Experimental Measurements of Full-scale Fire Growth for Fire Model Validation

Tenth Triennial International Aircraft Fire and Cabin Safety Research Conference
Atlantic City, New Jersey, USA

M. Heck, I. Leventon, M. Bundy, K. McGrattan, R. Davis

October 18, 2022

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Disclaimer
Some of the data in this presentation has not been through the NIST review process and should be considered experimental / draft results. However, the data has been analyzed by subject matter experts within the research team and is believed to be scientifically sound and consistent with the integrity expected of NIST research.

NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Overview

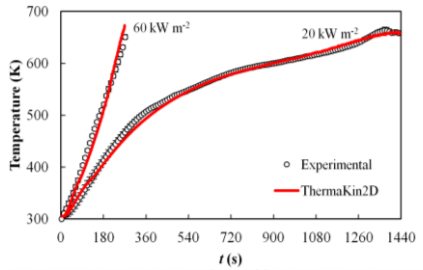
- Background
- Experimental Design
- Results
- Further Work

Background – Big Picture

The NIST Fire Research Division is currently developing the experimental and computational analysis tools needed to enable quantitative prediction of material flammability behavior; e.g. ignition, steady burning, fire growth.

Thermophysical Properties

$$\begin{array}{lll} A & E & \nu \\ c_p & h_i & \Delta H_c \\ k & \rho & \\ \alpha & \varepsilon & \end{array}$$

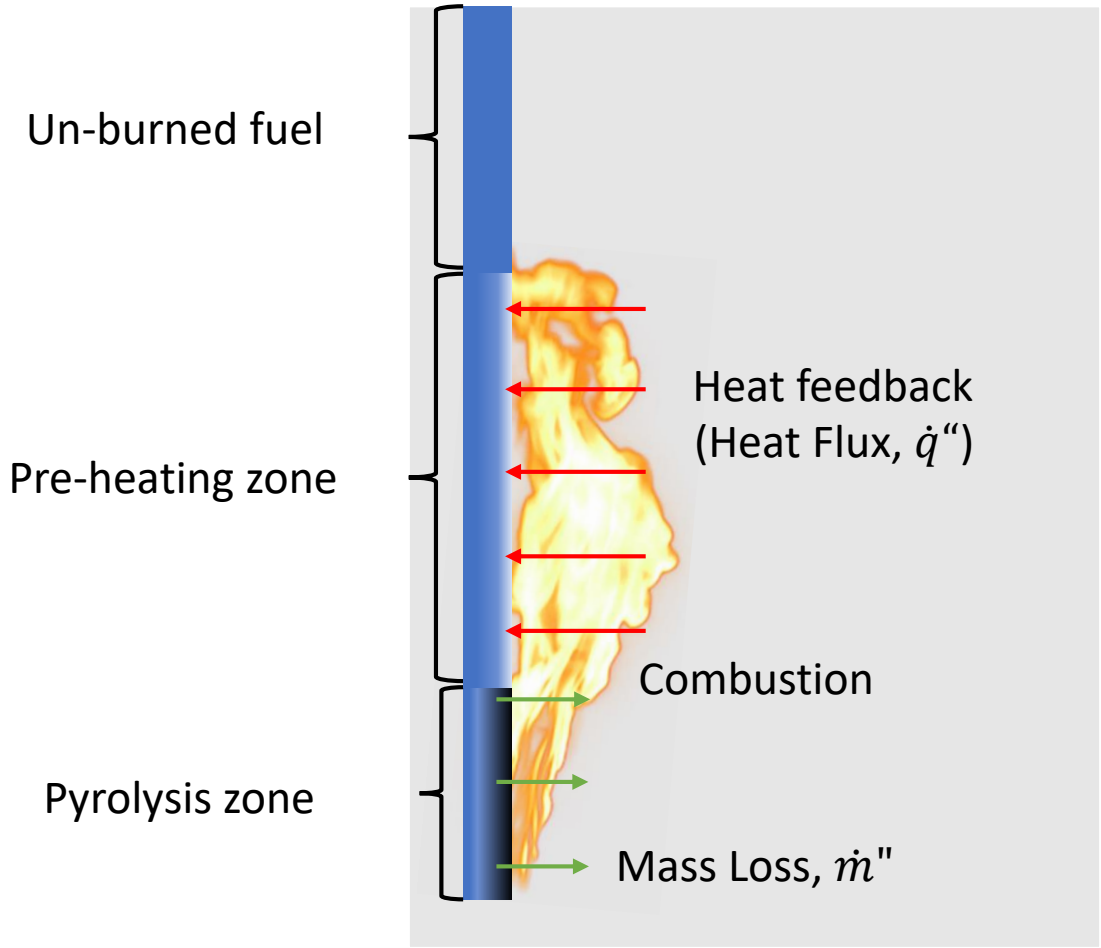


Background – Material Flammability

- Current assessment of a material's flammability:
  - Classifies a material's reaction to fire
  - Cannot be taken out of context
- Full-scale testing:
  - Too expensive
  - Too many possible combinations of materials, configurations, ignition sources
- Computation Fluid Dynamics (CFD) has the potential to predict large-scale burning behavior
  - There is a knowledge gap in flame spread physics
  - Coupling of condensed-phase and gas-phase processes

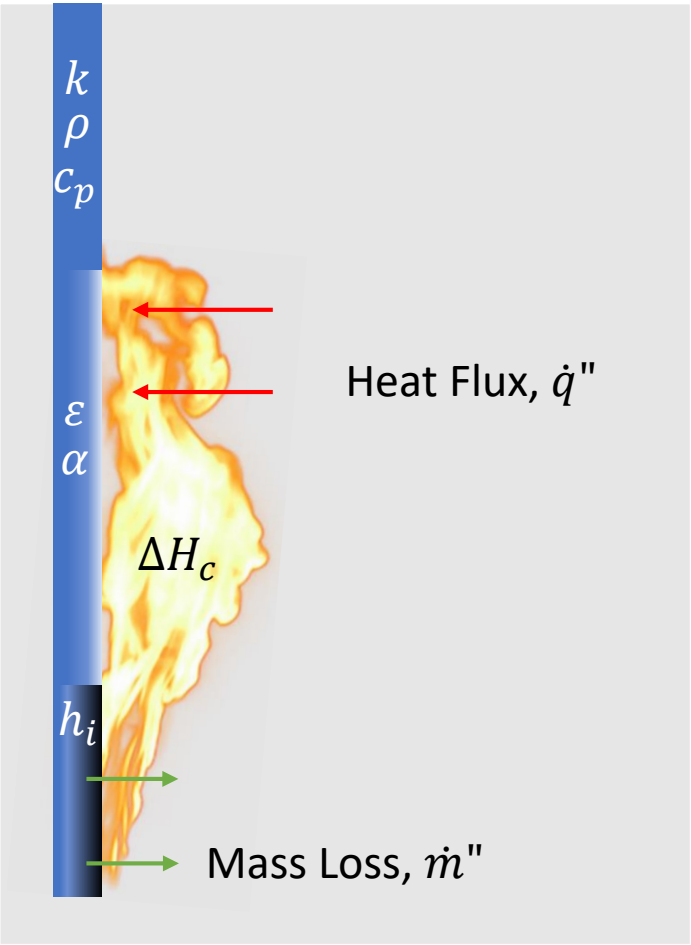
Background – Flame Spread

- Positive feedback loop
  - Pyrolysis
    - Heat transport
    - Thermal degradation
  - Combustion
  - Heat feedback
- Flame-to-surface heat flux is the driving component of fire growth

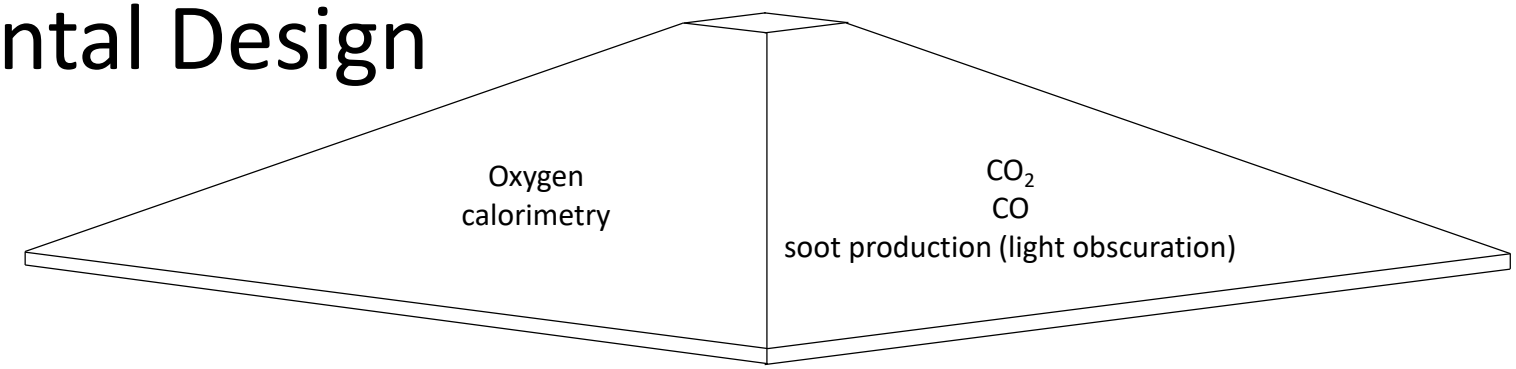


Background – Flame Spread

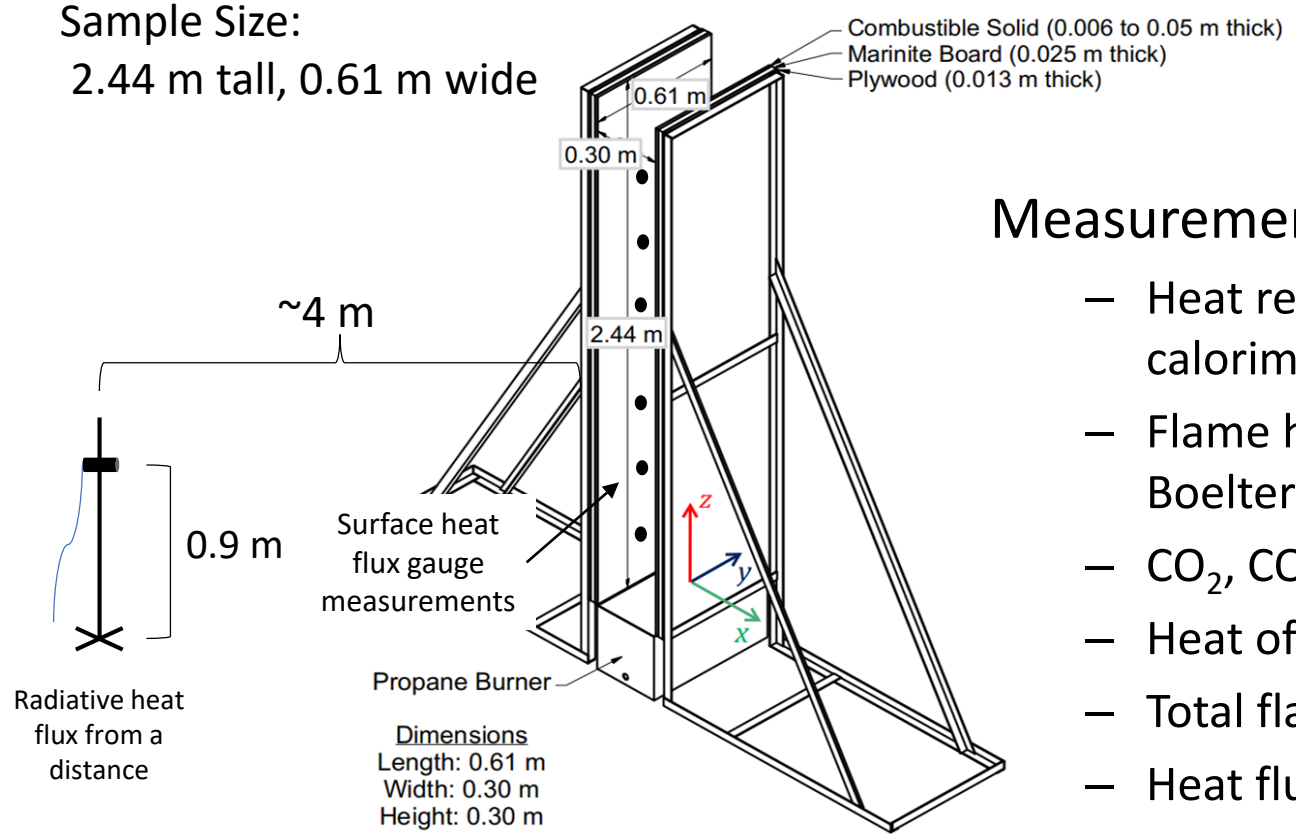
- Material Properties
  - Degradation Kinetics (A, ε, v)
  - Heat of Reaction (h_i)
  - Heat Capacity (c_p)
  - Heat of Combustion (ΔH_c)
  - Thermal Conductivity (k)
  - Absorption Coefficient (α)
  - Emissivity (ε)
- Key Parameters
  - Mass Loss ($\dot{m}$")
  - Heat Flux ($\dot{q}$")



Experimental Design



Sample Size:
2.44 m tall, 0.61 m wide

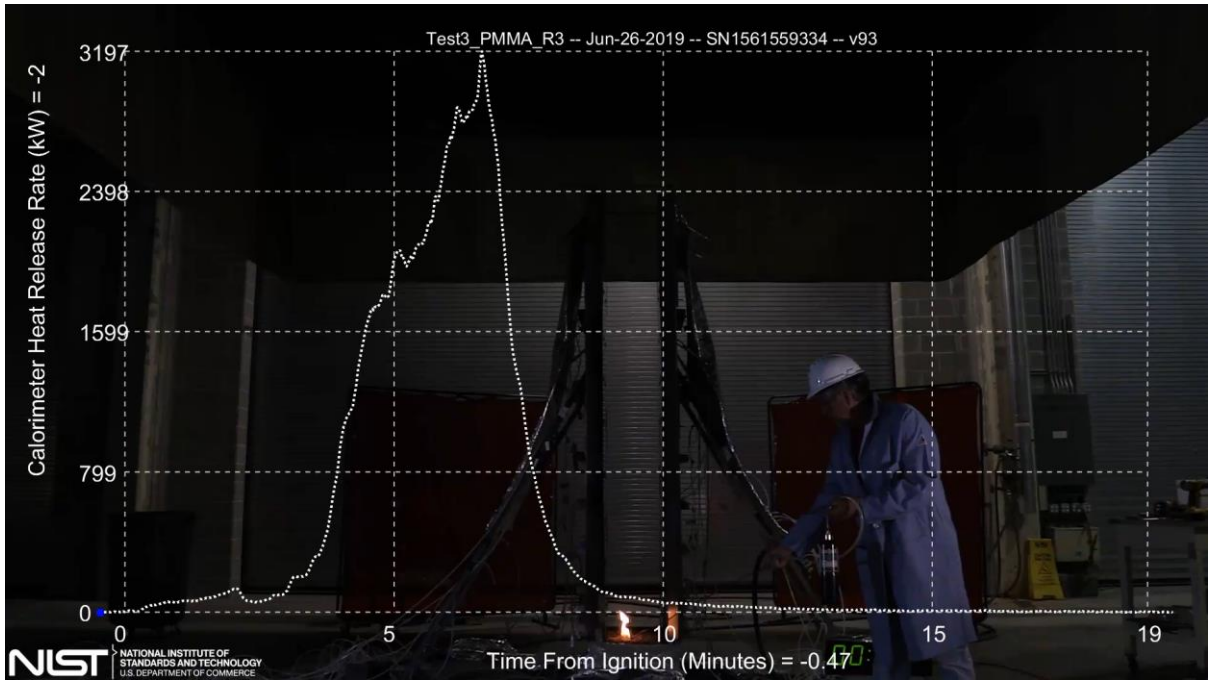


Measurement capabilities

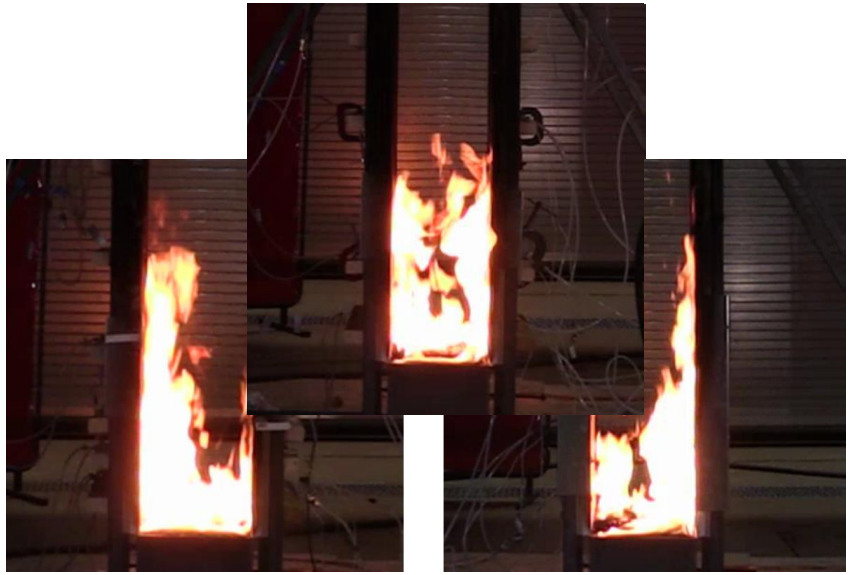
- Heat release rate: 3 MW oxygen calorimetry hood
- Flame heat flux: up to 14 Schmidt-Boelter heat flux gauges
- CO_2, CO, soot production
- Heat of combustion: sample mass
- Total flame to surface heat flux
- Heat flux at a distance
- Fraction of the total flame heat flux attributed to radiation

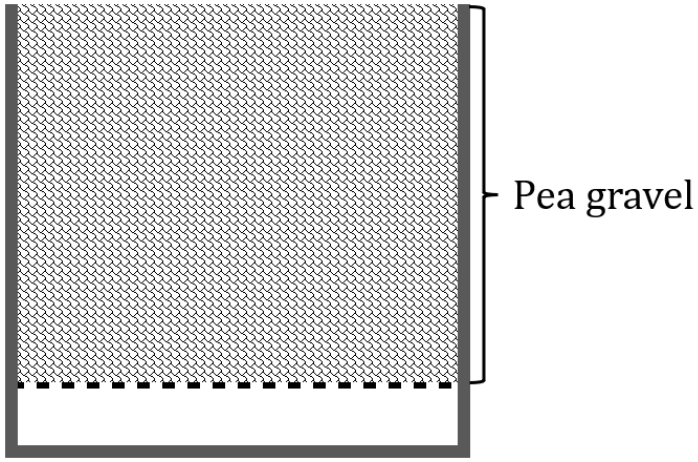
Experimental Design – Variety of Materials

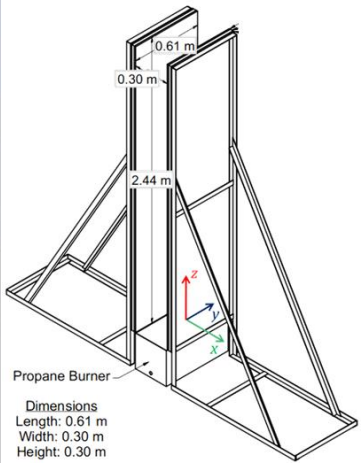
- 18 combustible solids:
  - Natural and synthetic polymers
  - Copolymers
  - Fiberglass-reinforced composite materials
  - Porous polymer foams
  - Electrical cables
- Charring, sooting, dripping
- Same material; varying thickness, density

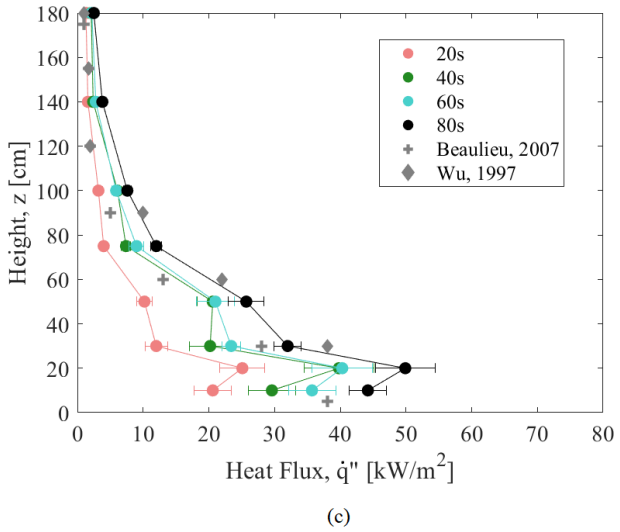


Burner Characterization

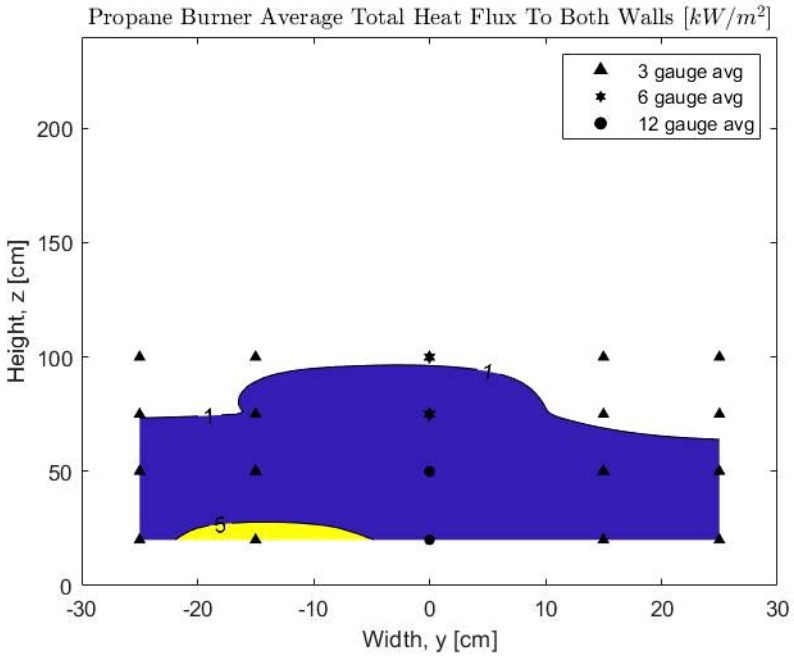


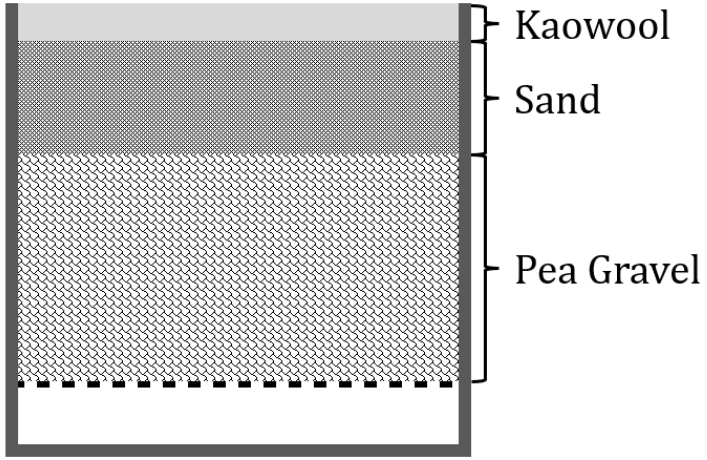


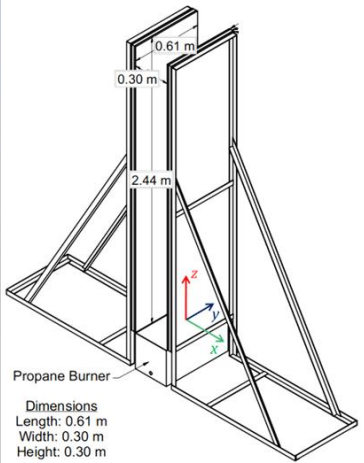


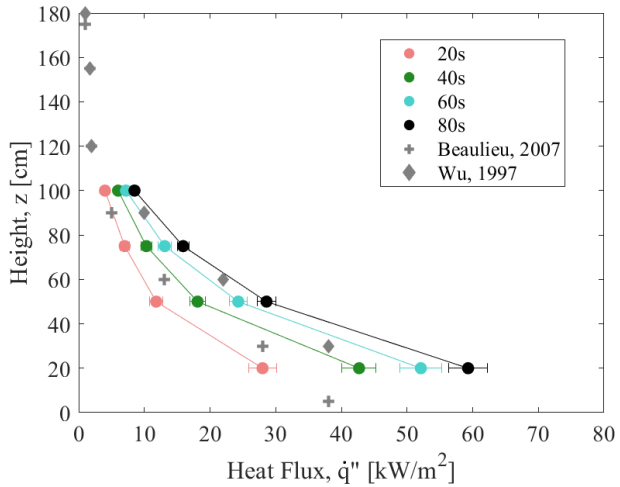


Burner Characterization



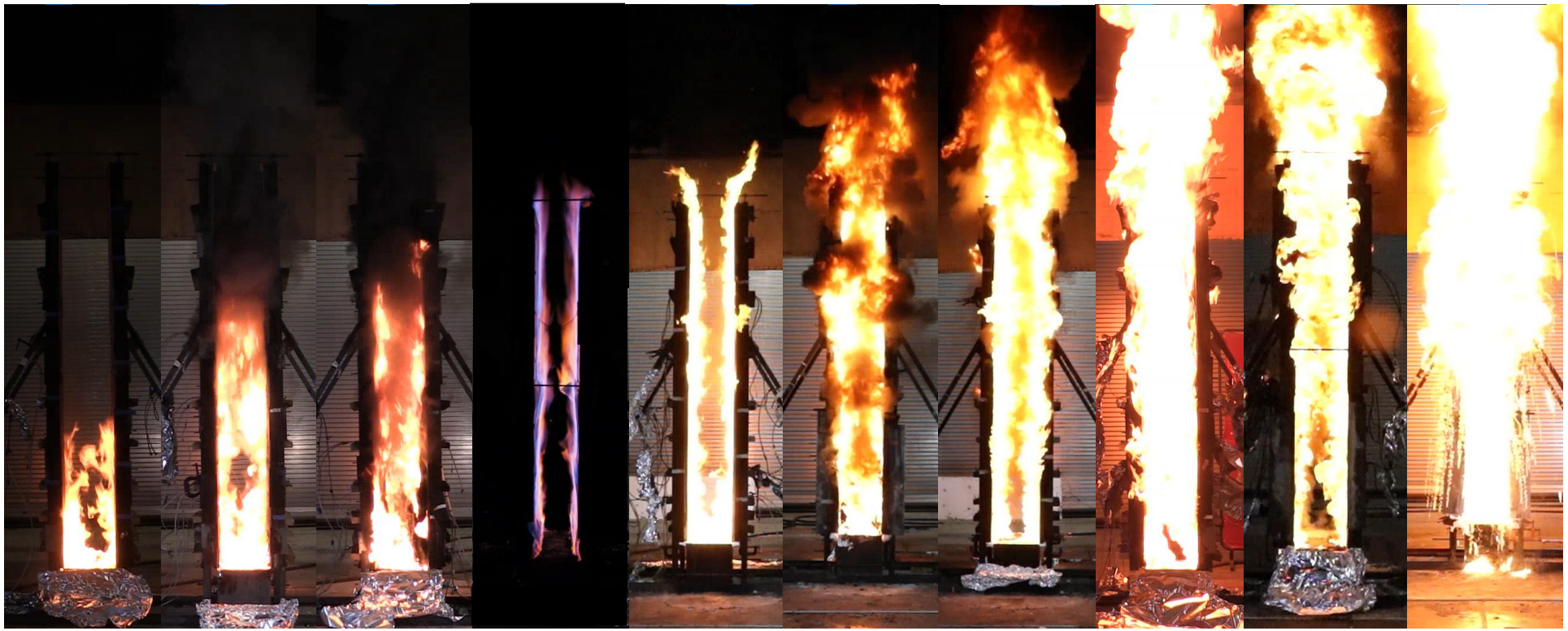






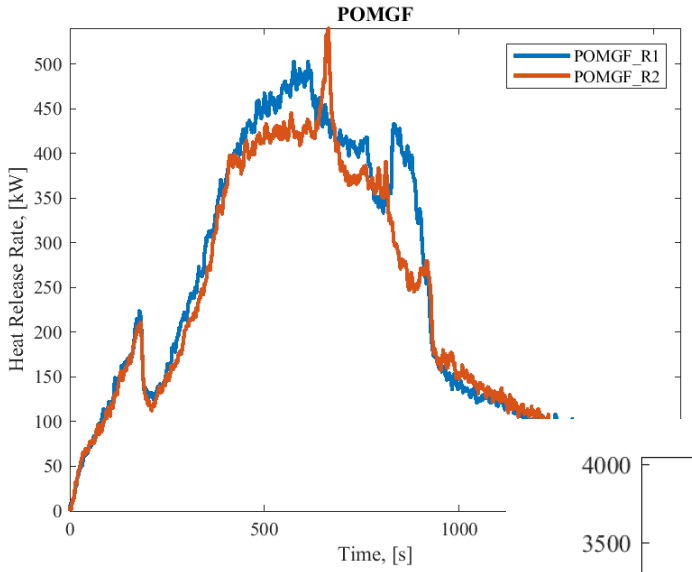
(d)

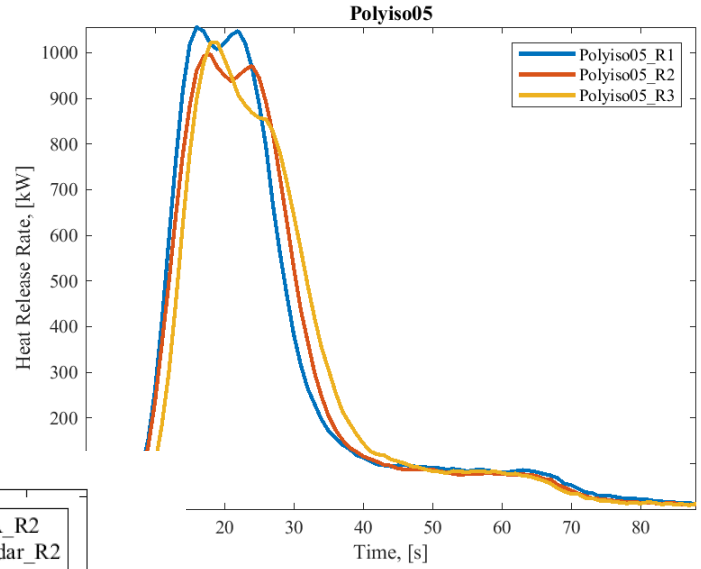
Results – Burning Behavior

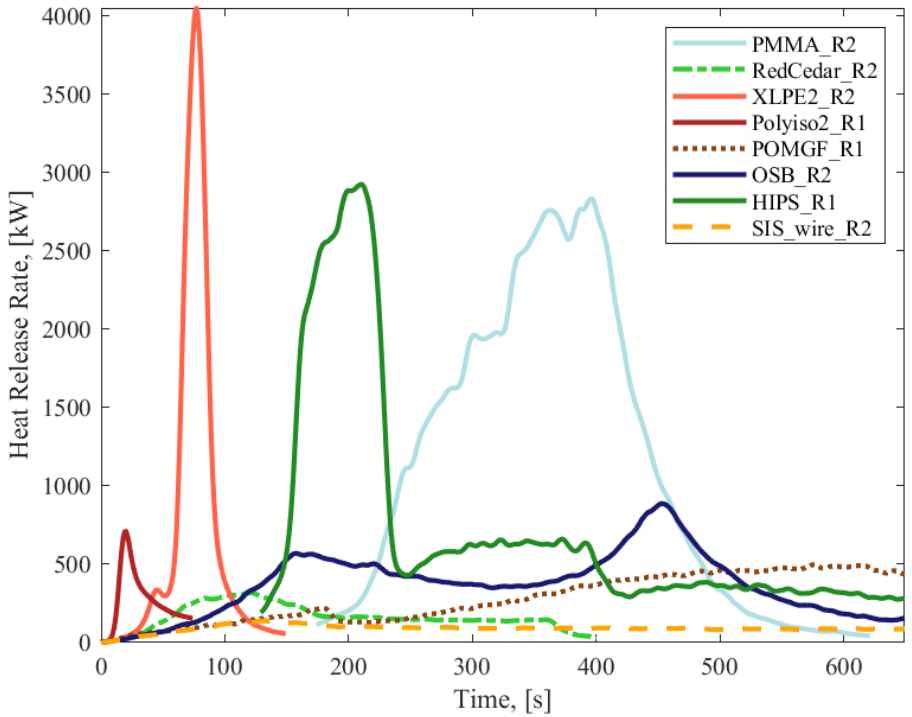


Red Board SIS Wire PVC POMGF Red Cedar Kydex PolyIso05 PMMA HIPS XLPE2

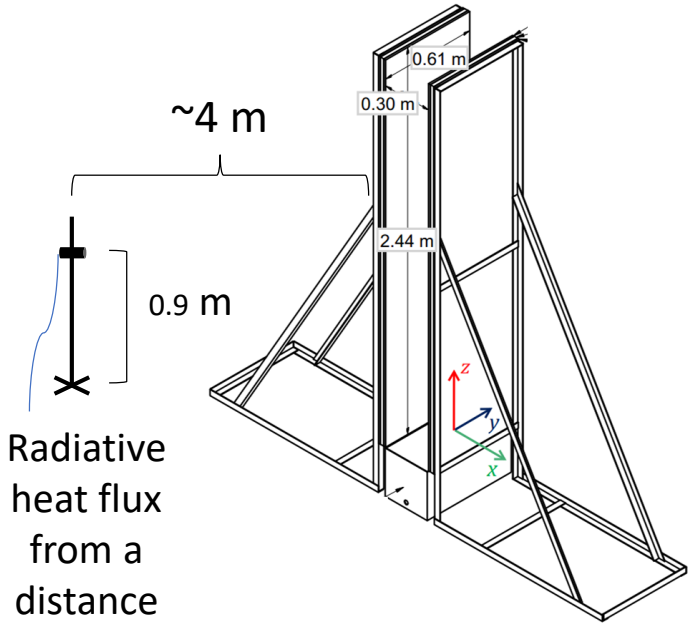
Results – Variety of Materials – HRR



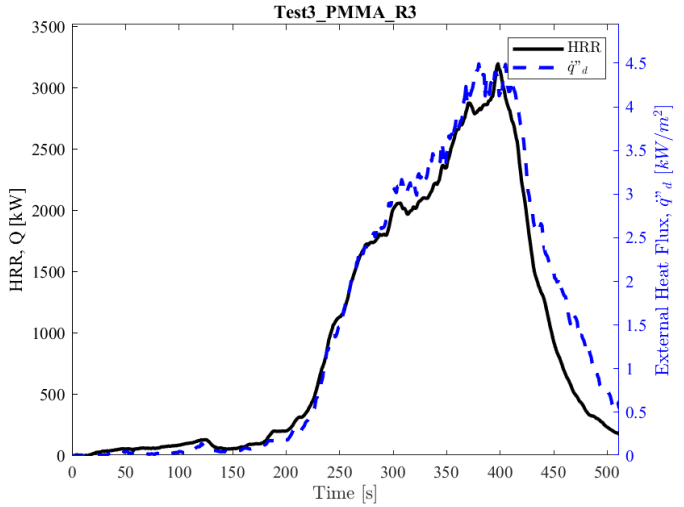


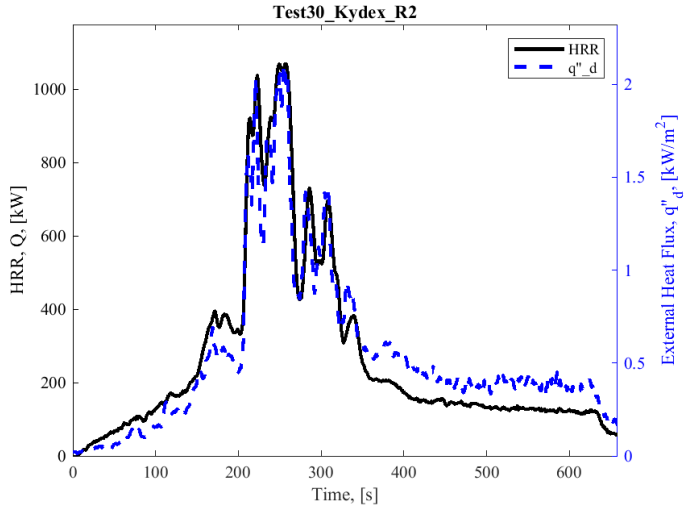


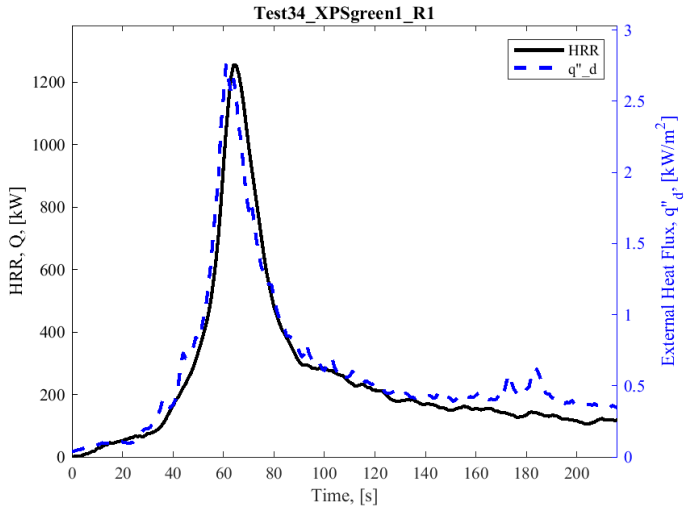
Results – Radiation At A Distance

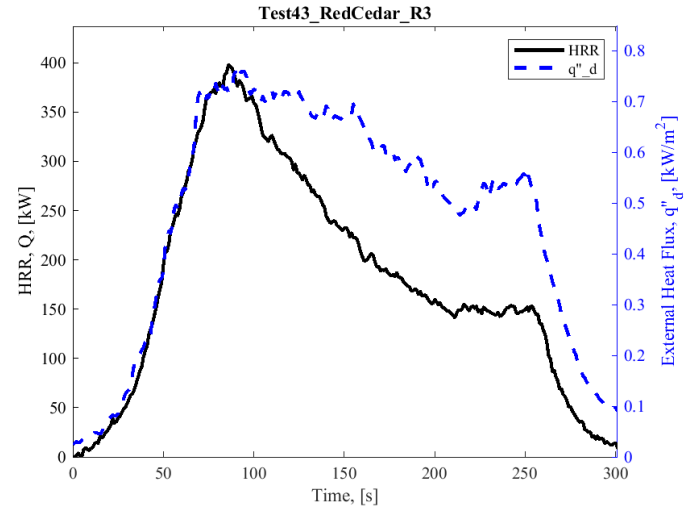


Radiative heat flux from a distance

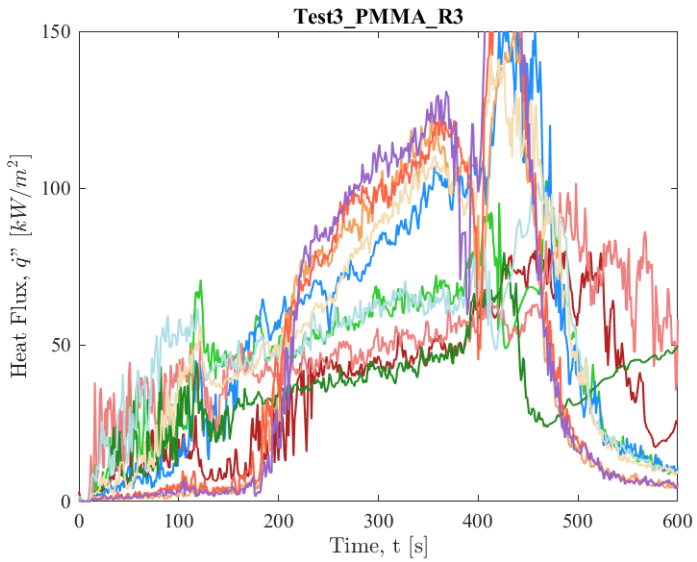


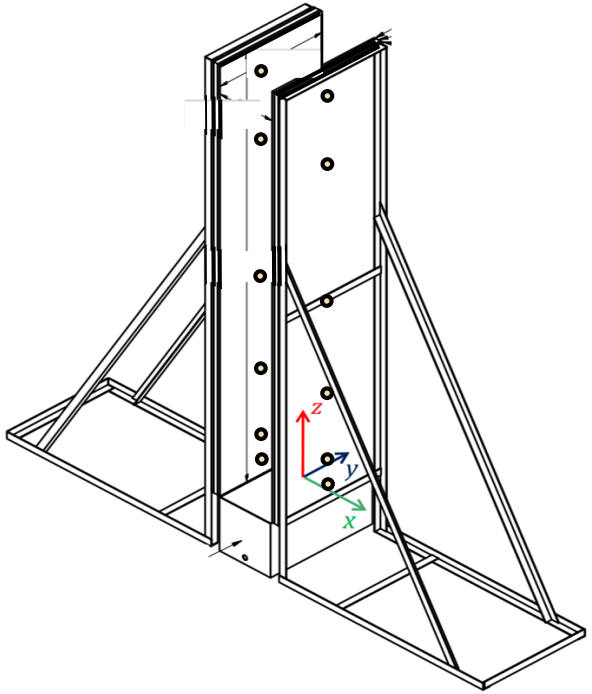


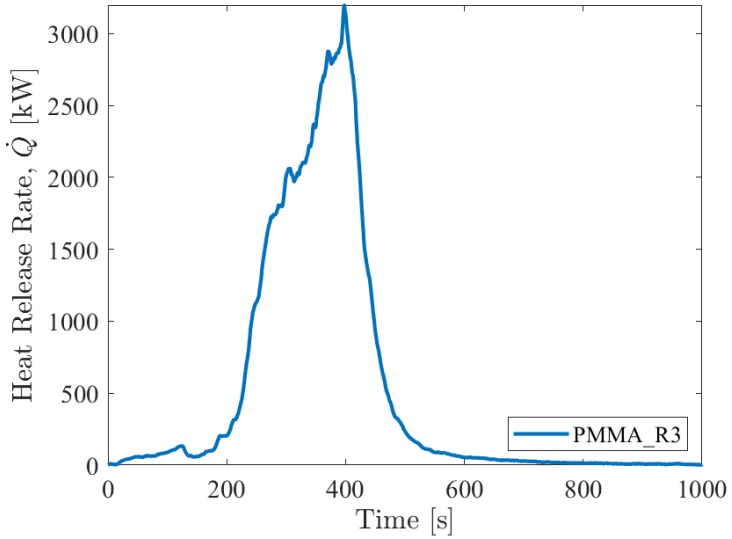




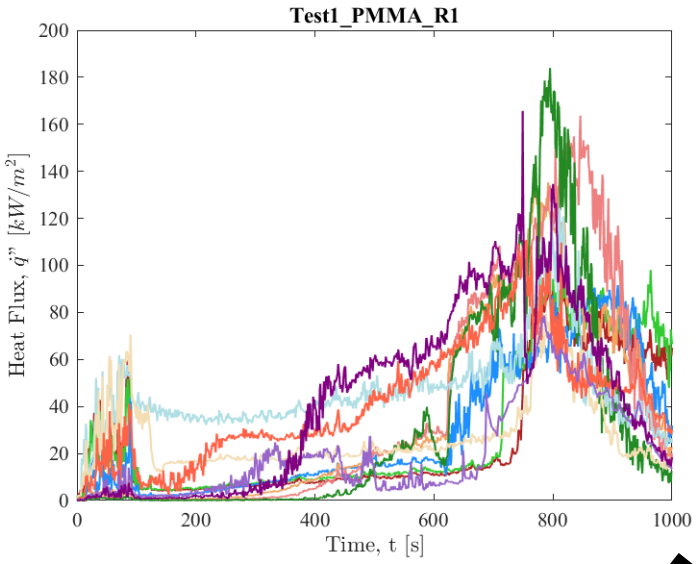
Results – Heat Flux Data – Sample Case

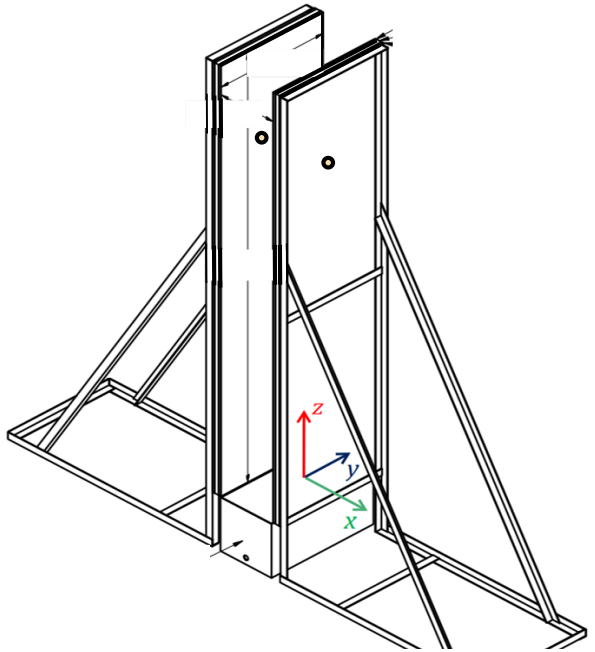


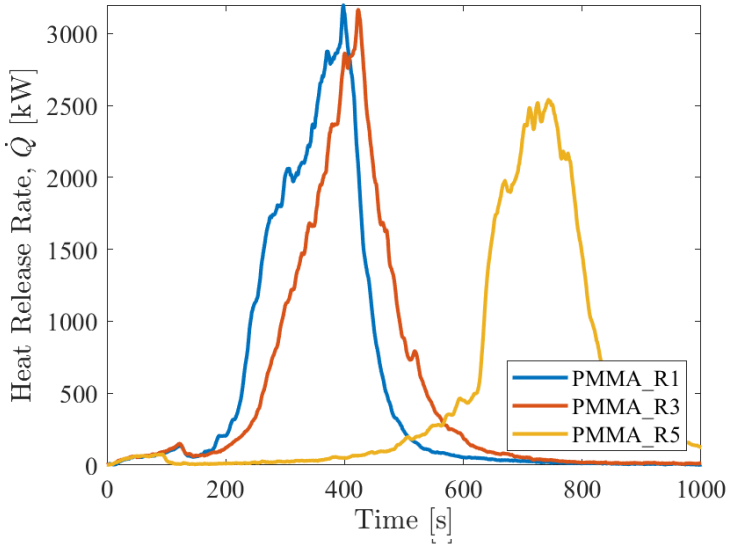


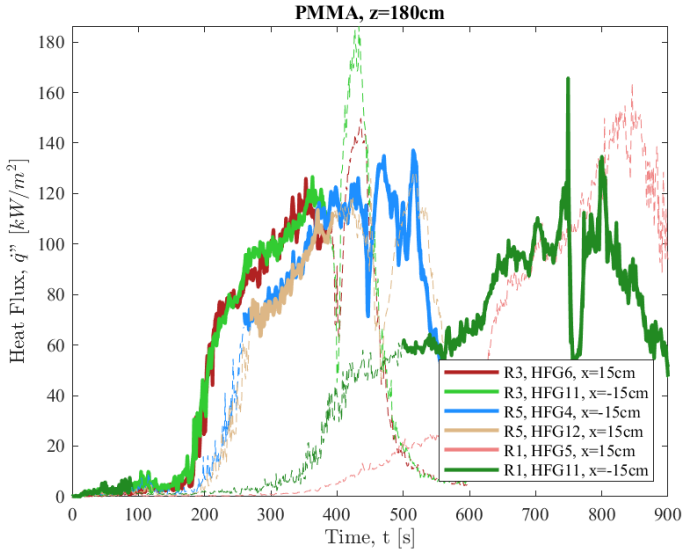


Results – Heat Flux Data – Sample Case

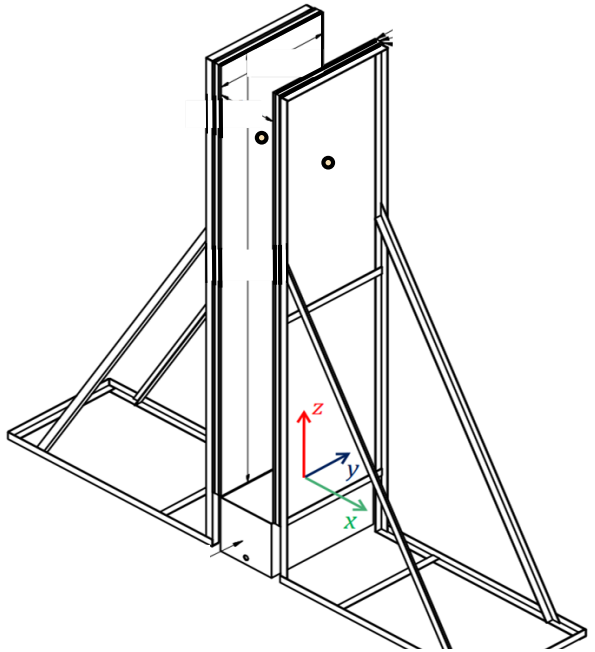


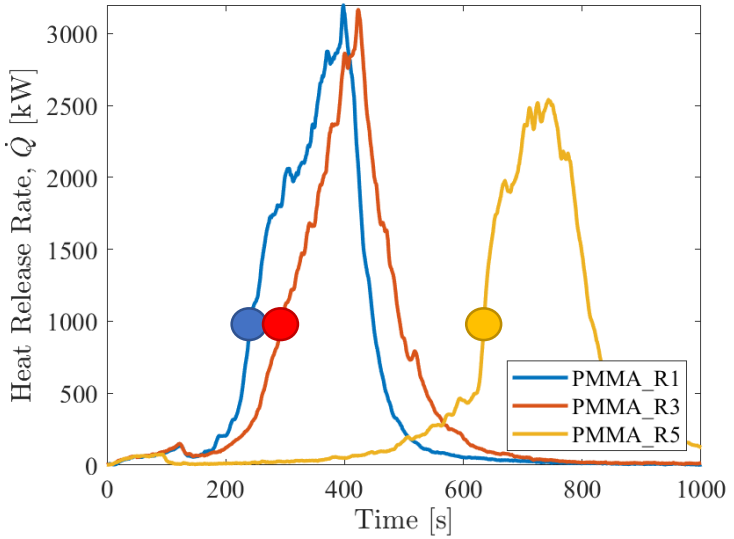


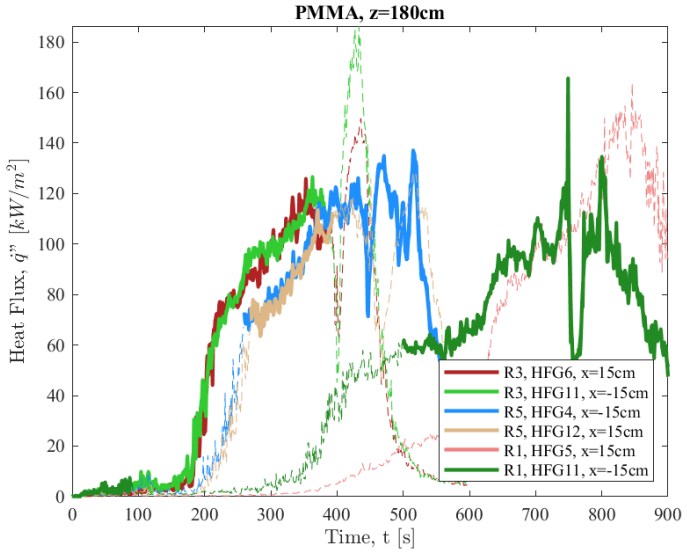


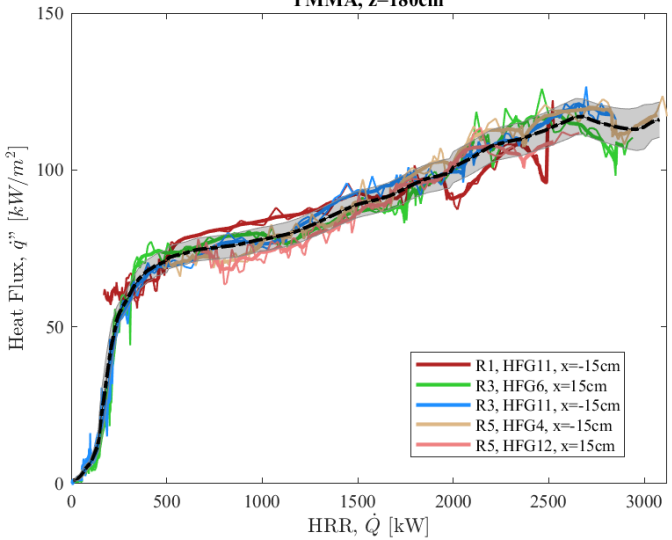


Results – Heat Flux Data – Sample Case

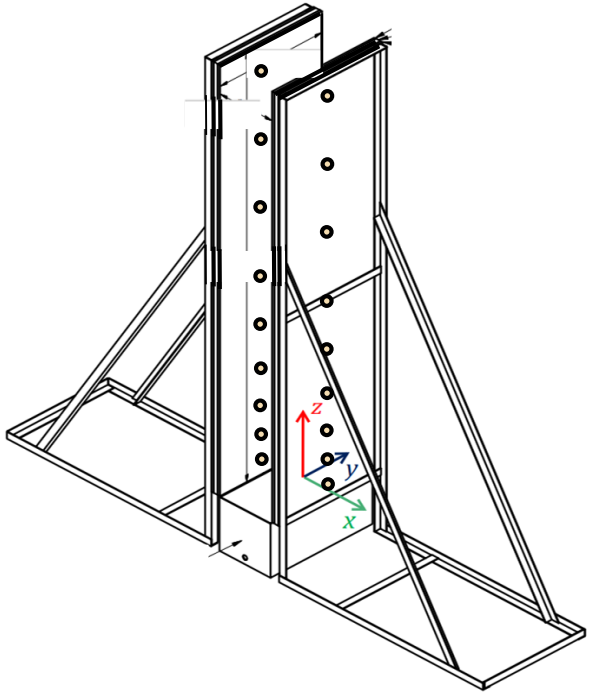


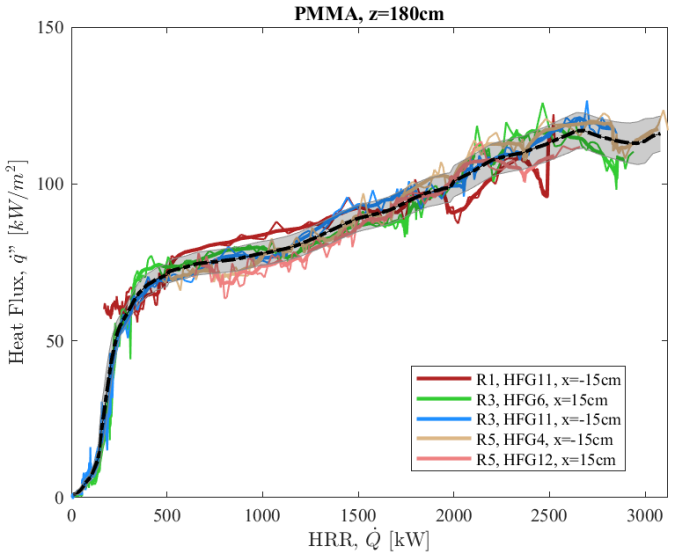


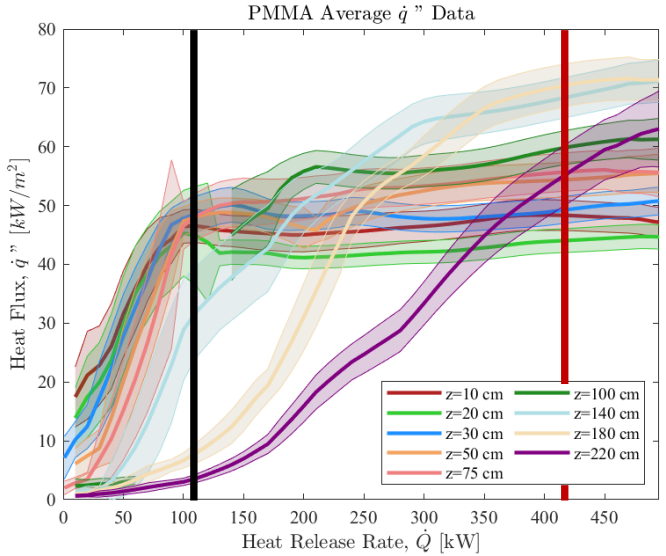


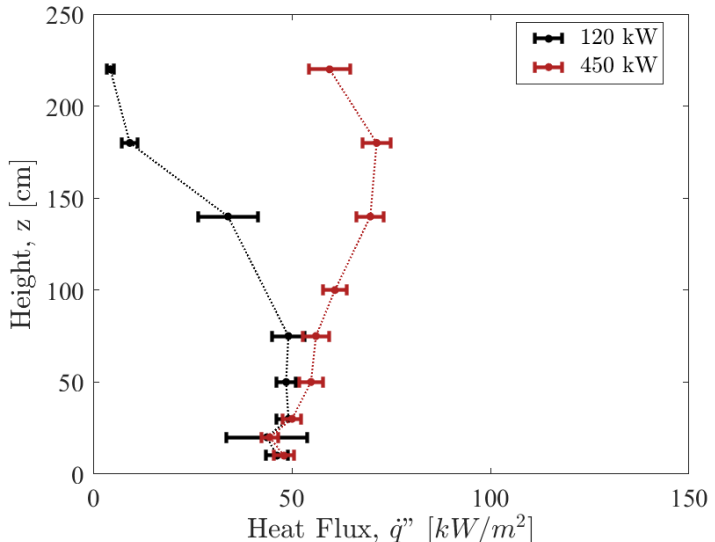


Results – Heat Flux Data – Sample Case

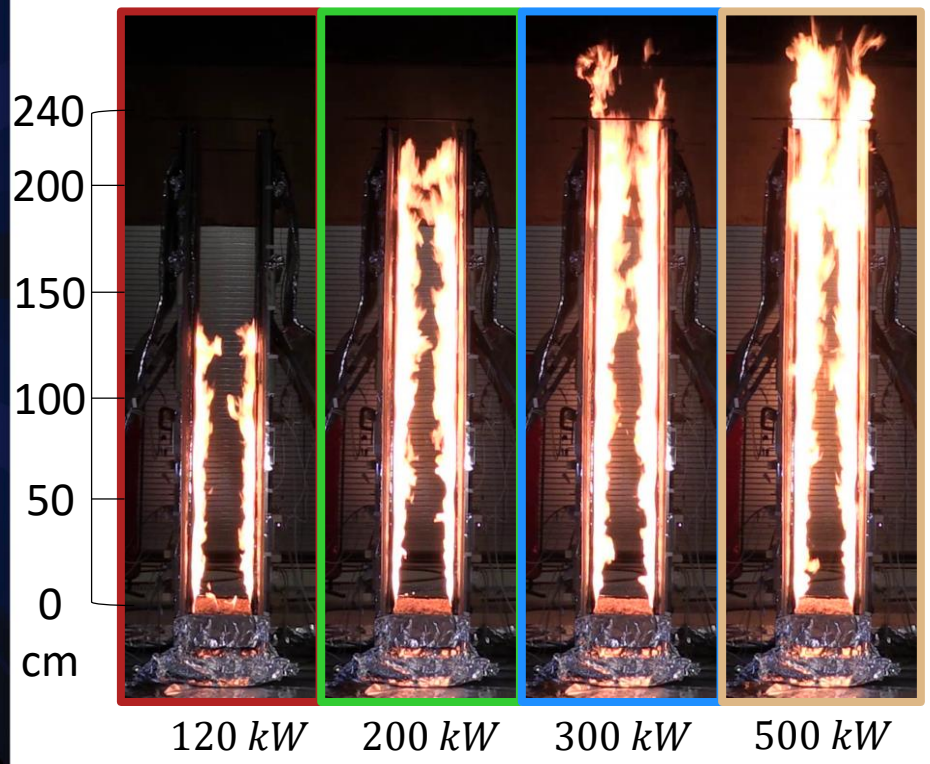


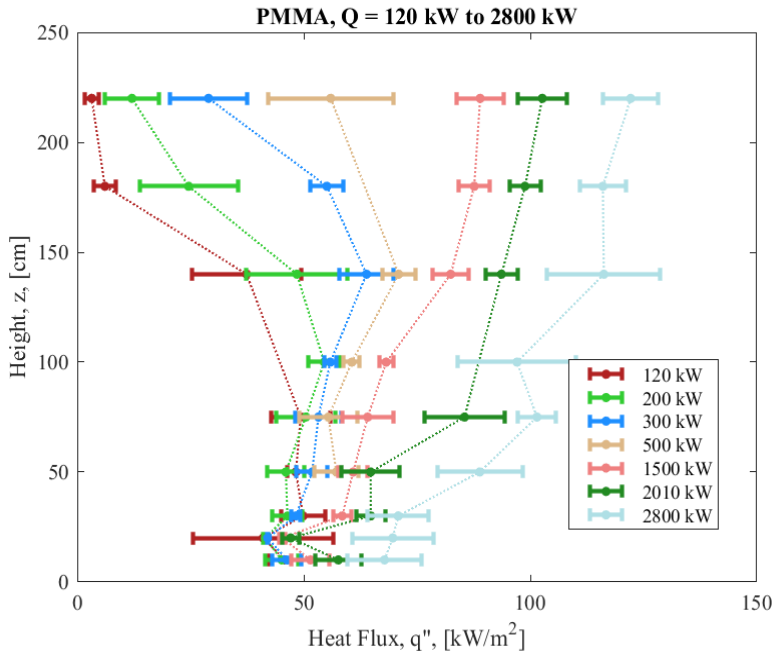




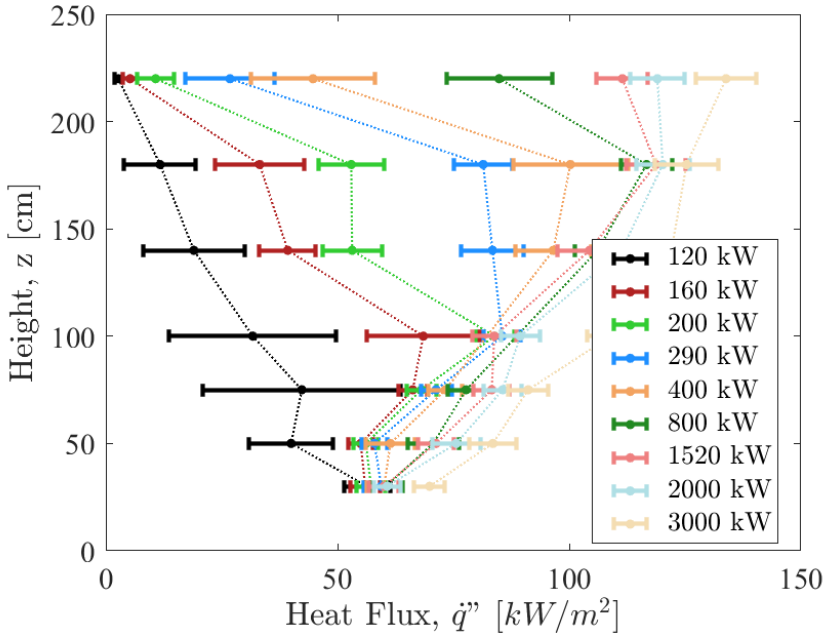


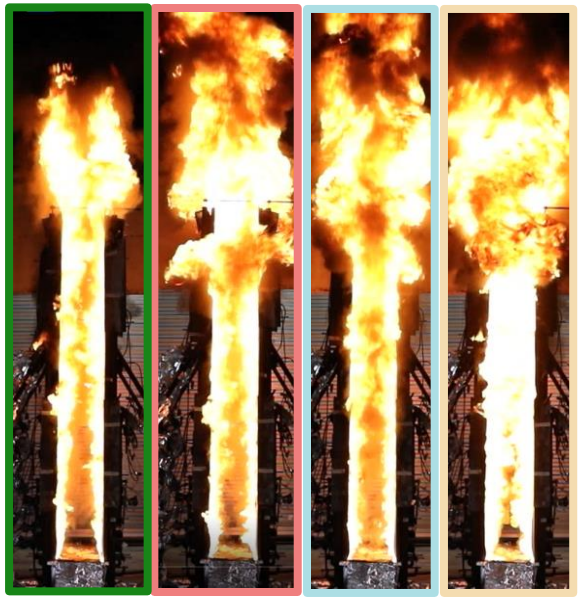
Results – Flame Heat Flux Profile - PMMA





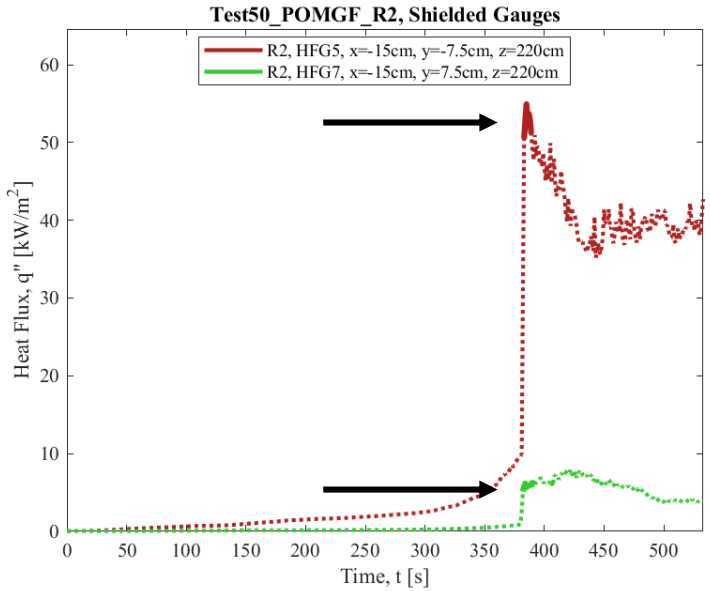
Results – Flame Heat Flux Spatial Profile – ABS

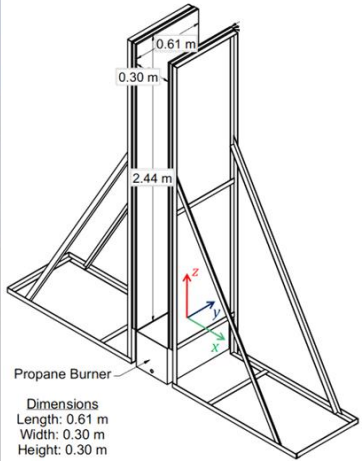




Doing this for all materials provides a comprehensive data set for validation

Results – Fraction of Heat Flux Attributed to Radiation



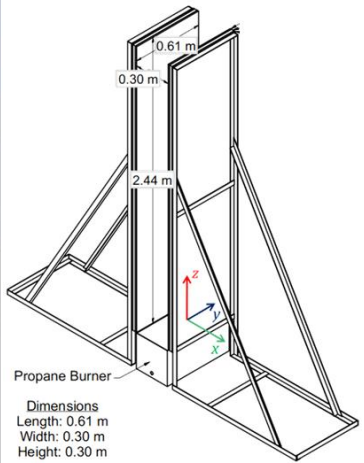


Radiation fraction of total heat flux to walls

$$q_{rad}(\%) = \frac{q''_{rad}}{q''_{total}}$$

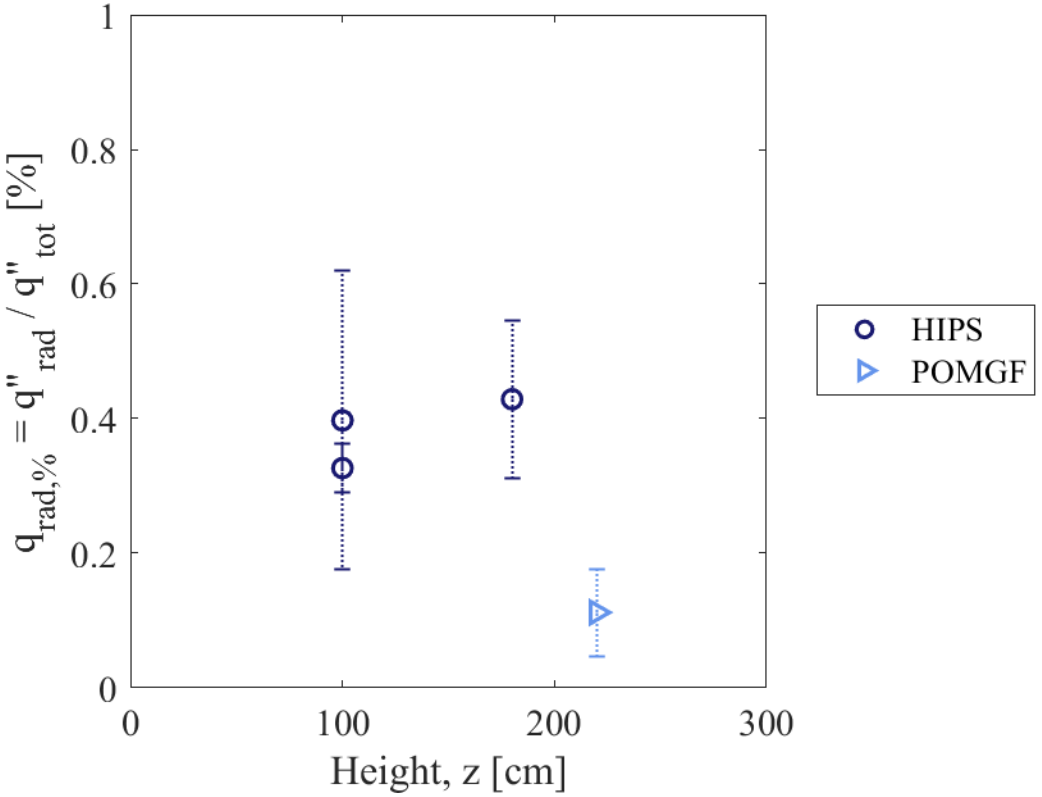
$$\frac{q''_{rad}}{q''_{total}} = \frac{\sim 6\ \frac{kW}{m^2}}{\sim 52\ \frac{kW}{m^2}} \cong 12\%$$

Results – Fraction of Heat Flux Attributed to Radiation



Radiation fraction of total heat flux to walls

$$q_{rad}(\%) = \frac{q''_{rad}}{q''_{total}}$$

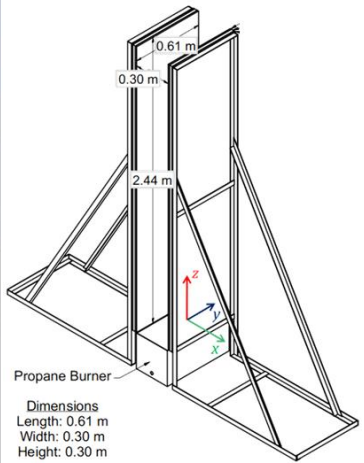


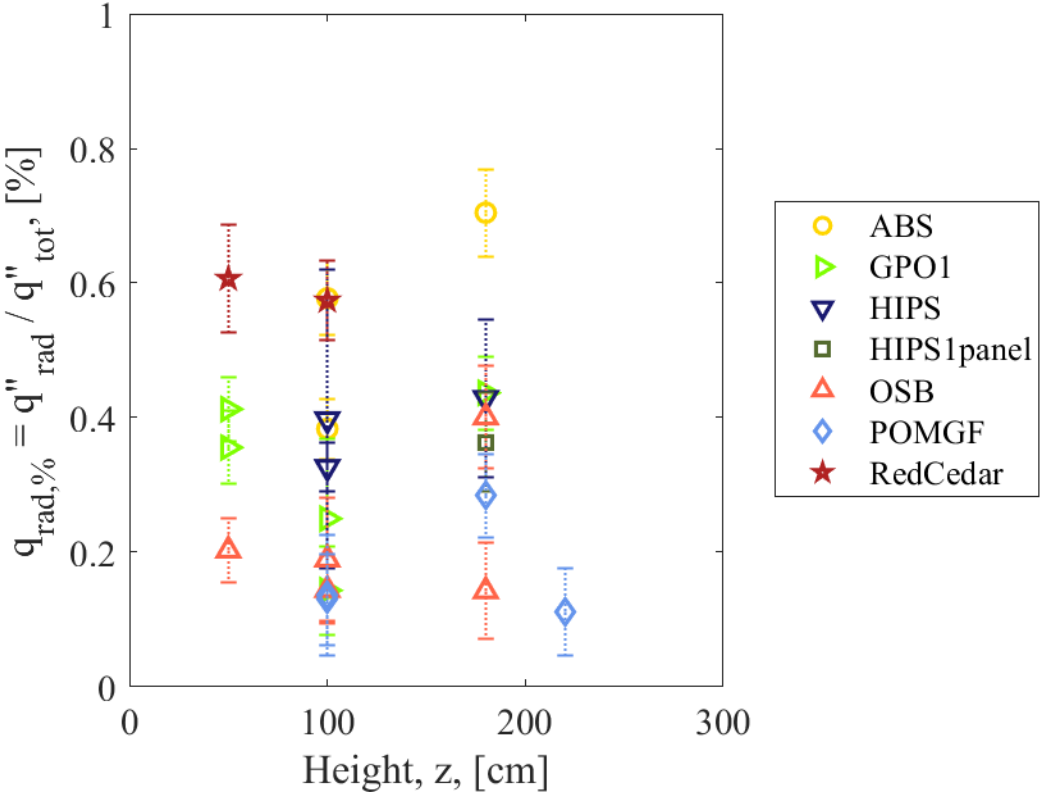
Results – Fraction of Heat Flux Attributed to Radiation

First ever direct measurements of

$$q_{rad}(\%) = \frac{\dot{q}''_{rad}}{\dot{q}''_{total}}$$

For multiple: fuels, HRR, locations





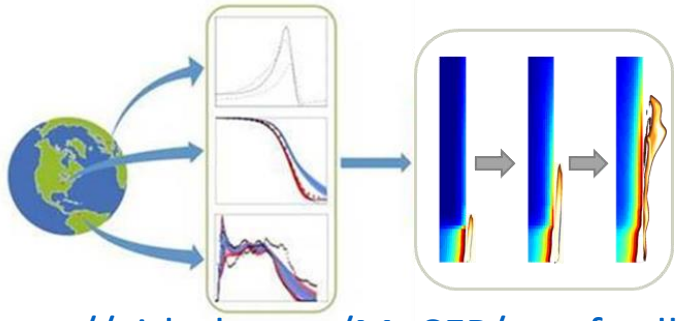
Results - Summary

- Comprehensive set of validation data for computational fluid dynamics (CFD) simulations of large-scale fire growth due to flame spread over the surface of combustible solids
  - Fire Size
    - Time resolved & Peak HRR
    - Total Heat Released
    - Fire Growth Rate
    - Heat of Combustion
  - Heat Transfer
    - Spatially resolved flame heat feedback profiles
    - Flame to wall heat transfer mechanism
    - Radiation heat transfer at a distance
  - Species Yields
    - Y_{CO}, Y_{CO_2}, Y_{soot}

Further Work

NIST Technote, The Impact of Material Composition on Ignitability and Fire Growth

- FDS Validation Guide
- Fire Calorimetry Database: https://www.nist.gov/el/fcd
- Material Flammability Database: https://flammability.el.nist.gov/
- MaCFP-3 Workshop (DOI: https://doi.org/10.18434/mds2-2812)



https://github.com/MaCFP/macfp-db

NIST Technical Note 22xx

The Impact of Material Composition on Ignitability and Fire Growth. Volume 1: Full-Scale Burning Behavior of Combustible Solids Commonly Found in Nuclear Power Plants

Isaac T. Leventon
Michael V. Heck
Kevin B. McGrattan
Matthew F. Bundy
Rick D. Davis

This publication is available free of charge from: https://doi.org/10.6028/NIST.TN.22xx

NIST National Institute of Standards and Technology U.S. Department of Commerce

NIST Special Publication 1018-3
Sixth Edition

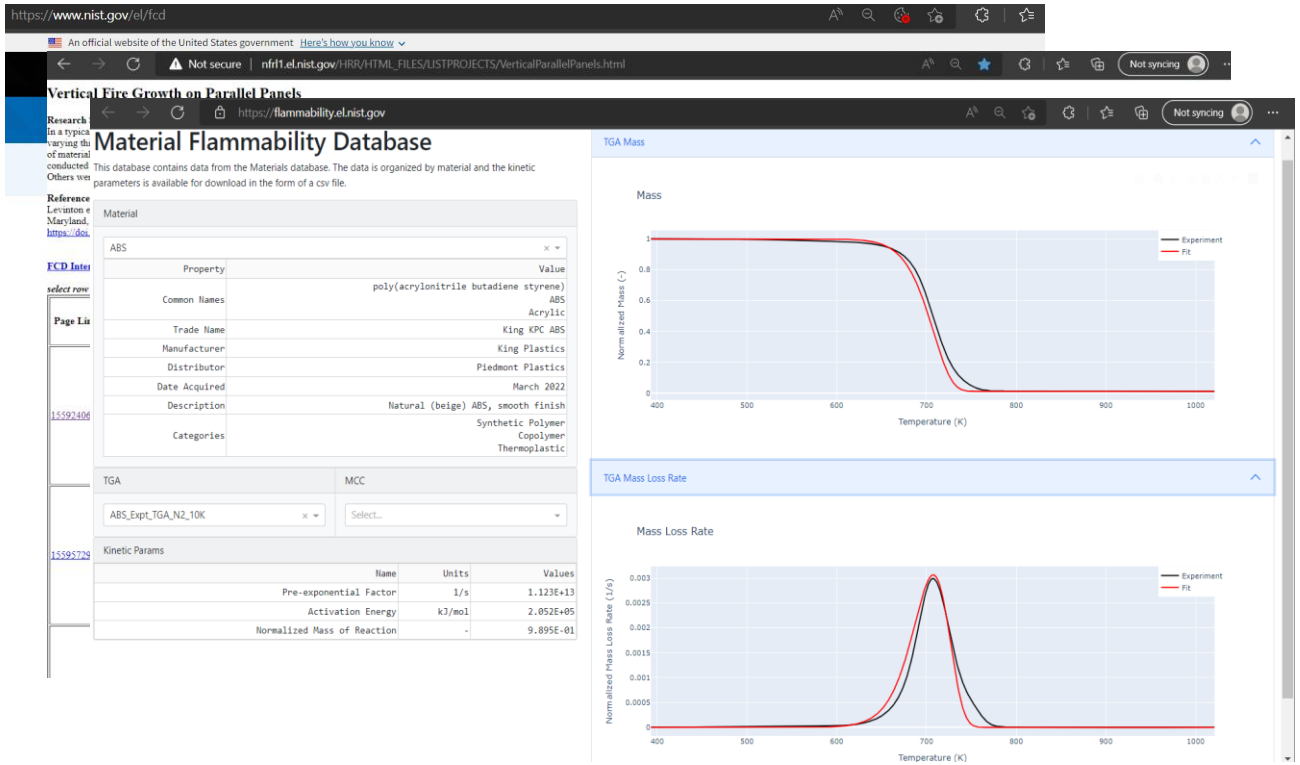
Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation

Kevin McGrattan
Simo Hostikka
Jason Floyd
Randall McDermott
Marcos Vanella

http://dx.doi.org/10.6028/NIST.SP.1018

VTT Technical Research Centre of Finland

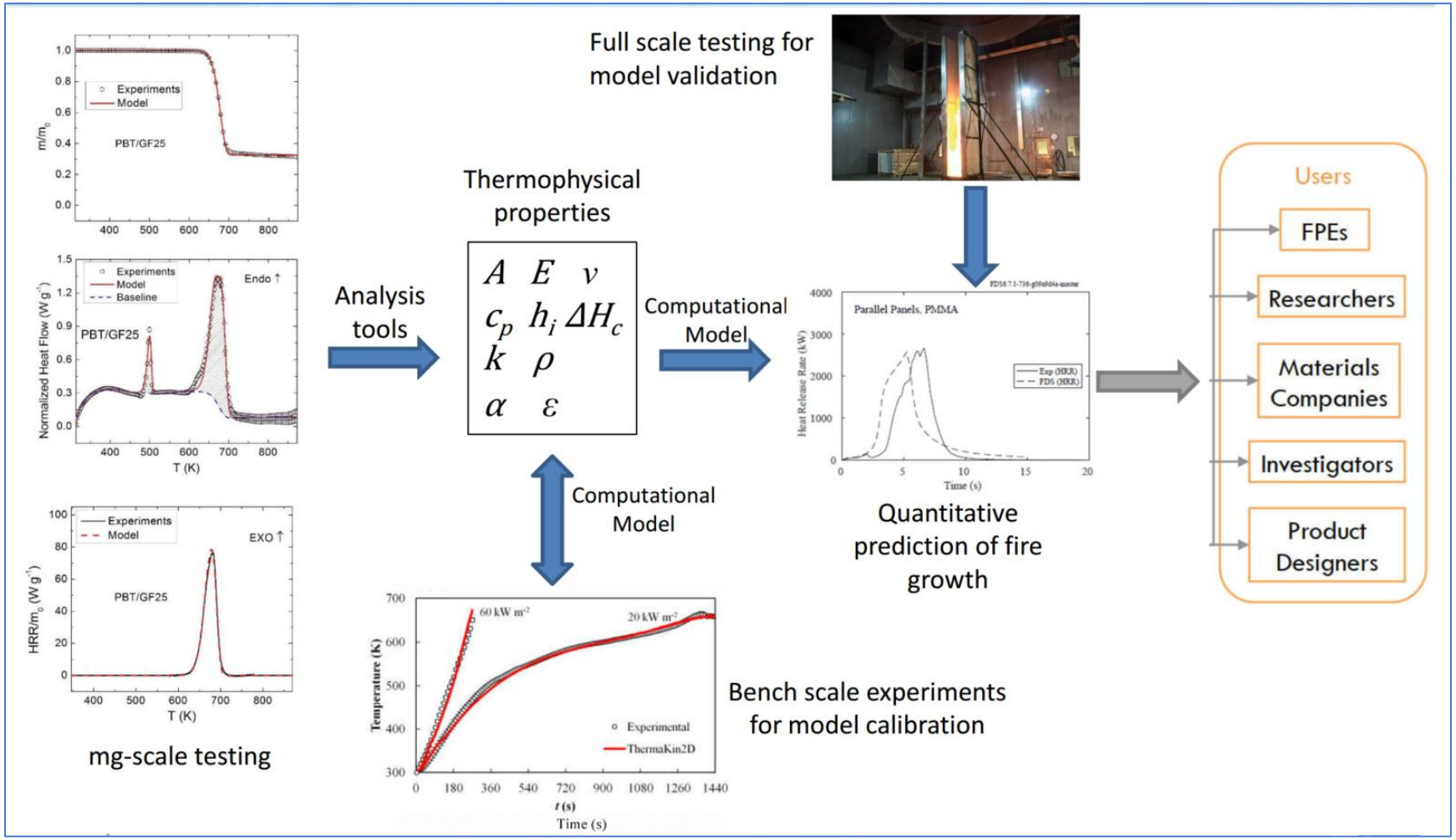
NIST National Institute of Standards and Technology U.S. Department of Commerce



Acknowledgements

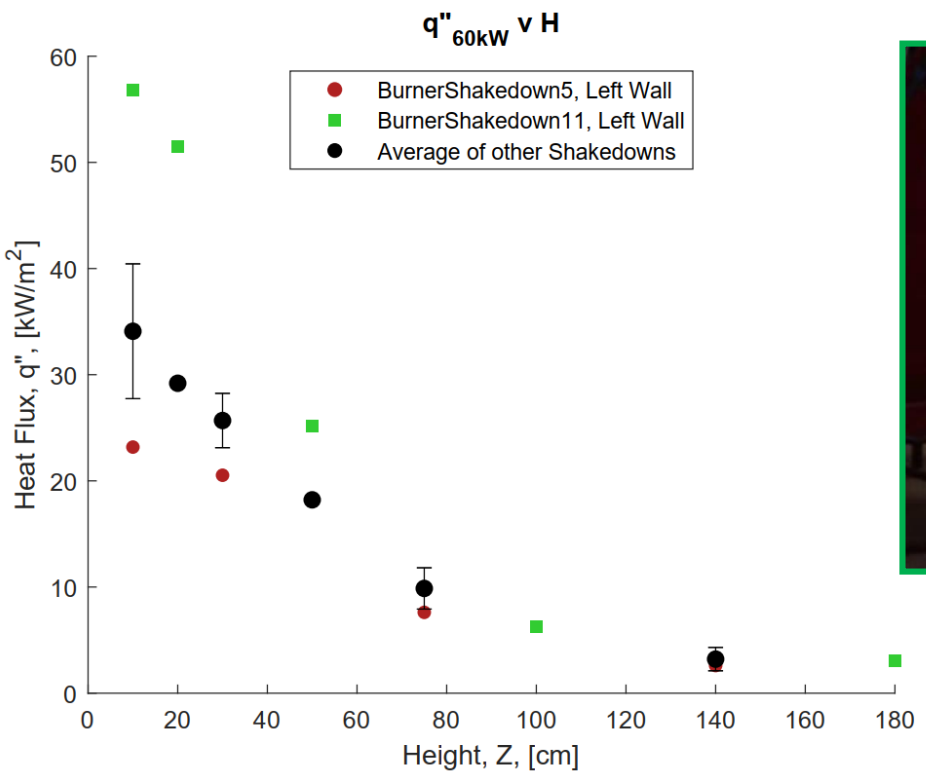
- Nuclear Regulatory Commission (NRC)
  - This work was supported by the Office of Nuclear Regulatory Research (RES) of the US Nuclear Regulatory Commission (US NRC)
  - Directed by: Mark Henry Salley
  - Support from: Kenneth Hamburger, Nicholas Melly, Gabriel Taylor, and David Stroup
- National Fire Research Laboratory (NFRL)
  - This facility is directed by Matt Bundy
  - Apparatus construction and maintenance: Marco Fernandez
  - Technical support: Matthew Bundy, Anthony Chakalis, Artur Chernovsky, Philip Deardorff, and Laurean DeLauter

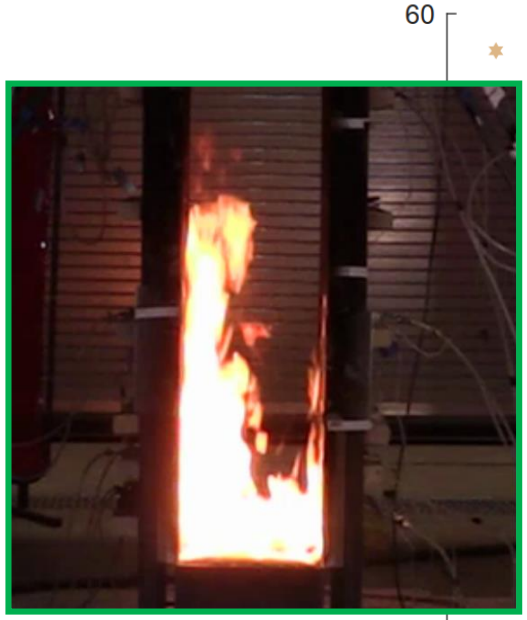
Thank you – Questions?



Burner Characterization

- Non-uniform flaming

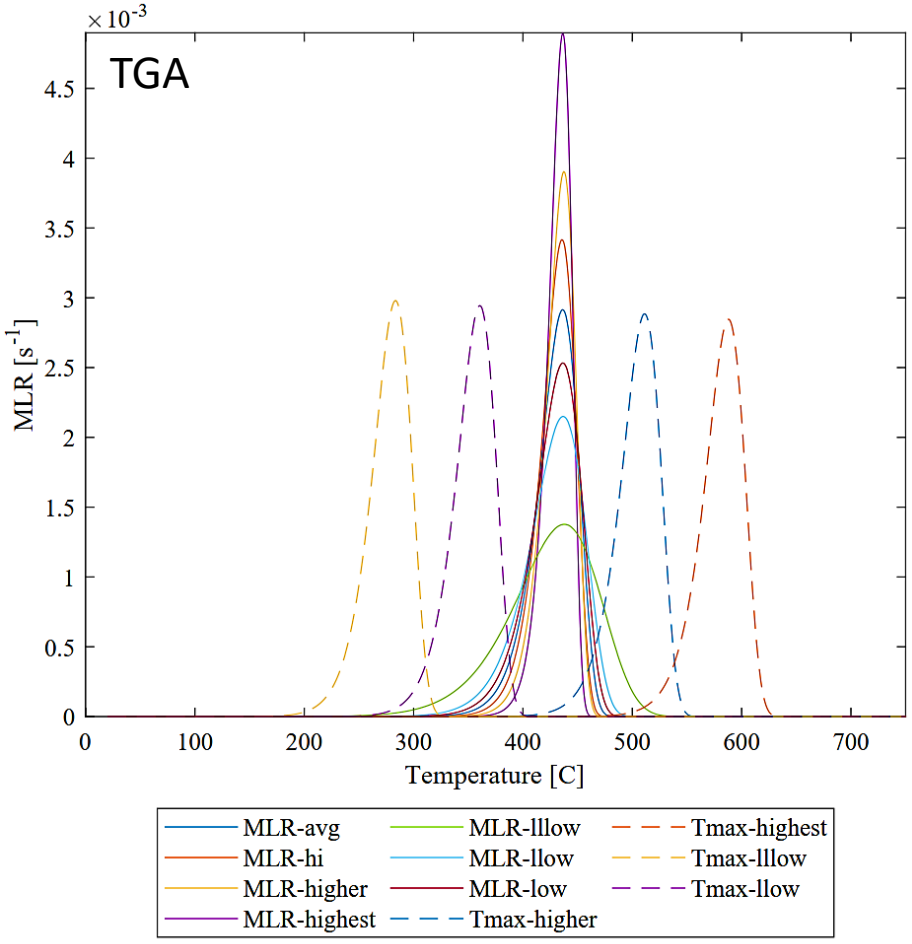


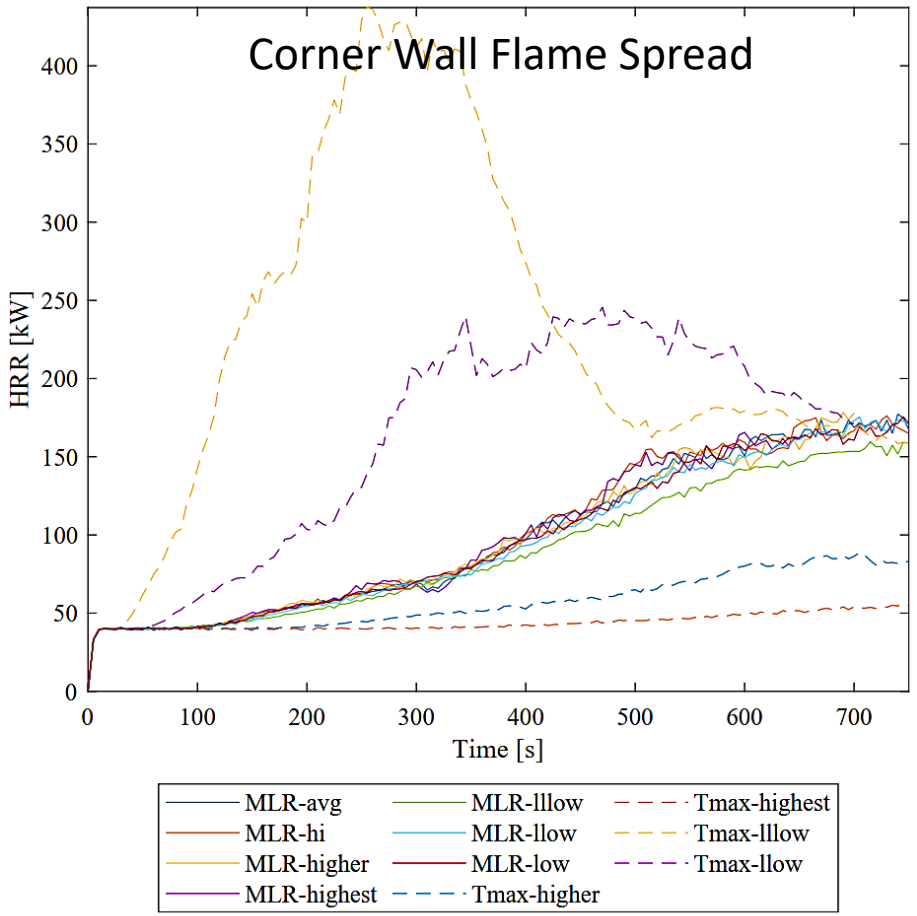


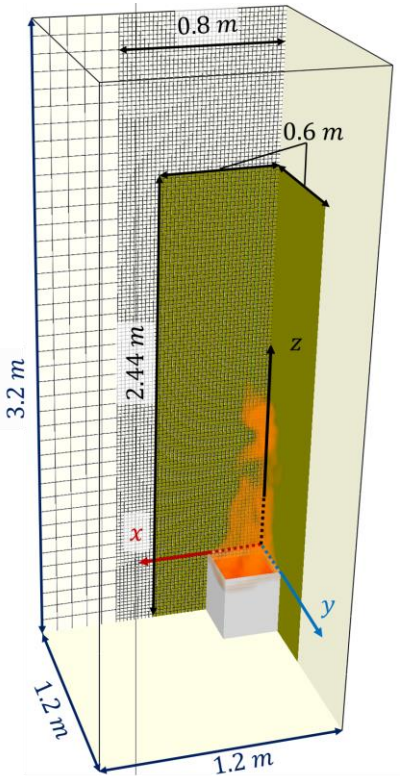
Interpretation of Measurement Results

Disclaimer

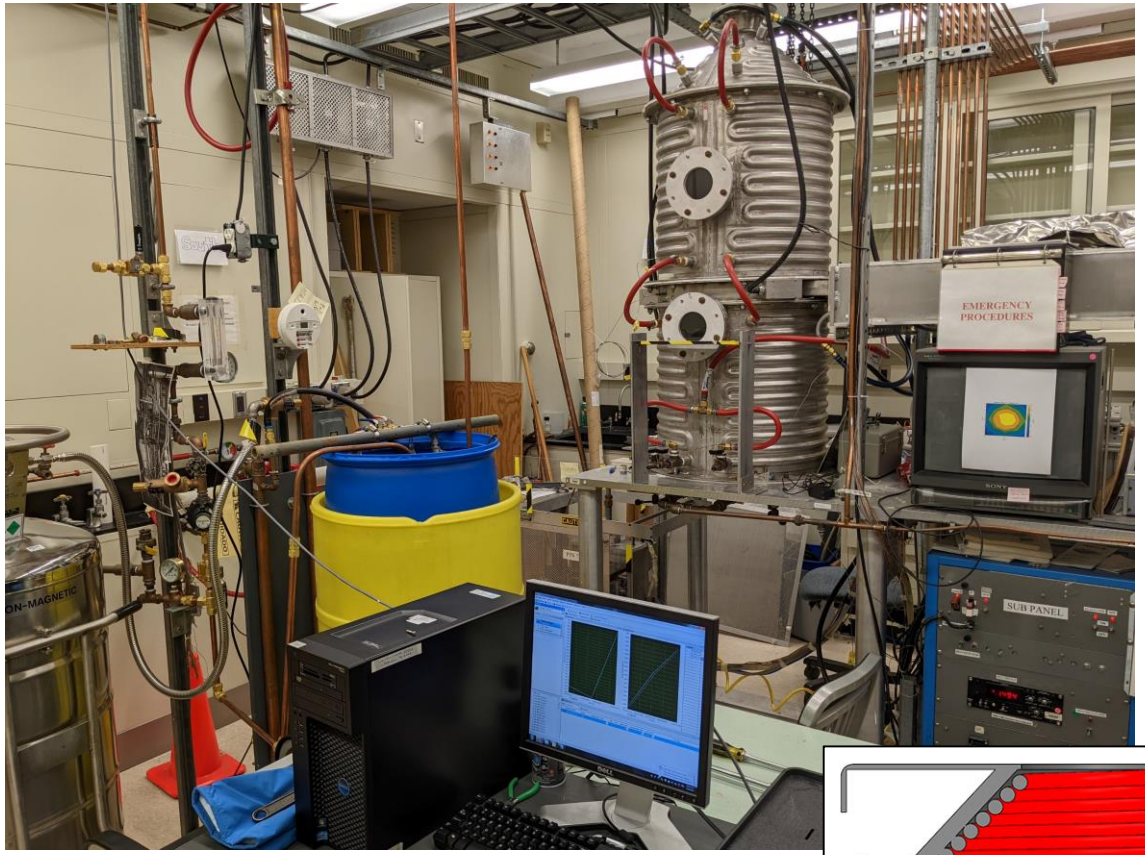
Some of the data in this presentation has not been through the NIST review process and should be considered experimental / draft results. However, the data has been analyzed by subject matter experts within the research team and is believed to be scientifically sound and consistent with the integrity expected of NIST research.

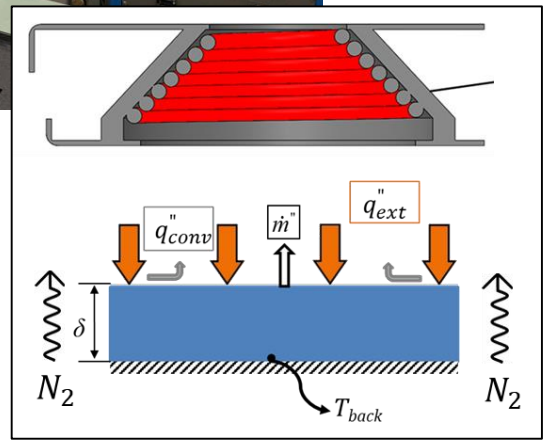


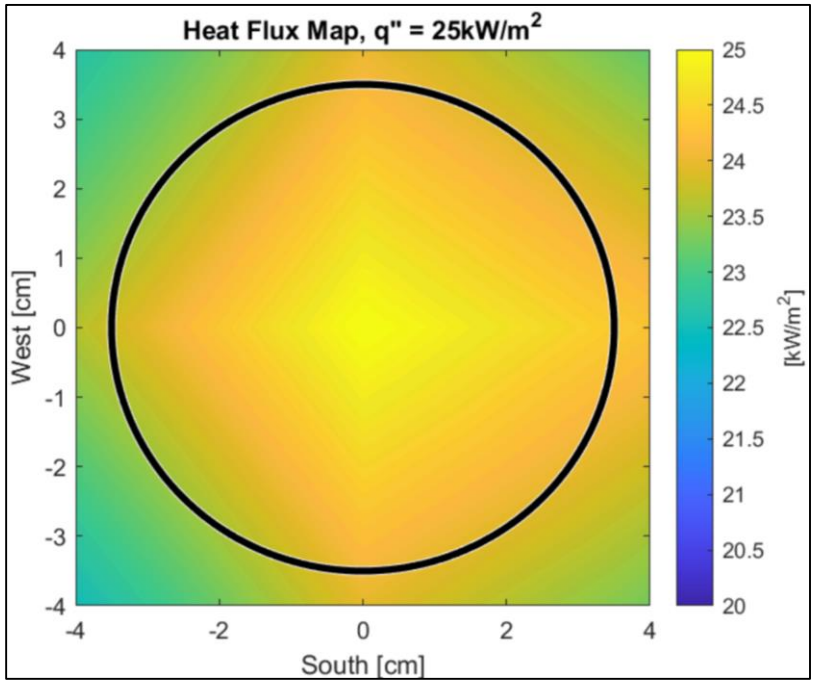


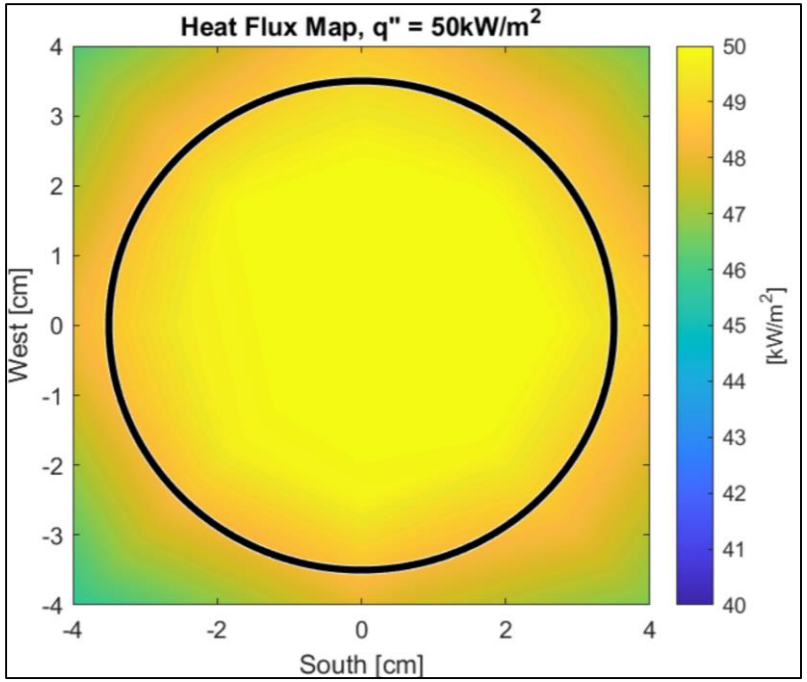


Bench Scale


EMERGENCY PROCEDURES
SUB PANEL


q''_{conv}
$\dot{m}''$
q''_{ext}
δ
N_2
N_2
T_{back}


Heat Flux Map, q" = 25kW/m^2
West [cm]
South [cm]
[kW/m^2]


Heat Flux Map, q" = 50kW/m^2
West [cm]
South [cm]
[kW/m^2]