Modeling Composite Burning -- Identifying Key Material Parameters

By

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Outline

- Part 1. Model Development
  - Assumptions and Calibration (Ref. 1)
- Part 2. Description of FAA Test Data
  - Test conditions and results (Ref. 2)
  - Key finding: some self extinguish
- Part 3. Model Predictions & Agreement with Test Data
  - Interpret self extinguishment
  - Identify key material parameters

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Introduction

- Scope:
  - Carbon fiber epoxy laminates
  - Conditions of an in-flight fire with constant or time variant Heat flux
- Fairly generalized computer model with properties varying with:
  - Temperature
  - Temperature-time history
- Model can be applied to glass fiber composites and post crash fire conditions
- Model can be extended to structural response of composites

Part 1. Model Development
(All properties data are taken from Ref. 1)

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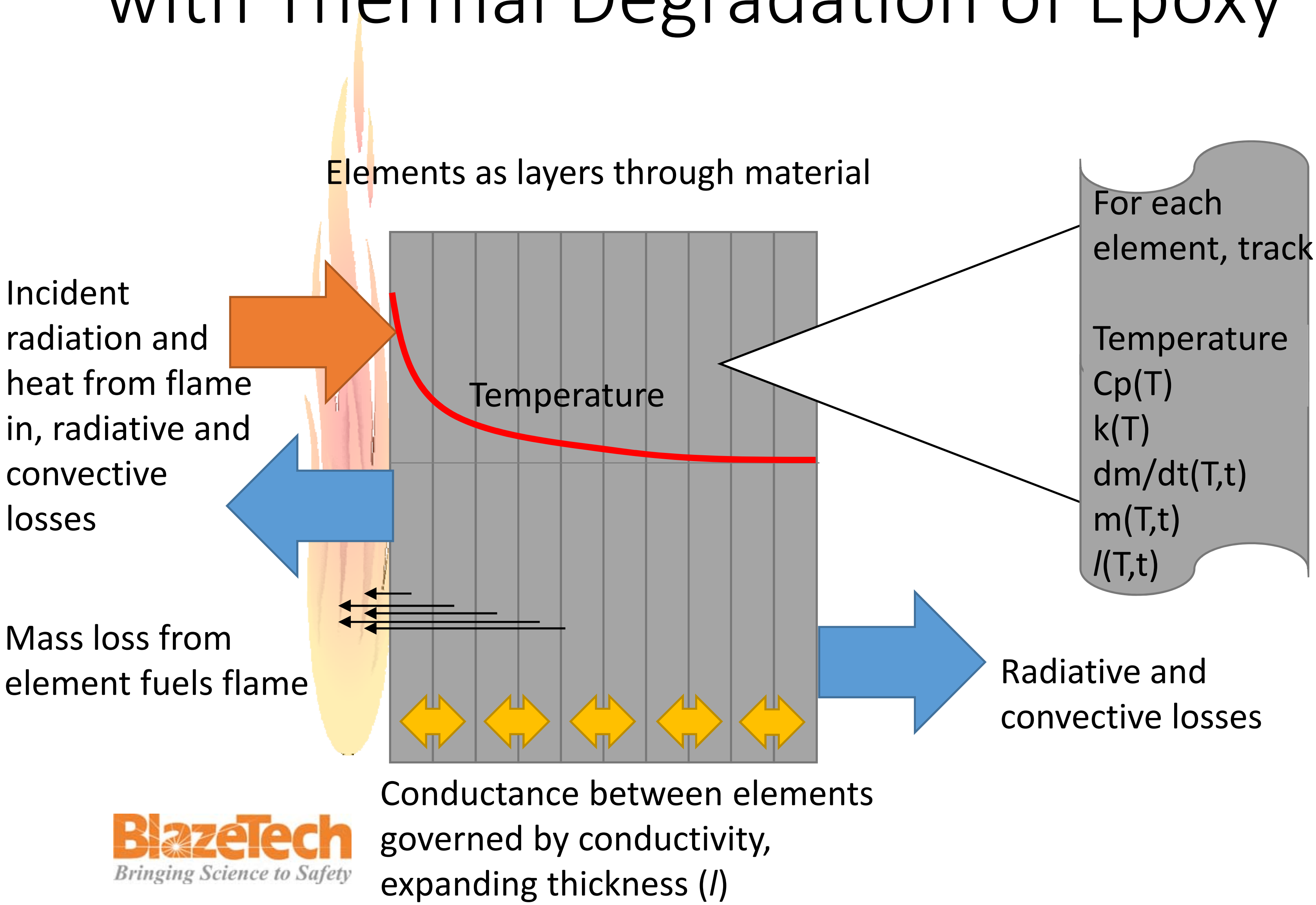
1D Transient Heat Transfer Model with Thermal Degradation of Epoxy



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Discretized Equations

- Heat conduction and thermal degradation ($0<x<l_f$):

$$m_i c_p \frac{dT_i}{dt} + \Delta h_{decomp} \frac{dm_i}{dt} = \frac{(k_{i-1}+k_i)(T_{i-1}-T_i)}{(l_{i-1}+l_i)} - \frac{(k_i+k_{i+1})(T_i-T_{i+1})}{(l_i+l_{i+1})}$$

- Heat Fluxes at front face (x=0)

$$\dot{q}''_{ff} = \dot{q}''_{incident} + HRR\,\eta_{fire} - \dot{q}''_{rad} - \dot{q}''_{conv}$$

- Heat loss at rear face ($x=l_f$)

$$\dot{q}''_{rf} = -\dot{q}''_{rad} - \dot{q}''_{conv}$$

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Thermal Degradation and Combustion of Epoxy

- Carbon inert; epoxy degrades per following kinetics:
- $k(T)=a_p \exp(-E_a/RT)$
- E_a = 182 kJ/mol, a_p = 9.67 x 10^{10} s^{-1}
- Extent of thermal degradation or mass loss = $\alpha(k(T),t)$

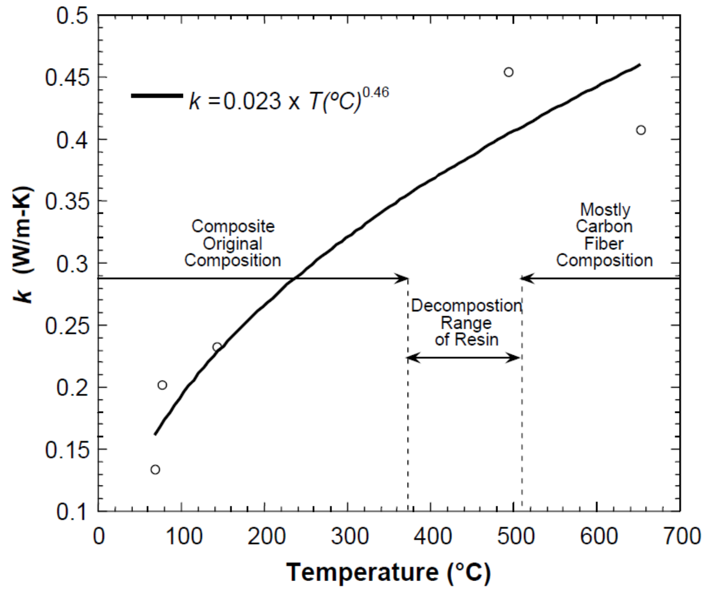
$$\alpha = \frac{m - m_0}{m_f - m_0}$$

- Epoxy (1) → Volatiles (0.75) + Char (0.25)
  - Volatiles ↓ Flame; Char ↓ Smolder/glow
- With air: Flame; Smolder/glow
- We account for heat feedback from volatile flame only: heat of combustion = 20 ±3 kJ/g-resin vapor

Property Variations with Temp. & Time

1. Thermal conductivity :

$$k(T) = 0.023(T - 273)^{0.46}$$

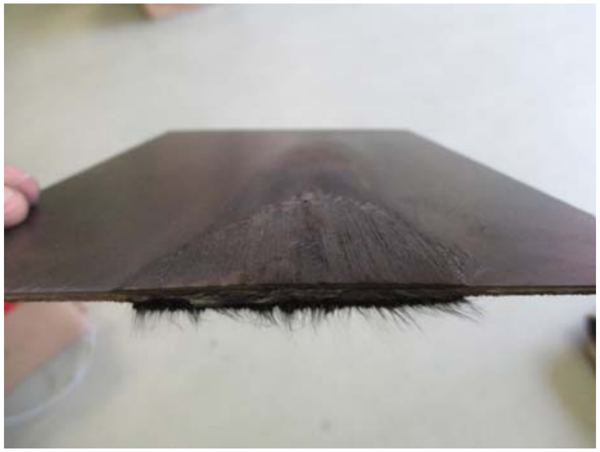


2. Specific heat: $c_p(T) = 1000(0.75 + 0.0041(T - 273))$

3. Swelling of laminate:

$$l = l_0 + \alpha(l_f - l_0)$$

α = extent of thermal degradation



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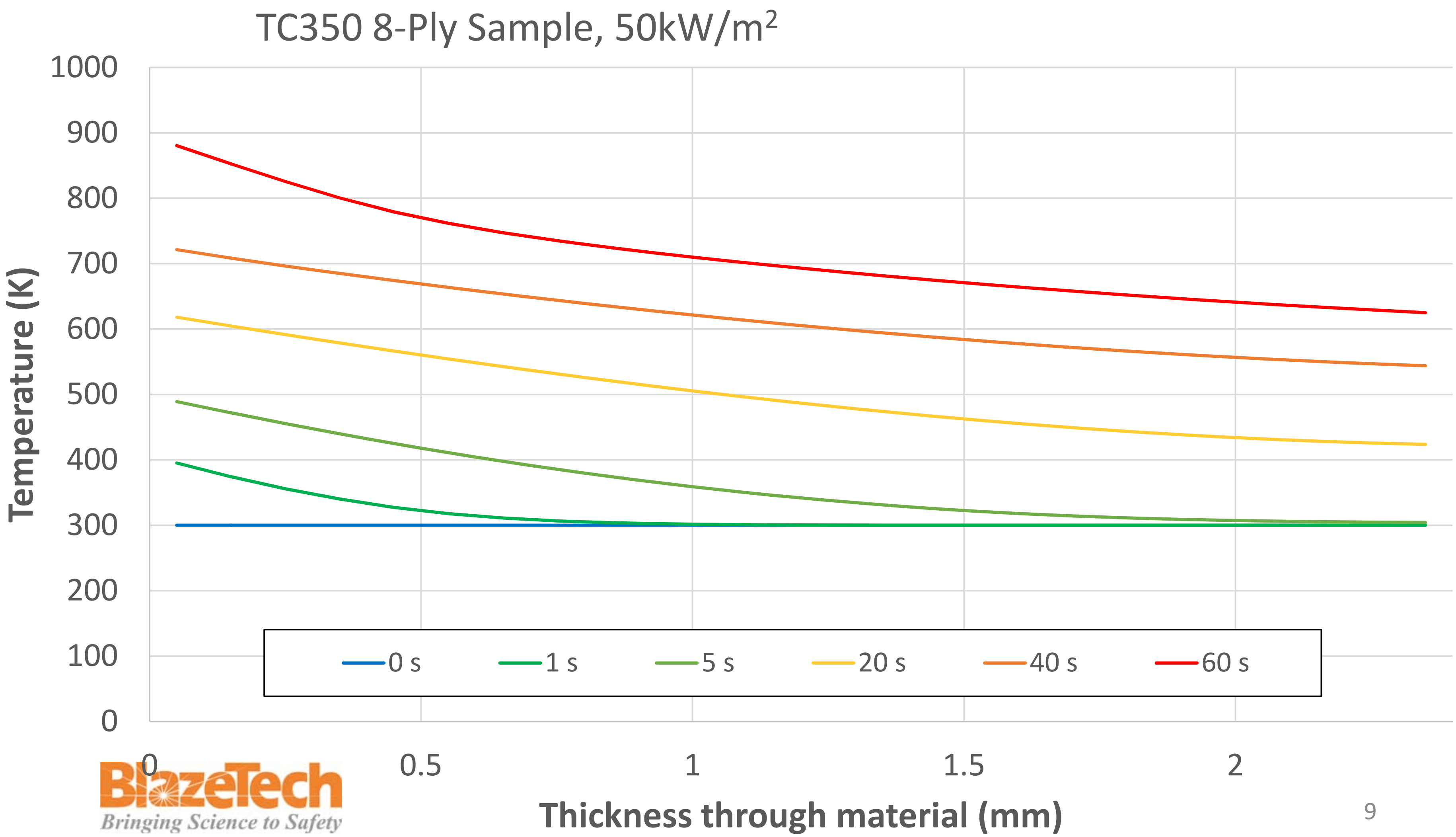
Predicted Temperature Profile at Various Times for Constant Heat Flux



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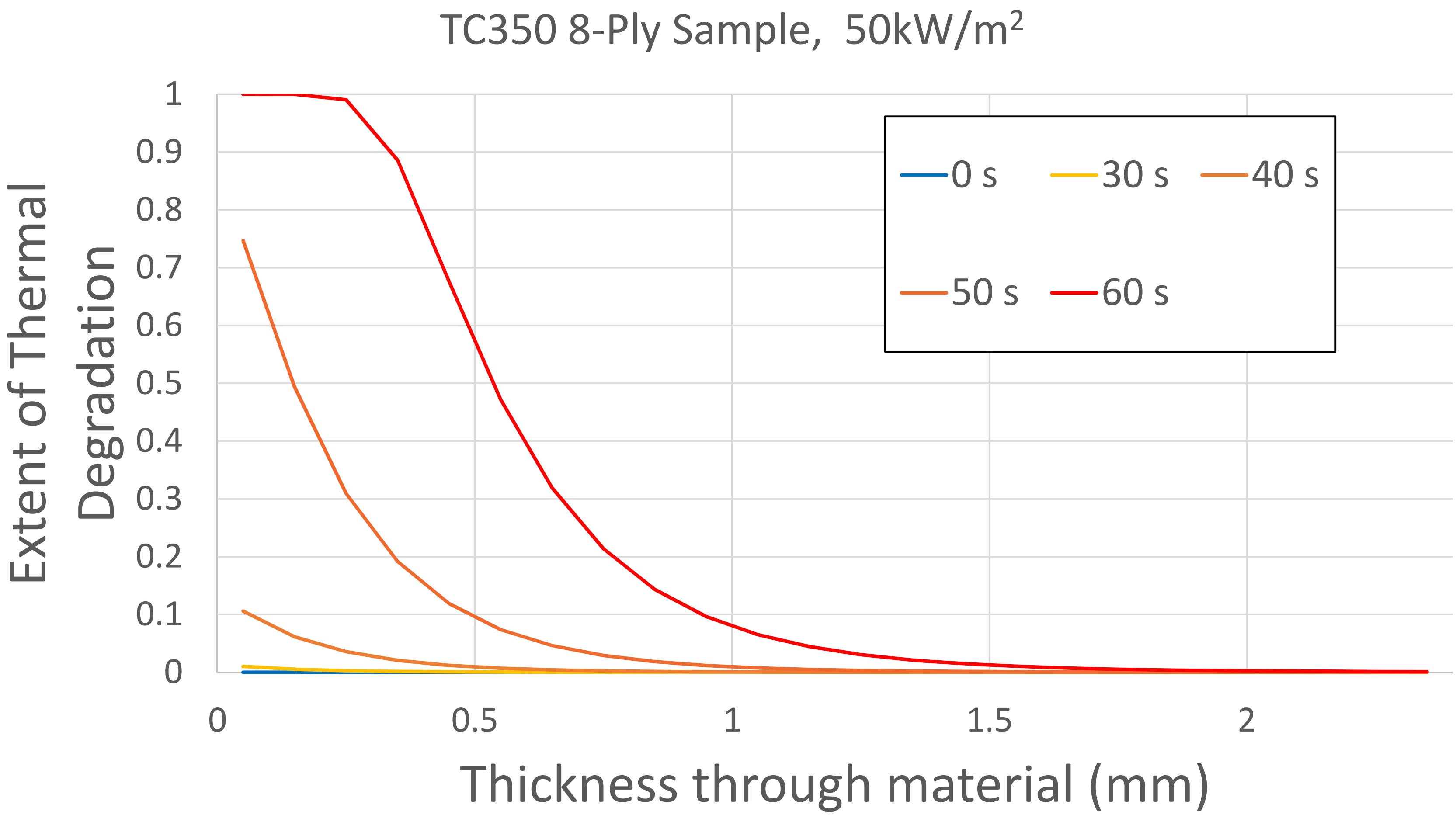
Predicted Epoxy Thermal Degradation Profiles at Various Times under Constant Heat Flux



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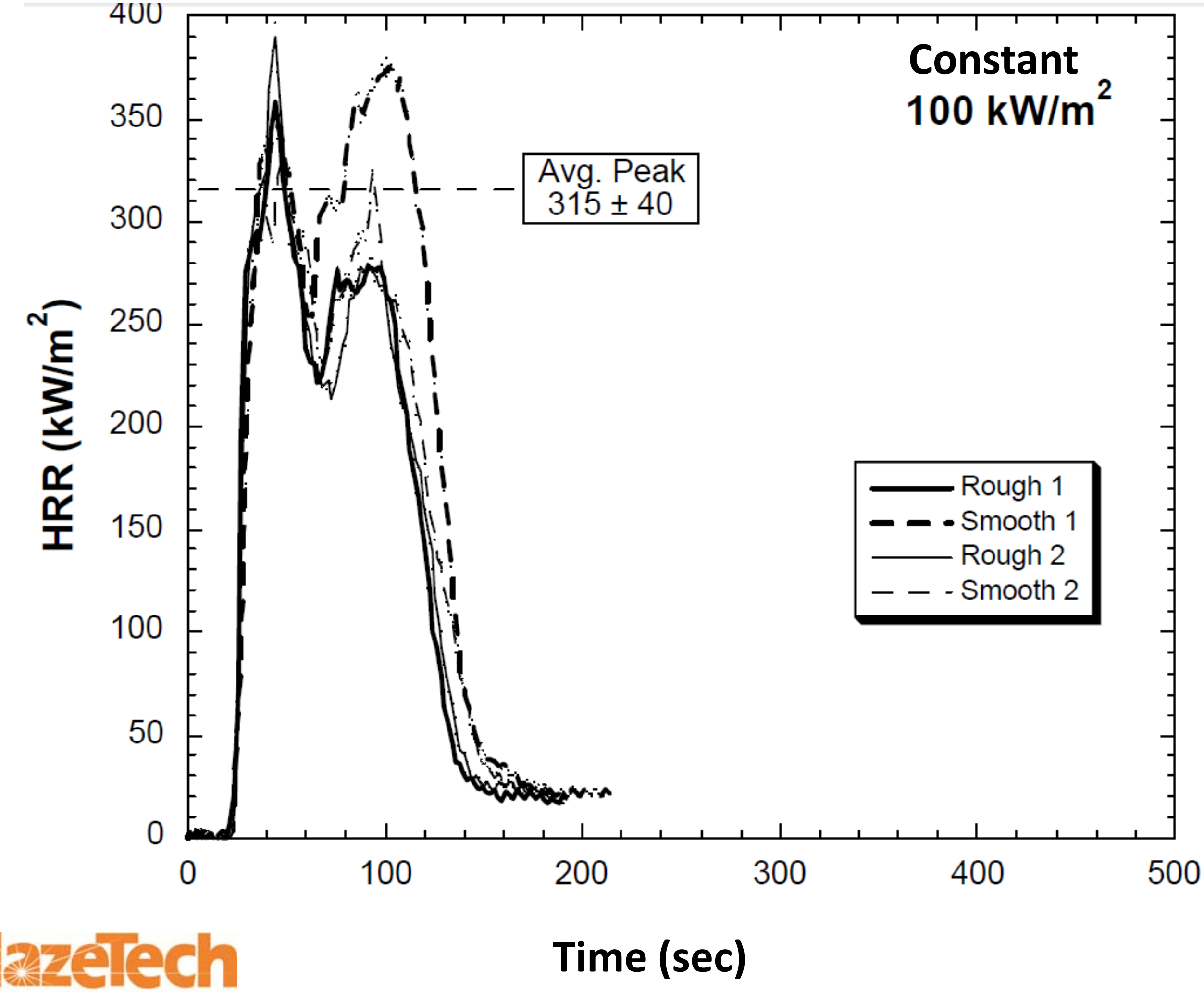
Measured Heat Release Rate (HRR)
Cone calorimeter from Ref. 1



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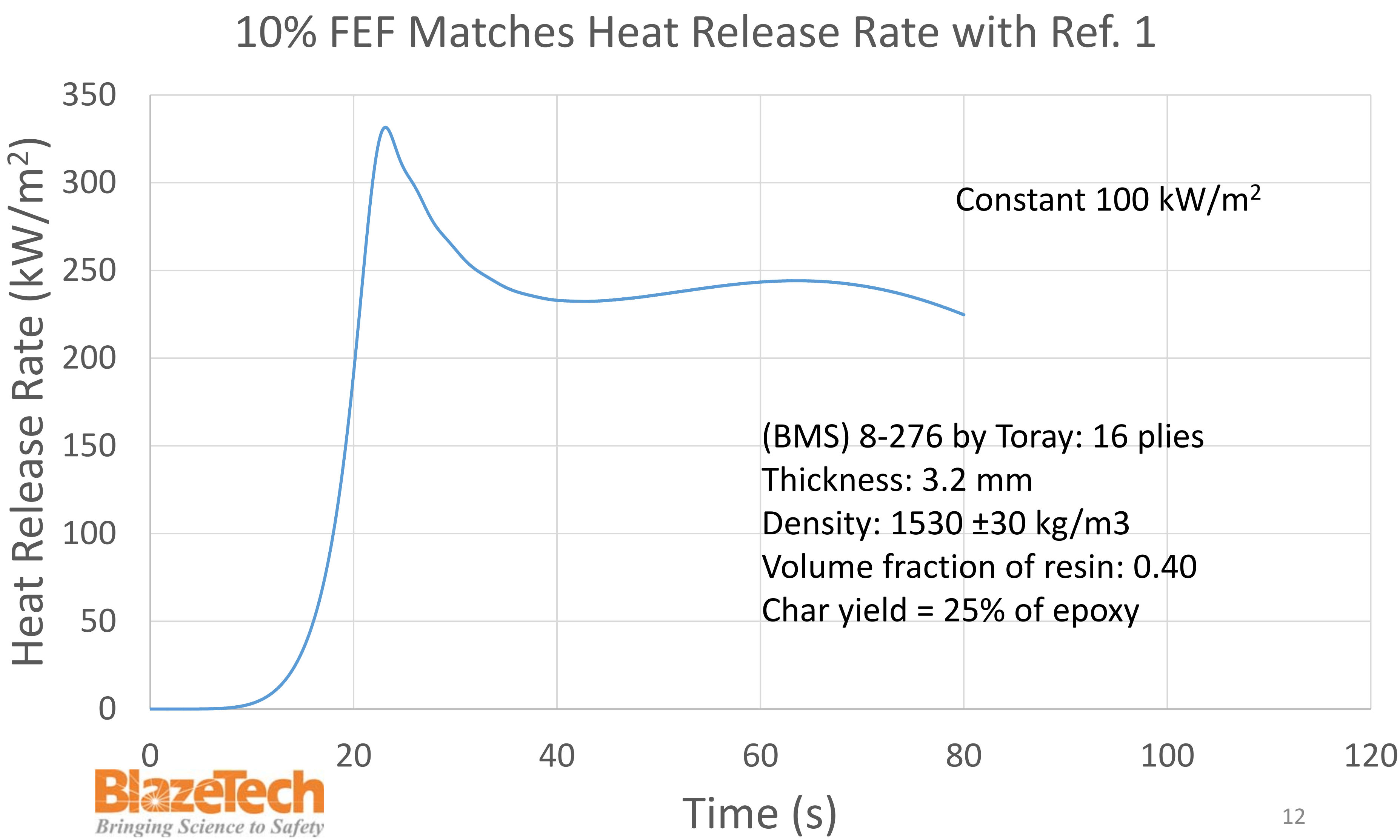
Calibration of Model Flame Energy Feedback (FEF)



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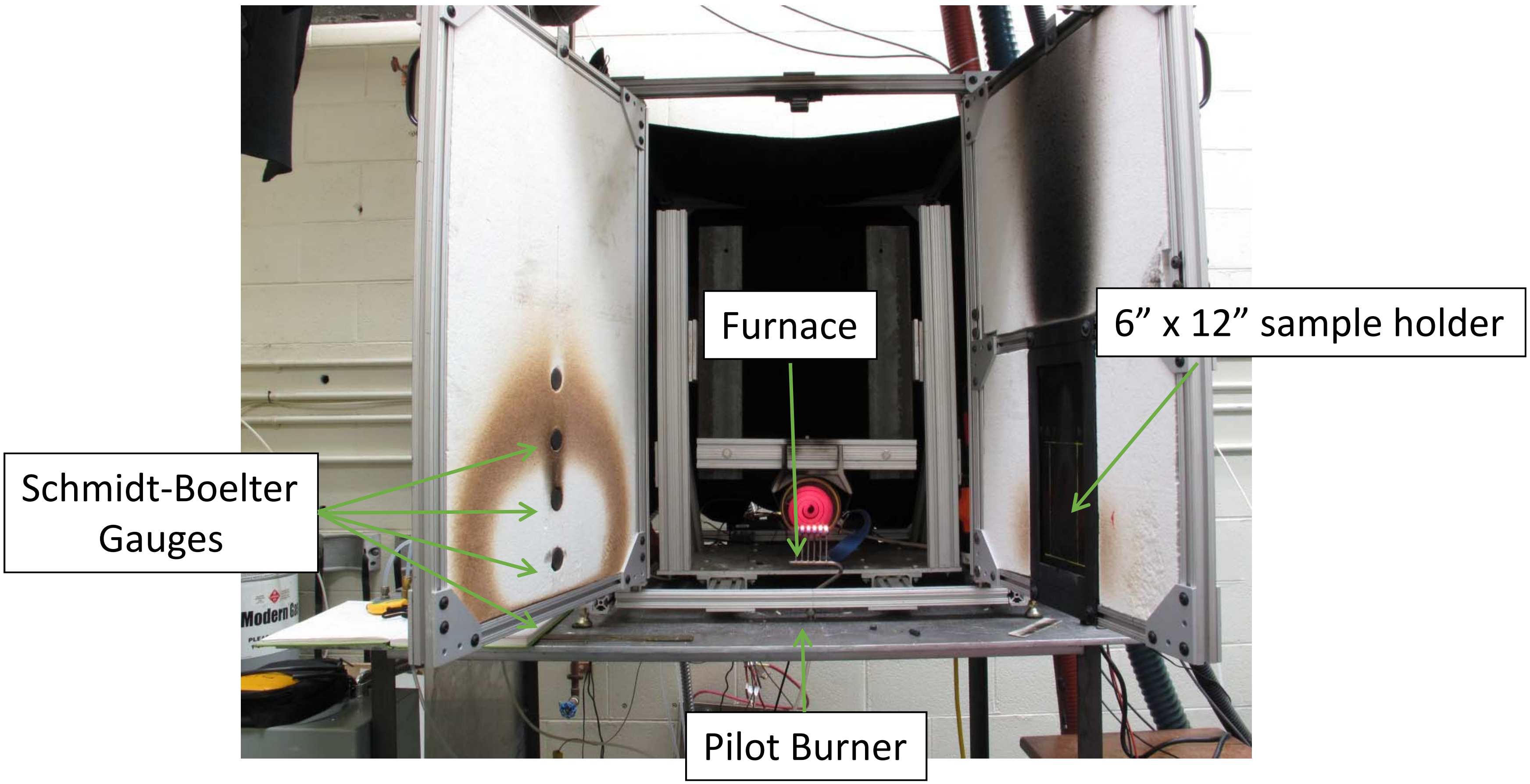
Part 2. FAA Test Data (from Ref. 2)

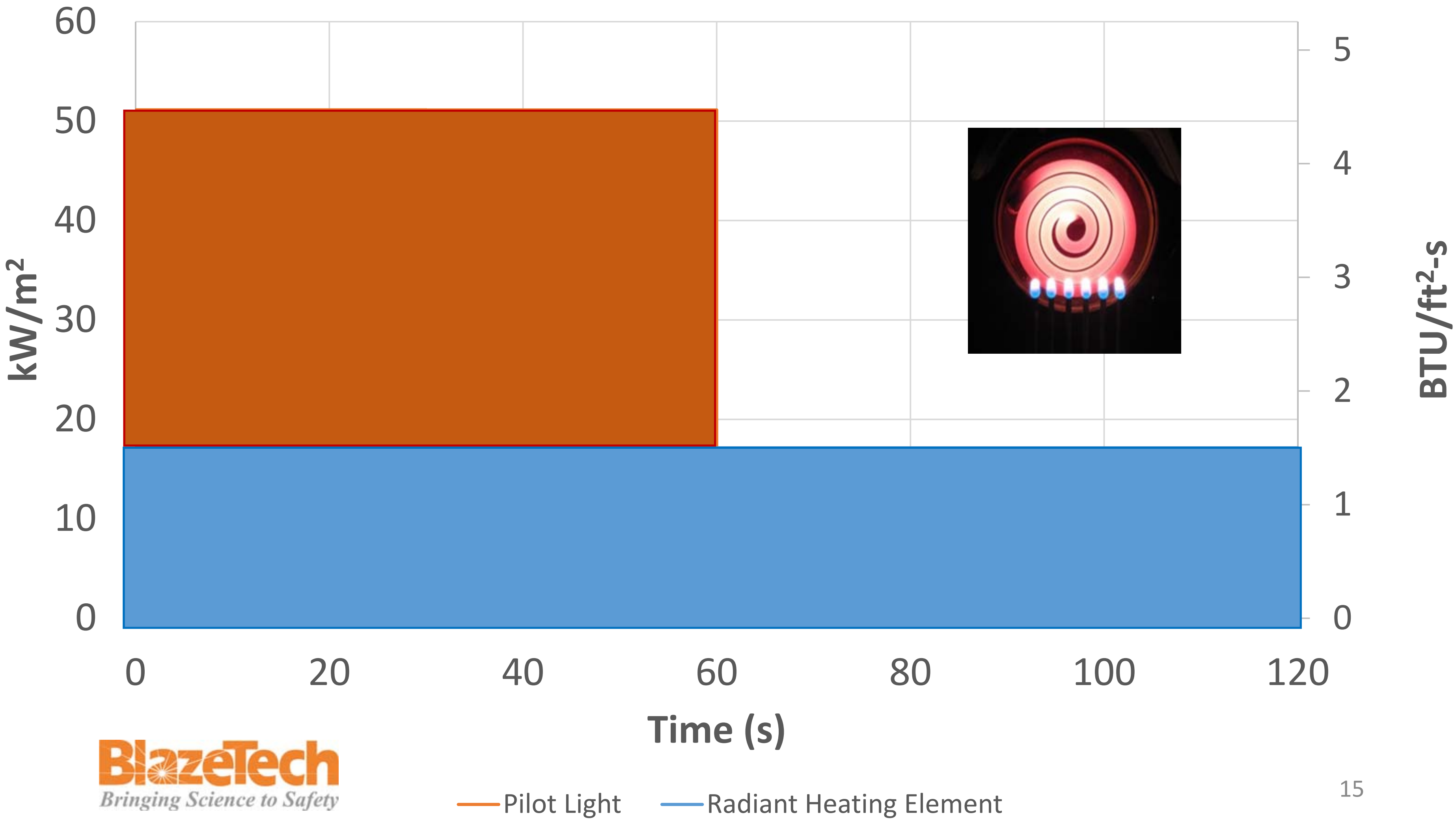
FAA Vertical Radiant Panel (VRP)

Under Development for Internal Fires (from Ochs)



Variable Incident Heat Fluxes in VRP Furnace

Simulates a Foam Block Fire



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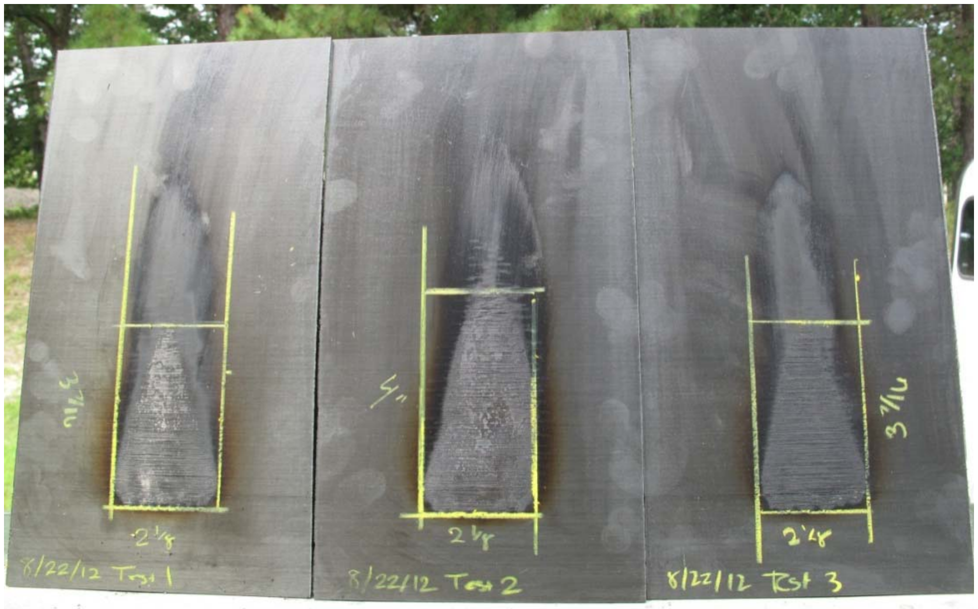
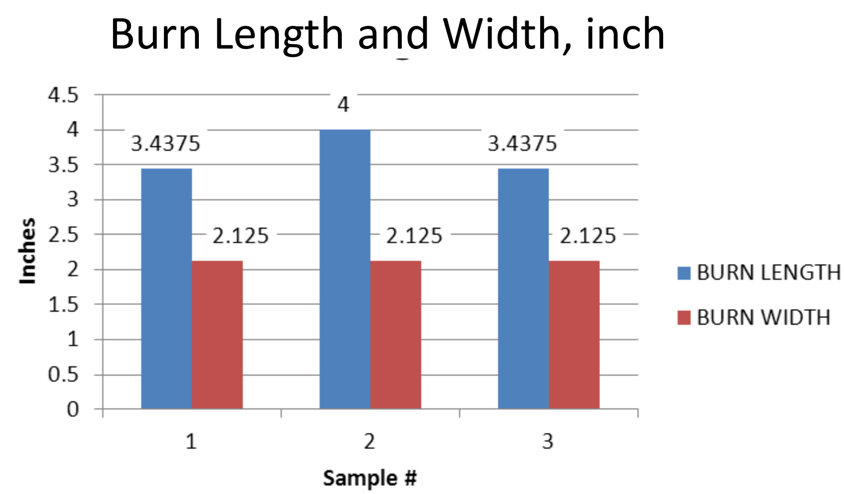
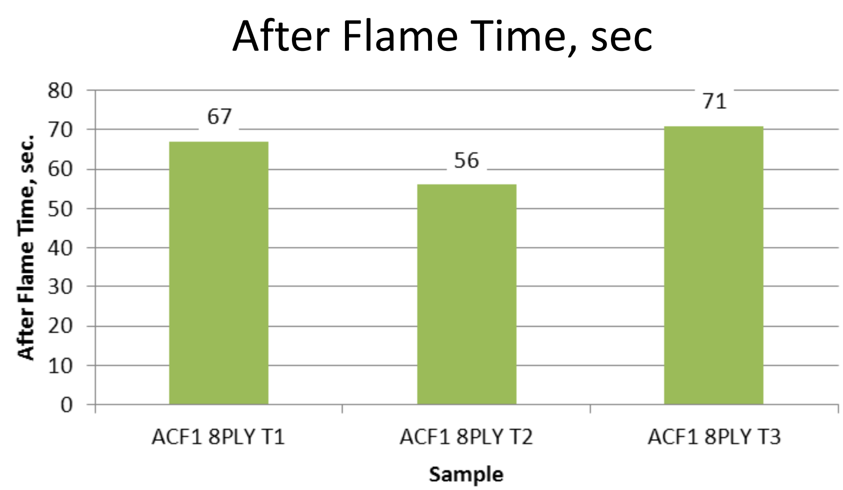
Sample Results in VRP (from Ochs)







- BL_{avg}=3.625”
  - %sd=8.95%
- BW_{avg}=2.125”
  - %sd=0%
- AF_{avg}=64.67 sec.
  - %sd=12.011%

~ 18 tests per specimen.

Lots of variability in results; back side conditions important

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Materials Used in Comparison of Predictions with Measurements

Material Composition and % Mass	Plies	Thickness (mm)
Carbon fiber: T700 Epoxy TC250 (41 +/-3%)	4	1.1
	8	2.0
	12	2.8
	16	3.8
Carbon fiber: T700 Epoxy TC350 (34 +/-3%)	4	1.4
	8	2.5
	12	3.7
	16	4.9

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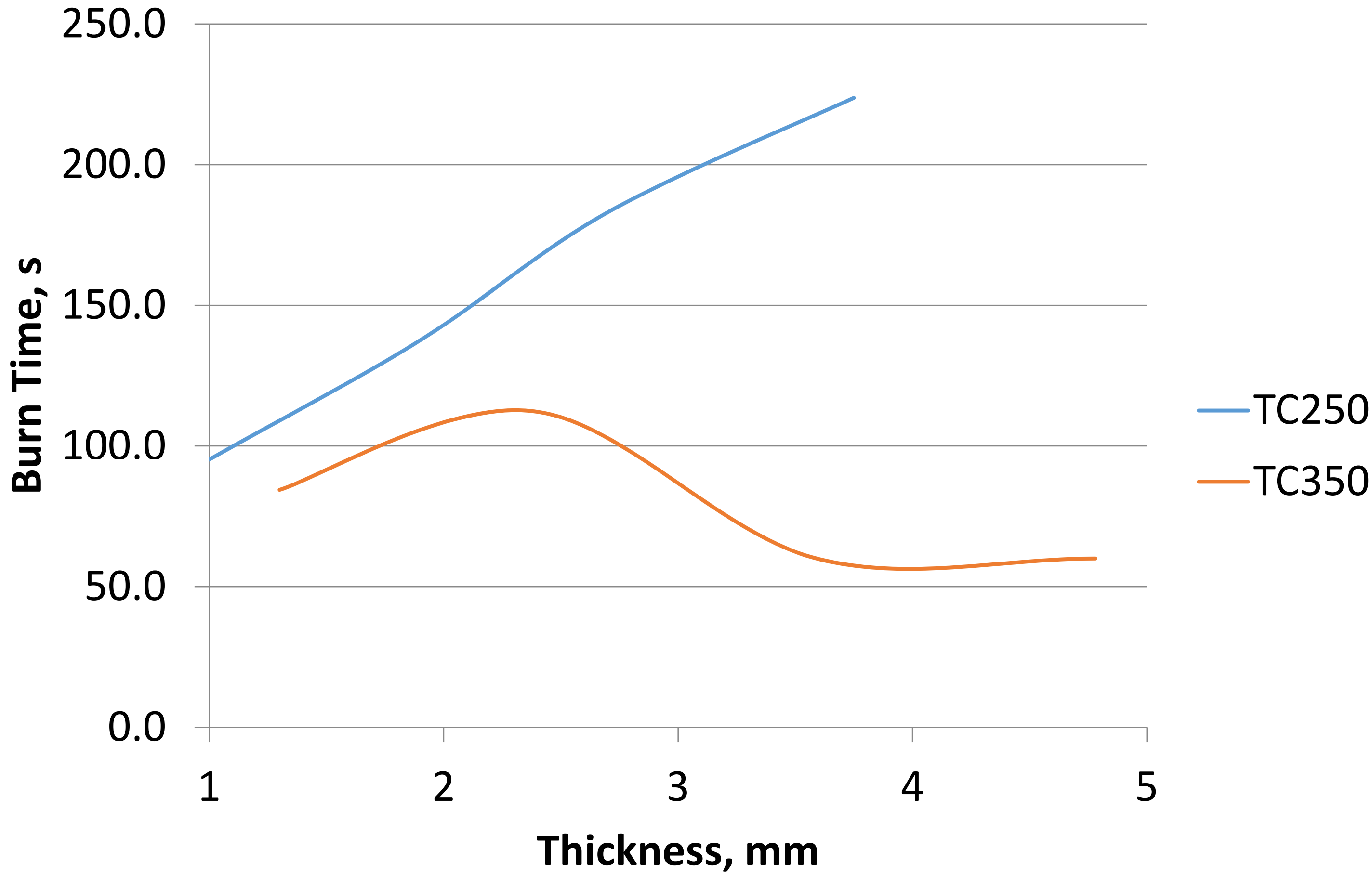
Measured Burn Time vs. Panel Thickness for the 2 Materials



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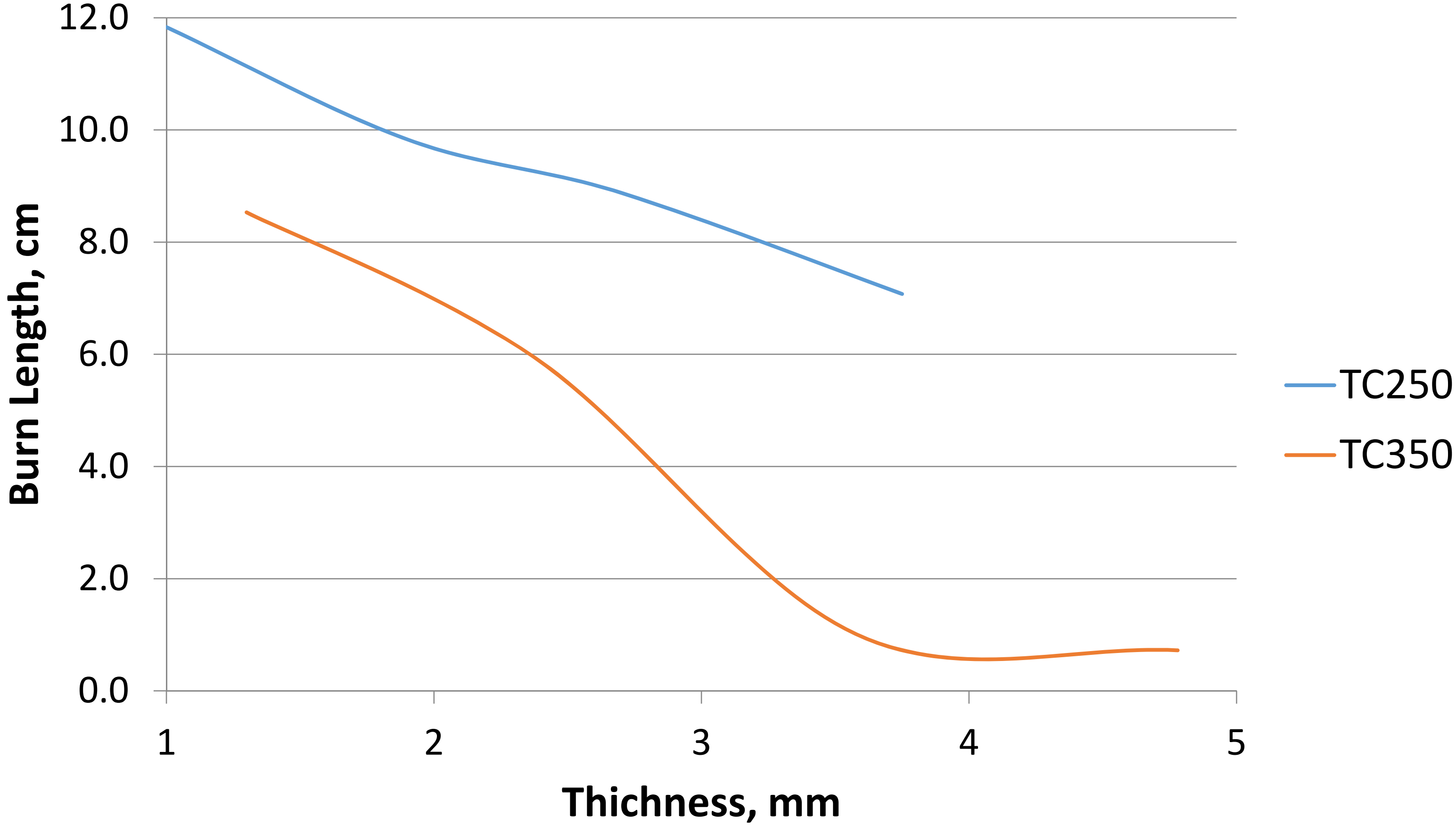
Measured Charred Length vs. Panel Thickness for the 2 Materials



Part 3. Model Predictions and Comparison with FAA Test Data

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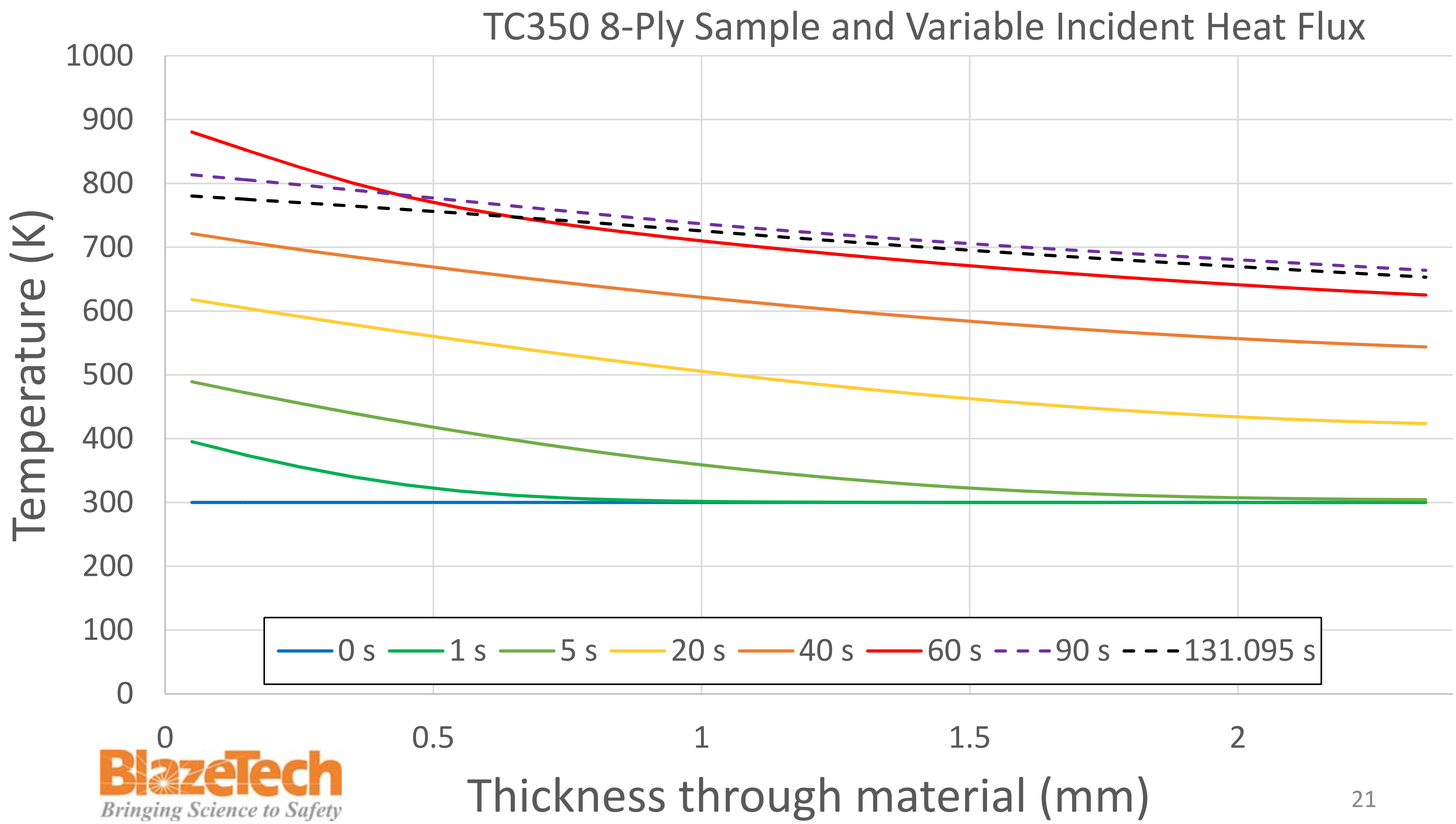
Temperature Profile at Various Times up to Extinguishment in VRP



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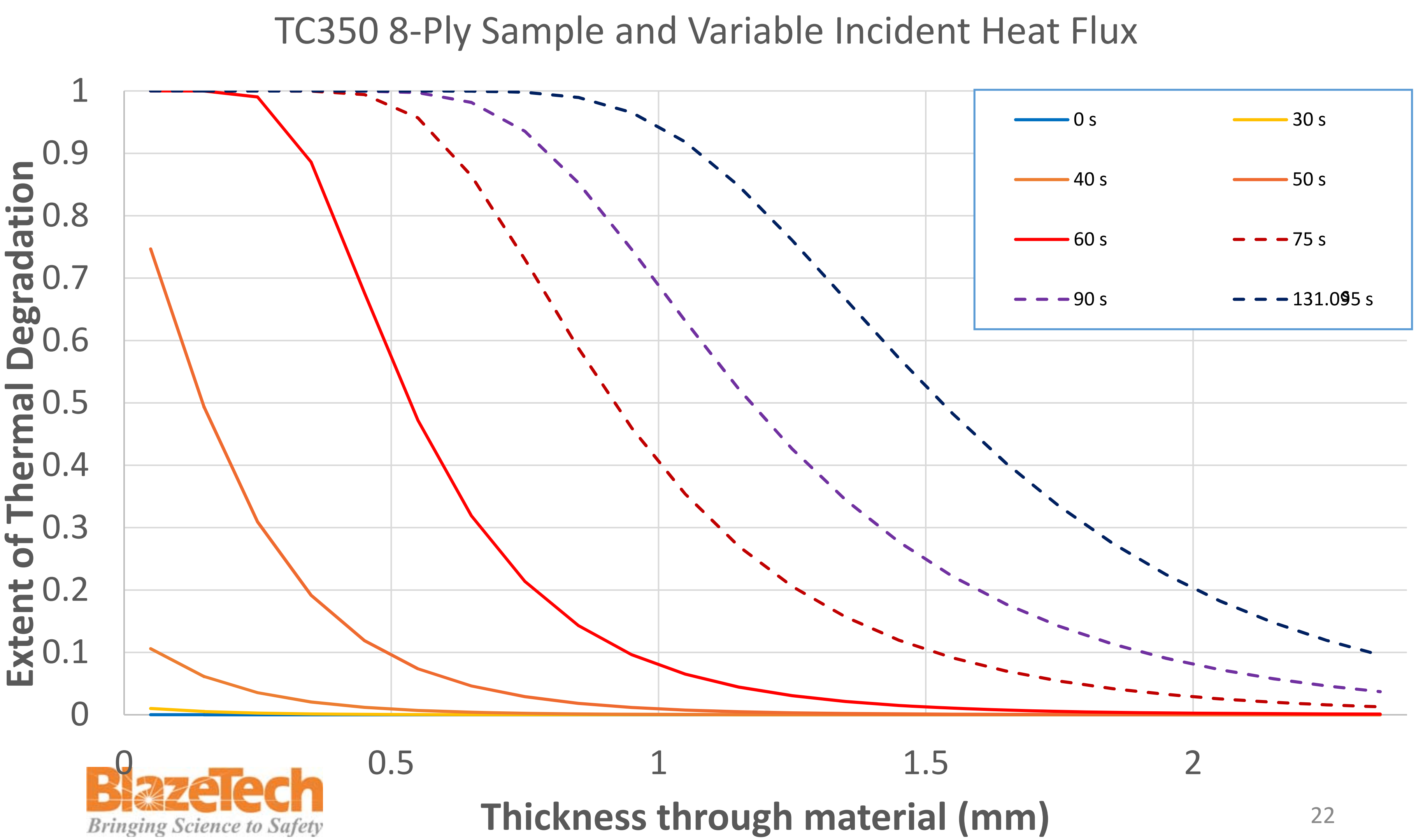
Epoxy Thermal Degradation Profiles at Various Times up to Extinguishment in VRP



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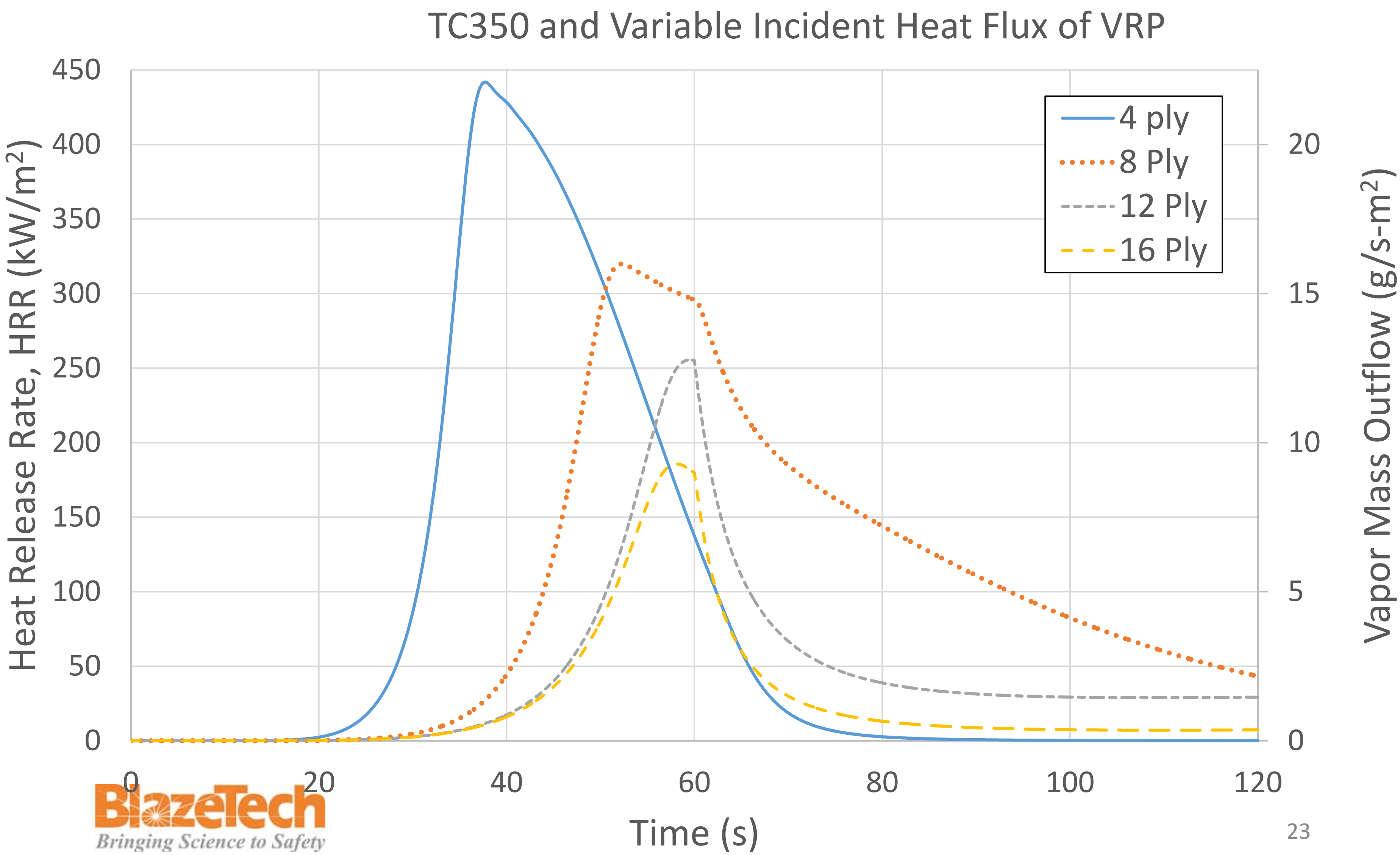
Predicted Time Histories for HRR and Resin Vapor Mass Outflow Rate for Various Thicknesses



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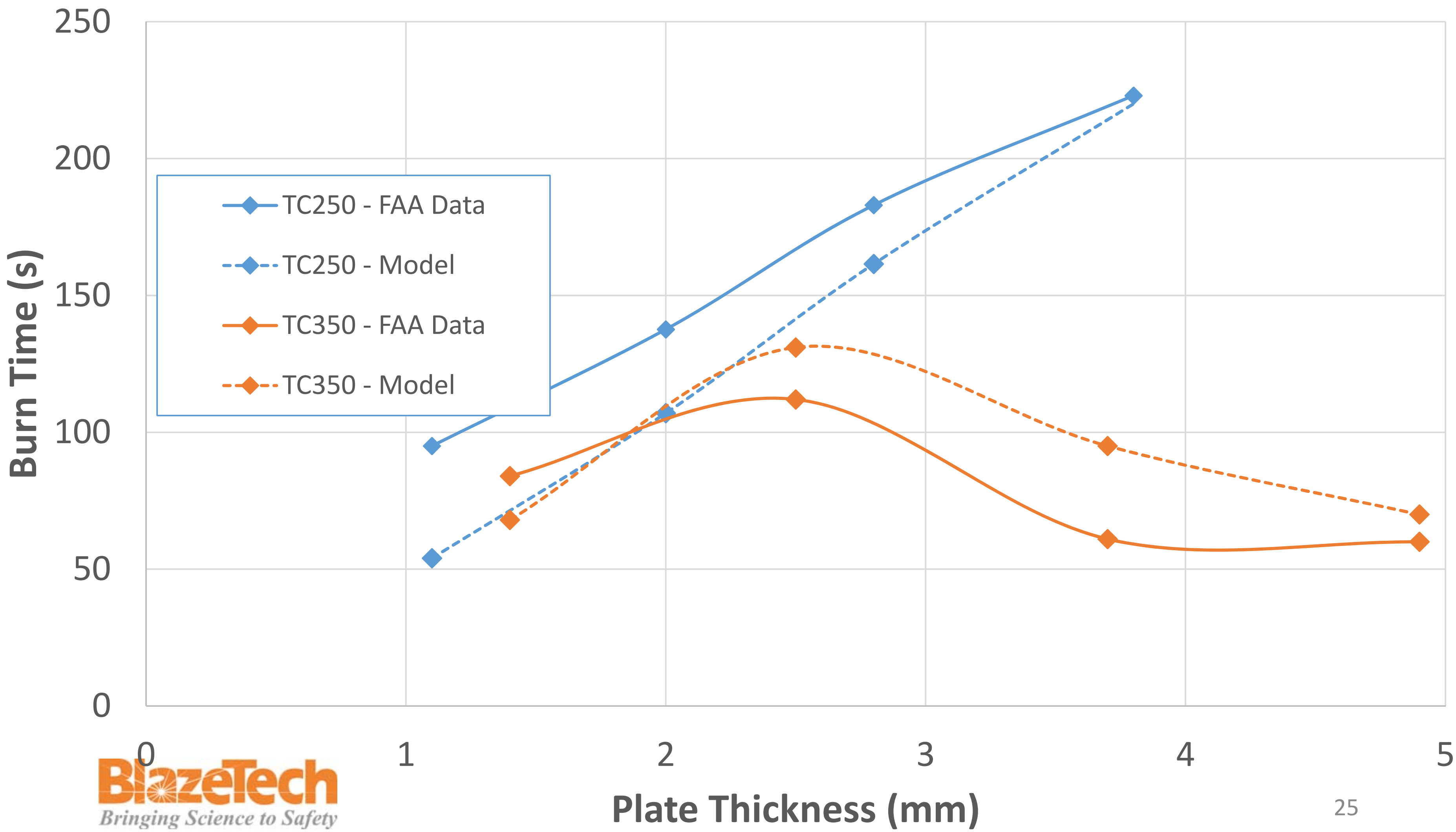
Predicted Total Burn Time

Based on 1.5 g/s-m^2 Mass Flow Cut-Off

Material (Resin)	Plies	Thickness (mm)	Total Burn Time (s)
TC250 (41%)	4	1.1	54
	8	2.0	107
	12	2.8	161
	16	3.8	180+
TC350 (34%)	4	1.4	68
	8	2.5	131
	12	3.7	95
	16	4.9	70

Predicted vs. Measured Burn Times vs. Various Panel Thicknesses

Extinguishment when resin vapor flow rate <1.5 g/s-m²



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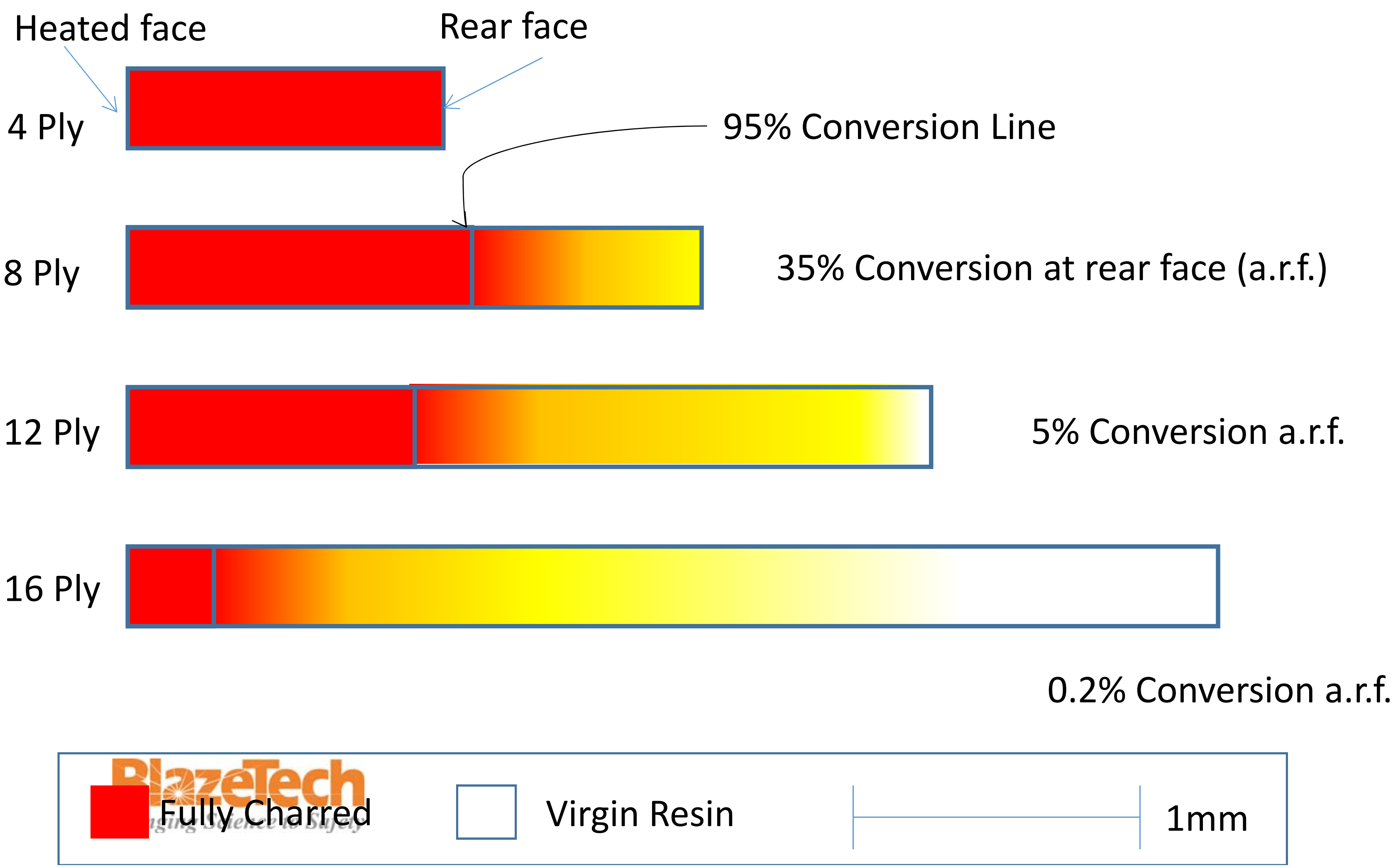
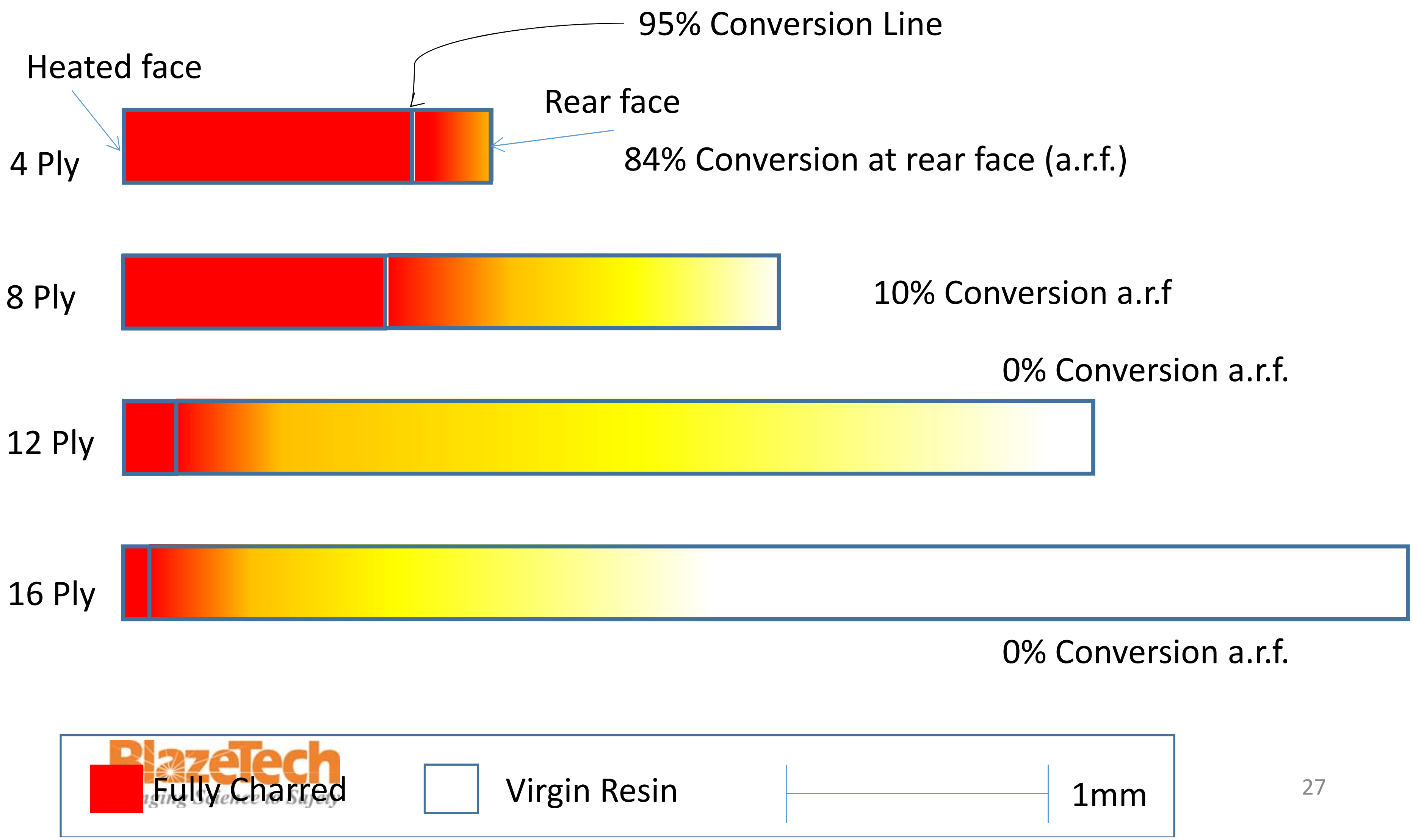
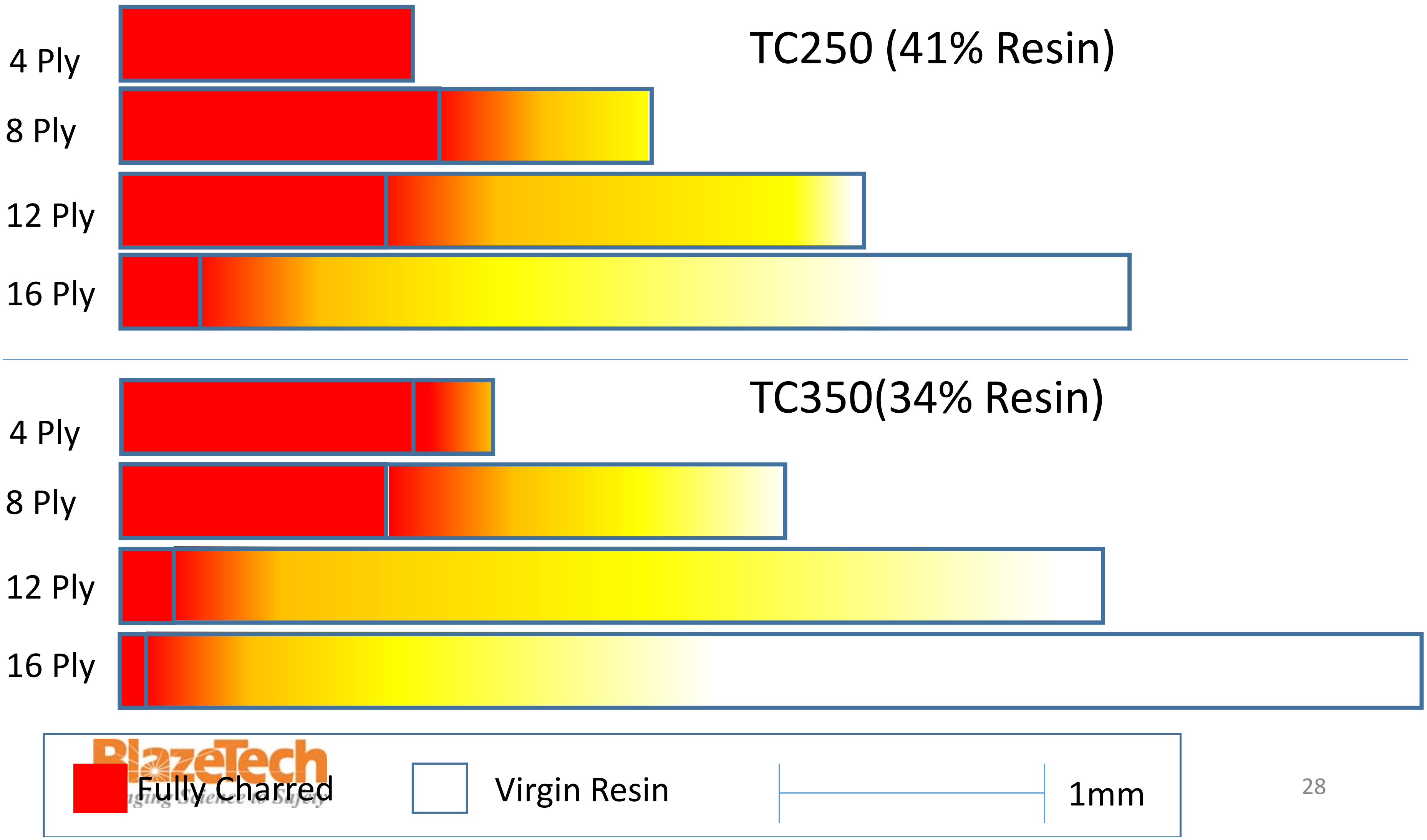
Extent of Thermal Degradation for TC250 (41% Resin)



Extent of Thermal Degradation for TC350 (34% Resin)



Comparison of TC250 and TC350



Closure

- Composite Burning Model agrees well with test data in predicting burn time and self extinguishment
- Entire Process is transient → self extinguishment depends on:
  - Incident heat flux level and duration (may not occur in a post crash fire)
  - Material properties

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Implications of Model

- Model quantifies the following:
  - Importance of resin content – fuels the flame → minimize it while satisfying mechanical properties
  - Importance of panel thickness – transfers heat inward and lowers surface temp. → thicker is more likely to self extinguish weight and volume penalty
  - Importance of heat loss from rear for thin panels → design issue

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Closure

- Other model implications:
  - Confirms that carbon is essentially inert
  - Challenges reported thermal insulating effect of char
- Extinguishment occurs – Good but are we safe?
  - Toxic gases? Negligible in FAA tests (Marker and Speitel, Ref. 3)
  - Residual strength for structural composites?
- Model can be coupled to applied mechanics to calculate residual strength and failure

References

1. Quintere J., Walters R. N. and Sean Crowley ,“Flammability Properties of Aircraft Carbon-Fiber Structural Composite”, DOT/FAA/AR-07/57 , October 2007.
2. Ochs, Robert, “Development of a Lab-Scale Fire Test Method for Composite Structure”, FAA Presentation at IAMFTWG, Indianapolis, IN, October 16-17, 2012.
3. Marker, Timothy R. and Louise C. Speitel, Evaluating the Decomposition Products Generated Inside an Intact Fuselage During a Simulated Postcrash Fuel Fire”, DOT/FAA/AR-09/58, June 2011.

Questions?

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