($E_{ign,0}$)

Create and Analyze Energy (NRG) Diagram

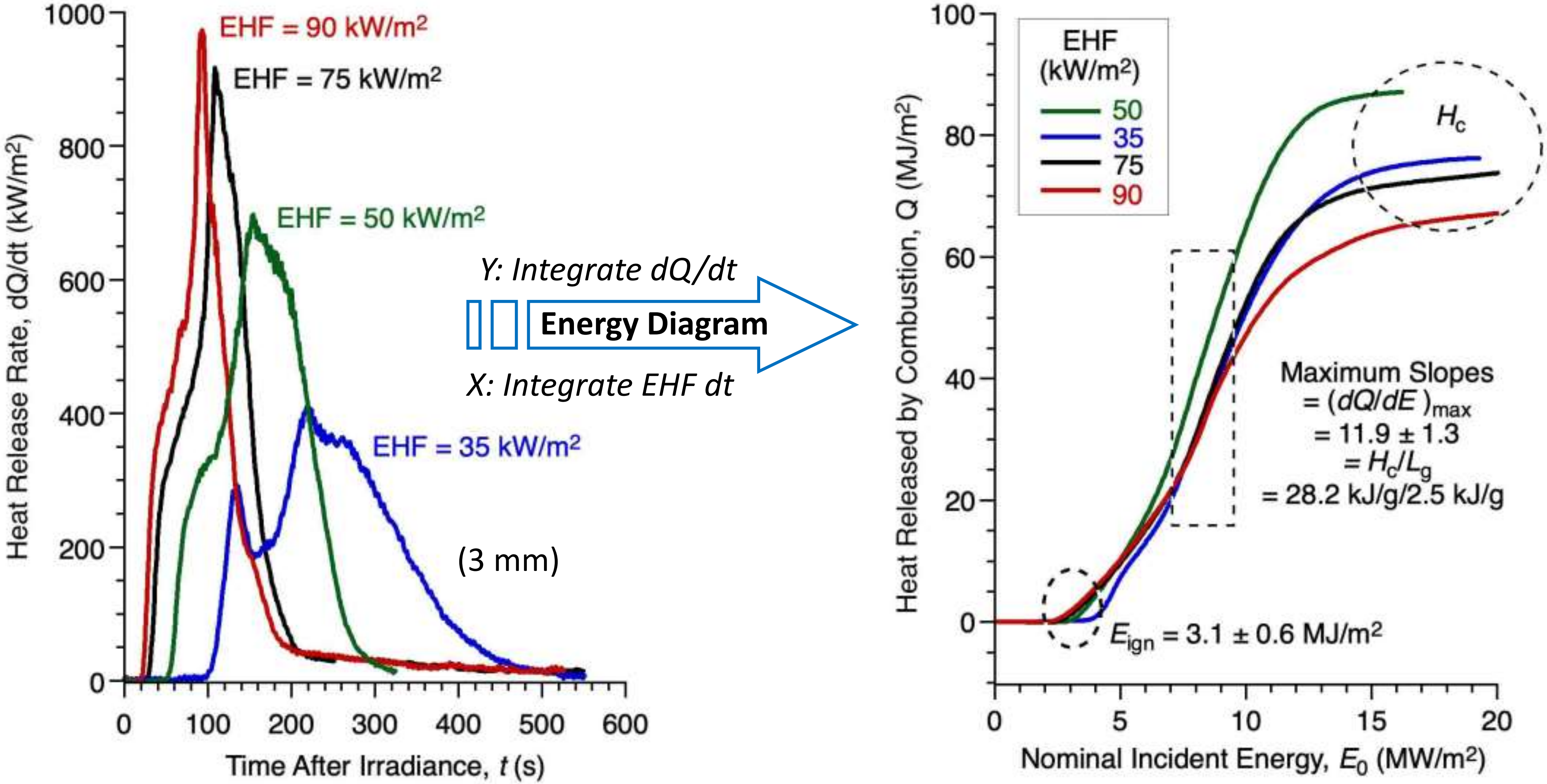


Heat Release Parameter (HRP)
Total Heat Release (THR)

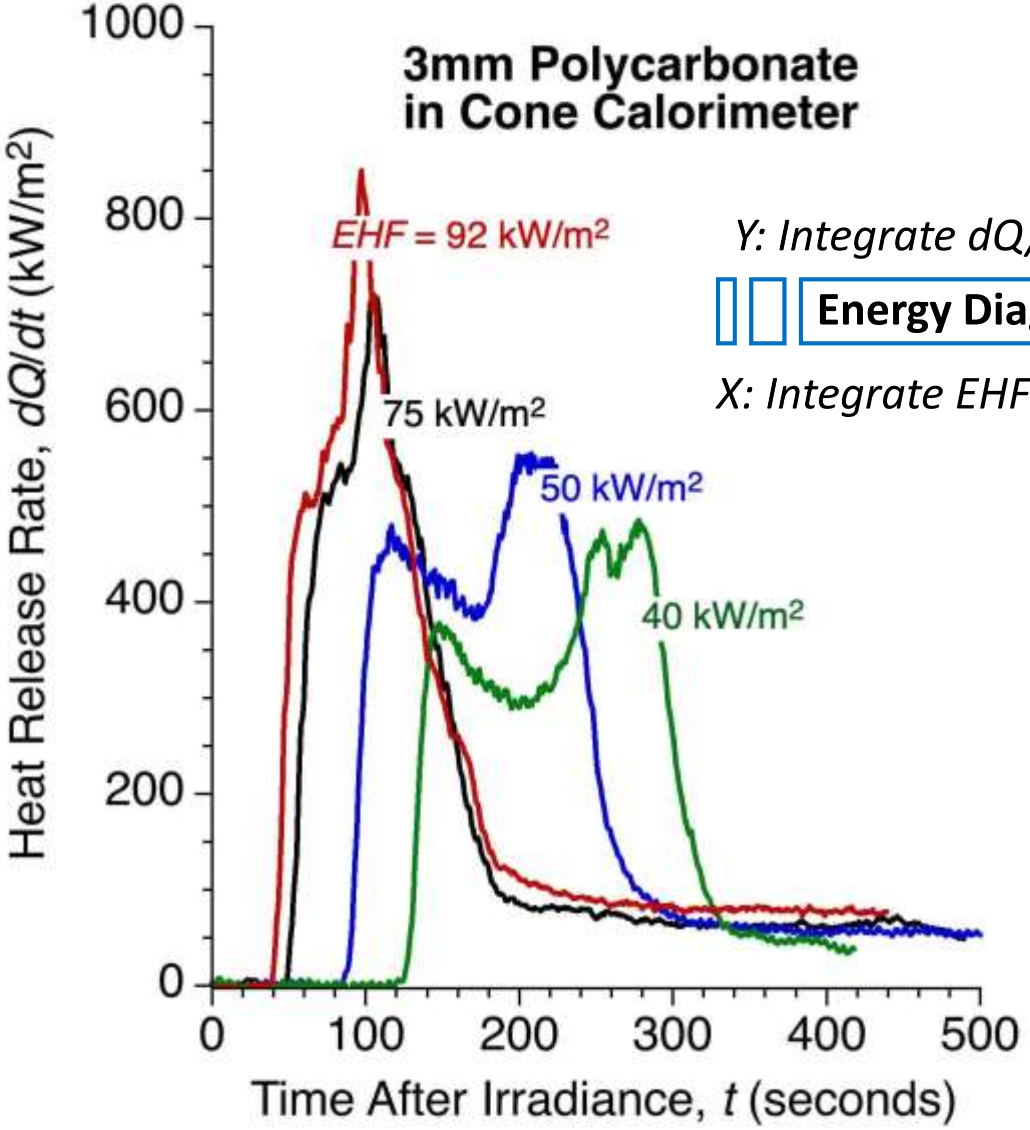
Energy Diagram for High Density Polyethylene (HDPE)



Energy Diagram for Nylon 66 (PA66)



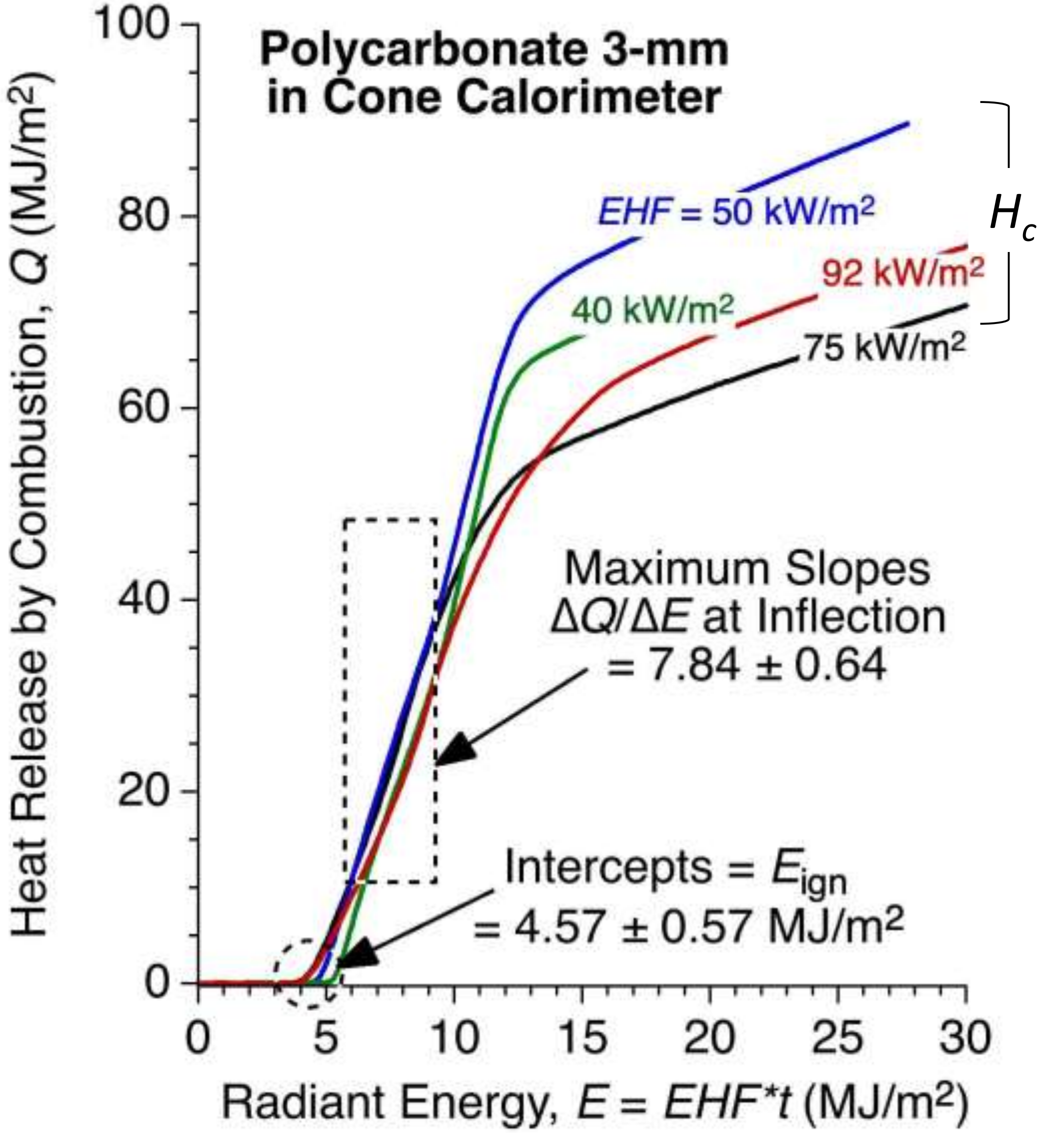
Energy Diagram for Polycarbonate of Bisphenol-A (PC)



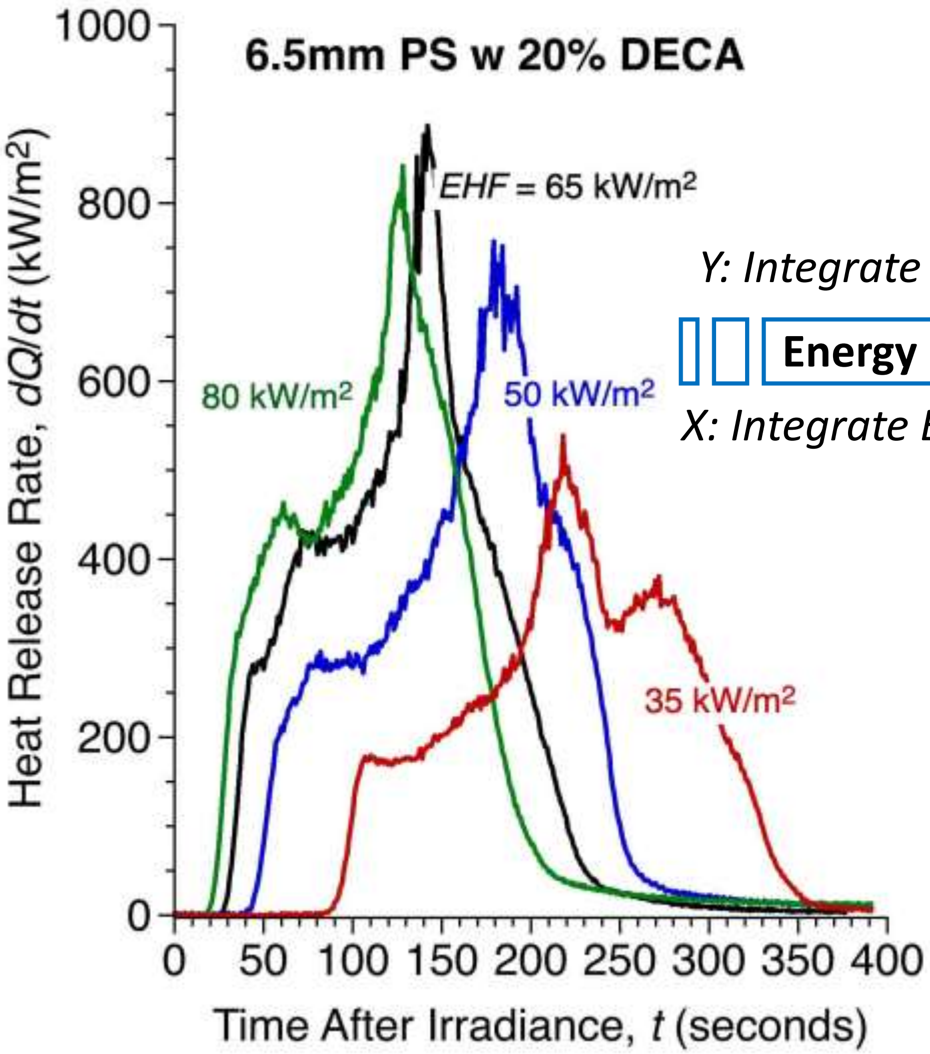
Y: Integrate dQ/dt

Energy Diagram

X: Integrate EHF dt



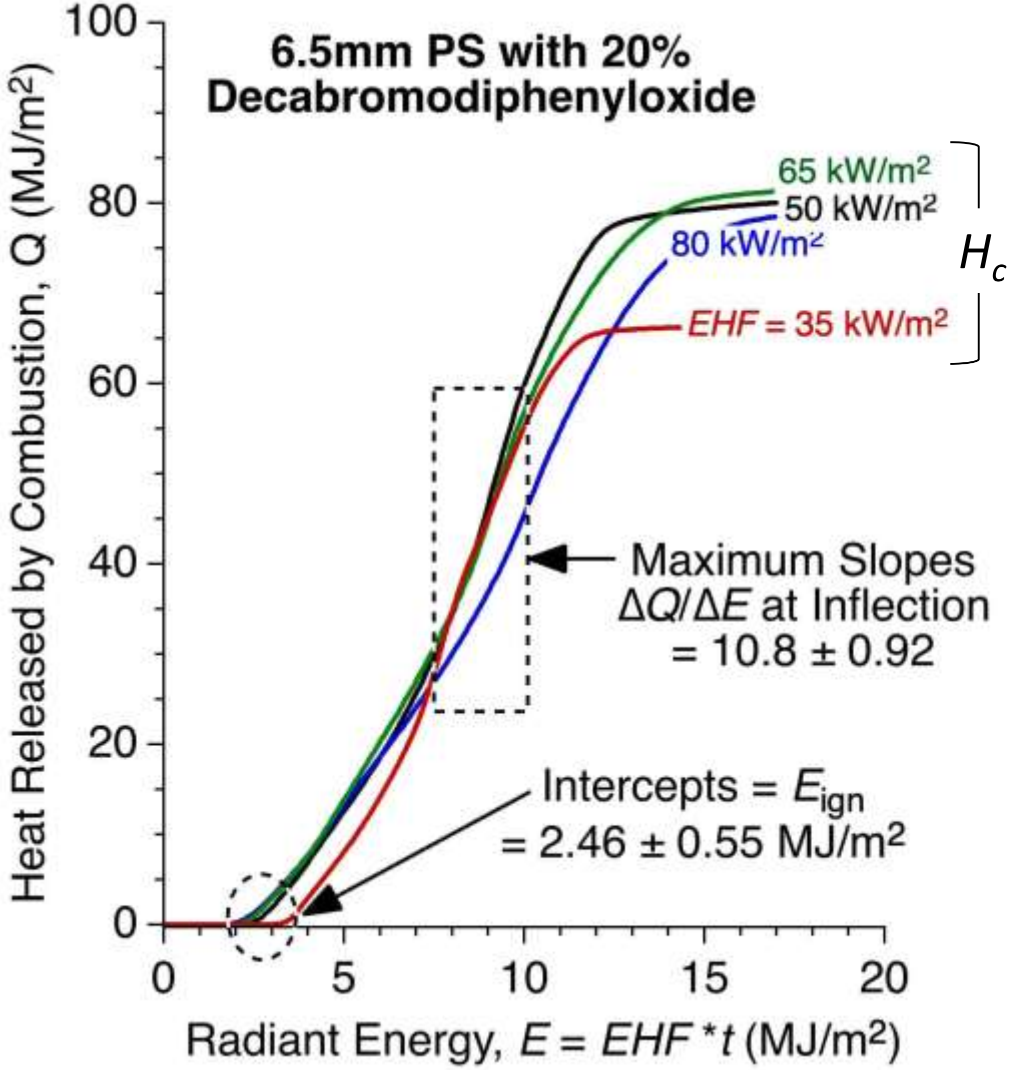
Energy Diagram for Fire Retardant Polystyrene (PS FR)



Y: Integrate dQ/dt

Energy Diagram

X: Integrate EHF dt



Available from Standard Cone Calorimeter Experiments

Physical Quantity	Engineering Notation	Acronym
External Heat Flux/Irradiance (kW/m^2)	$\dot{q}''_{ext}$	EHF
Time to Piloted Ignition (s)	t_{ign}	TTI
Nominal Ignition Energy (MJ/m^2)	$\dot{q}''_{ext} t_{ign}$	E_{ign}
Peak Heat Release Rate (kW/m^2)	$\dot{Q}''_{max}$	PHRR
Test Average Heat Release Rate (kW/m^2)	$\dot{Q}''_{avg}$	$\mathrm{HRR}_{\mathrm{avg}}$
Heat of Combustion/Fire Load (MJ/m^2)	H''_c	H_{c}
Sample Thickness (m)	b	b

Calculate Fire Growth Potential λ from Energy Diagram

Slope

$$\boldsymbol{\lambda = \left(\frac{1}{E_{ign}}\right)\left(\frac{\Delta Q}{\Delta E}\right) \approx \left(\frac{1}{\dot{q}''_{ext} t_{ign}}\right)\left(\frac{\dot{Q}''_{max}}{\dot{q}''_{ext}}\right) = \frac{PHRR/TTI}{EHF^2}} \quad , \quad \frac{m^2}{MJ}$$

Intercept

$$EHF = External\ Heat\ Flux = \dot{q}''_{ext}\ (MW/m^2)$$

$$TTI = Time\ to\ Ignition = t_{ign}\ (s)$$

$$PHRR = Peak\ Heat\ Release\ Rate = \dot{Q}''_{c,max}\ (MW/m^2)$$

Calculate Product Fire Hazard, Π from λ and H_c

$$\boldsymbol{\Pi = \lambda H_c = \frac{PHRR/TTI}{EHF^2} H_c}\ , \qquad \frac{\cancel{m^2}}{\cancel{MJ}} * \frac{\cancel{MJ}}{\cancel{m^2}} = Dimensionless$$

Asymptote

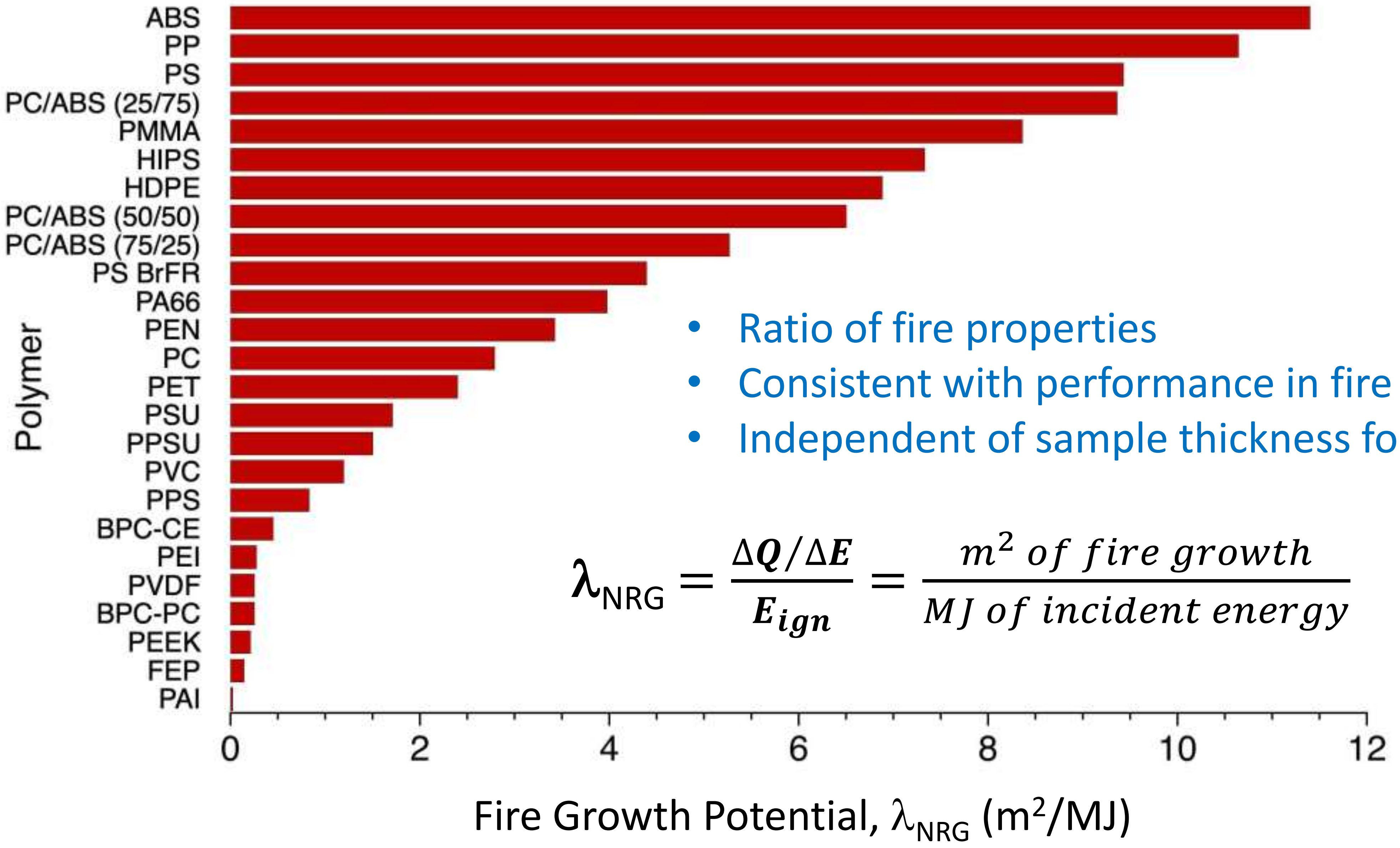
$$H_c = Areal\ Heat\ of\ Combustion = \int_0^\infty \dot{Q}_c''(t)dt\,, \quad \text{MJ/m}^2$$

Calculate Material Fire Hazard, π from λ and $H_{c,v}$

$$\pi = \lambda H_{c,v} = \frac{\Pi}{b}\,, \quad m^{-1}$$

$H_{c,v}$ = Volumetric Heat of Combustion, MJ/m^3; b = Sample Thickness, m

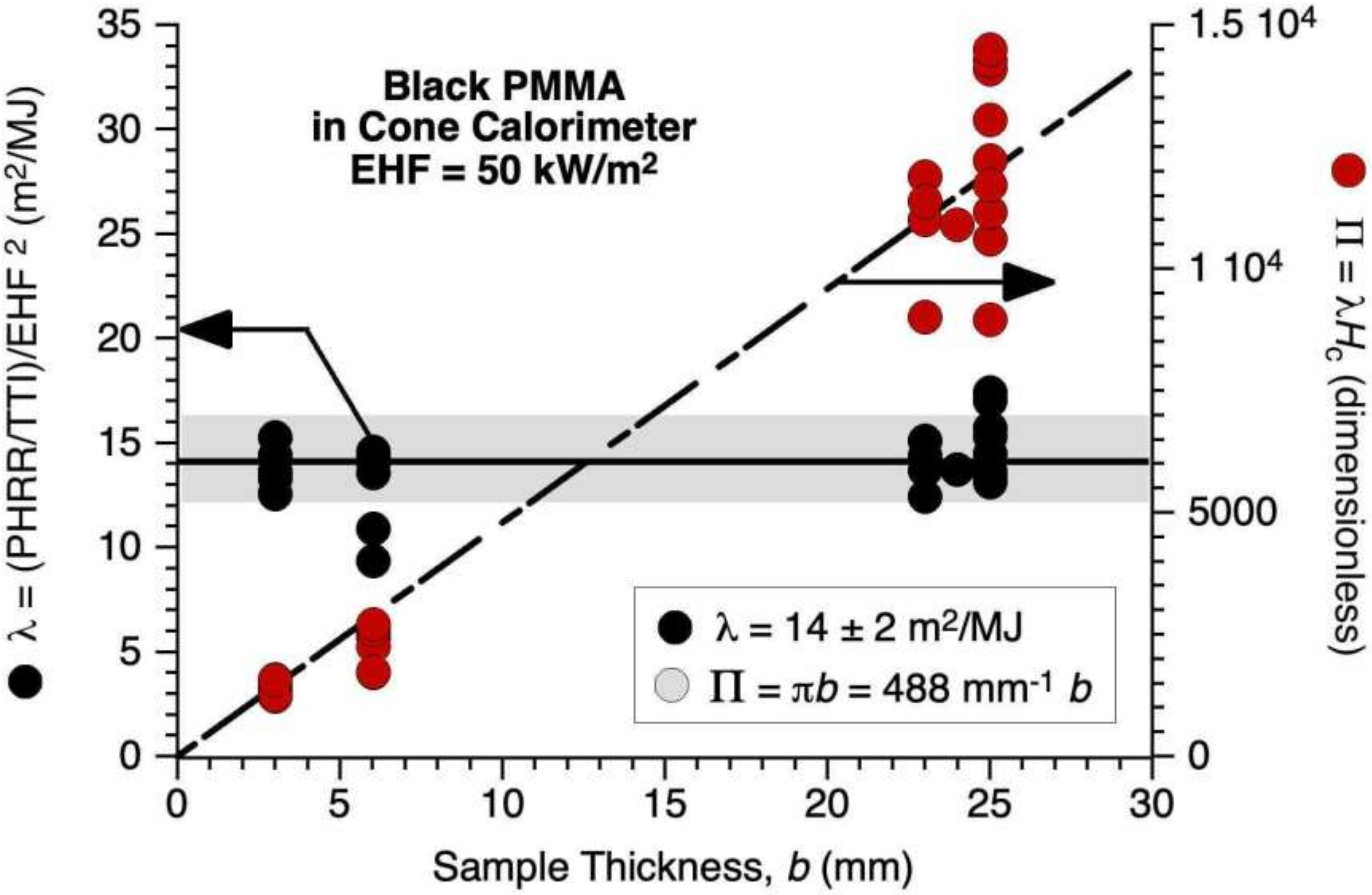
Fire Growth Potential λ_{NRG} From Energy Diagrams



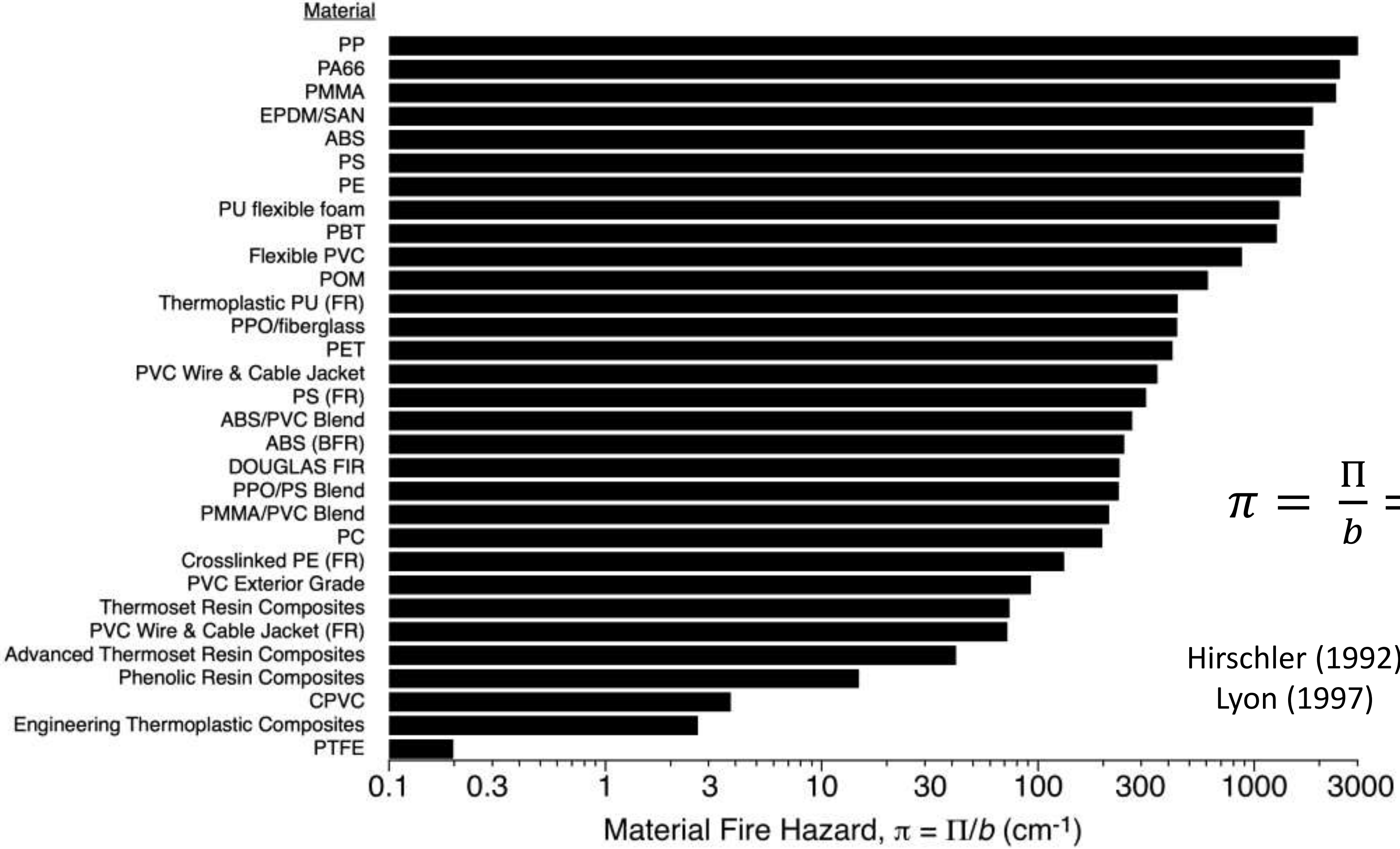
- Ratio of fire properties
- Consistent with performance in fire tests
- Independent of sample thickness for $\delta << b$

$$\lambda_{NRG} = \frac{\Delta \boldsymbol{Q}/\Delta \boldsymbol{E}}{\boldsymbol{E_{ign}}} = \frac{m^2 \; of \; fire \; growth}{MJ \; of \; incident \; energy}$$

λ Is Independent of Sample Thickness, but Π is Proportional to Thickness



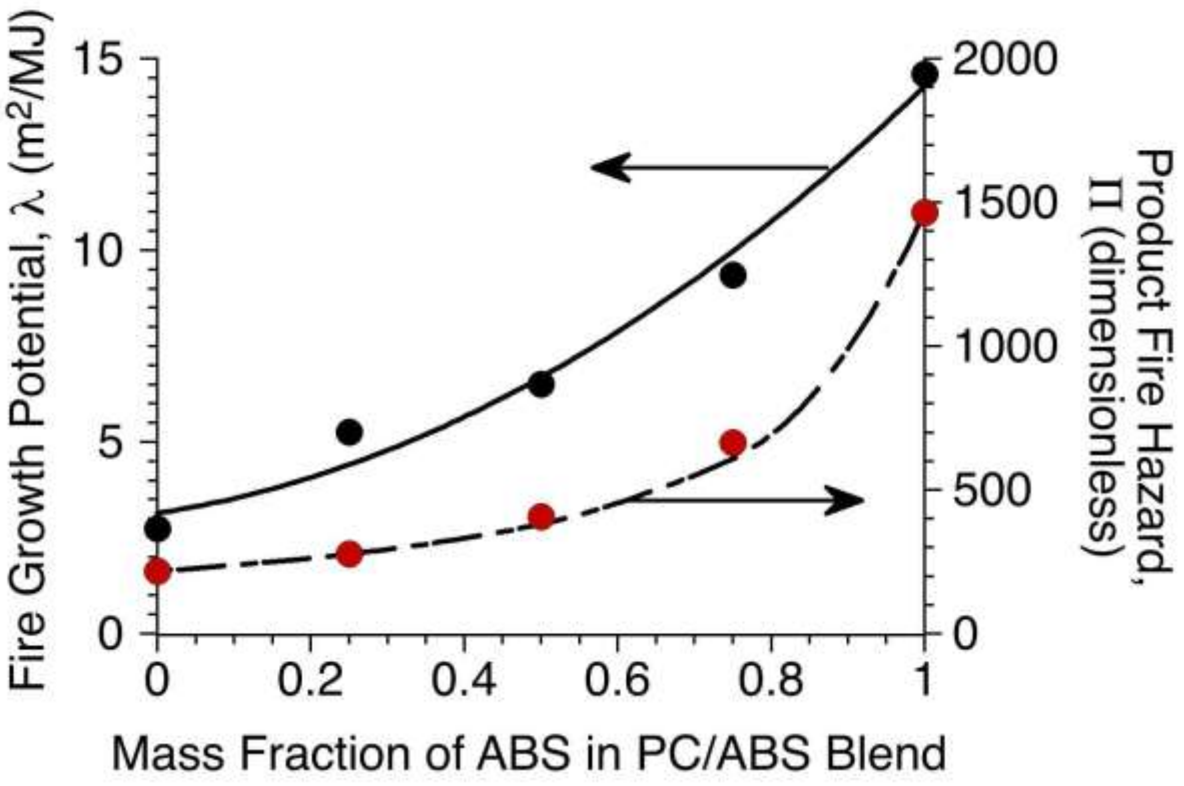
Material Fire Hazard From Published Cone Data

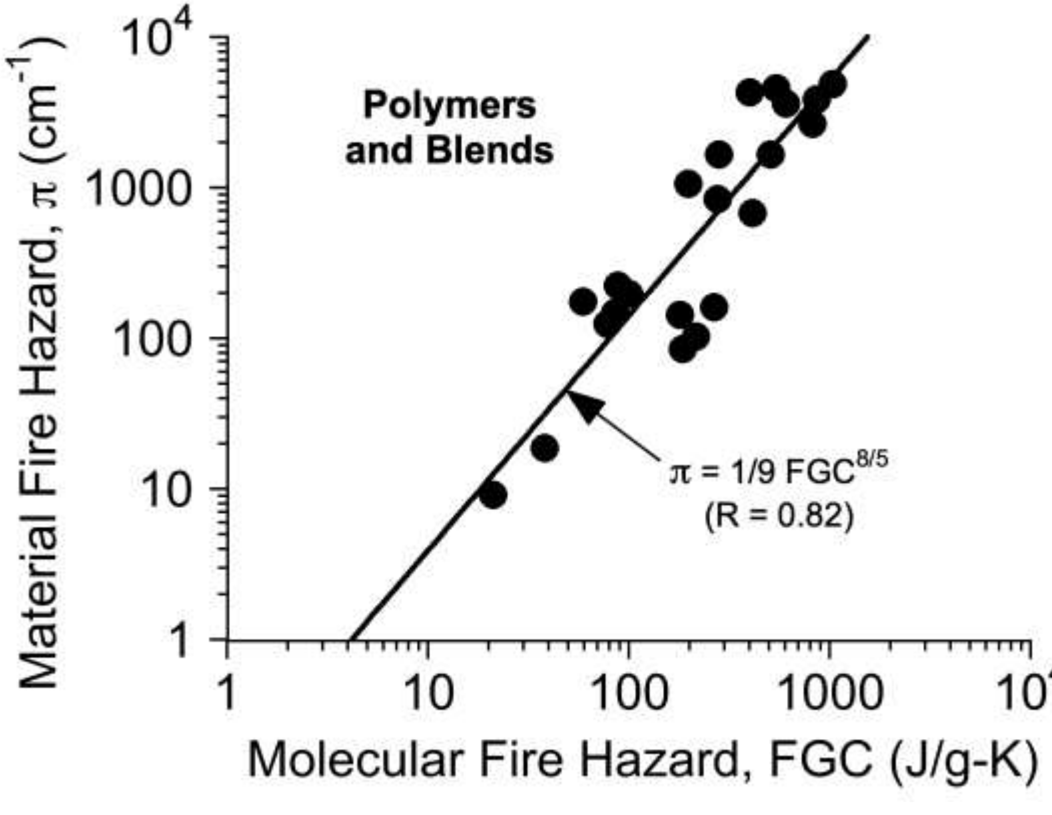


$$\pi = \frac{\Pi}{b} = \frac{\lambda_{max} H_c}{b}$$

Hirschler (1992)
Lyon (1997)

Fire Hazard at Bench Scale (λ, Π and π) Correlates With Fire Hazard at the Molecular Scale (Chemical, FGC) …

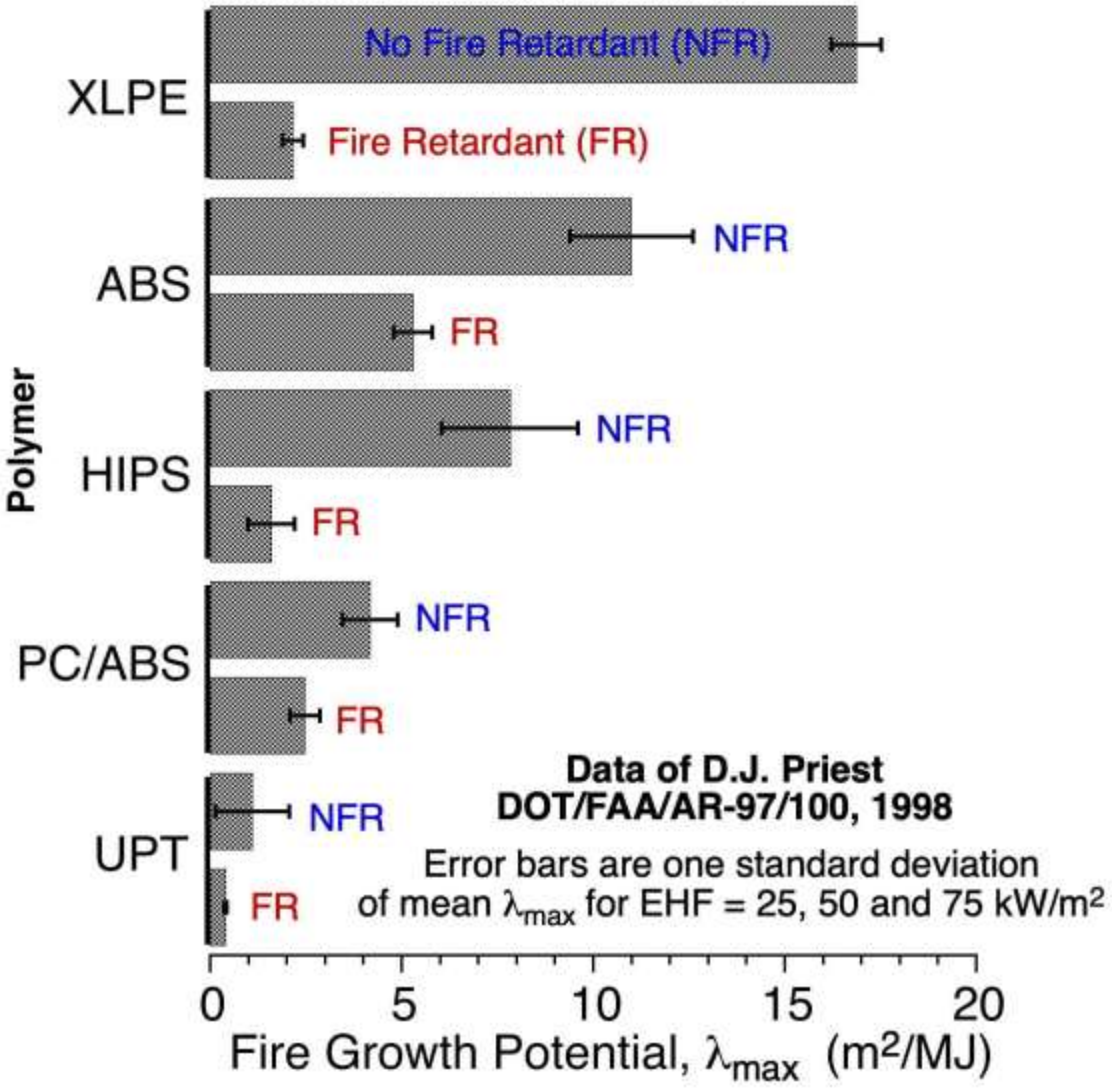




A Molecular Level Fire Growth Parameter, *Polymer Degradation and Stability*, 186, 109478 (2021)

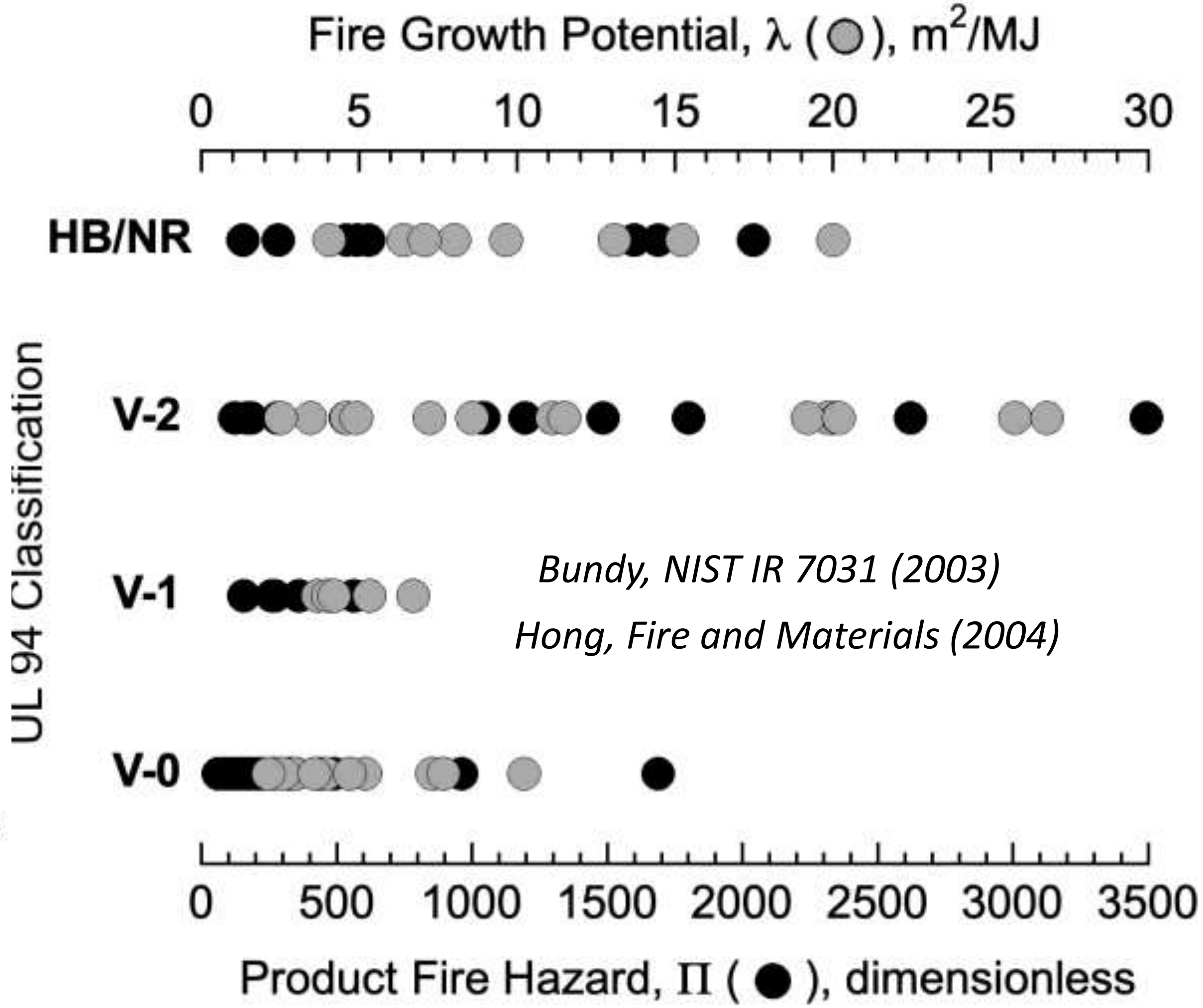
… but What About Small- and Full-Scale?

λ is Consistent With Flame Test Results *Within* Chemical Types

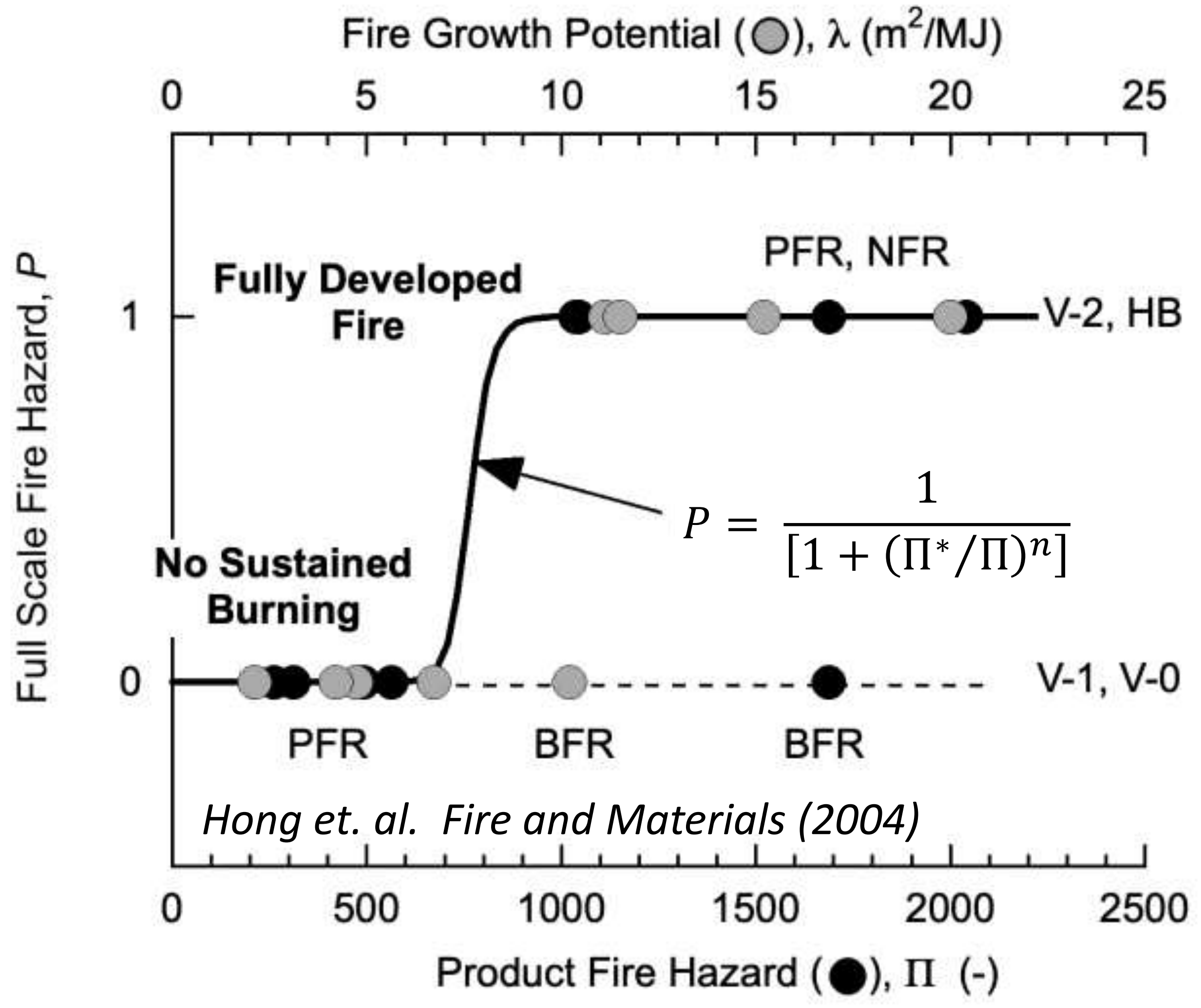


λ, Π are Inconsistent With Flame Test Results *Between* Chemical Types

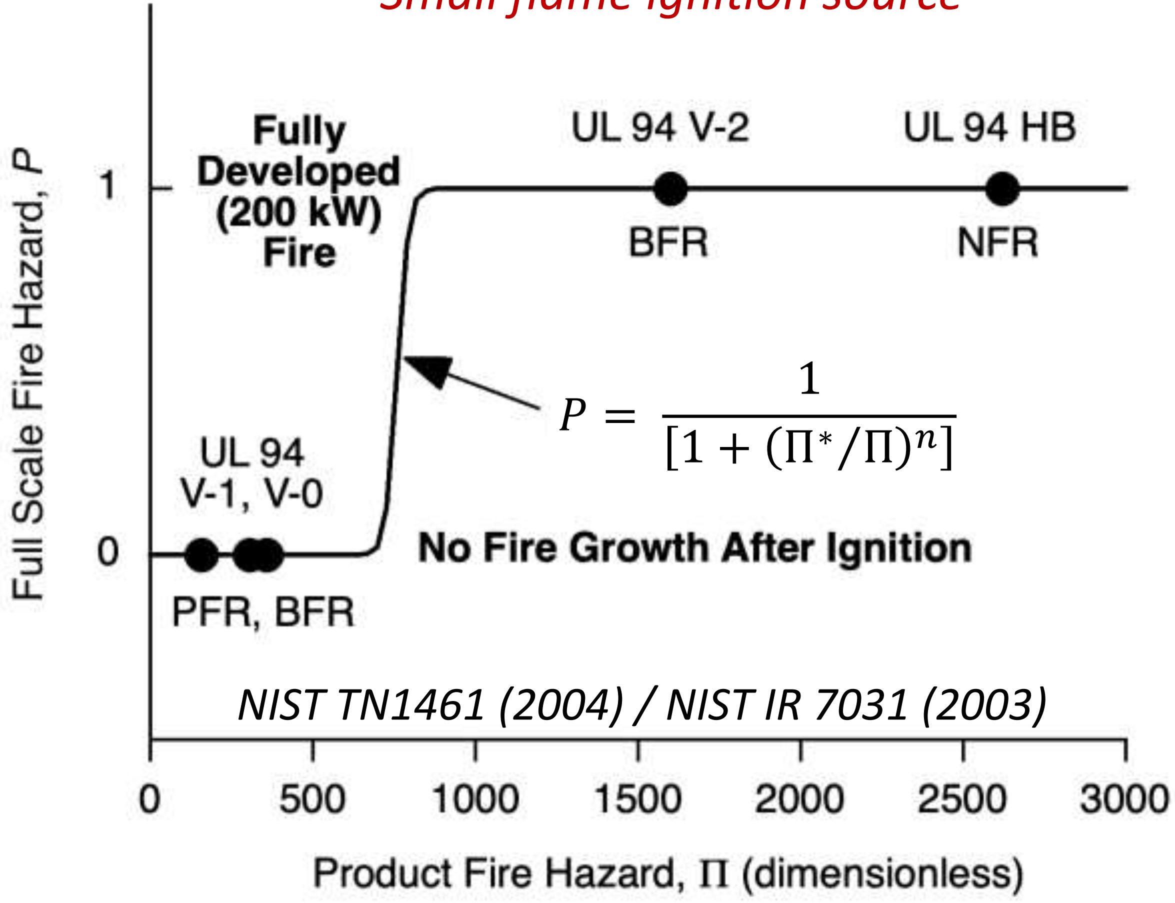
(*Because of Physical Effects*)



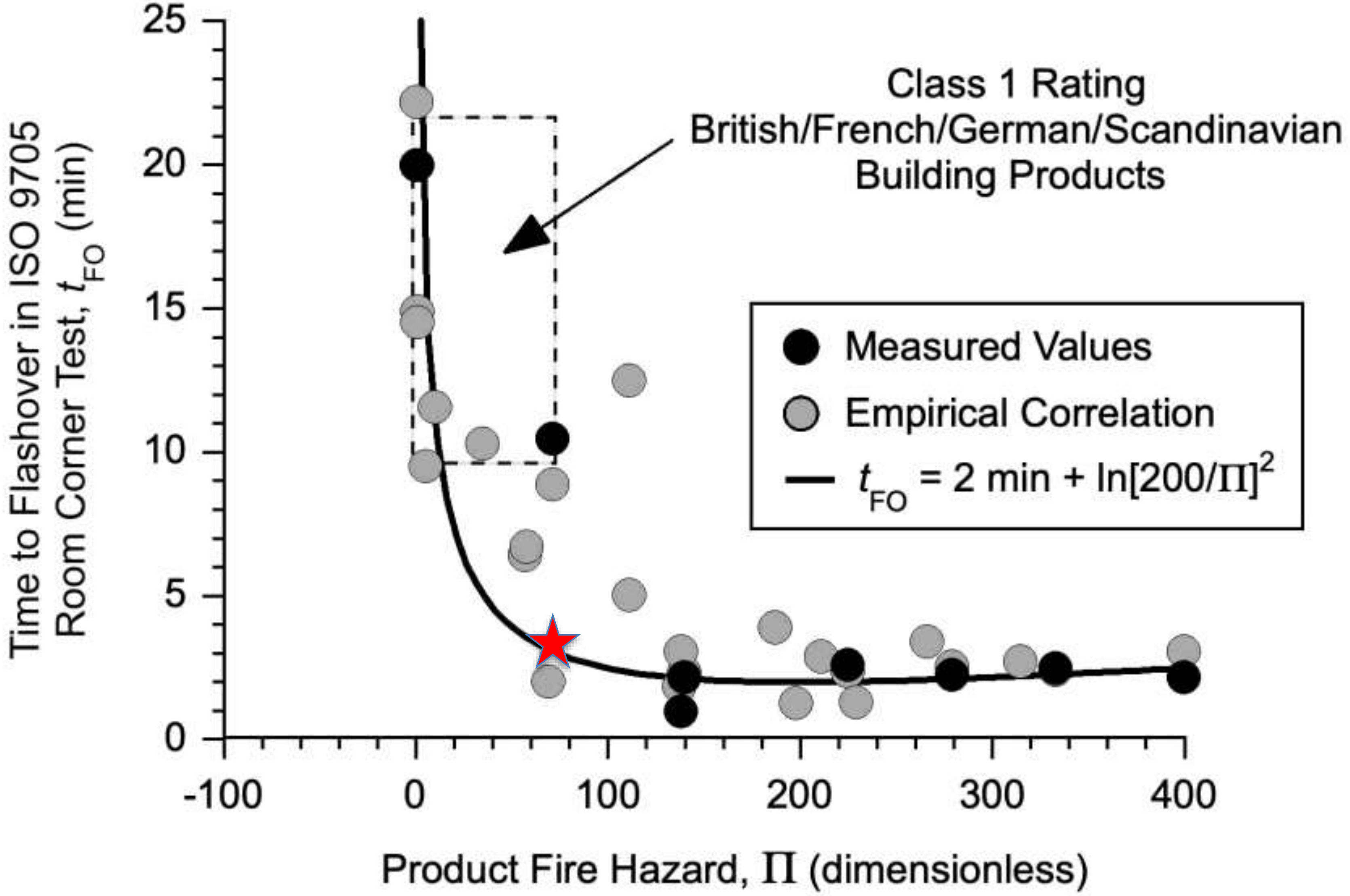
Full-Scale Fire Tests of Televisions and Computer Monitors Show That Rapid Fire Growth Commences at Π > 760 $\pm$ 8



- *Isolated test articles*
- *Small flame ignition source*



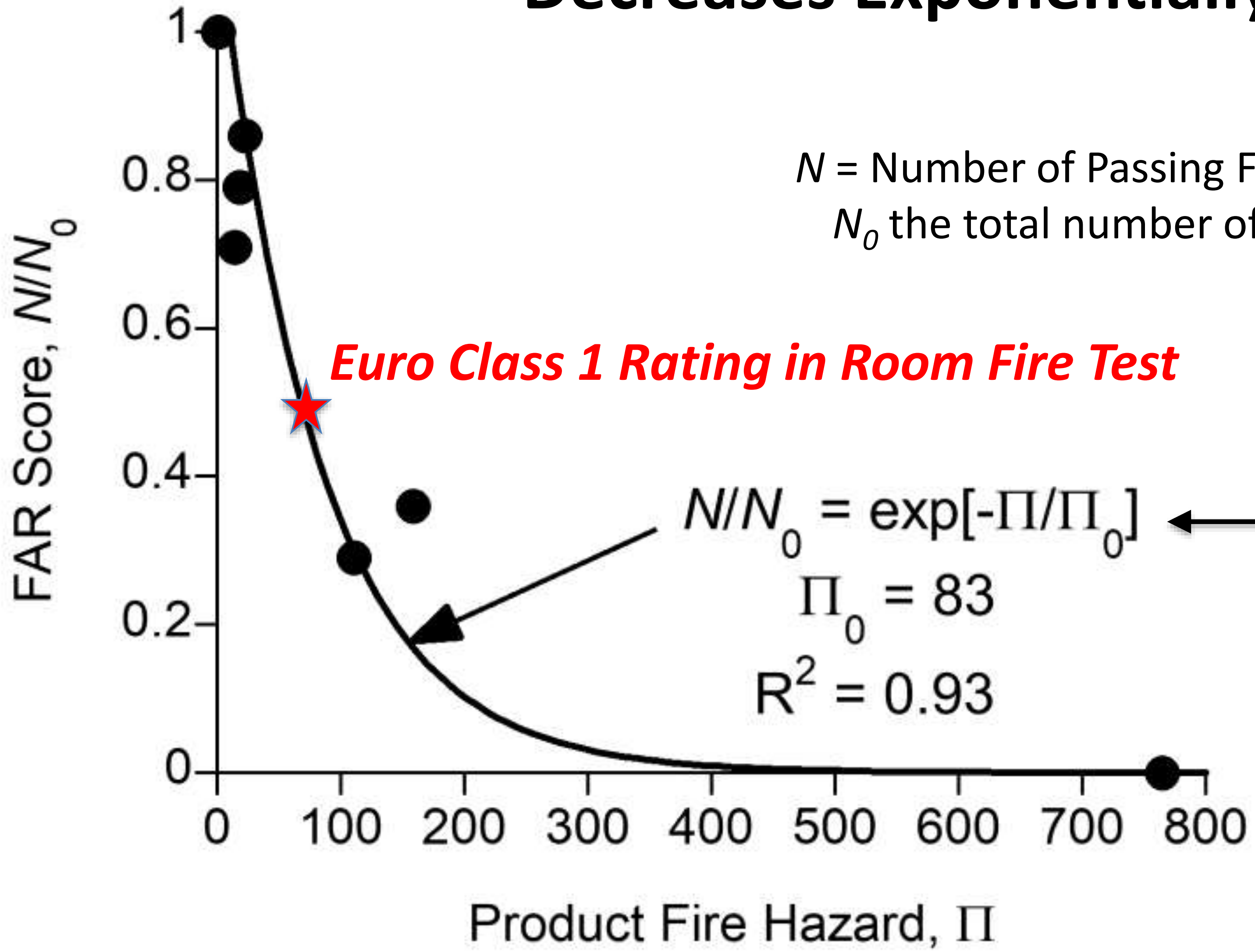
Full-Scale Room Fire Tests (ISO 9705) of Building Products and Wall Linings Show that Fire Growth is Slow When $\Pi < 75$



- *Radiant feedback from adjacent materials*
- *100 kW and 300 kW propane burner ignition*

Ostman & Tsantaridis, Fire and Materials (1994, 1995)

Number of Passing FAA Tests (FAR Score) for a Material Decreases Exponentially with Π



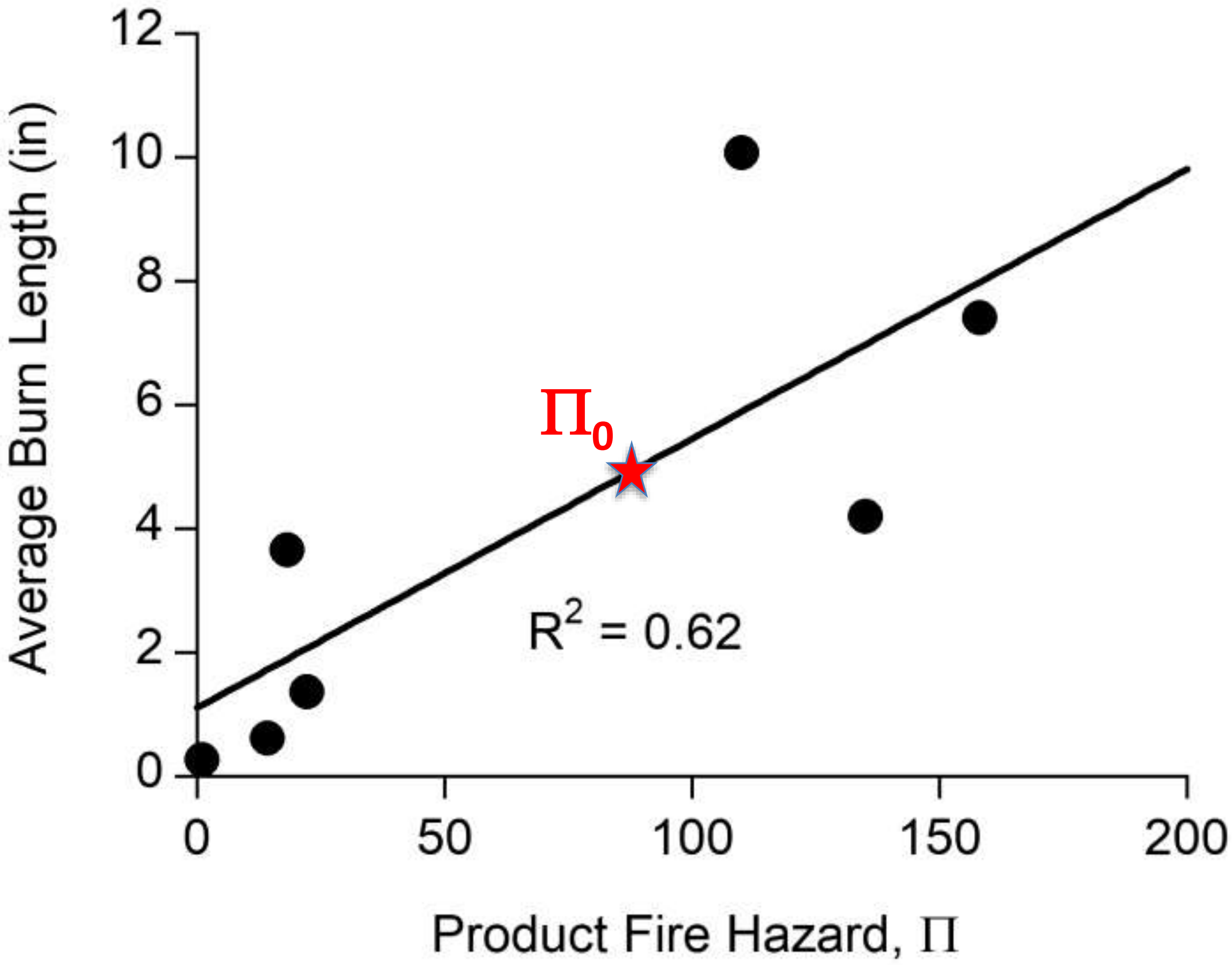
N = Number of Passing FAR Fire Tests
N_0 the total number of FAR tests.

$$-\frac{dN}{d\Pi} = \frac{N}{\Pi_0}$$

$$-\int_{N_0}^{N} \frac{dy}{y} = \int_{0}^{\Pi} \frac{dx}{\Pi_0}$$

$$\frac{N}{N_0} = \exp\left[-\frac{\Pi}{\Pi_0}\right]$$

VFP Burn Length versus Product Fire Hazard Π



$\Pi_0 \leq 80$ is a Euro Class 1 Rating in the ISO 9705 Full Scale Room Fire Test

Conclusions

The <u>potential</u> of a material to grow a fire,

$$\boldsymbol{\lambda \equiv Ignitability\ * Combustibility \equiv \left(\frac{1}{E_{ign}}\right)\left(\frac{H_c}{L_g}\right)}, \qquad \frac{m^2}{MJ}$$

The potential of a product to be a fire hazard is only realized if the total heat released by the burning product (fire load) is sufficient to sustain the fire,

$$\boldsymbol{Product\ Fire\ Hazard, \Pi\ \equiv\ \lambda H_c} \qquad dimensionless$$

The fire hazard of the material in a product depends on the heat of combustion of the product per unit volume, $H_{c,V}$ (MJ/m^3)

$$\boldsymbol{Material\ Fire\ Hazard, \pi\ \equiv\ \lambda H_{c,V} = \frac{\Pi}{b}}, \qquad m^{-1}$$