Workshop on Fire Growth and Spread on Objects
NIST, Gaithersburg, MD
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Development of FDMS Tools to Generate Data for Fire Safety Engineering and Modeling

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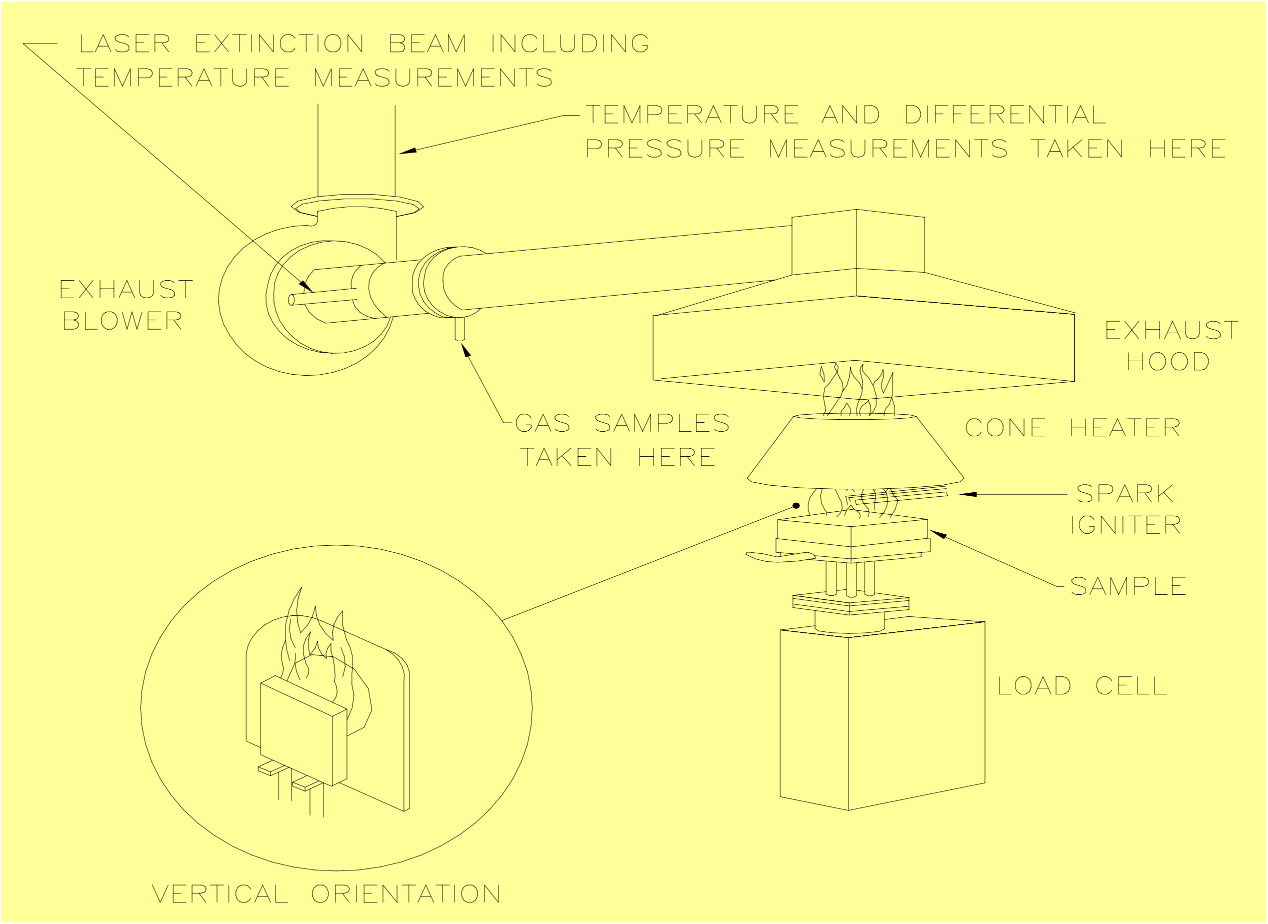
INTRODUCTION (1 OF 2)

- UNC Charlotte initiated a 3-year research program in September 2001 under a grant from NIST
- Objectives of the program
  - Year 1: Develop software tools to calculate ignition, flame spread, and heat release rate properties of materials
  - Year 2: Develop algorithms and computer programs to calculate the fire curve for different types of fuel packages
  - Year 3: Evaluate predictive capability of these sub-models
- This paper provides an overview of year 1 activities and invites comments from workshop attendees

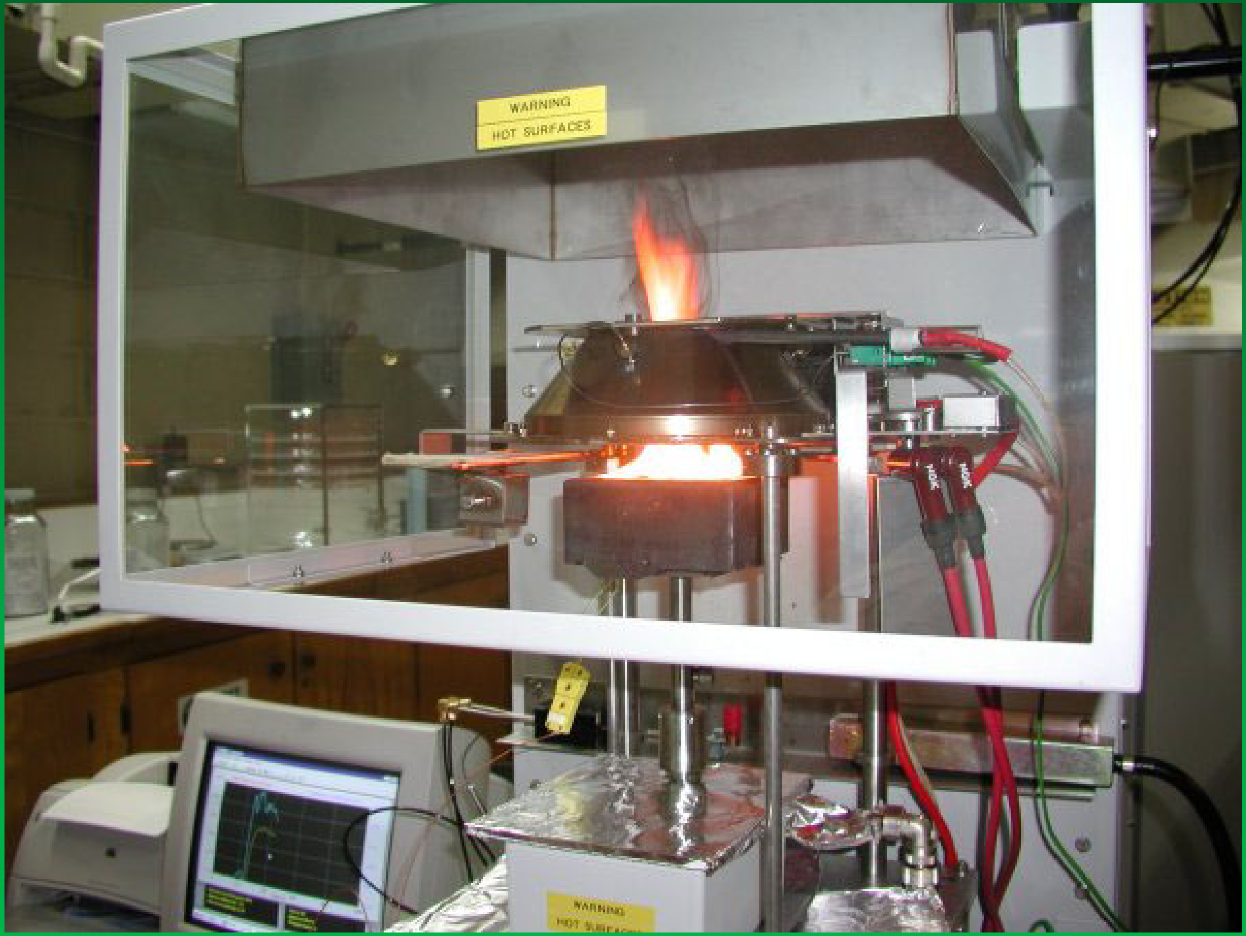
INTRODUCTION (2 OF 2)

- The main limitation of compartment fire models is that they do not predict the fire (Babrauskas, 1996)
- Extensive database of fire curves is not feasible
- More practical approach involves the development of correlations and sub-models
  - Items found in residences (chairs, TV sets, etc.)
  - Larger fuel packages (commodities, cars, etc.)
  - Room/corner test is the most common geometry
- Sub-models require material property data for ignition, flame spread, and heat release

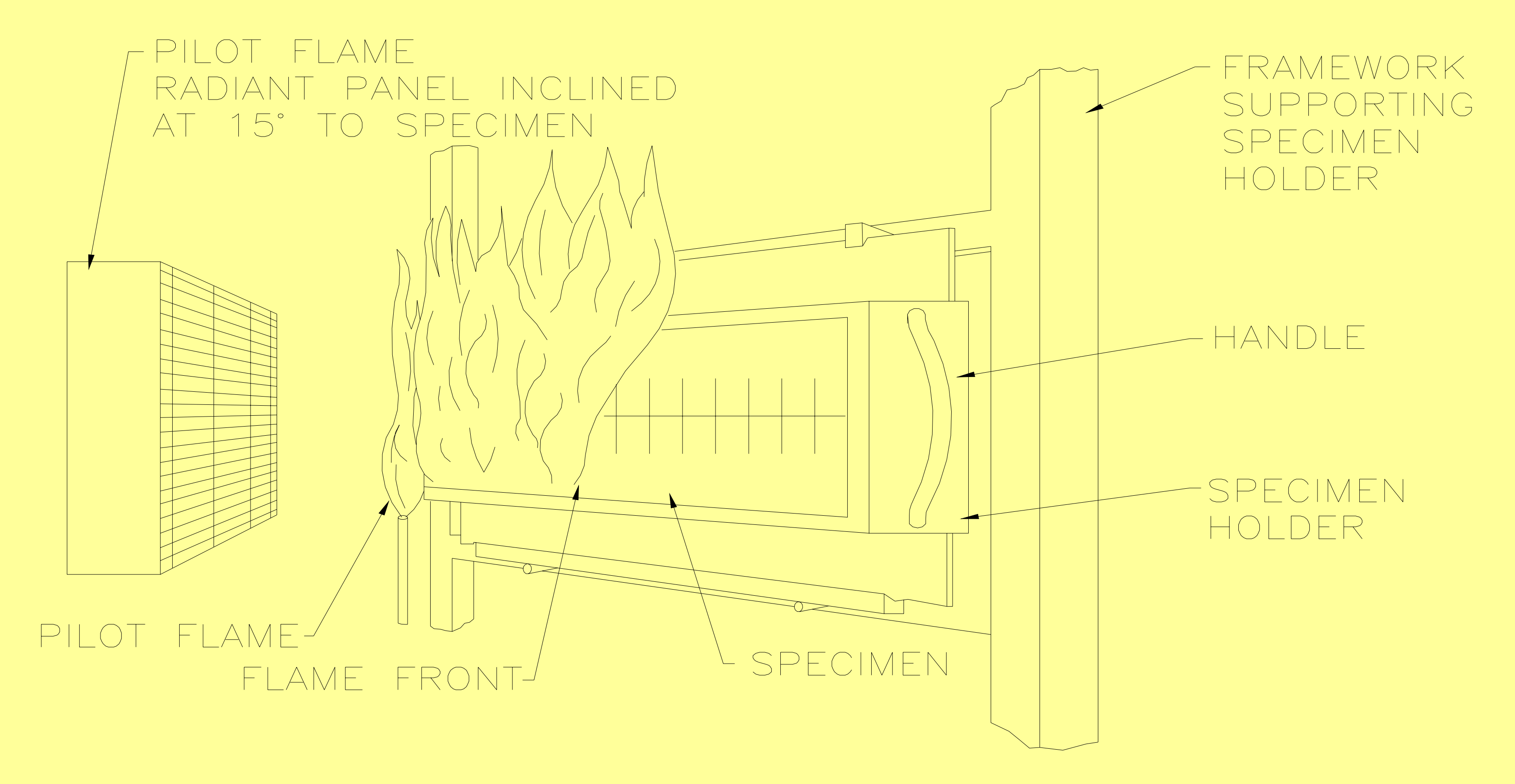
TEST EQUIPMENT
Cone Calorimeter (1 of 2)



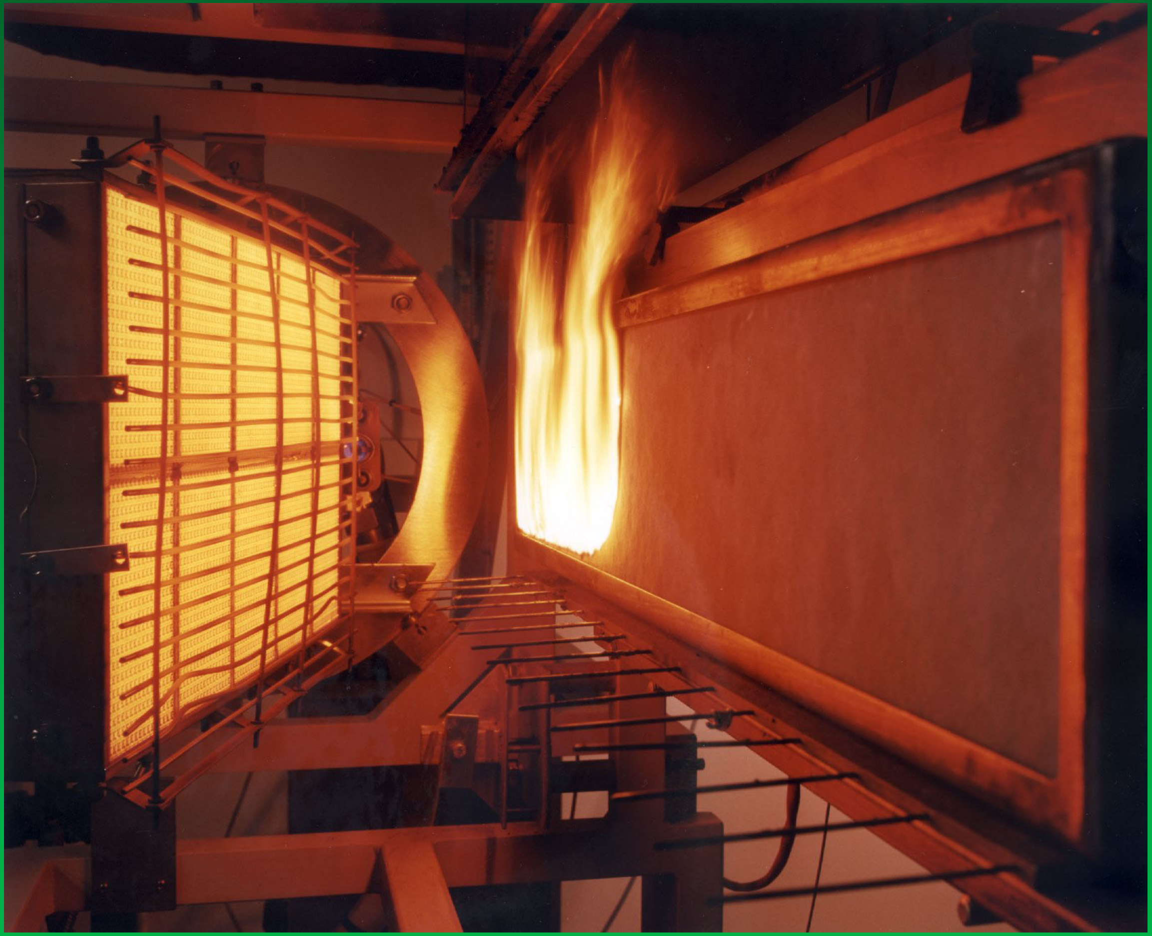
TEST EQUIPMENT
Cone Calorimeter (2 of 2)



TEST EQUIPMENT
LIFT Apparatus (1 of 2)



TEST EQUIPMENT
LIFT Apparatus (2 of 2)

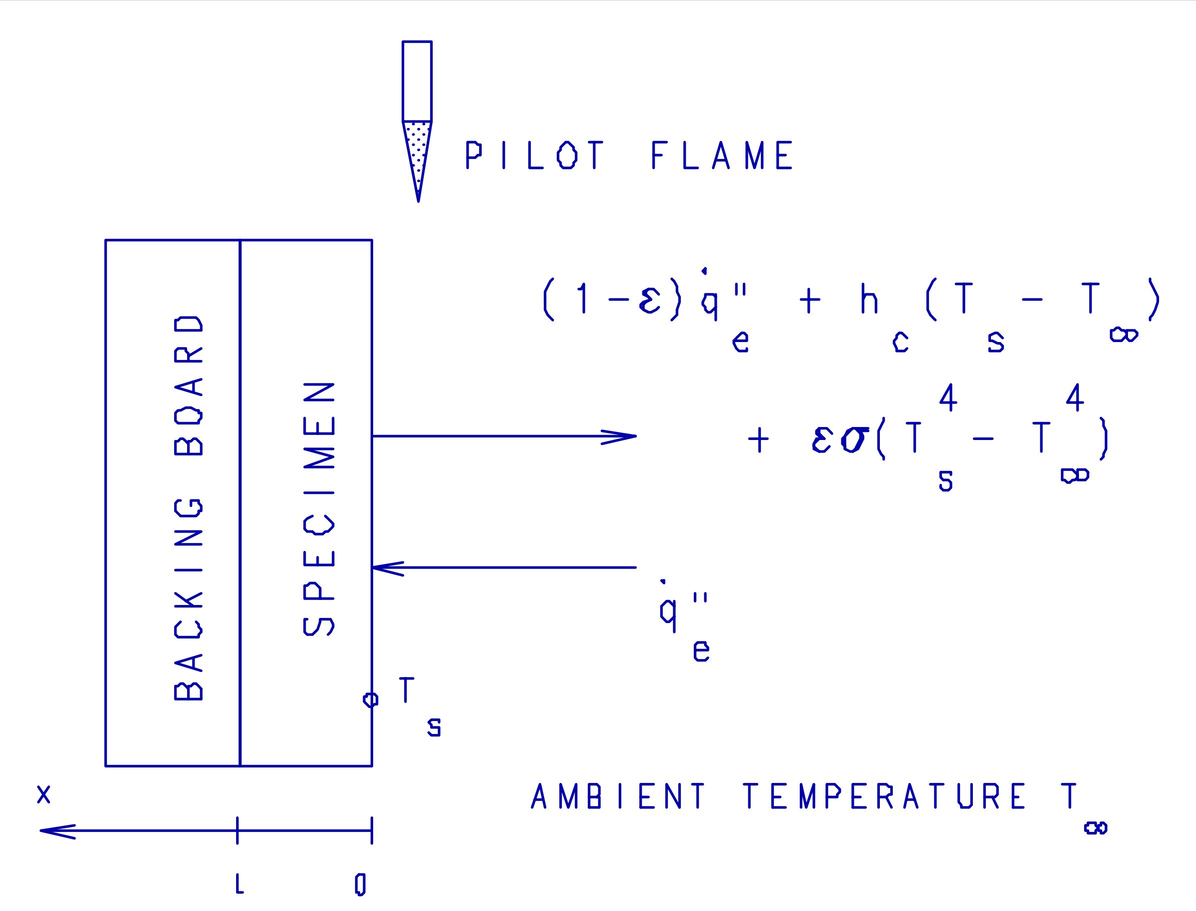


PILOTED IGNITION PROPERTIES
Introduction

- Ignition properties are determined on the basis of time to ignition measured at different heat fluxes
- Data analysis leads to material properties that can be used to predict ignition under real fire conditions
- Procedures for analysis of ignition data of thick solids generally consist of two steps
  - Determine minimum or critical heat flux for ignition
  - Plot a function of t_{ig} (e.g. $1/\sqrt{t_{ig}}$) vs. heat flux and calculate thermal inertia from the slope of a linear fit through the data
- Eight different procedures are being examined

PILOTED IGNITION PROPERTIES

Schematic



PILOTED IGNITION PROPERTIES
Quintiere & Harkleroad (1984)

- **Developed for analyzing LIFT data (ASTM E 1321)**
- **Assumptions: ε = 1 and h_c = 15 W/m^2-K**
- **Determine *CHF* by bracketing (=minimum heat flux)**
- **Calculate T_{ig} and h_{ig} from**

$$CHF = 0.015\left(T_{ig} - T_\infty\right) + \sigma\left(T_{ig}^4 - T_\infty^4\right) \equiv h_{ig}\left(T_{ig} - T_\infty\right)$$

- **Plot CHF to heat flux ratio as a function of $\sqrt{t_{ig}}$**

$$\frac{CHF}{\dot{q}_e''} = \begin{cases} \dfrac{2h_{ig}\sqrt{t_{ig}}}{\sqrt{\pi k\rho c}} & t_{ig} \le t^* \\ 1 & t_{ig} > t^* \end{cases}$$

PILOTED IGNITION PROPERTIES
Mikkola & Wichman (1989)

- Based on two analyses of thermal ignition model
  - Laplace transform solution of linearized heat conduction
  - Integral solution of problem with non-linear heat losses
- Plot $1/\sqrt{t_{ig}}$ as a function of heat flux ($n = 2$)

$$t_{ig} = \frac{\pi}{4} k\rho c \frac{\left(T_{ig} - T_{\infty}\right)^{n}}{\left(\dot{q}_e'' - CHF\right)^{n}}$$

- *CHF* is estimated from intercept with abscissa
- T_{ig} is calculated from

$$CHF = h_c\left(T_{ig} - T_{\infty}\right) + \varepsilon\sigma\left(T_{ig}^4 - T_{\infty}^4\right)$$

PILOTED IGNITION PROPERTIES
Toal, Silcock & Shields (1989)

- Uses concept of constant flux-time product (first introduced by Smith at OSU in 1981)
- Plot heat flux versus $(1/t_{ig})^{1/n}$

$$FTP = \left(\dot{q}_e'' - CHF\right)^n t_{ig}$$

- Value for *n* is found by trial and error to get a best-fit line through the data points
- Typically *n* is between 1 and 2

PILOTED IGNITION PROPERTIES
Delichatsios, Panagiotou & Kiley (1991)

- Specimens are blackened ⇨ $\varepsilon = 1$
- Convective surface heat losses are ignored
- High heat fluxes (> 3×*CHF*)

$$\frac{1}{\sqrt{t_{ig}}} = \frac{2}{\sqrt{\pi k \rho c}\left(T_{ig} - T_\infty\right)}\left(\dot{q}_e'' - 0.64CHF\right)$$

- Low heat fluxes (< 1.1×*CHF*)

$$\frac{1}{\sqrt{t_{ig}}} = \frac{\sqrt{\pi}}{\sqrt{k \rho c}\left(T_{ig} - T_\infty\right)}\left(\dot{q}_e'' - CHF\right)$$

- High heat flux fit crosses abscissa at 0.64×*CHF*

PILOTED IGNITION PROPERTIES
Janssens (1991)

- Based on finite difference solution of thermal ignition problem with non-linear heat losses
- Plot $(1/t_{ig})^{0.55}$ as a function of heat flux

$$\dot{q}_e'' = CHF\left[1 + 0.73\left(\frac{k\rho c}{h_{ig}^2 t_{ig}}\right)^{0.55}\right]$$

- *CHF* is estimated from intercept with abscissa
- T_{ig} and h_{ig} are calculated from

$$CHF = h_c\left(T_{ig} - T_\infty\right) + \varepsilon\sigma\left(T_{ig}^4 - T_\infty^4\right) \equiv h_{ig}\left(T_{ig} - T_\infty\right)$$

PILOTED IGNITION PROPERTIES
Tewarson (1995)

- Plot $1/\sqrt{t_{ig}}$ as a function of heat flux
- Correlate data according to

$$\frac{1}{\sqrt{t_{ig}}} = \sqrt{\frac{4}{\pi}}\,\frac{\left(\dot{q}_e'' - CHF\right)}{TRP}$$

- Find *CHF* from intercept of a straight-line fit with the abscissa
- Calculate Thermal Response Parameter (*TRP*) from the slope

PILOTED IGNITION PROPERTIES

Moghtaderi, Novozhilov, Fletcher & Kent (1997)

- Based on integral solution
- Accounts for T_{ig} increase with decreasing heat flux
- Plot $1/\sqrt{t_{ig}}$ as a function of heat flux
  - CHF is the intercept of a straight-line fit with the abscissa
  - Calculate T_{ig} at *CHF*
  - Determine kρc from the slope of a linear fit through the data

$$k\rho c = \frac{8}{3}\left(\frac{S}{T_{ig} - T_\infty}\right)^2$$

- h_c = 11 W/m^2-K for horizontal Cone calorimeter

PILOTED IGNITION PROPERTIES
Spearpoint & Quintiere (2001)

- Based on integral solution
- Assumes $\varepsilon = 1$
- Plot $1/\sqrt{t_{ig}}$ as a function of heat flux

$$t_{ig} = \frac{4}{3}\frac{1}{(2-\beta_{ig})(1-\beta_{ig})}\frac{(T_{ig}-T_\infty)^2}{\dot{q}_e''^2}$$

- Intercept with the abscissa is 0.76×CHF
- h_c = 18 W/m^2-K for horizontal Cone calorimeter

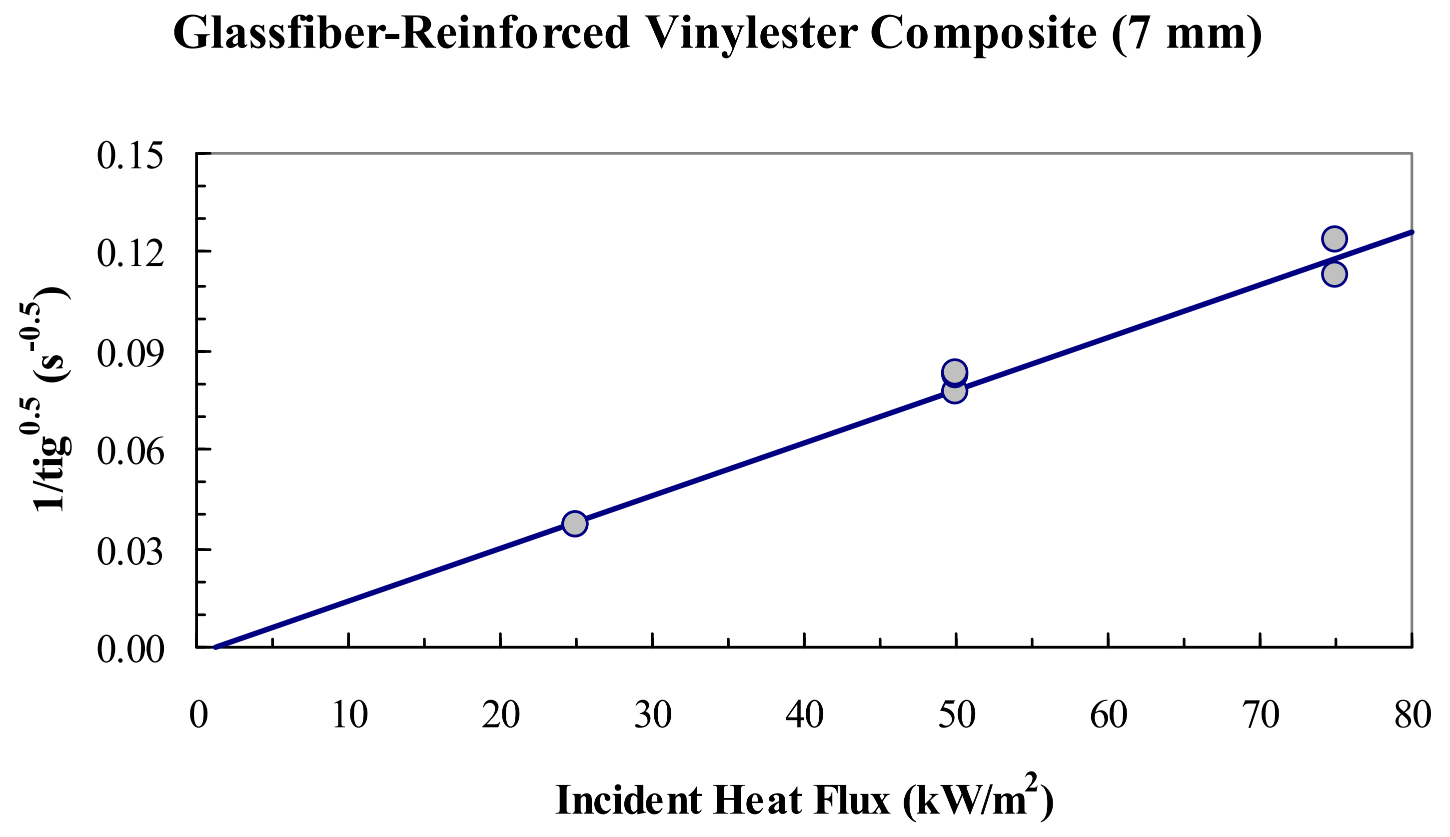
PILOTED IGNITION PROPERTIES
And the winner is?

- Each procedure has unique features
- None of the procedures are perfect (Ngu)
- Properties have to be used in a manner consistent with the assumptions of the ignition data analysis
- Include all procedures in the FDMS software tools?
- Procedures need to be modified to address the following issues
  - Thermally thin and intermediate specimens
  - Some layered products present major problems
  - h_c is not constant but varies with heat flux

PILOTED IGNITION PROPERTIES
Specimen Thickness and Composition

- Thermally thin and intermediate specimens
  - Mikkola and Wichman: *n* = 1 for thin, *n* = 2/3 for intermediate
  - Janssens and Grenier: focus on data in thick regime
  - Dietenberger: weighted average of thin and thick solutions
- Layered materials
  - Veneer over combustible core often presents problems (e.g. marine composites tested by Jacobi and Dembsey)
  - Larger-scale test (ICAL) may be more appropriate

PILOTED IGNITION PROPERTIES
Thickness Effects (1 of 4)



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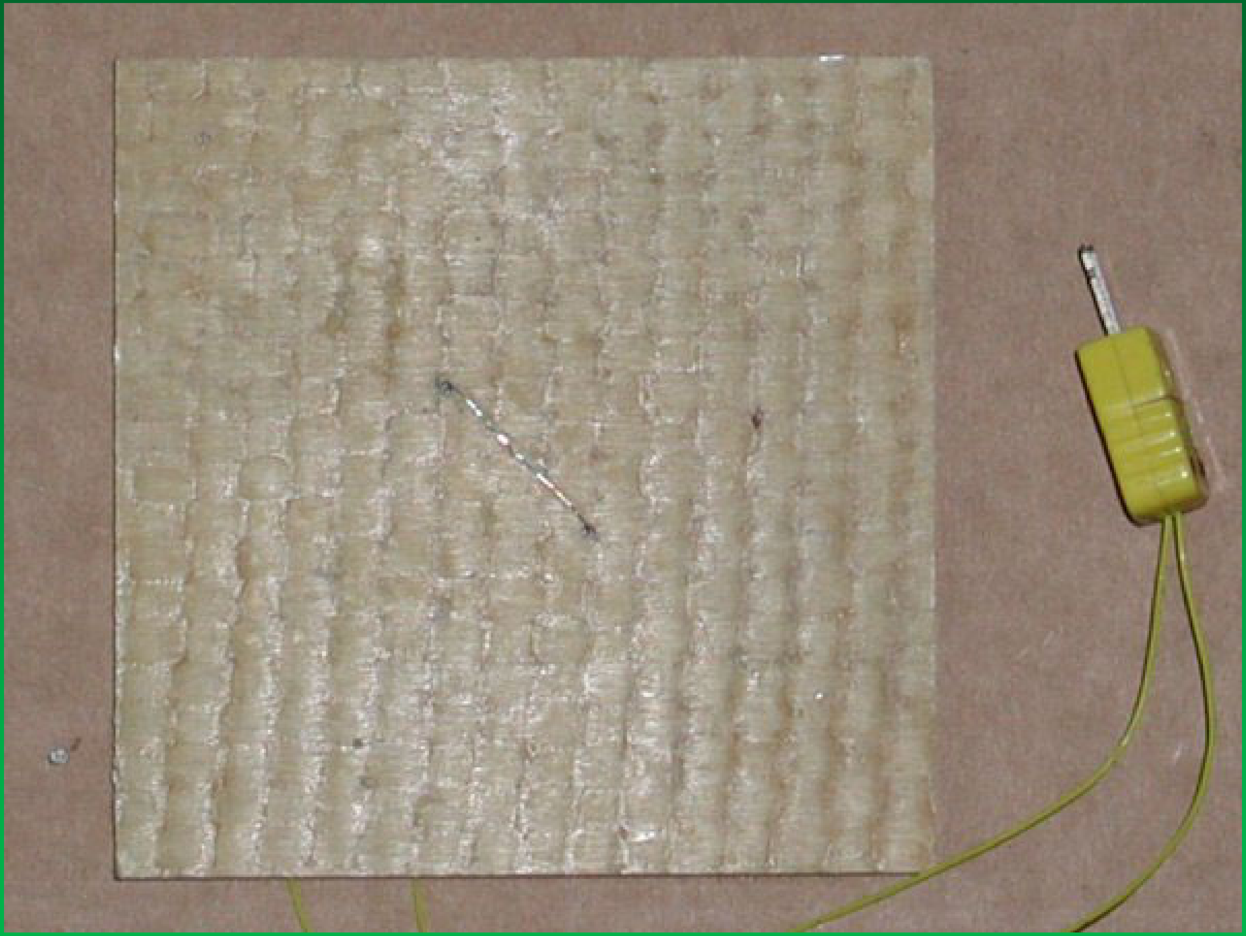
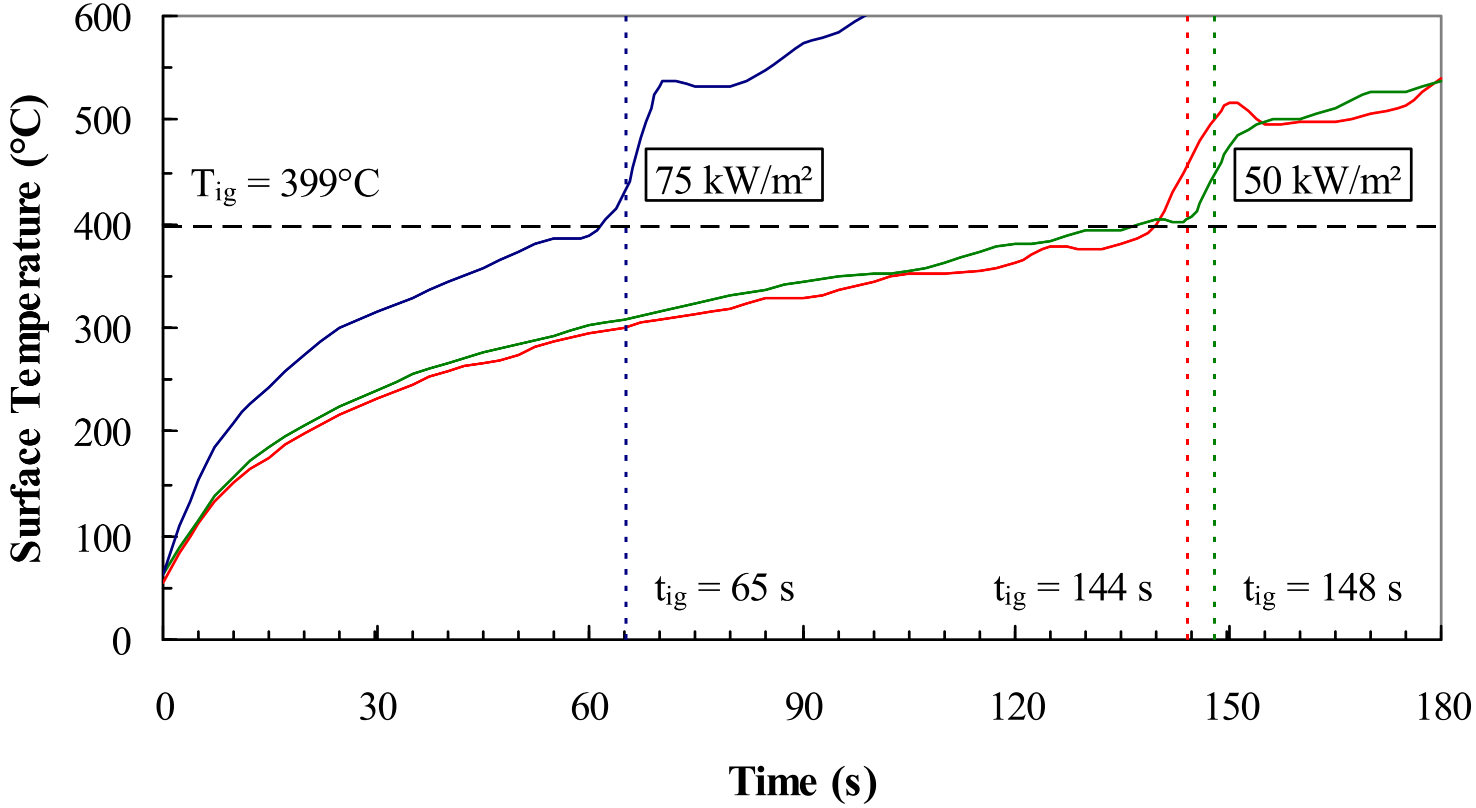
PILOTED IGNITION PROPERTIES
Thickness Effects (2 of 4)



PILOTED IGNITION PROPERTIES
Thickness Effects (3 of 4)



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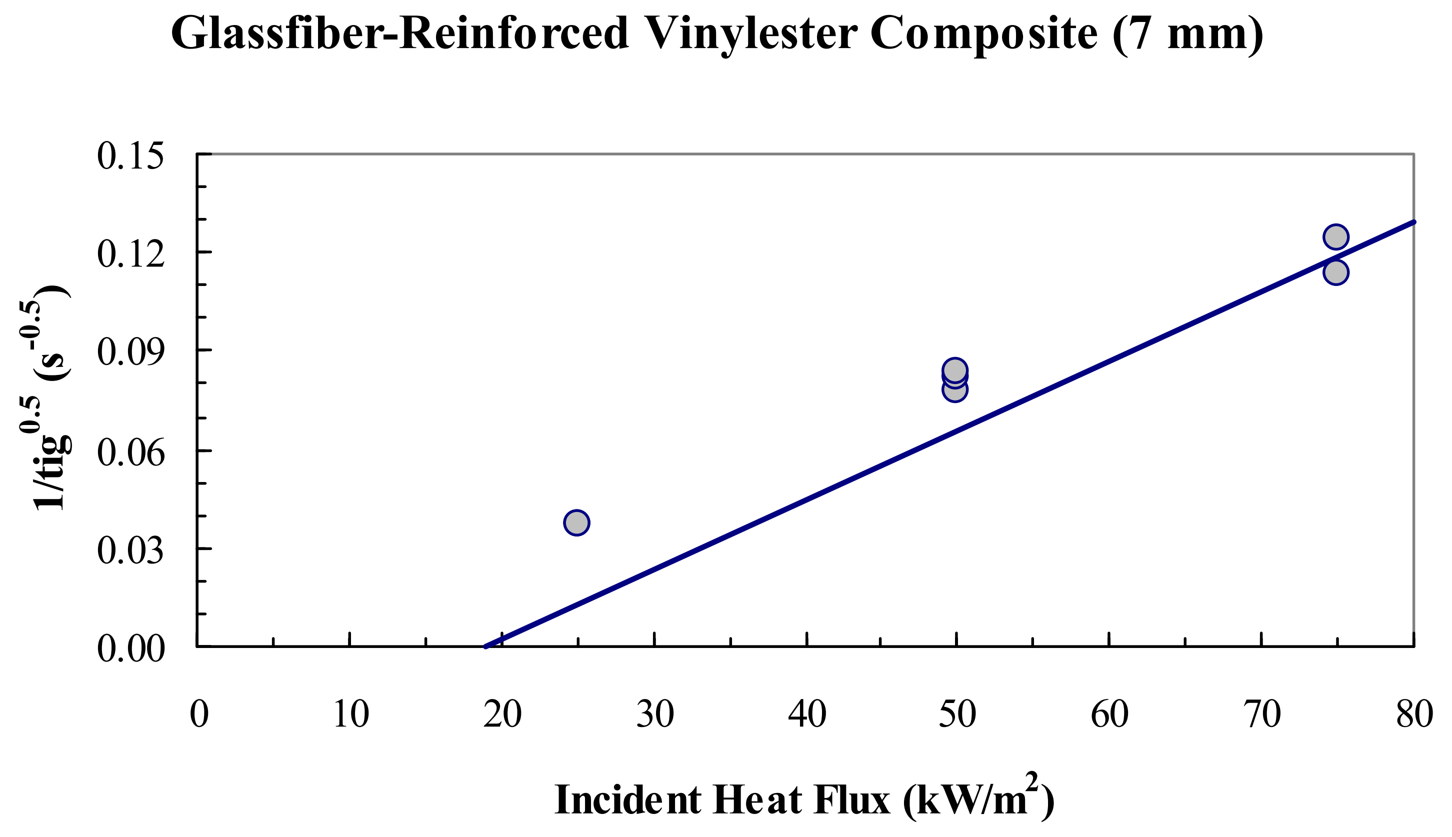
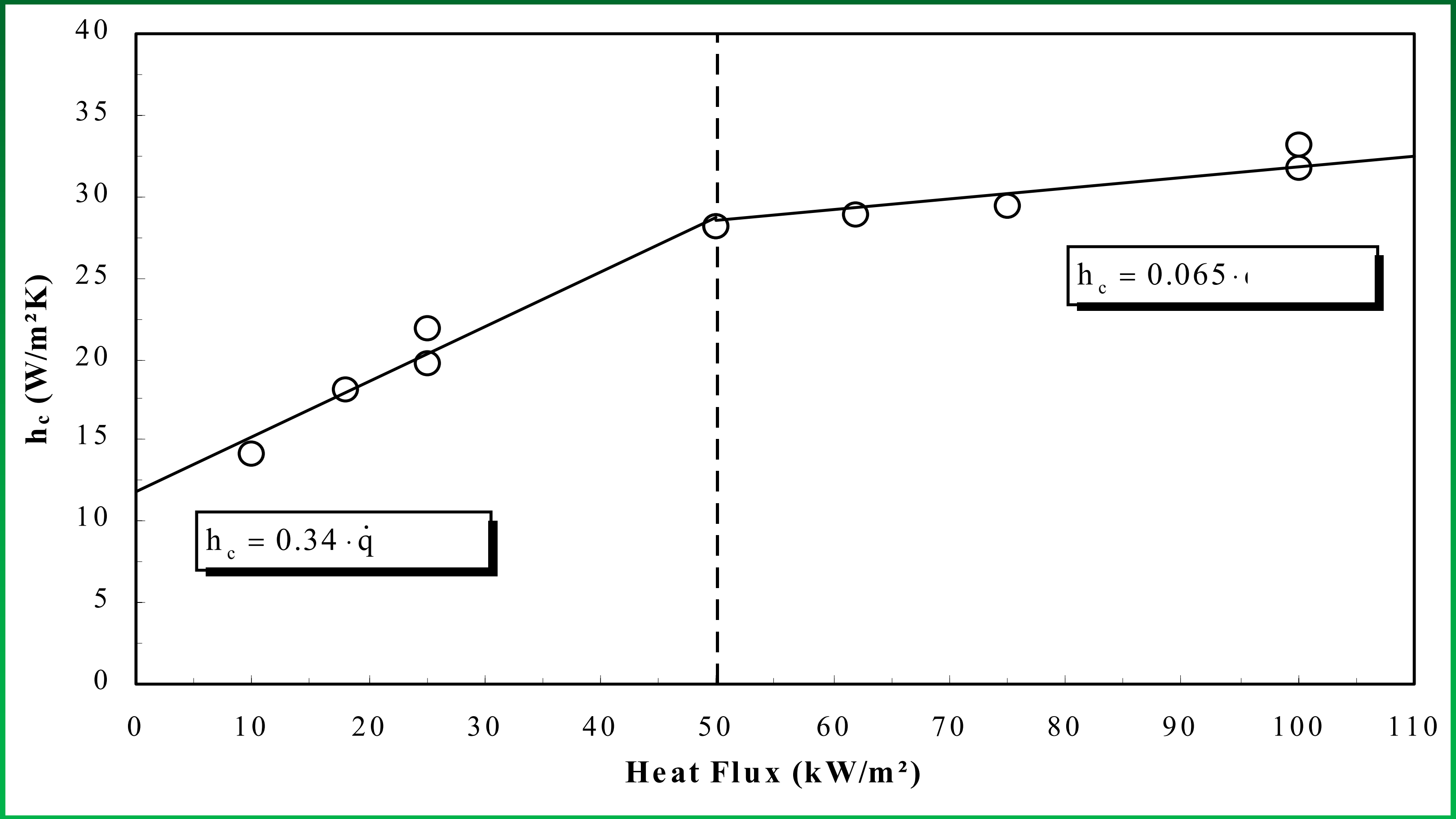
PILOTED IGNITION PROPERTIES
Thickness Effects (4 of 4)



PILOTED IGNITION PROPERTIES
Convection Coefficient (1 of 6)

- The convection coefficient in ignition tests appears to vary as a function of heat flux setting
  - Cone calorimeter horizontal: Janssens and Dillon (2001)
  - Cone calorimeter vertical: Janssens (1991)
  - LIFT: Dietenberger (1994)
- Some data analysis procedures can be modified to account for varying h_c, others cannot
- Measurements will be repeated as part of NIST grant research at UNCC

PILOTED IGNITION PROPERTIES
Convection Coefficient (2 of 6)



PILOTED IGNITION PROPERTIES
Convection Coefficient (3 of 6)

- Measurements indicate that h_c is a piece-wise linear function of $\dot{q}''_e$

$$h_c \equiv h_0 + h_1 \dot{q}''_e$$

- Correlating function can be rewritten as

$$\dot{q}''_e = \sigma(T_{ig}^4 - T_\infty^4) + \frac{h_c}{\varepsilon}(T_{ig} - T_\infty) + \frac{0.71(T_{ig} - T_\infty)}{\varepsilon}\left(\frac{k\rho c}{t_{ig}}\right)^{0.5}$$

- This equation is still valid for h_c which varies with $\dot{q}''_e$

PILOTED IGNITION PROPERTIES
Convection Coefficient (4 of 6)

$$\left(\frac{k\rho c}{t_{ig}}\right)^{0.5} = C_1\dot{q}''_e - C_0$$

where

$$C_1 = \frac{\varepsilon}{0.71(T_{ig} - T_\infty)} - \frac{h_1}{0.71}$$

and

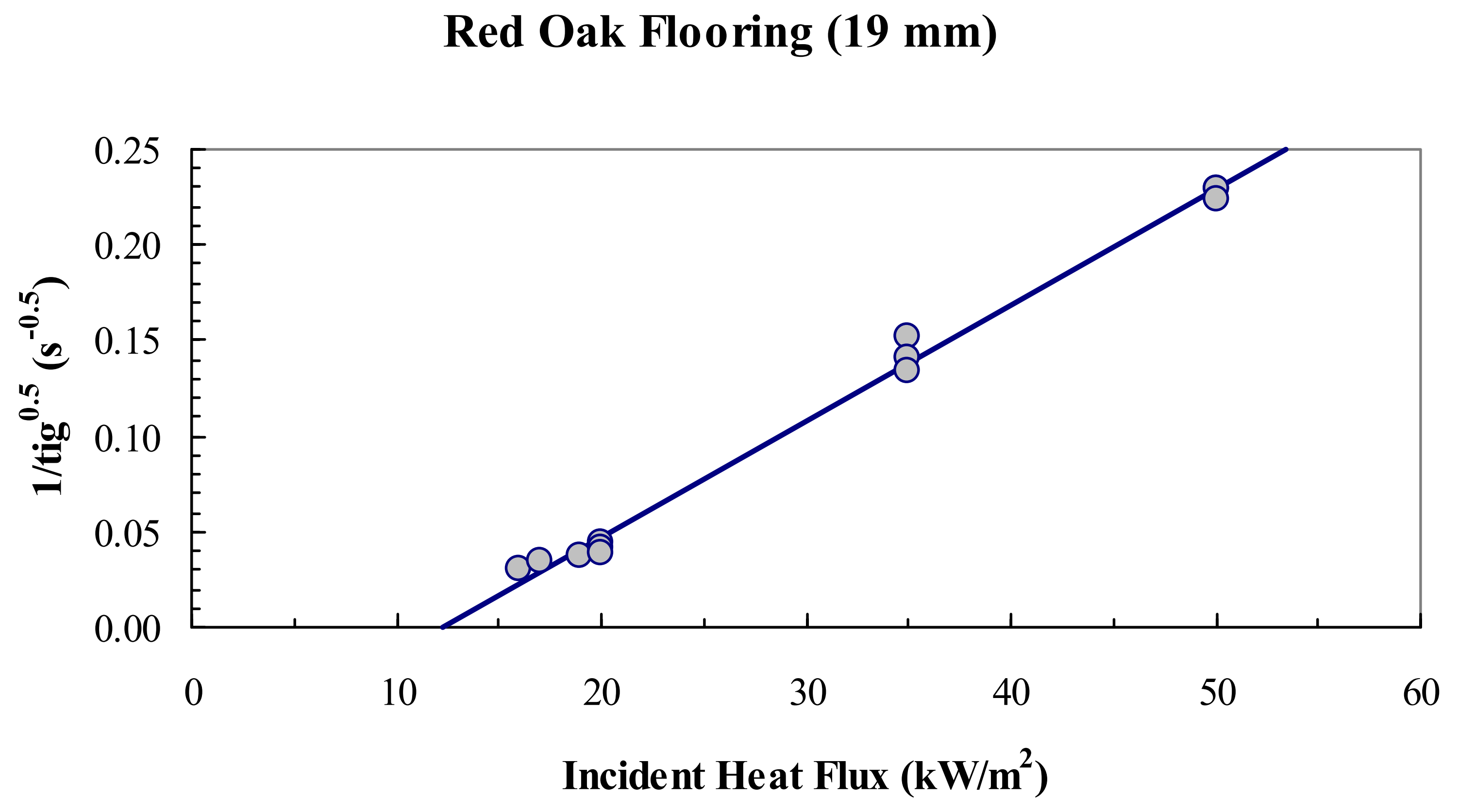
$$C_0 = \frac{\varepsilon\sigma(T_{ig}^4 - T_\infty^4)}{0.71(T_{ig} - T_\infty)} + \frac{h_0}{0.71}$$

- T_{ig} from intercept (C_0/C_1) and kρc from slope (C_1)

PILOTED IGNITION PROPERTIES
Convection Coefficient (5 of 6)

- Example: Red oak calibration decks for ASTM E 84
- Properties
  - Thickness : 25 mm
  - Density : 480 kg/m^3
  - Moisture content : ~ 6%
  - Emissivity : 0.88
- Duplicate tests at 20, 35, and 50 kW/m^2
- Additional tests below 20 kW/m^2 to determine $\dot{q}''_{cr}$
- $T_{ig} = 324°C$ (OK) and $k\rho c = 0.35\ kW^2 \cdot s/m^4 \cdot K^2$ (higher)

PILOTED IGNITION PROPERTIES
Convection Coefficient (6 of 6)



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FLAME SPREAD PROPERTIES
Introduction

- **Opposed-flow flame spread data analysis is based on deRis' formula**

$$V = \frac{\Phi}{k\rho c\left(T_{ig} - T_s\right)^2}$$

- **Different practical procedures have been developed**
  - **Quintiere and Harkleroad (consistent with ignition analysis)**
  - **Janssens (no preheat, integral solution to determine T_s)**
  - **Dietenberger (more fundamental)**

FLAME SPREAD PROPERTIES
Questions

- Is there a need for these data?
- Do opposed-flow flame spread parameters correlate with other flammability characteristics?
- Can a heat release rate apparatus be converted to obtain opposed-flow flame spread data?
- Can the same values be used for lateral and downward spread?

HEAT RELEASE PROPERTIES
Introduction

- **Three properties pertain to heat release rate**
  - **Heat of combustion, ΔH_c**

$$\Delta H_c(t) = \frac{\dot{Q}''(t)}{\dot{m}''(t)}$$

  - **Heat of gasification, L**

$$L(t) = \frac{\dot{q}''_{net}(t)}{\dot{m}''(t)} = \frac{\dot{q}''_e + q''_f(t) - \dot{q}''_l(t)}{\dot{m}''(t)}$$

  - **Total heat released**

HEAT RELEASE PROPERTIES
Heat of Combustion

- Heat release calorimeters measure heat release rate and mass loss rate ⇨ ΔH_c can easily be calculated
- Forms to report ΔH_c (Dillon et al., 1998)
  - Dynamic curve
  - Value at peak heat release rate
  - Average peak value
  - Overall value

HEAT RELEASE PROPERTIES
Heat of Gasification

- Much more difficult to determine because some elements in the equation are not routinely measured
  - Flame heat flux must be estimated
  - Surface temperature must be measured or calculated
- Forms to report *L* (Dillon et al., 1998)
  - Dynamic curve
  - Value at peak heat release rate
  - Average peak value
  - Overall value

POSSIBLE DATA SETS

- Focus on materials that were tested in small scale and a in room/corner test (ISO 9705, NFPA 265, etc.)
  - ATMI
  - Eurefic
  - FCRC
  - FPL
  - LSF
  - SBI (?)
  - Solutia
  - SOPRO (?)
  - USCG

ACKNOWLEDGEMENT

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QUESTIONS?

SUGGESTIONS?

COMMENTS?