Progress in 3-D Modeling of Wood Fire Growth using a PC

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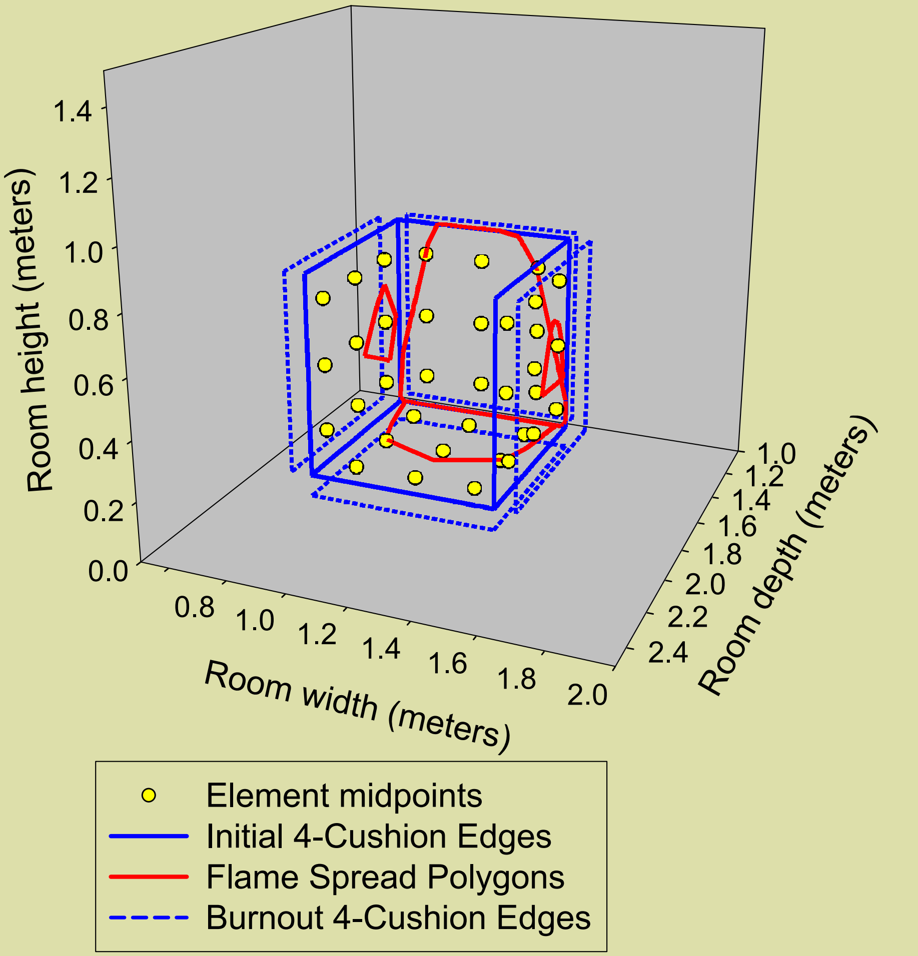
Importance to FPL and Fire Safety

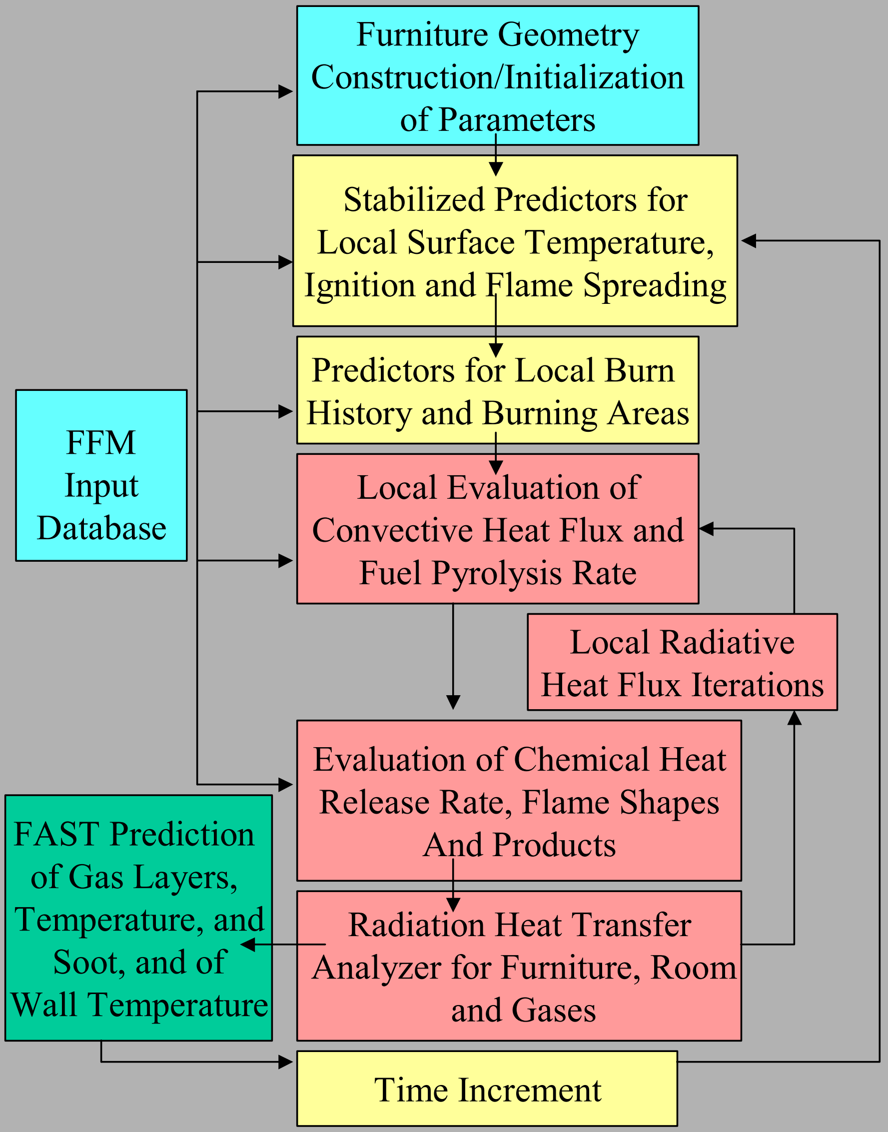
- Importance of ASTM E 84 tunnel test to wood industry
- Future impact of performance-based codes on use of wood products in U.S. and world-wide
- Impact of flammability requirements on use of composites
- Improved evaluation of FRT wood products
- Increasing requests for our fire test data for research studies in fire growth

Presentation Outline

- Refresher on FFM-FAST18 Model
- Furniture Burn in ISO9705 Room
- Evaluation of Bench-Scale Data for Wood
- Insights from Bomb Calorimeter and PyroCat Data for Wood
- Fire Growth Modeling via Analytical Solutions

Simulation of Fire Growth on Mockup in ISO9705 Room's center (at 203 s)





FFM Input Database

Furniture Geometry Construction/Initialization of Parameters

Stabilized Predictors for Local Surface Temperature, Ignition and Flame Spreading

Predictors for Local Burn History and Burning Areas

Local Evaluation of Convective Heat Flux and Fuel Pyrolysis Rate

Local Radiative Heat Flux Iterations

Evaluation of Chemical Heat Release Rate, Flame Shapes And Products

Radiation Heat Transfer Analyzer for Furniture, Room and Gases

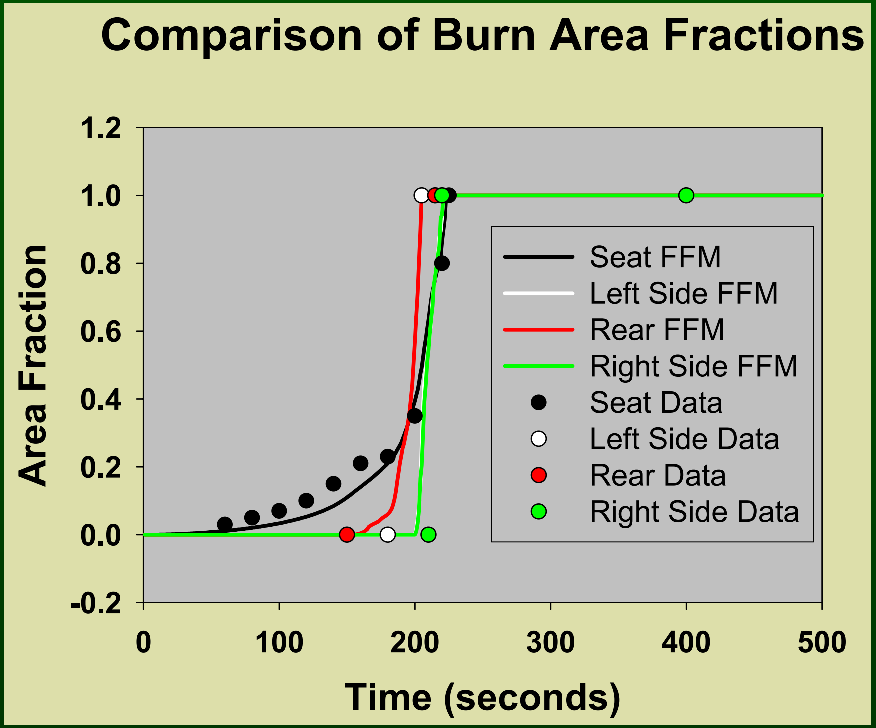
FAST Prediction of Gas Layers, Temperature, and Soot, and of Wall Temperature

Time Increment

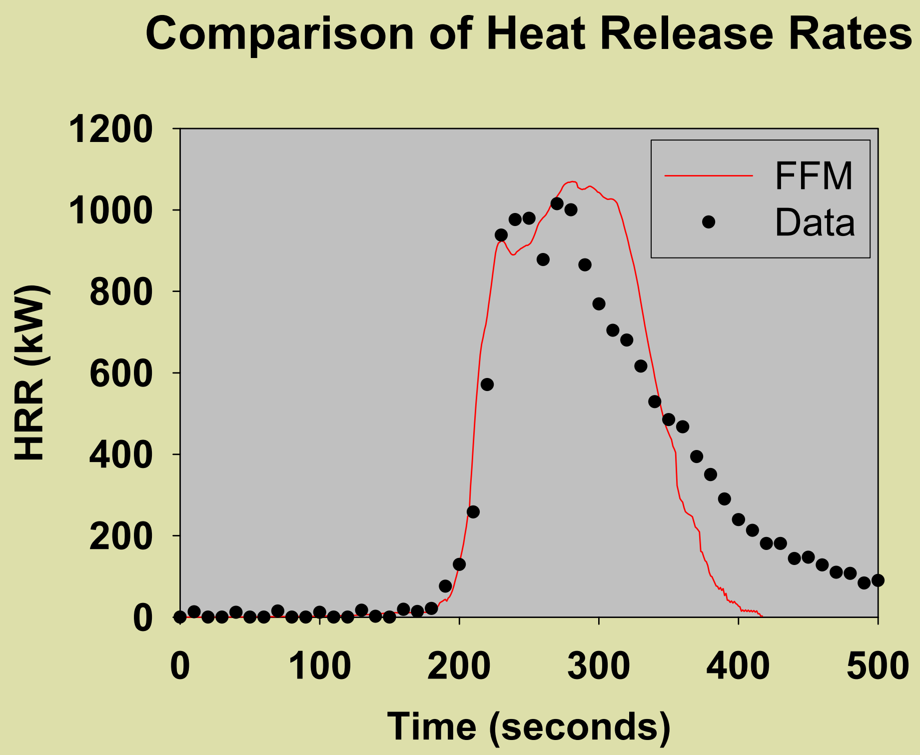
FFM/FAST18 Calculation System

Flame Spread for Heavy Olefin fabric/ FR Polyurethane foam 4-Cushion Chair

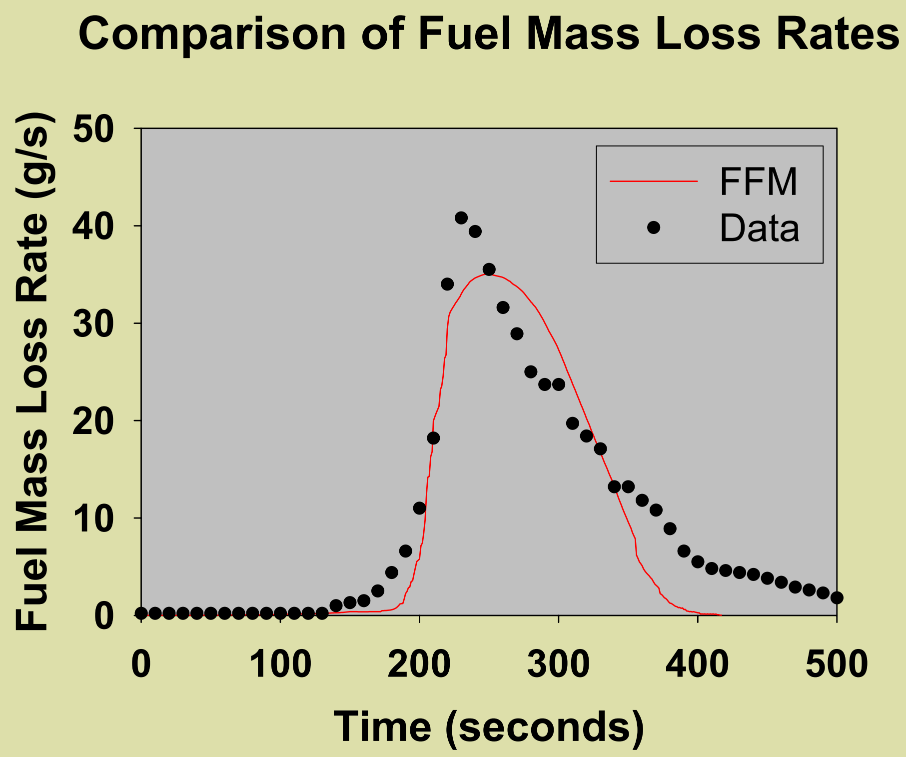
- Calibration of Parameter for Creeping Flame Spread
- CPU time of 3 minutes on Windows 2000, Pentium III
- Fractional Burn Area from VCR Records of Tests
- VCR Records also Show Arm Side Ignitions as Predicted by FFM



HRR & MLR for Heavy Olefin fabric / FR Polyurethane Foam Chair



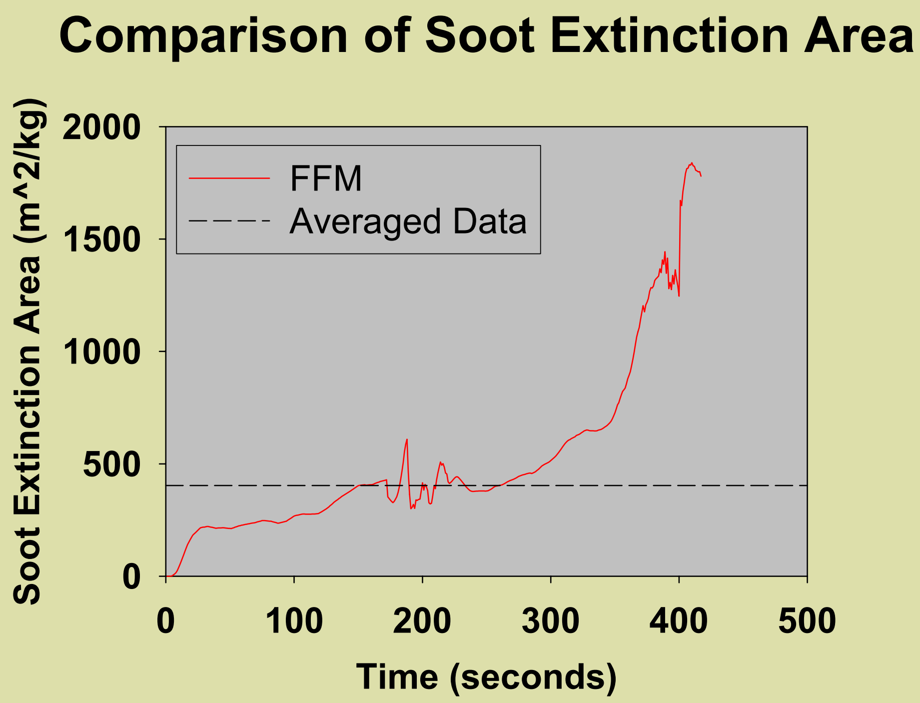
Comparison of Heat Release Rates



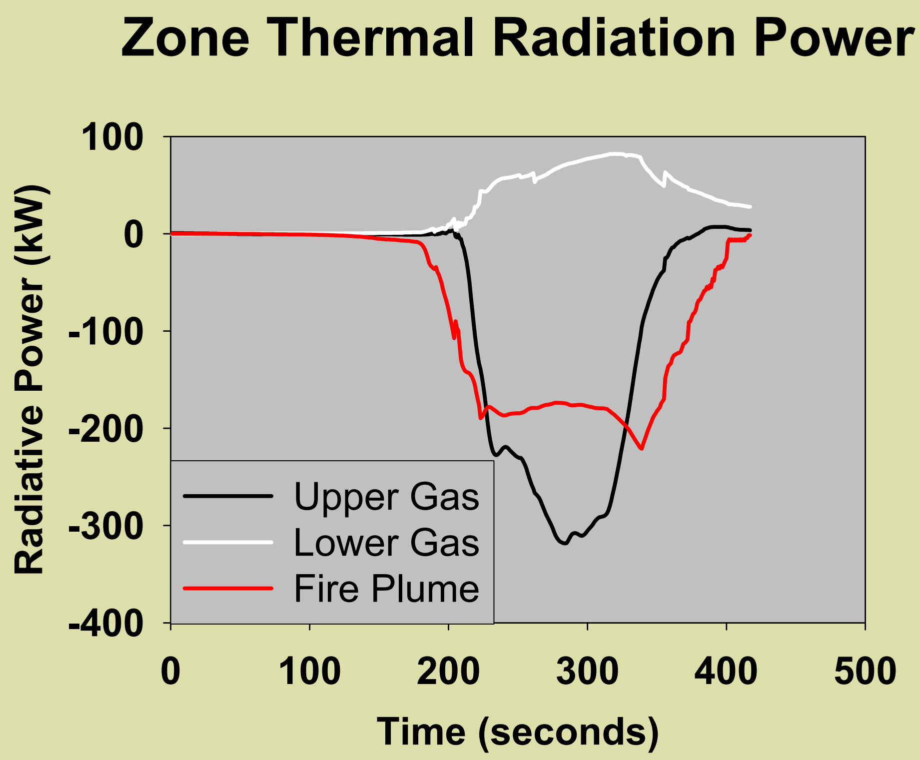
Comparison of Fuel Mass Loss Rates

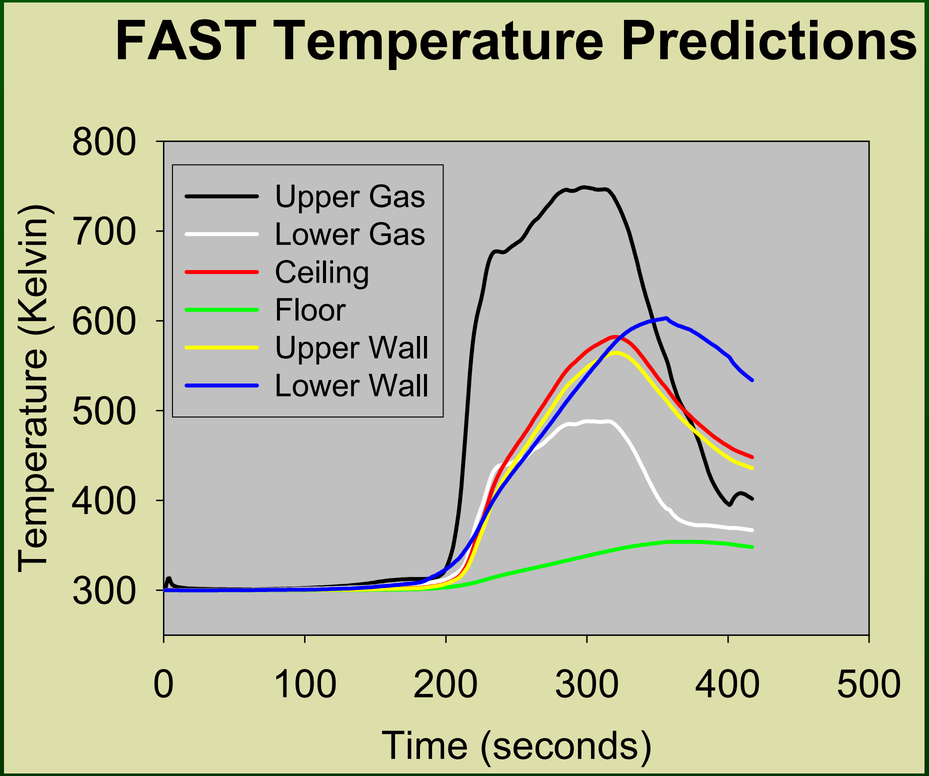
SEA for Heavy Olefin fabric / FR Polyurethane foam 4-cushion Chair

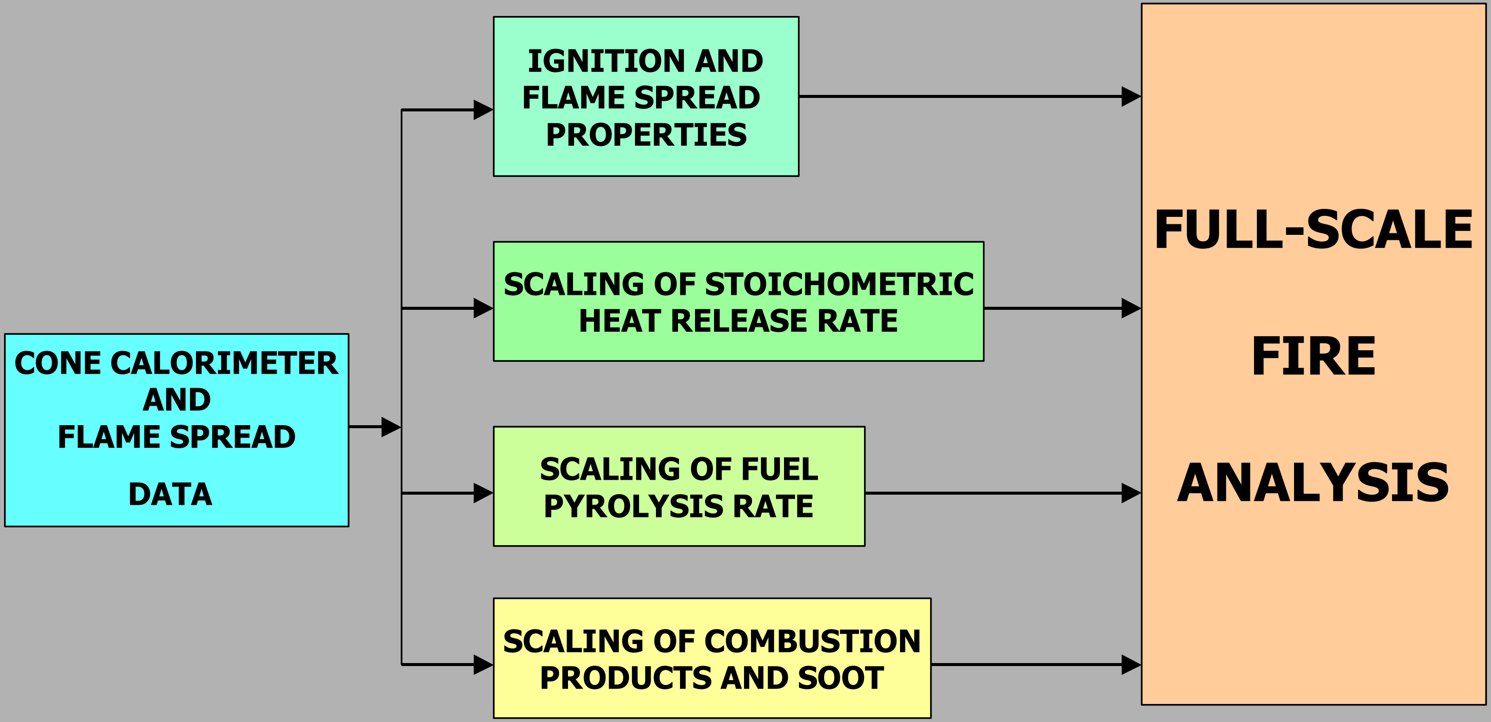
- Black Smoke Exiting the Flame is assumed to be Soot within the Flame
- Maximum Extinction Coefficient is as Measured by Pagni, et.al.
- Soot and CO Flow Rate used to Reduce Stoichiometric HRR



FFM/FAST Predictions for ISO9705 Room with Door Soffit Removed







CONE CALORIMETER
AND
FLAME SPREAD
DATA

IGNITION AND
FLAME SPREAD
PROPERTIES

SCALING OF STOICHOMETRIC
HEAT RELEASE RATE

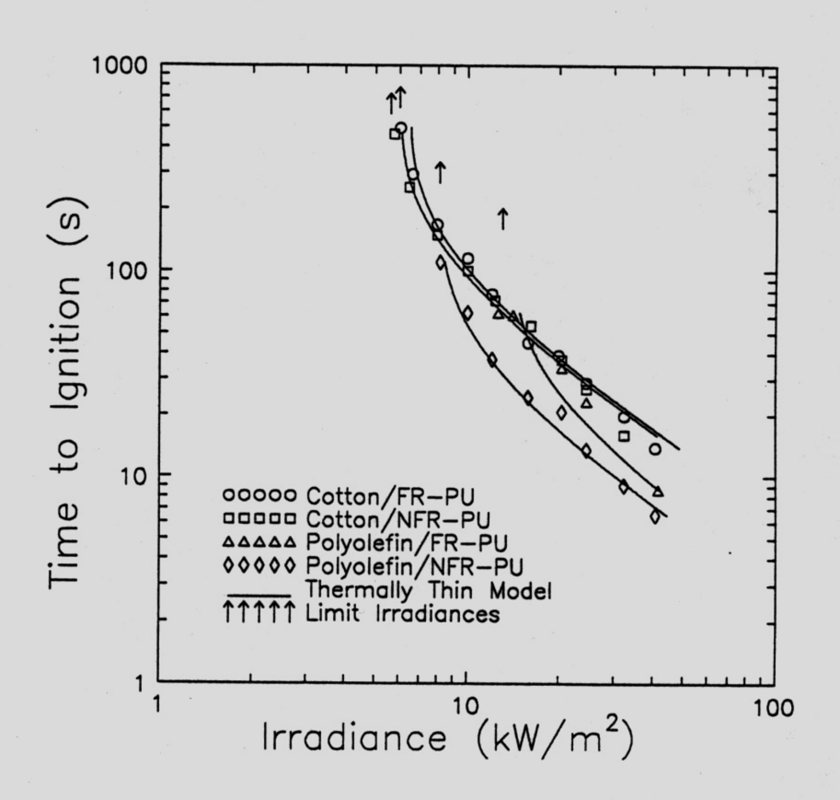
SCALING OF FUEL
PYROLYSIS RATE

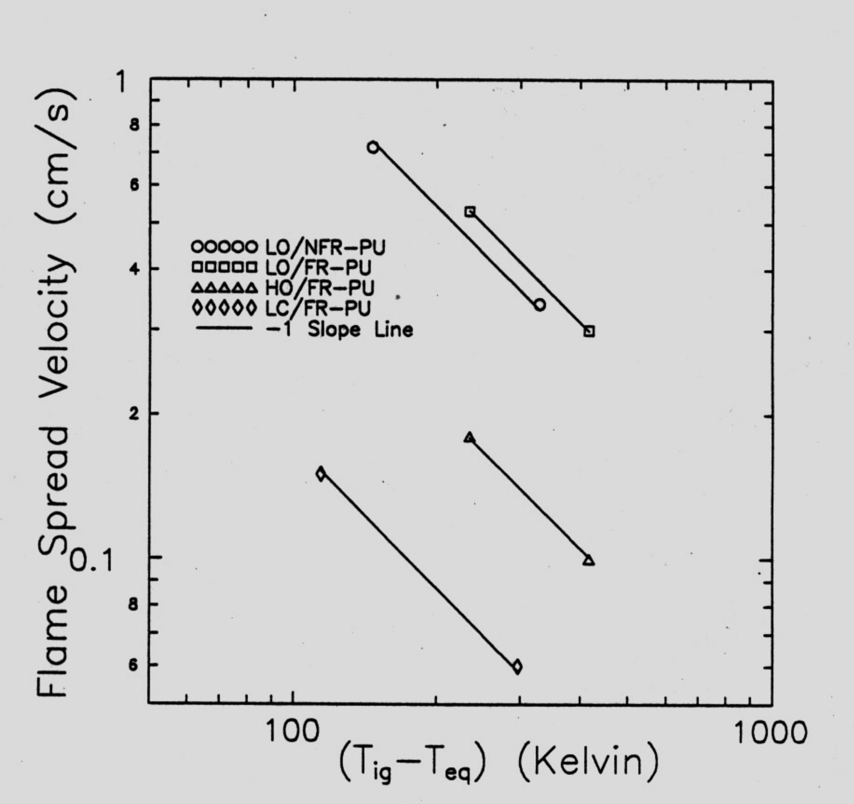
SCALING OF COMBUSTION
PRODUCTS AND SOOT

FULL-SCALE
FIRE
ANALYSIS

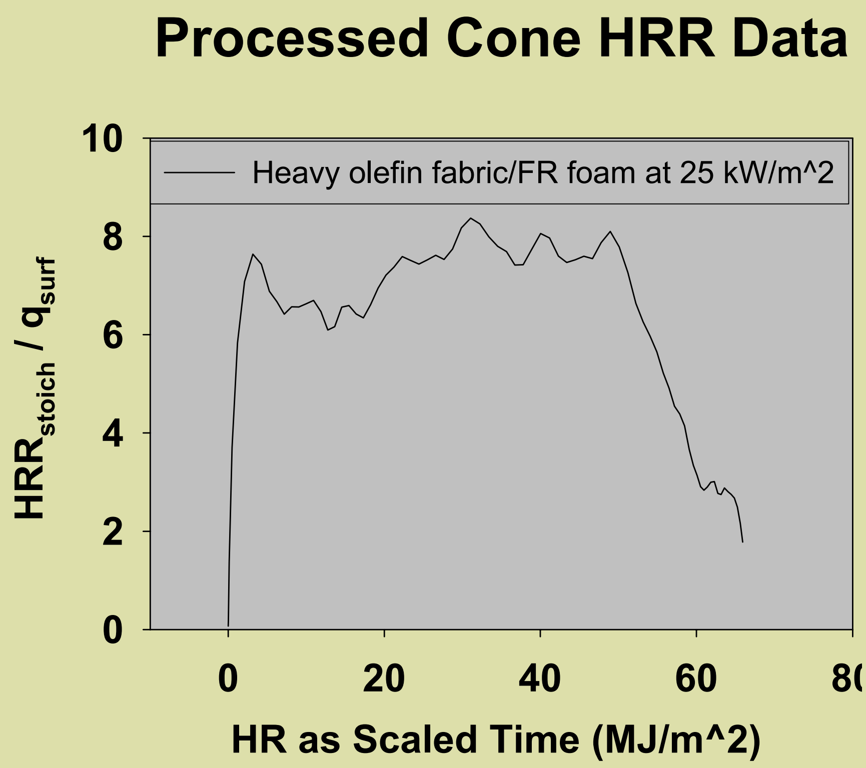
Evaluation of Bench Scale Database

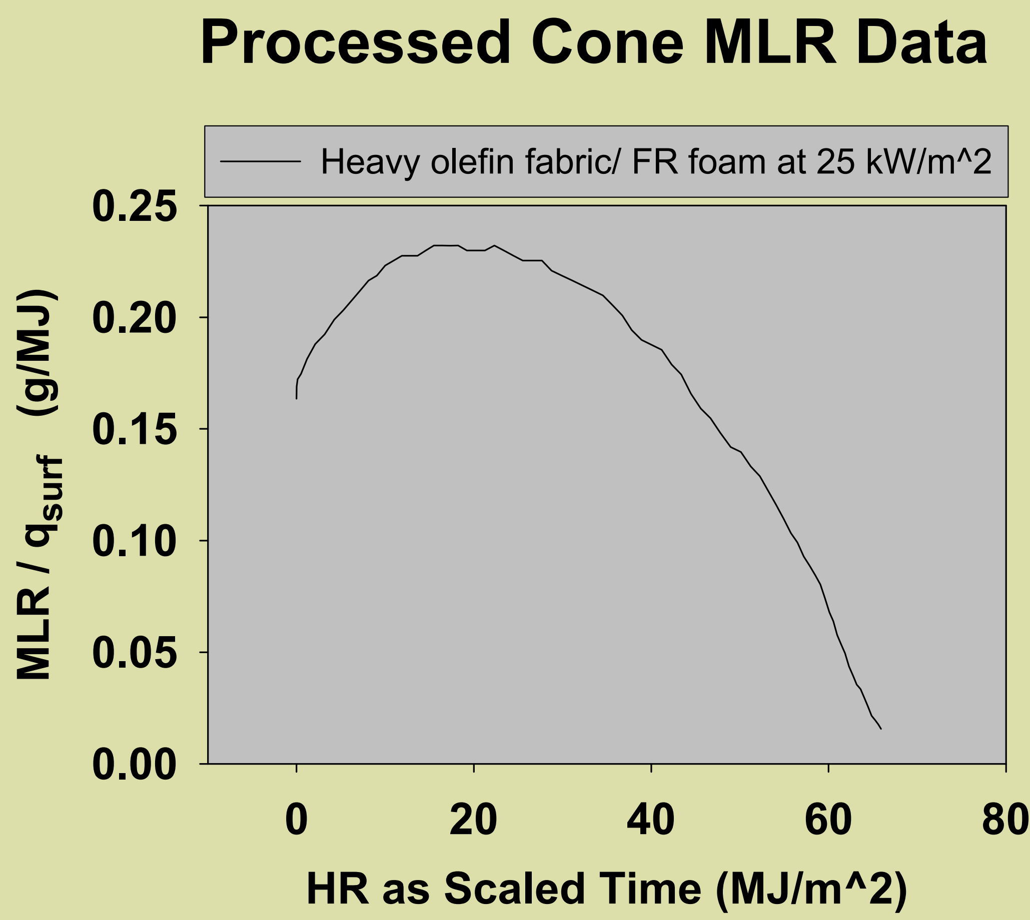
Thermally Thin Behavior for Ignition and Flame Spread on Furniture Cushions



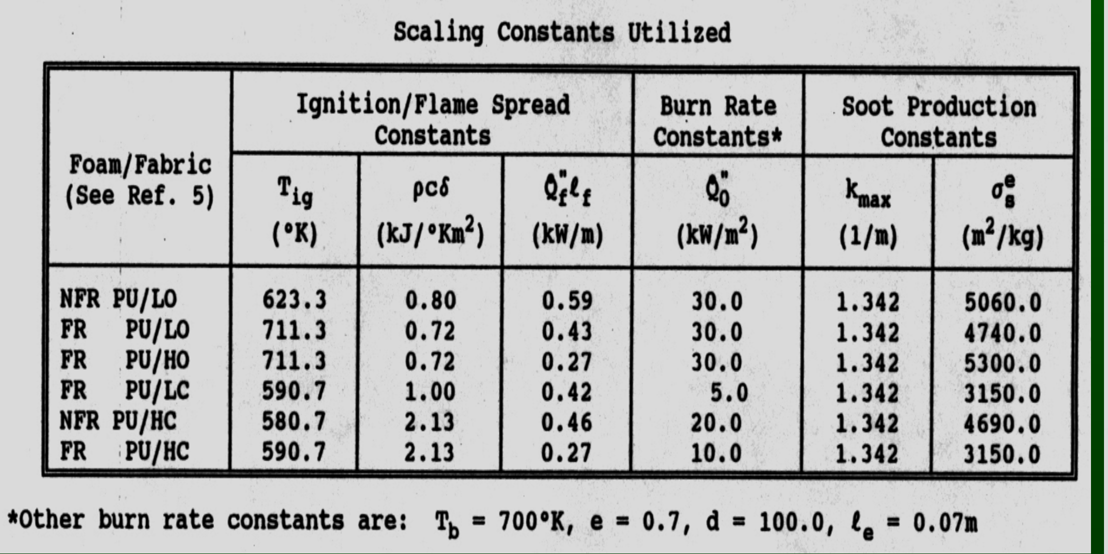


Scaled Cone Data for Heavy Olefin fabric / FR Polyurethane Foam





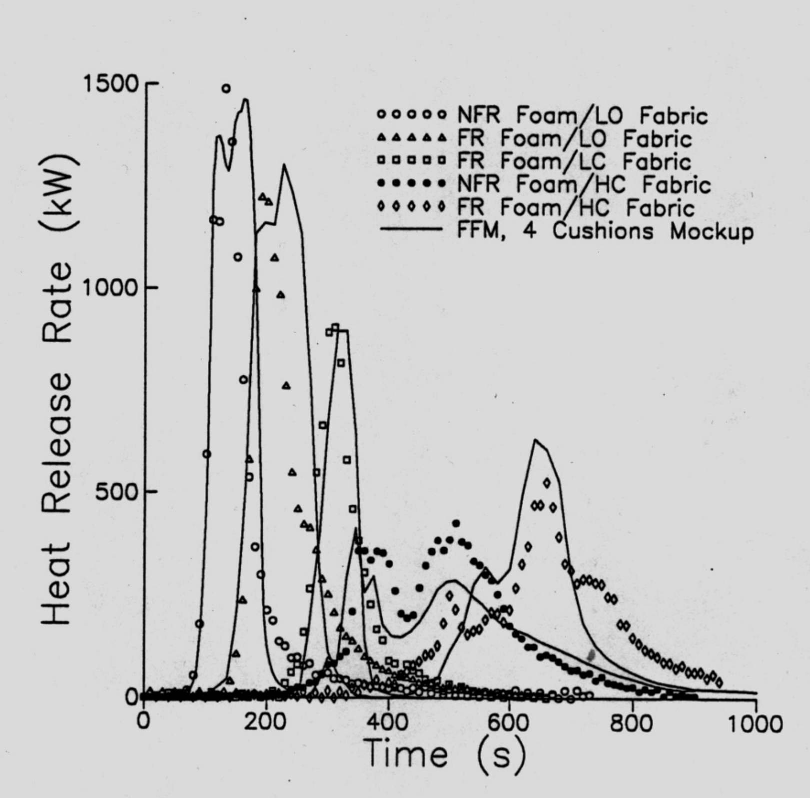
Prediction of HRR of Five Different Materials on 4-Cushion Mockup



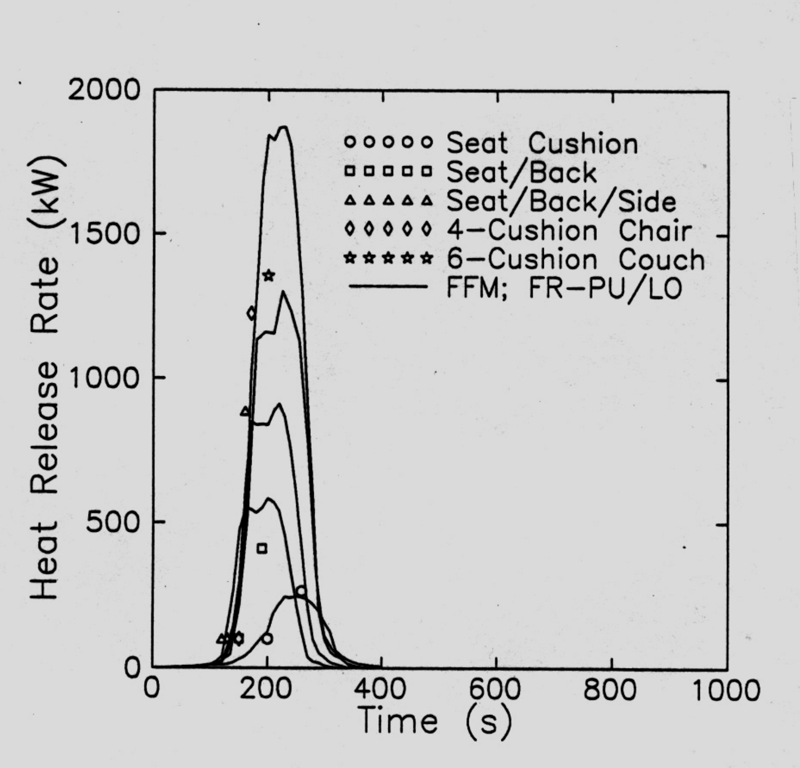
Scaling Constants Utilized

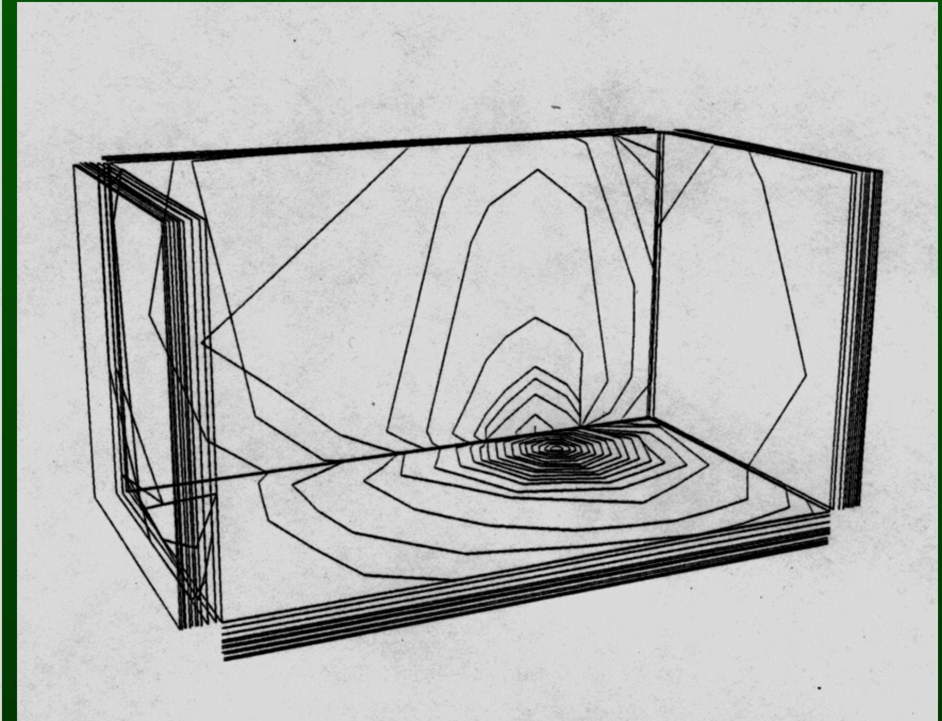
Foam/Fabric (See Ref. 5)	Ignition/Flame Spread Constants			Burn Rate Constants*	Soot Production Constants	
	T_{ig} (°K)	$\rho c \delta$ (kJ/°Km^2)	$\dot{Q}''_f \ell_f$ (kW/m)	$\dot{Q}''_0$ (kW/m^2)	k_{max} (1/m)	σ^e_s (m^2/kg)
NFR PU/LO	623.3	0.80	0.59	30.0	1.342	5060.0
FR PU/LO	711.3	0.72	0.43	30.0	1.342	4740.0
FR PU/HO	711.3	0.72	0.27	30.0	1.342	5300.0
FR PU/LC	590.7	1.00	0.42	5.0	1.342	3150.0
NFR PU/HC	580.7	2.13	0.46	20.0	1.342	4690.0
FR PU/HC	590.7	2.13	0.27	10.0	1.342	3150.0

*Other burn rate constants are: T_b = 700°K, e = 0.7, d = 100.0, ℓ_e = 0.07m



Prediction of HRR for Variation of Mockup Constructions

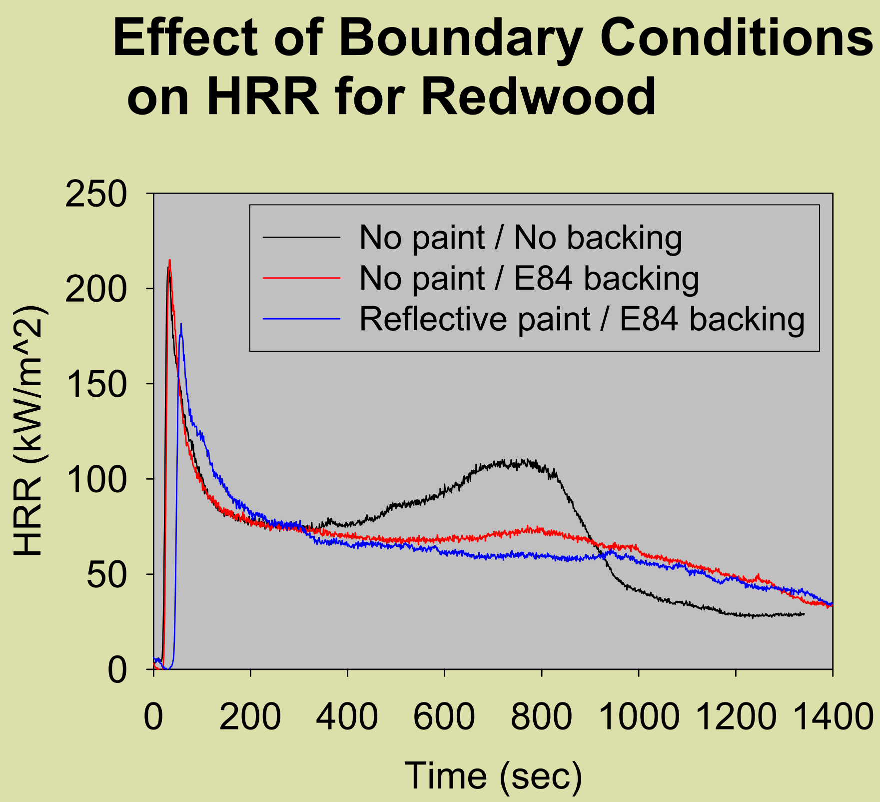


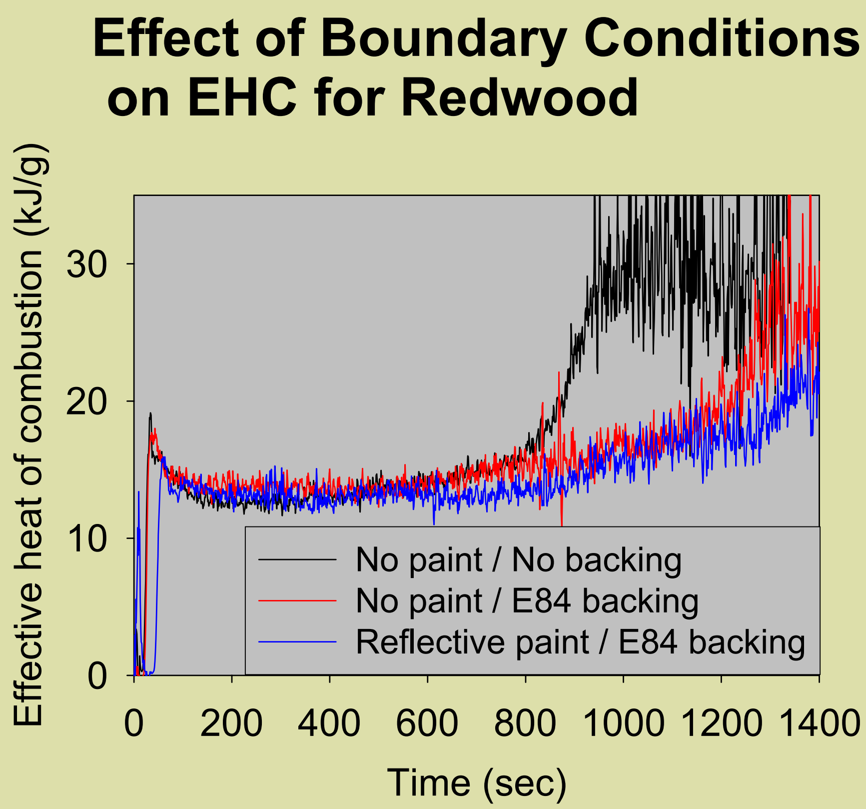


Cone Calorimeter Data Anomalies for Wood Materials

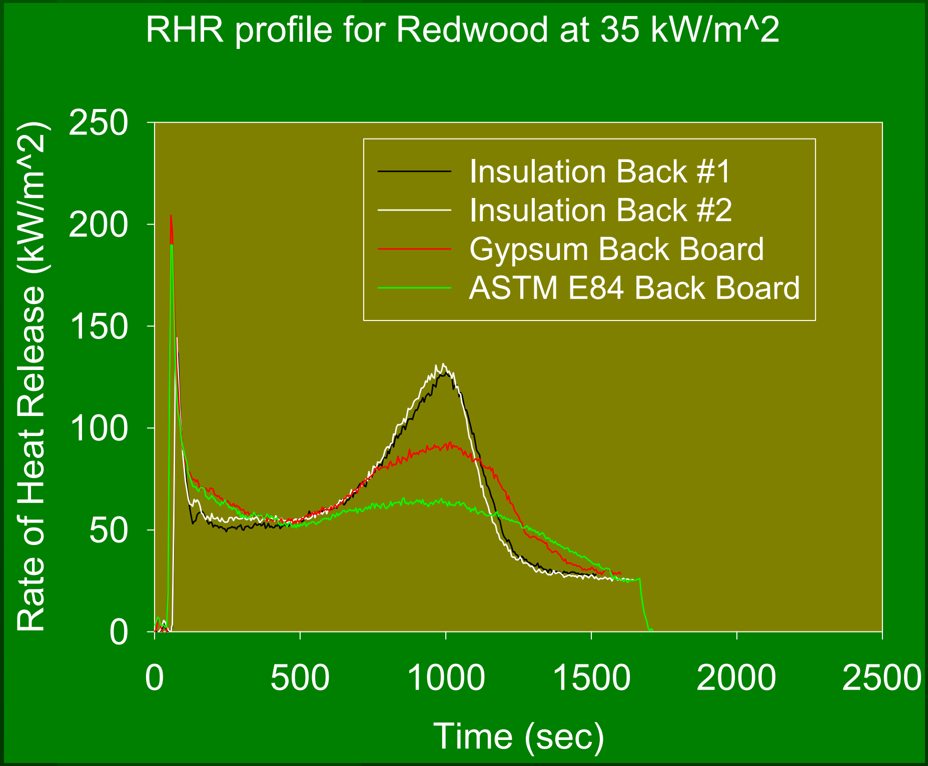
- Effect of backing on HRR profile
- Difficult spark ignition on FRT wood products
- Peak HRR is unreliable
- Choice of irradiant flux is ambiguous
- Smoke production rate affected by smoke-point

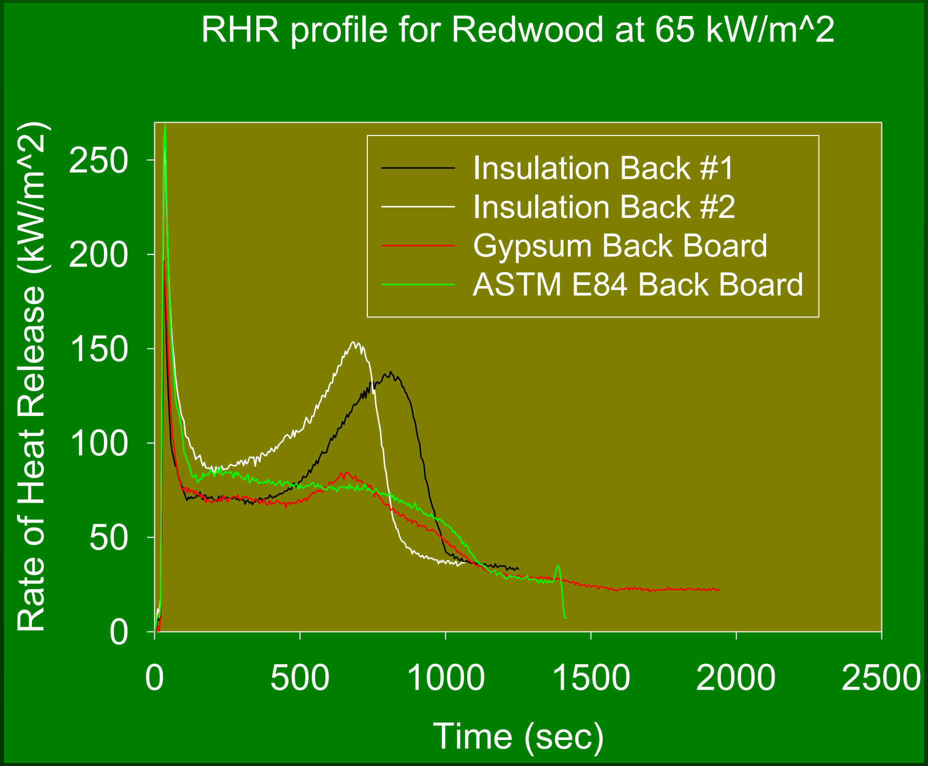
Scaling Wood HRR and MLR is Not Practical Because of Unique Pyrolysis


Effect of Boundary Conditions on HRR for Redwood

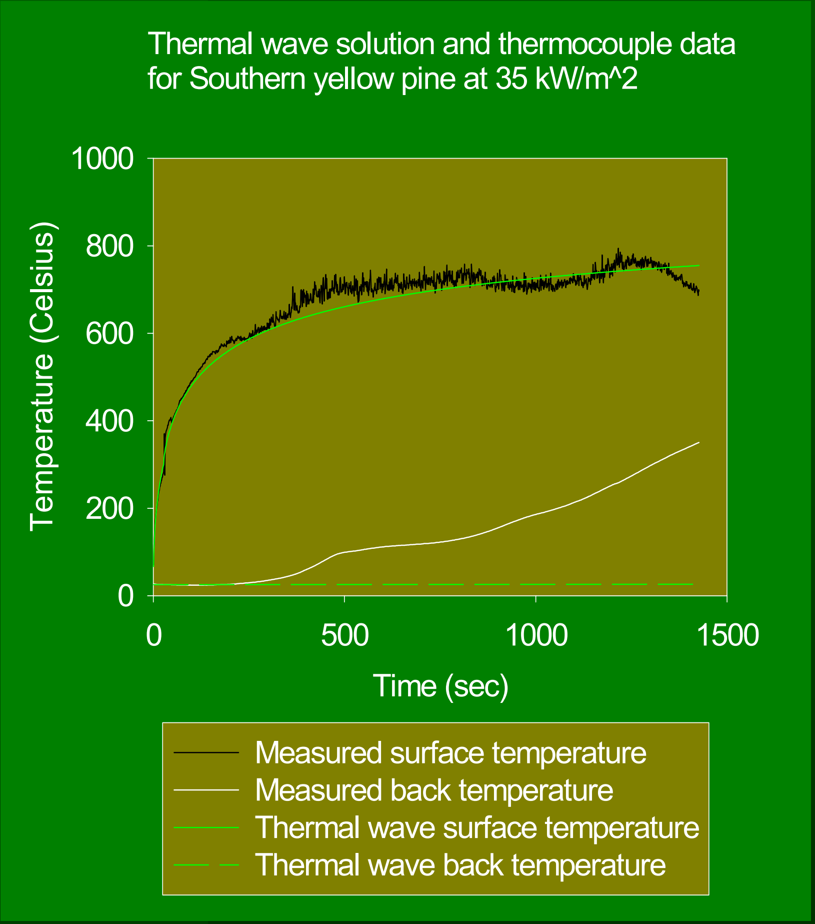

Effect of Boundary Conditions on EHC for Redwood

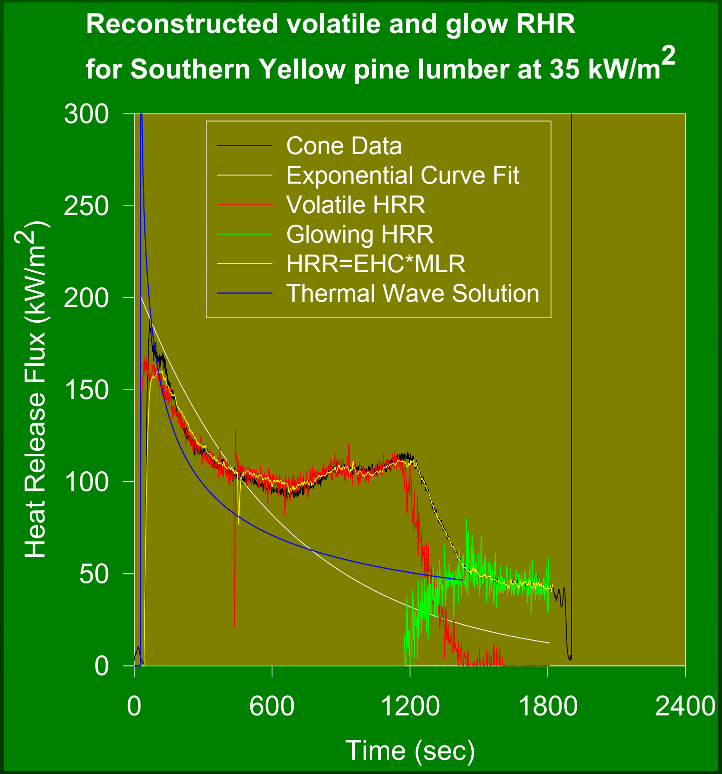
Effect of Backing and Heat Flux on HRR Profile for Redwood


RHR profile for Redwood at 35 kW/m^2


RHR profile for Redwood at 65 kW/m^2

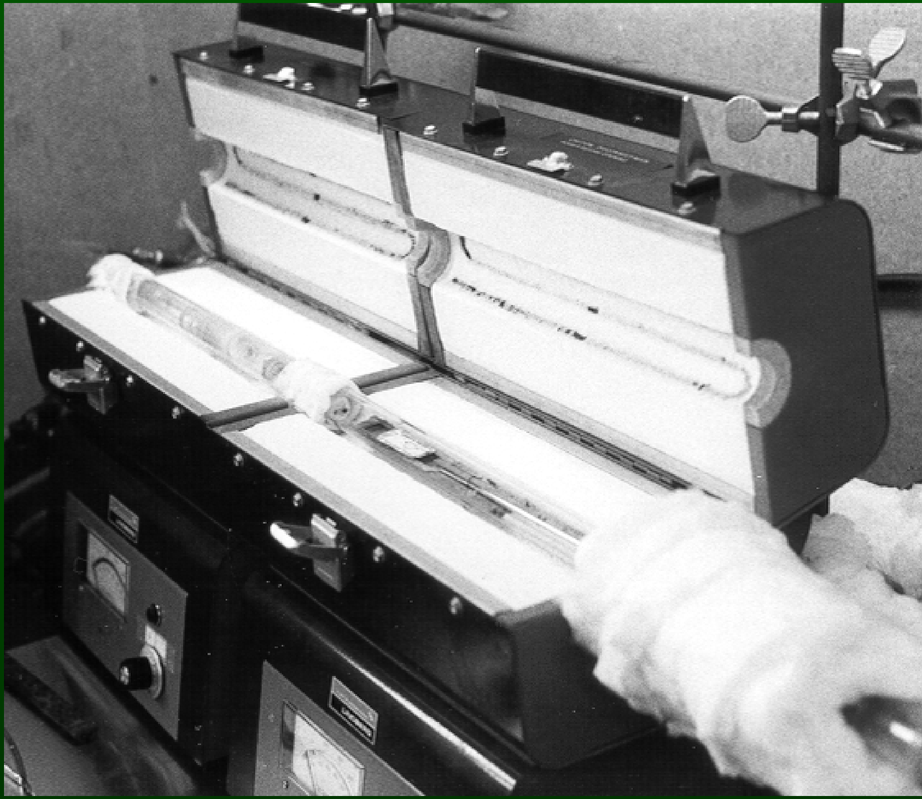
Inadequate Analytical Approximations ?

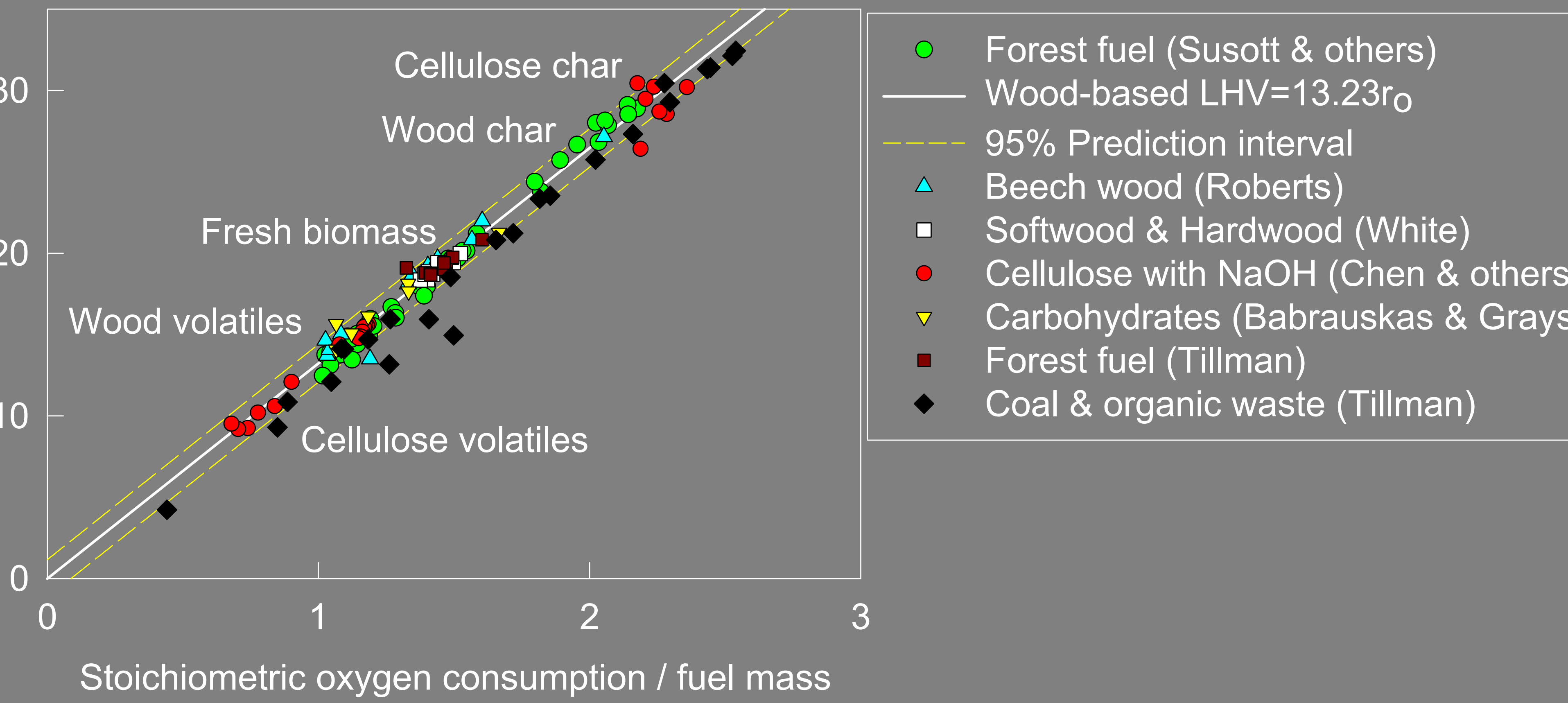

Thermal wave solution and thermocouple data for Southern yellow pine at 35 kW/m^2


Reconstructed volatile and glow RHR for Southern Yellow pine lumber at 35 kW/m^2

Wood Combustion Fundamentals

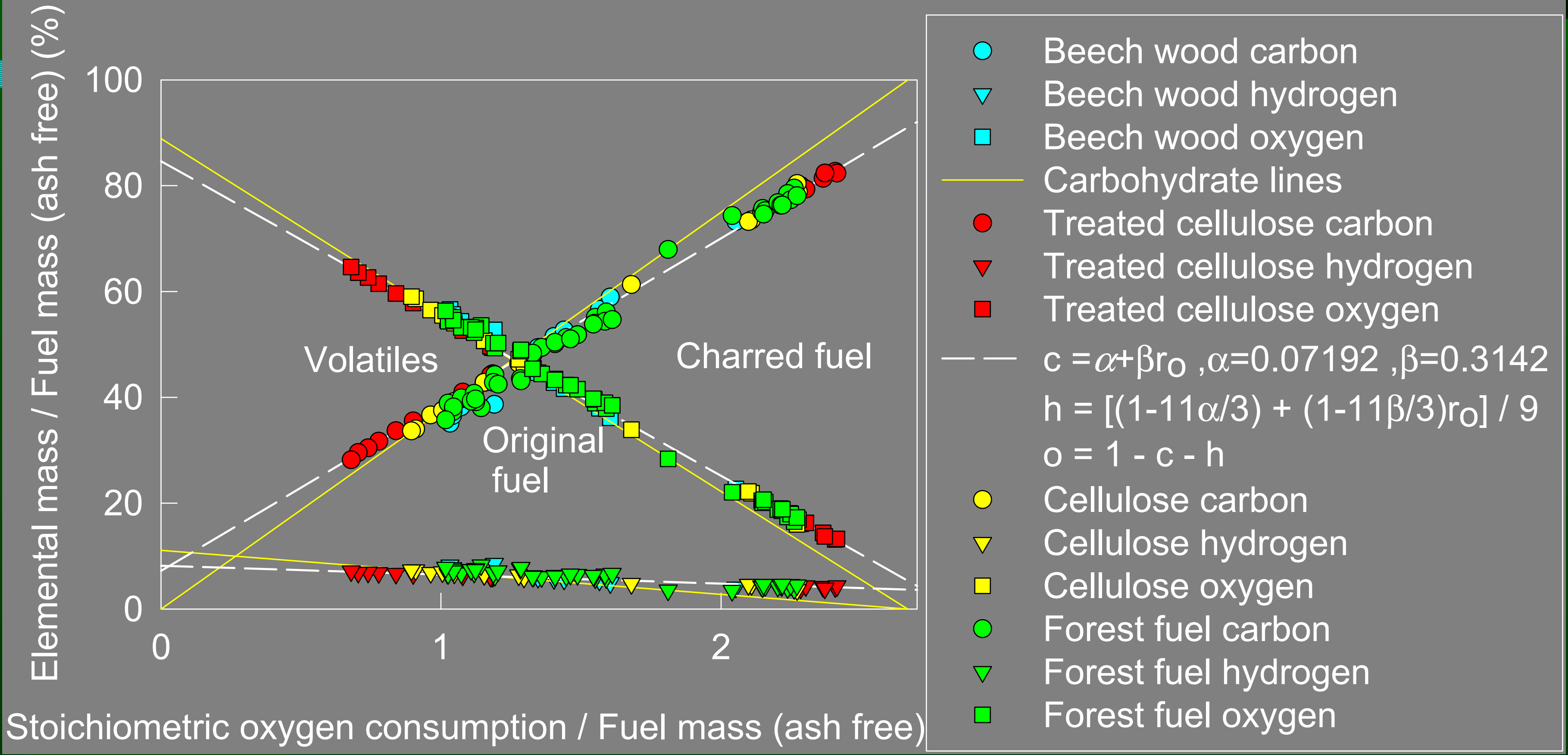
- Fundamental Wood Data Needed for Pyrolysis Modeling
- Re-analysis of Bomb Calorimeter and Ultimate Analysis Data
- Re-analysis of Unique PyroCat Data
- Adapting Cone Calorimeter for Fundamental Wood Data





Correlation for net heat of combustion

Correlation of elemental mass fractions



Combustion Exhaust Flow Analysis of PyroCat or Modified Cone Calorimeter

- Stoichiometric oxygen consumption of C & H / fuel ratio,

$$r_o = \left(\Delta\dot{m}_{ox} + \tfrac{16}{28}\dot{m}_{CO} + \tfrac{32}{12}\dot{m}_{soot} - \tfrac{32}{64}\dot{m}_{SO2}\right) / \dot{m}_f$$

- Carbon mass fraction of volatiles,

$$c = \left(\dot{m}_{soot} + \tfrac{12}{28}\dot{m}_{CO} + \tfrac{12}{44}\Delta\dot{m}_{CO2}\right) / \dot{m}_f$$

- Hydrogen mass fraction of volatiles,

$$h = (1 + r_o - 11c/3 - n - s)/9$$

- Oxygen mass fraction of volatiles,

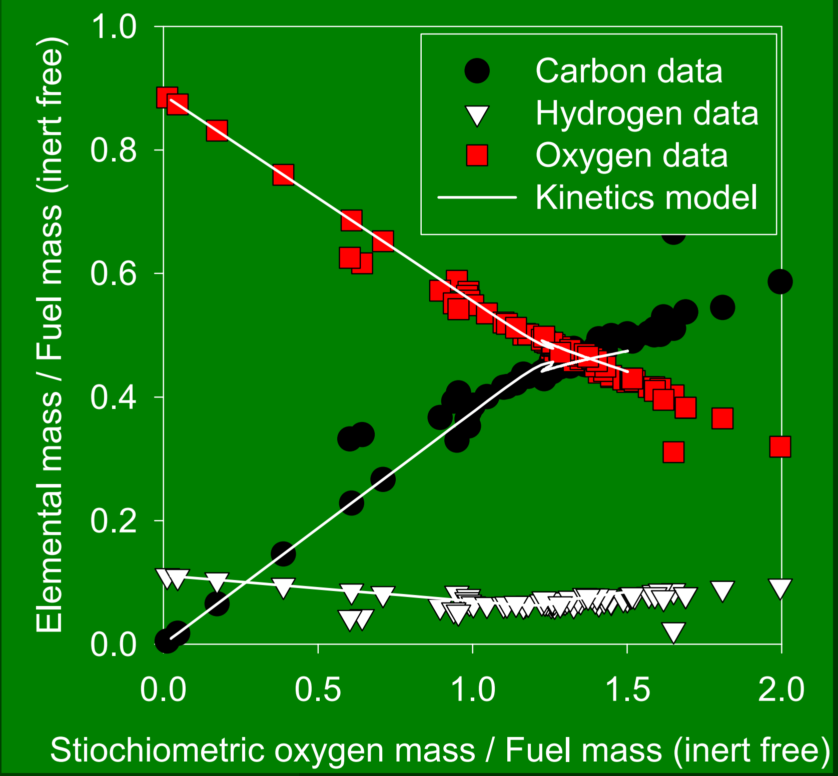
$$o = (8 - r_o - 16c/3 - 8n - 8s)/9$$

- Volatile rate (PyroCat needs only CO2, H2O, O2, and N2),

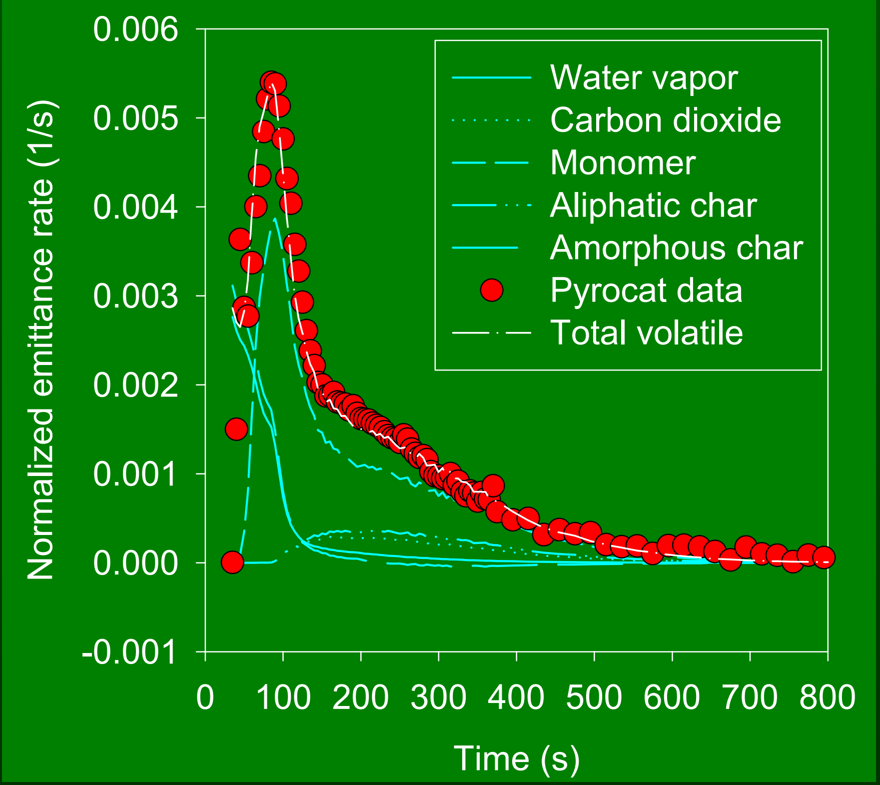
$$\dot{m}_f = \dot{m}_{soot} + \dot{m}_{CO} + \Delta\dot{m}_{CO2} + \dot{m}_{H2O} + \dot{m}_{SO2} + \Delta\dot{m}_N - \Delta\dot{m}_{ox}$$

Results with PyroCat Data and Kinetics Pyrolysis Model

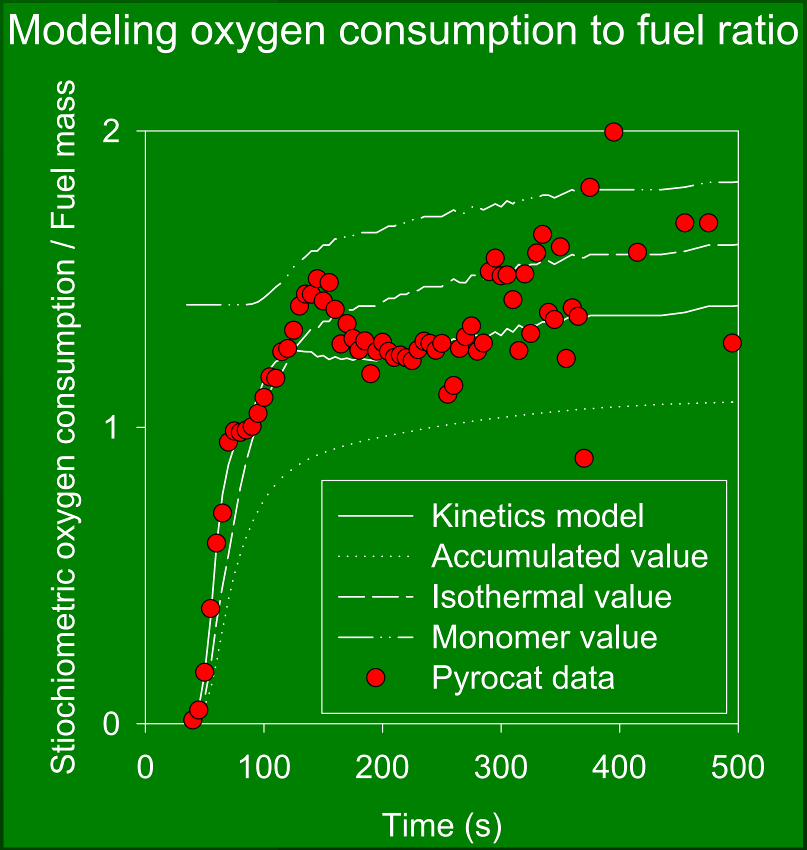
Elemental fractions of Douglas-fir volatiles

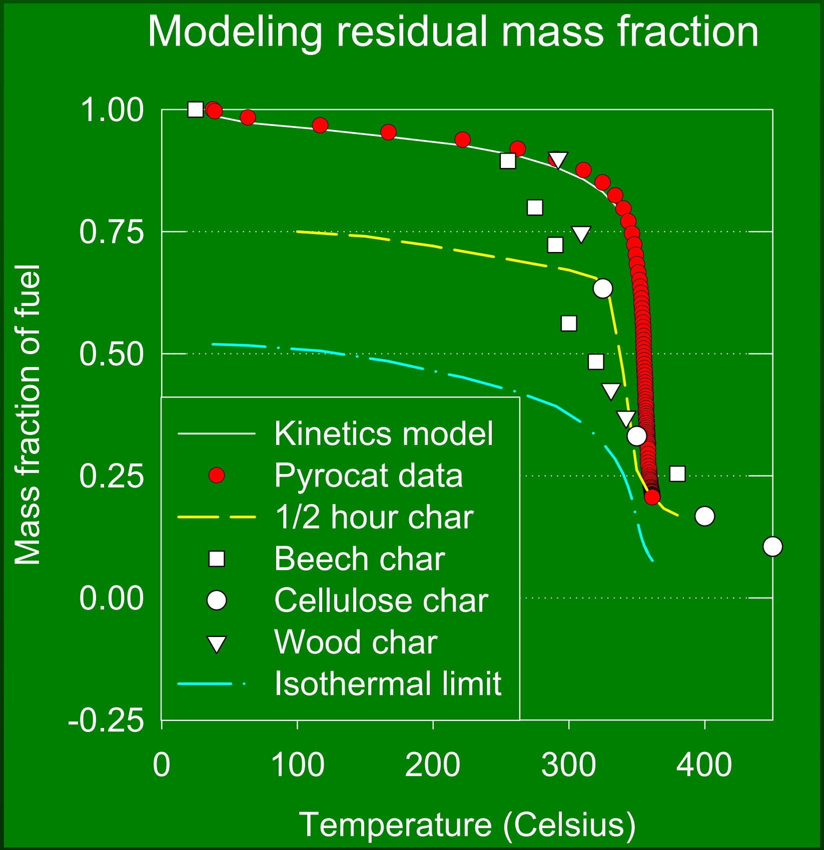


Modeling rates of volatile and char contents

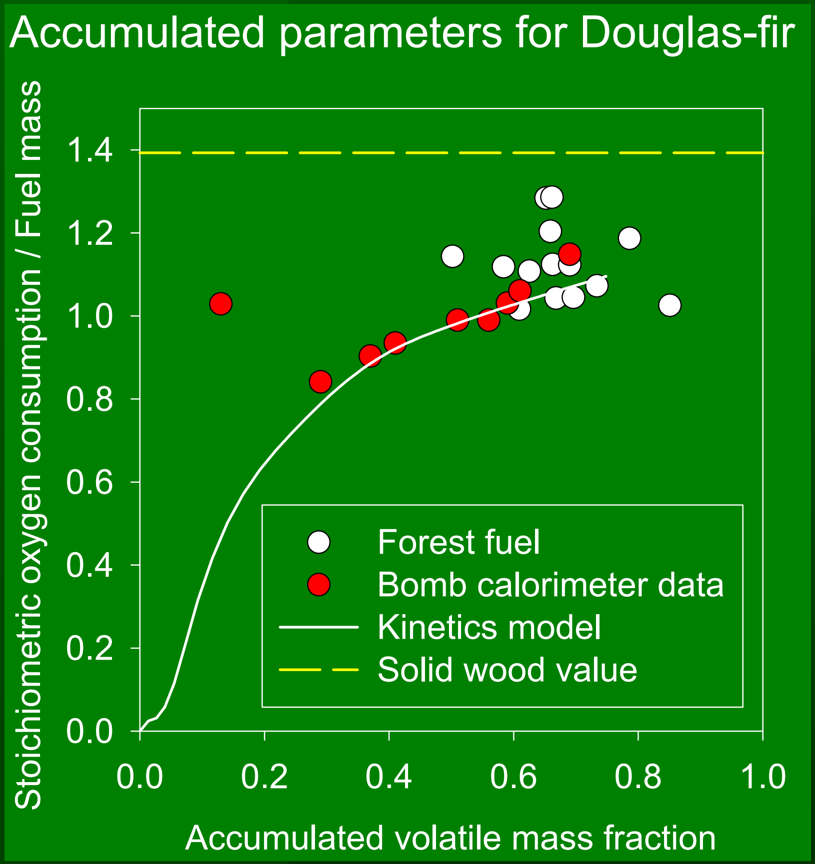


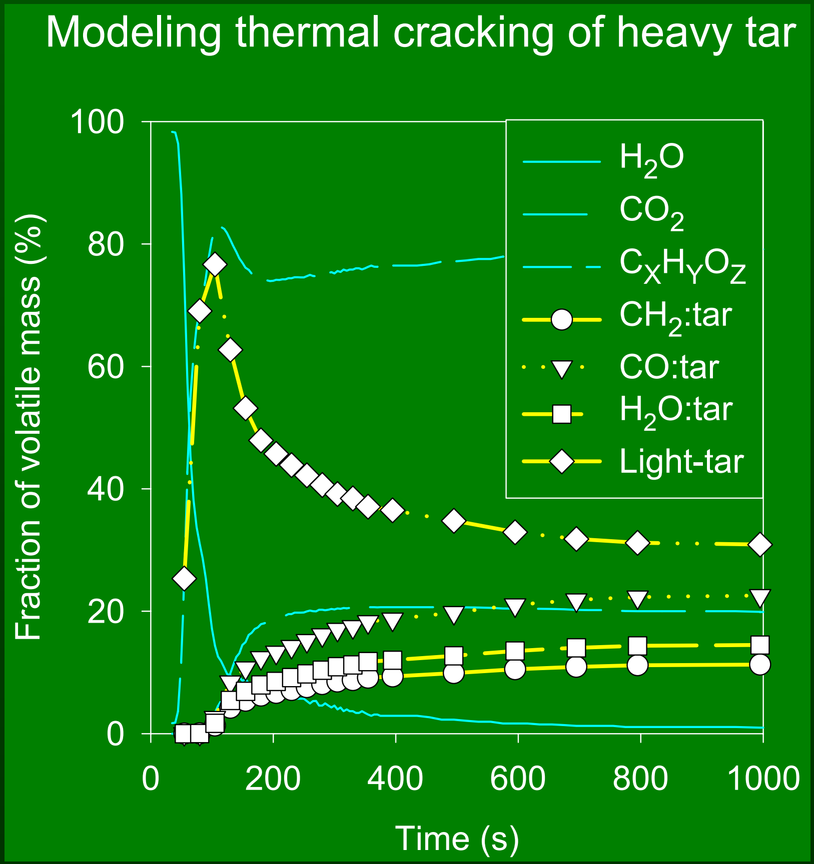
More on PyroCat Data and Kinetics Model





More on Pyrolysis Kinetics Model Results


Accumulated parameters for Douglas-fir


Modeling thermal cracking of heavy tar

Modifications to Cone Calorimeter to Emulate PyroCat Functions

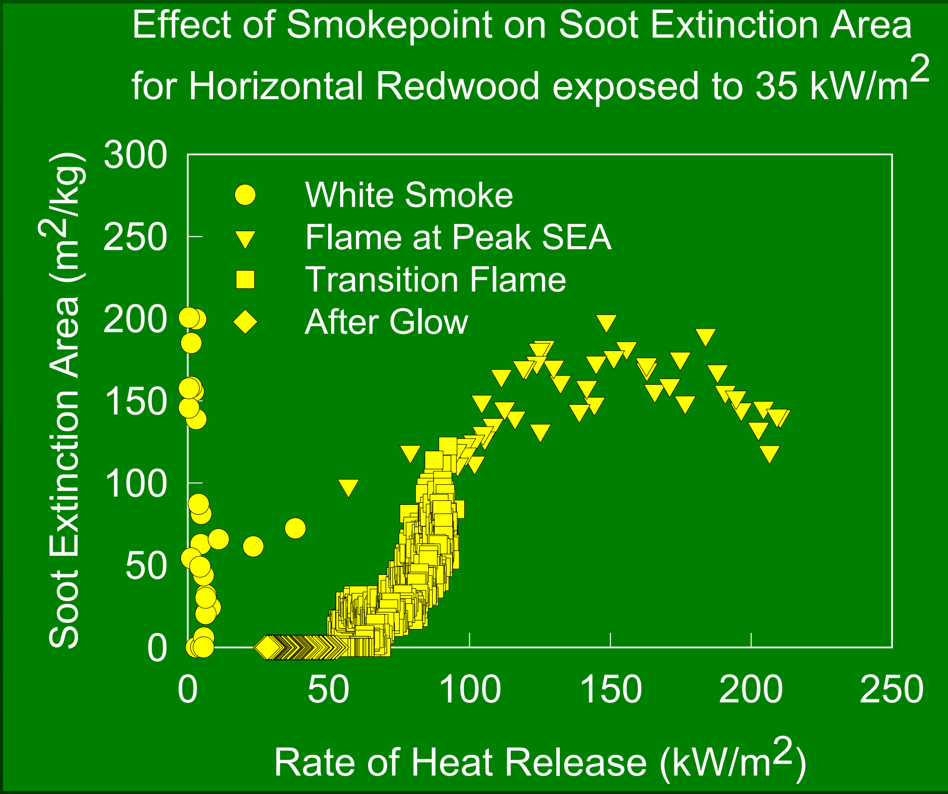
- Sample Holder Modified for Thermally Thin Samples
- Accurate Temperature with Inserted Tiny Thermocouples
- Constructed Methane Burner to Burn Volatiles Completely
- Installed Precise and Rapid RH Sensor in Gas Sampling Line
- Digital Camera to Observe Wood Shrinkage as Function of Time

Smoke Correlation at Different Scales

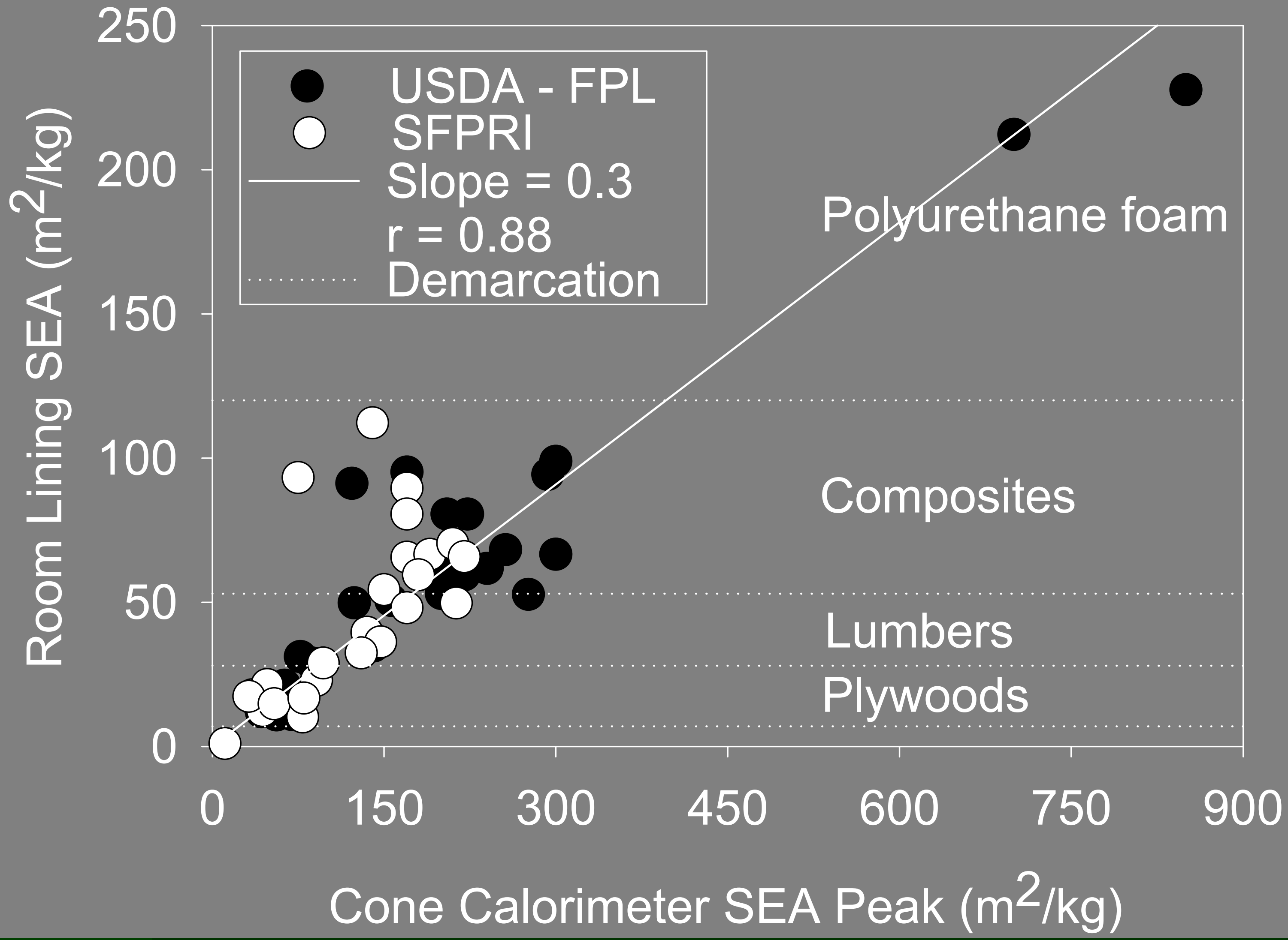
- 18 room tests
- Very extensive cone calorimeter tests
- Smoke literature is nil for wood products
- Need category levels for Smoke Extinction Area (SEA) parameter

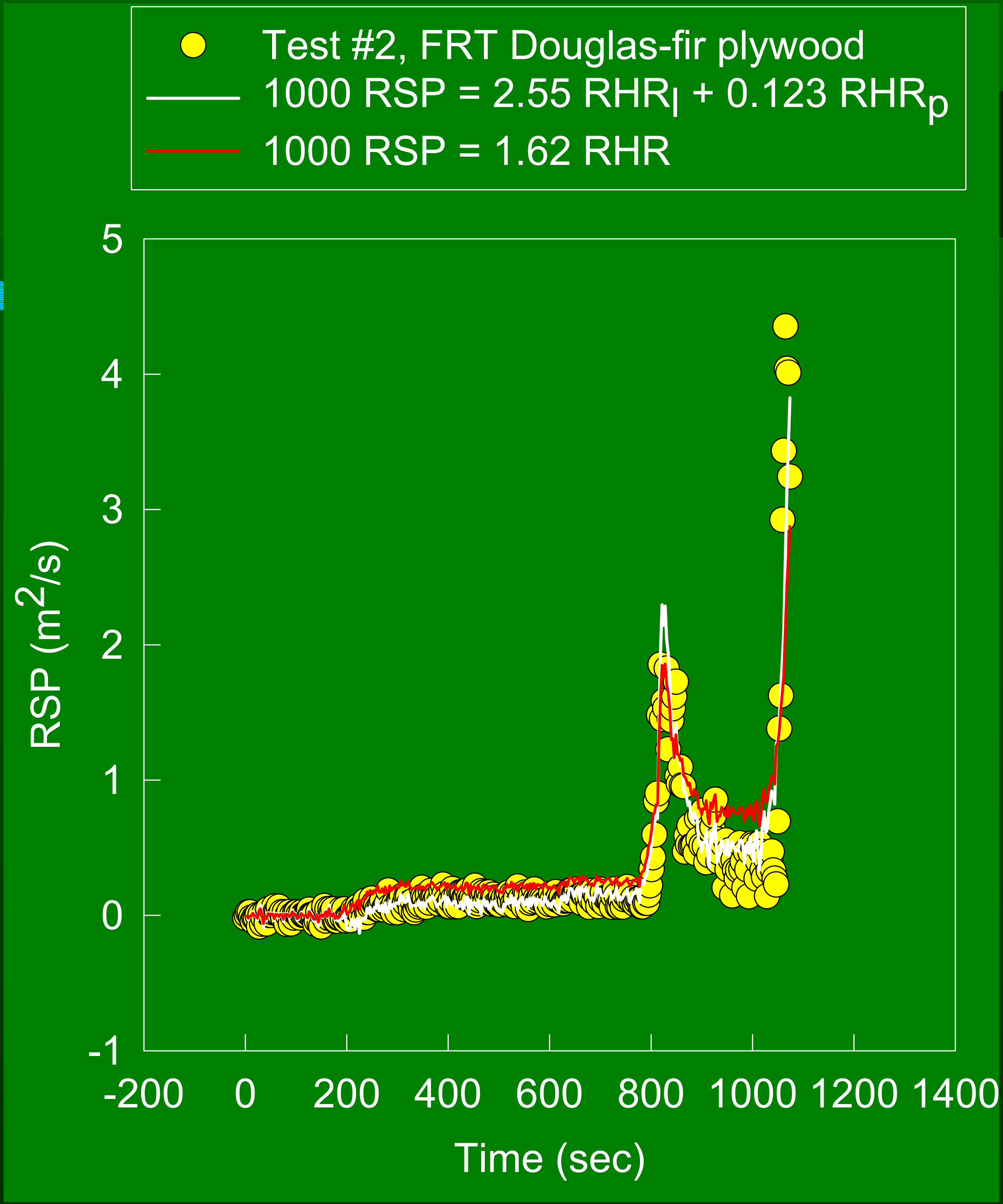
The Problem of Wood Smoke Production in Cone Calorimeter

- **SEA at High HRR is around 150 m2/kg**
- **HRR at Smokepoint is Around 100 kW/m2**
- **Peak HRR & Smokepoint vary little with imposed heat flux or back board**
- **Peak SEA more Reliable than Averaged SEA**



Prediction of lining SEA from SEA peak of cone calorimeter tests of horizontal specimen at 35 kW/m^2.

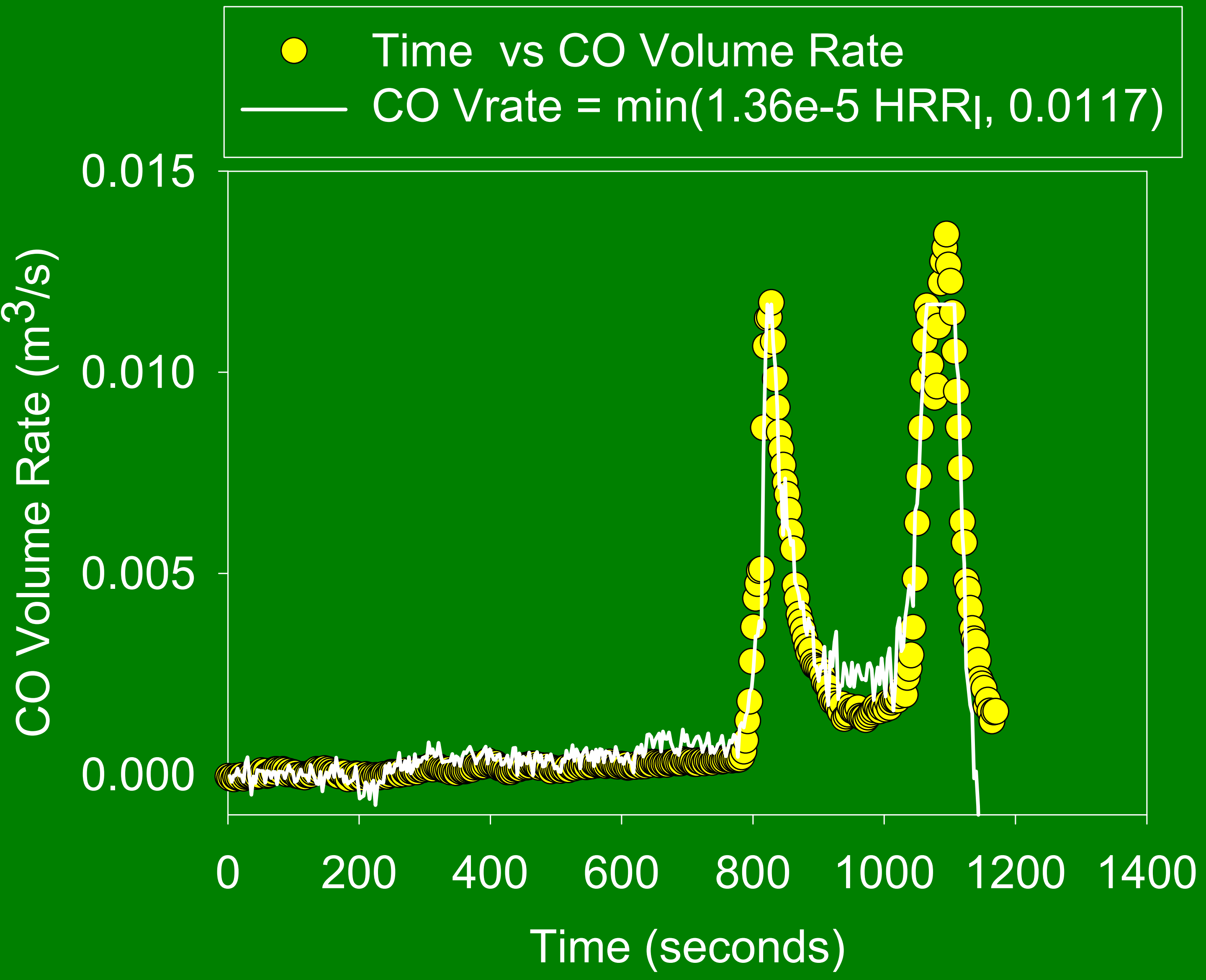



Test #2, FRT Douglas-fir plywood
$1000\ RSP = 2.55\ RHR_l + 0.123\ RHR_p$
$1000\ RSP = 1.62\ RHR$
RSP (m^2/s)
5
4
3
2
1
0
-1
-200
0
200
400
600
800
1000
1200
1400
Time (sec)

Derived Room Smoke Parameters

Material	Test #	a / EHC_{cone} (m^2/MJ)	b / EHC_{cone} (m^2/MJ*kW)	RSP_i / RHR_i (m^2/MJ)	$RHR_{smoke-point}$ (kW)
FRT Douglas-fir plywood	2	2.55	0.0	2.55	0.22
Oak veneer plywood	3	1.81	--	1.81	0.30
Douglas-fir plywood (ASTM)	5	0.94	--	0.94	0.58
FRT Polyurethane foam	6	33.0	0.0	33.0	0.017
Gypsum board – Type X	7	0.288	0.0	0.288	1.9
FRT SYP plywood	8	2.93	0.0	2.93	0.19
Douglas-fir plywood (MB)	9	1.23	--	1.23	0.45
Southern pine plywood	10	5.20	--	5.20	0.11
Particleboard	11	5.67	--	5.67	0.097
Oriented strand board	12	4.28	--	4.28	0.13
Hardboard	13	6.56	--	6.56	0.084
Redwood lumber	14	2.62	--	2.62	0.21
White spruce lumber	16	2.49	--	2.49	0.22
Southern pine boards	17	4.14	--	4.14	0.13
Waferboard	18	6.01	--	6.01	0.091
Red oak	21	1.6	0.028	4.4	0.12
Stucco on OSB	22	2.35	0.0175	7.6	0.072

Correlation of CO Volume Rate with HRR for Test #2



Cone HRR Data of OSB for ASTM E84 Analytical Flame Spread Model

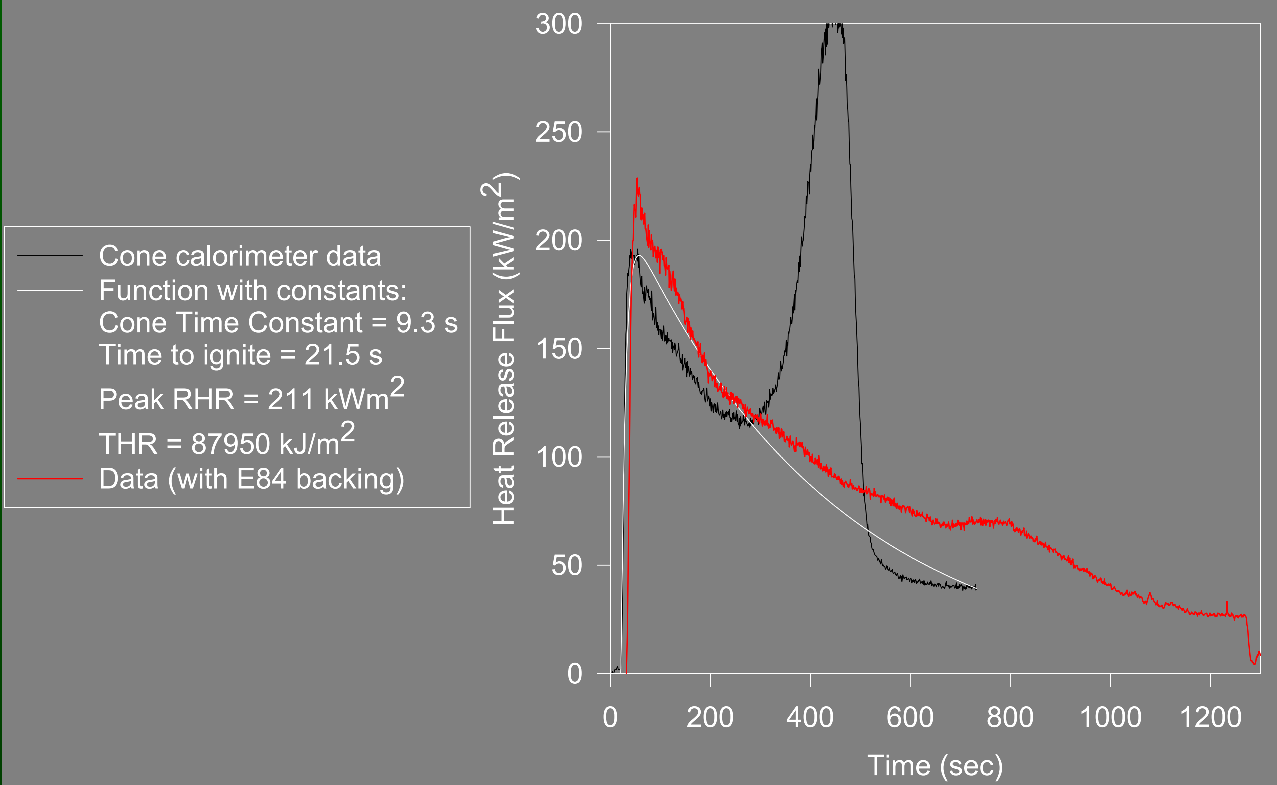


Figure 1. Untreated OSB data at 50 kW/m^2

Cone HRR Data of Coated OSB for E84 Analytical Flame Spread Model

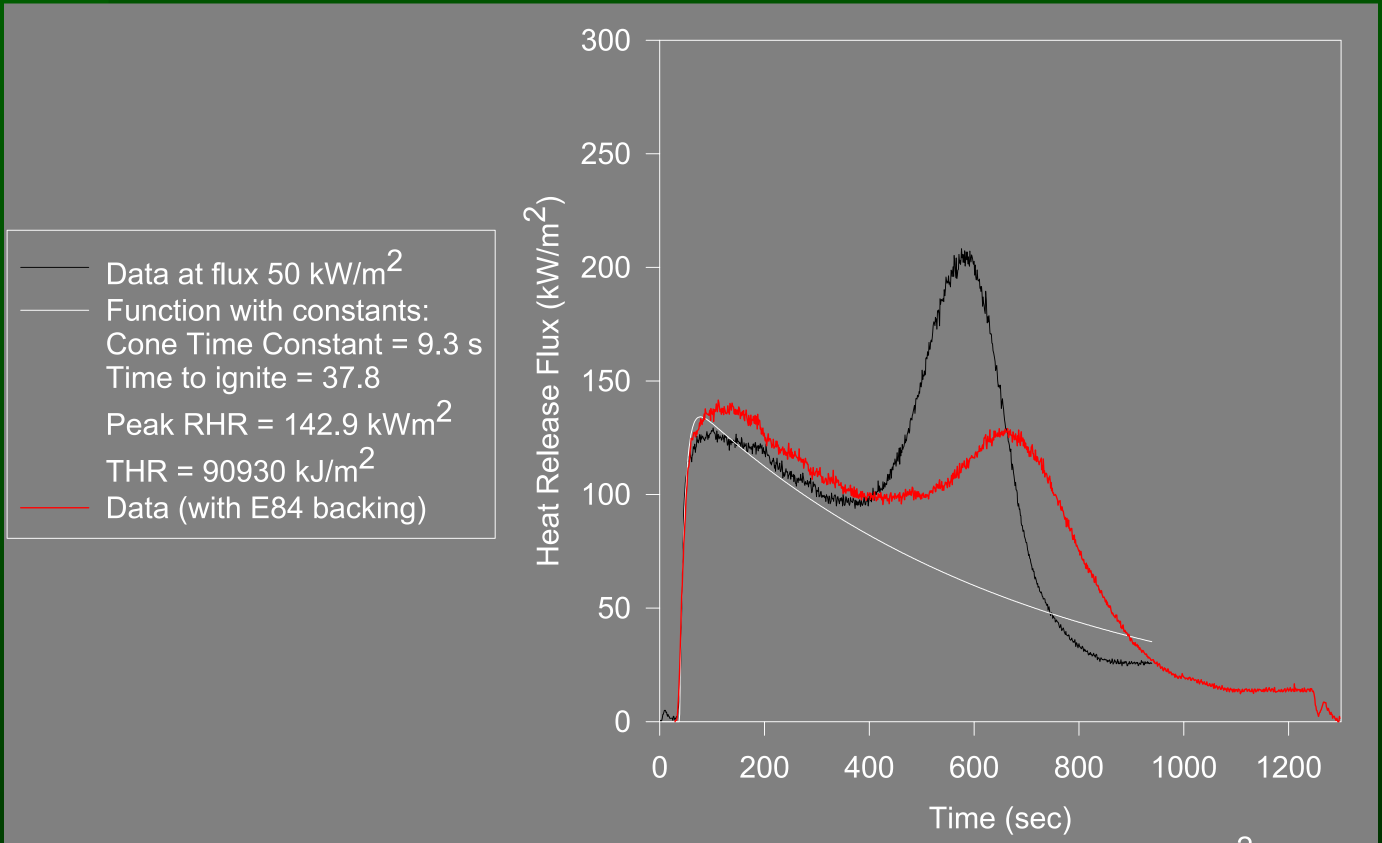


Figure 2. Coated OSB data at 50 kW/m^2

Cone HRR Data of FRT/Coated OSB for E84 Analytical Flame Spread Model

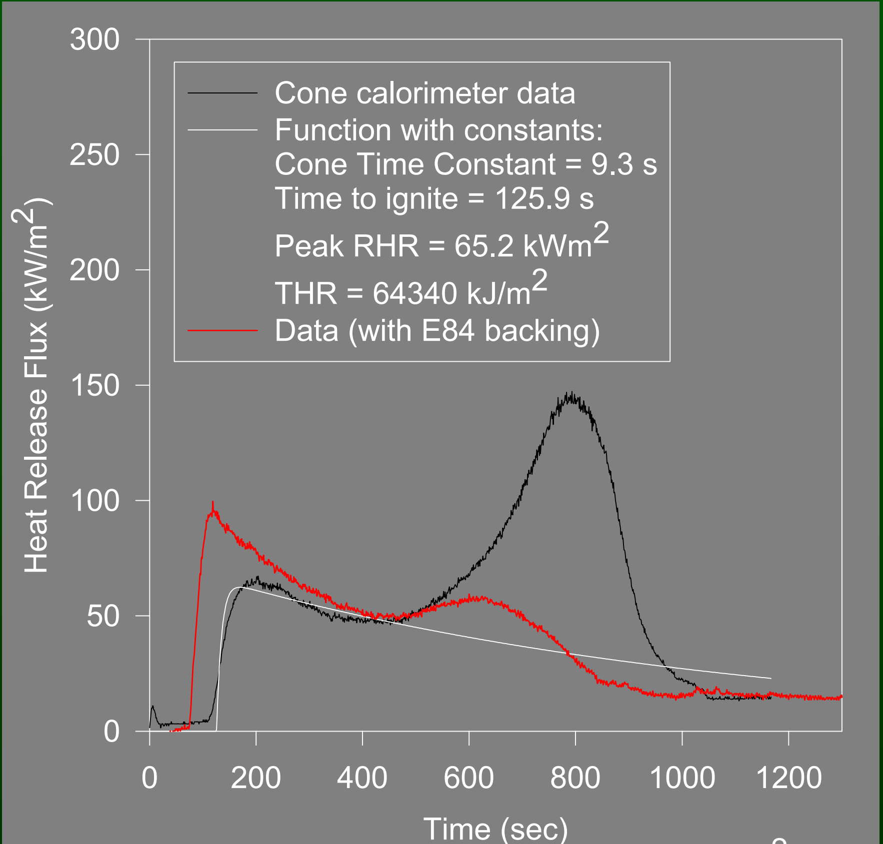


Figure 3. FRT/Coated OSB data at 50 kW/m^2

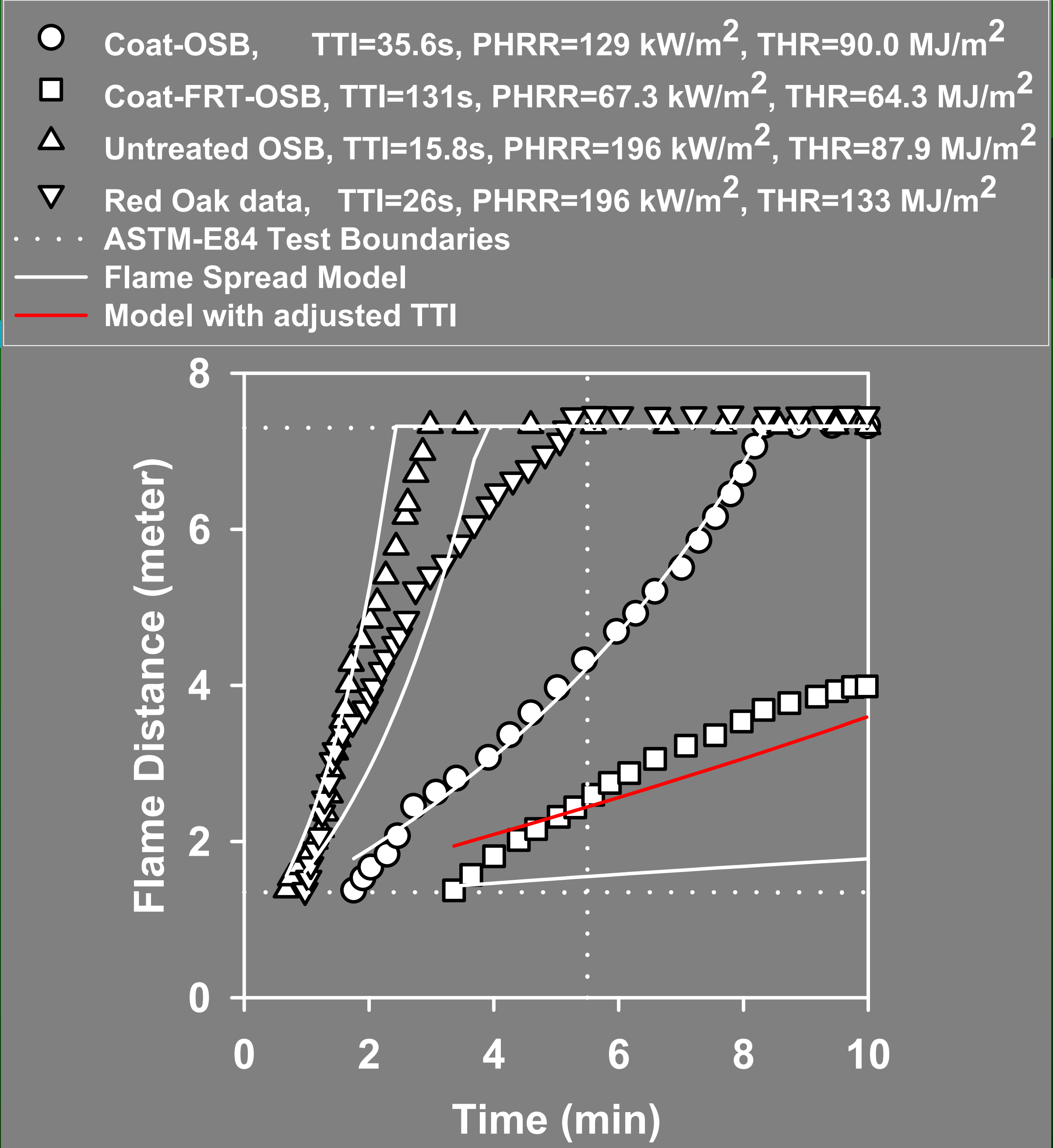
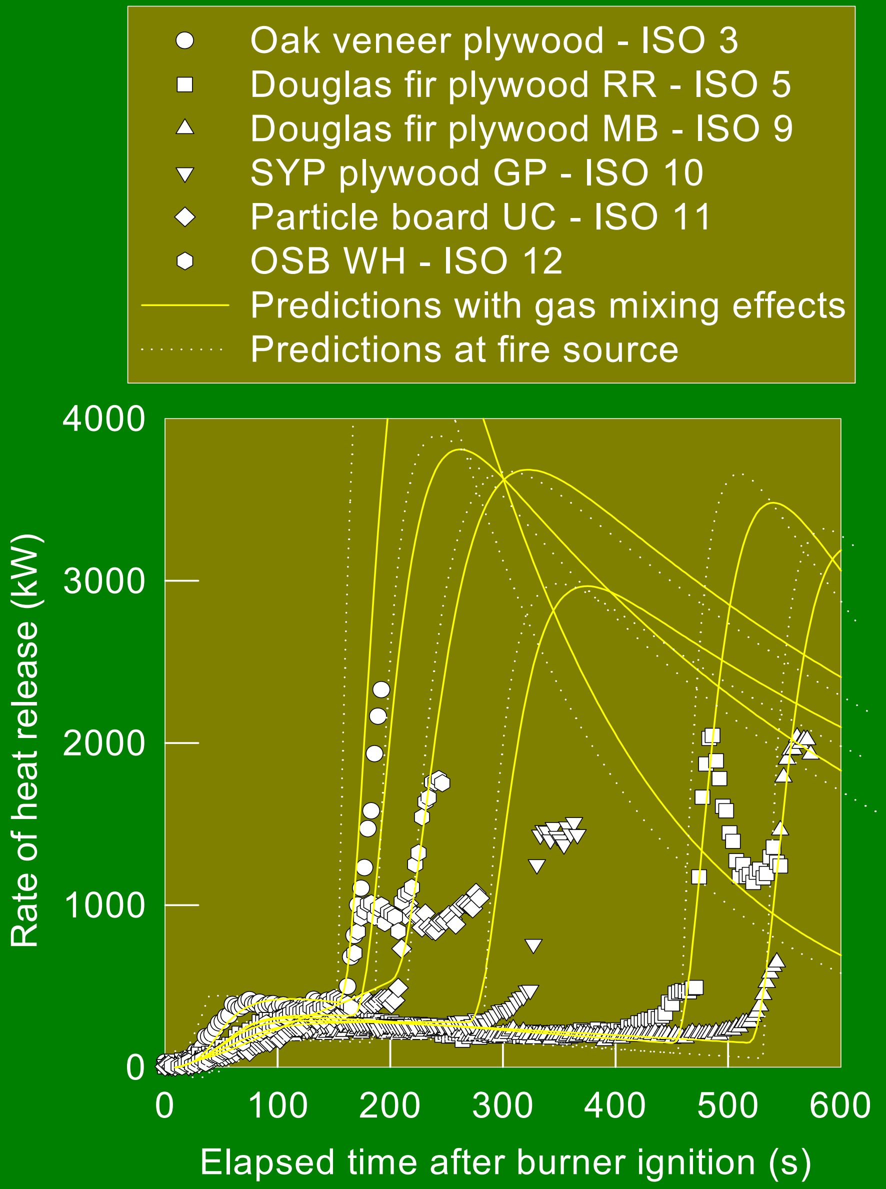
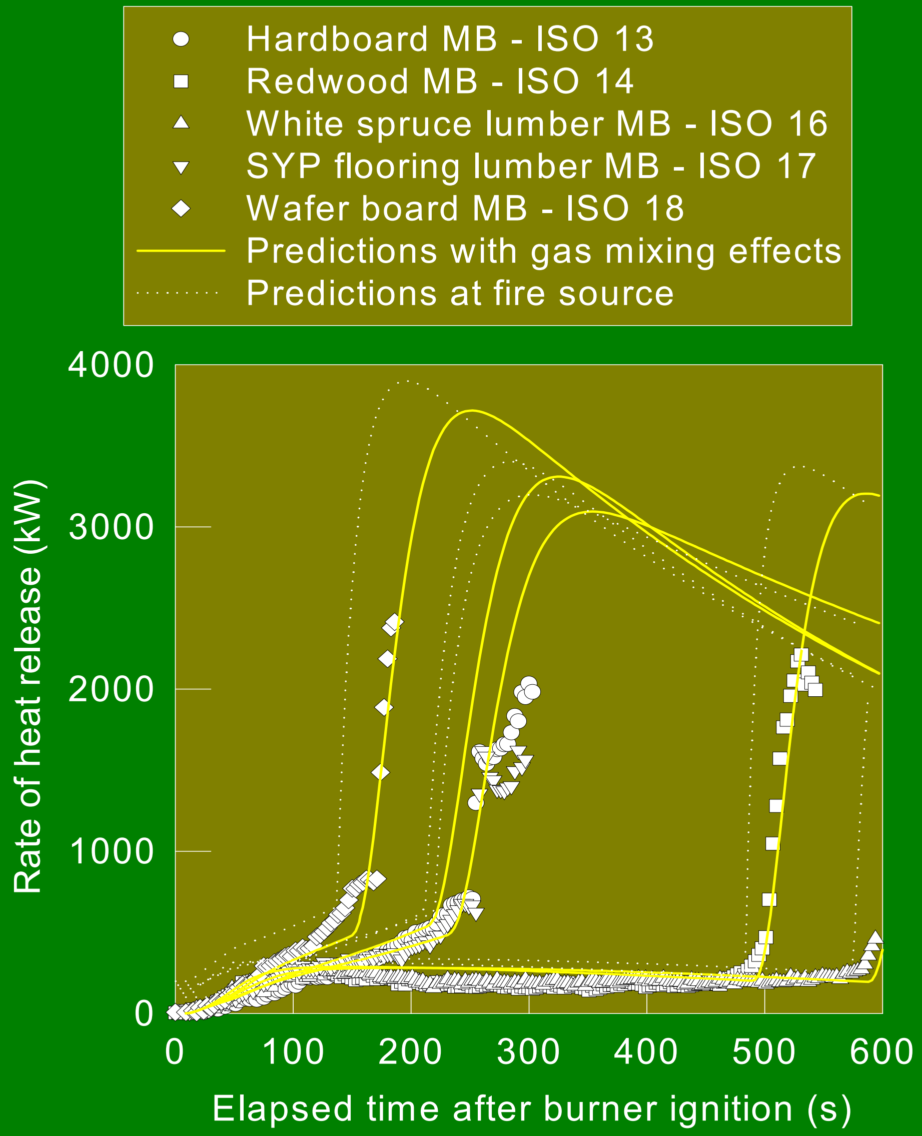


Figure 7. Prediction of Flame Spread Distance


○ Oak veneer plywood - ISO 3
□ Douglas fir plywood RR - ISO 5
△ Douglas fir plywood MB - ISO 9
▽ SYP plywood GP - ISO 10
◇ Particle board UC - ISO 11
⬡ OSB WH - ISO 12
Predictions with gas mixing effects
Predictions at fire source
Rate of heat release (kW)
4000
3000
2000
1000
0
0
100
200
300
400
500
600
Elapsed time after burner ignition (s)


○ Hardboard MB - ISO 13
□ Redwood MB - ISO 14
△ White spruce lumber MB - ISO 16
▽ SYP flooring lumber MB - ISO 17
◇ Wafer board MB - ISO 18
Predictions with gas mixing effects
Predictions at fire source
Rate of heat release (kW)
0
1000
2000
3000
4000
0
100
200
300
400
500
600
Elapsed time after burner ignition (s)

Results of Analytical Fire Growth Modeling

- Steiner tunnel and Room/corner tests complement as full-scale reaction-to-fire tests
- Fire growth is most sensitive to TTI and somewhat sensitive to peak HRR
- New acceleration parameter can classify several material types for both full-scale fire tests
- Guidance of fire retardancy for desirable values of TTI, peak HRR, and THR is obtained
- Serves as Benchmark to Test Numerical Algorithms of Fire Growth Models

Impacts of Smoke Study

- In the order of increasing lining-SEA: gypsum board, plywood, lumber, wood composites and polyurethane foam
- Predicted dynamic RSP profile for 18 room tests
- Paper presented at Wood & Fire Meeting
- Need revised protocol to reduce smoke variability in cone calorimeter

Impacts of Boundary Conditions on Wood MLR and HRR Modeling

- **Heavy back board reduced or eliminated the second RHR peak**
- **Reflective Coating on Surface Delays Ignition and Reduces first Peak HRR**
- **It could make a difference in fire growth being accelerated or damped**
- **Kinetics modeling of wood pyrolysis is possible with modified Cone Calorimeter**

Impact on Fire Growth Modeling

- **Better bench scale tests are needed for determining flame spreading parameters**
- **Keep focus on Steiner tunnel and Room/corner tests as primary fire growth scenarios using PC**
- **Quasi-steady predictions of smoke and CO development need some good models**
- **Robust modeling of wood pyrolysis is in demand by CFD simulations of fire growth and in FEM simulations of fire endurance**

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