Methods for Characterizing Theatrical Smoke for Smoke Detection Certification

Presented to: **International Aircraft Systems Fire Protection Forum**

By: **Matthew E. Karp**

Date: **May 14, 2019**

Federal Aviation Administration

Overview

- Section 1 Background
- Section 2 Methods and test equipment
- Section 3 Potential parameters
- Section 4 Simulating smoldering fires
- Section 5 Recommendations
- Section 6 Future testing

Test Apparatus

Section 1
Background

- Federal Aviation Administration (FAA) regulations require that a commercial aircraft cargo compartment smoke detection system must provide visual indication to the flight crew **within one minute** after the start of a fire [1].
- Further FAA guidance states that the smoke detection certification test is designed to demonstrate that the smoke detection system will detect a **smoldering fire** that produces a **small amount** of smoke [2].
- In an attempt to eliminate the frequency of **false alarms**, the FAA issued a Technical Standard Order to adopt the Minimum Performance Standards of smoke detector equipment, which includes criteria for resisting alarms from nuisance sources such as water vapor, insecticide aerosols, dust and light [3].

1 Title 14 Code of Federal Regulations (CFR) Part 25.858, 2/10/1998
2 Federal Aviation Administration Advisory Circular 25-9A
3 TSO C1e, 8/19/2014

Section 2
Methods and Test Equipment

- Testing is conducted in an altitude chamber with steady state conditions
- Theatrical smoke generators produce a non hazardous smoke
- Heater plate smolders foam and wood
- Lasers and photodiodes measure light obscuration
- Dual wavelength, blue and infrared, electromagnetic radiation scattering measurement (EMRSM) characterize particle size
  - Data is verified with scanning mobility particle sizer (SMPS)
- Vane anemometers characterize smoke transport

Test Apparatus

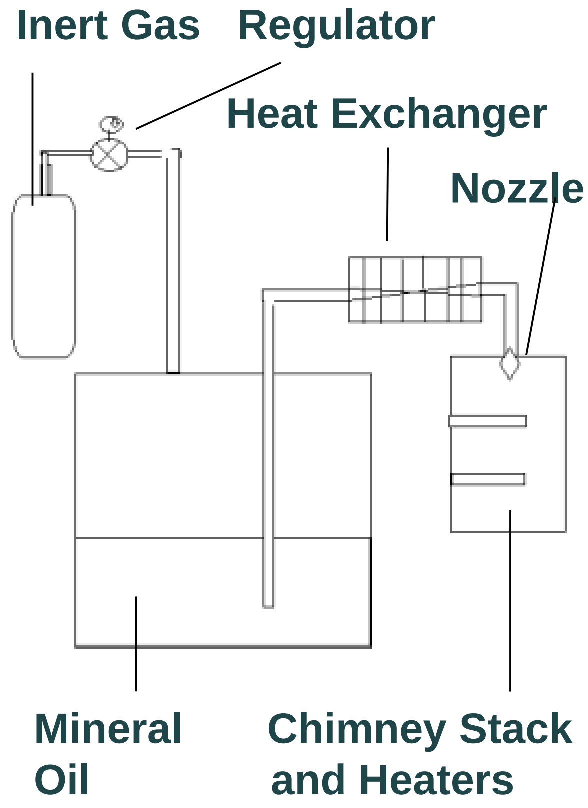
Altitude Chamber

- **240cm x 180cm x 180cm height**
- **Controls**
  - Temperature
    - As low as: **-**38C
  - Pressure
    - As low as: 2psia
- **Tested range**
  - Temperature
    - 10C – 30C

Altitude Chamber

Smoke Generators

- Theatrical smoke generators use an **inert gas** to propel **mineral oil** into a **heat exchanger**, where the solution is vaporized to create smoke.
- The theatrical smoke exits through a **chimney** incorporated with **heaters** to create a thermally-buoyant plume
- Important variables of smoke generators
  - Gas propellant
  - Gas propellant pressure
  - Chimney heater temperature
  - Mineral oil characteristics
    - Viscosity and refractive index



Simplified Smoke Generator Schematic

Aircraft Manufacturers' Setups

- Three major aircraft manufacturers' smoke generators and settings are tested and compared
- One manufacturer uses the Siemens Cerberus
- Two manufacturers use the Aviator 440
- One manufacturer uses nitrogen as the propellant gas
- Two manufacturers use carbon dioxide as the propellant gas
  - The setups will be annotated as
    - MFR 1a, 1b and 1c
    - MFR 2a and 2b
    - MFR 3

Concept Aviator

Siemens Cerberus

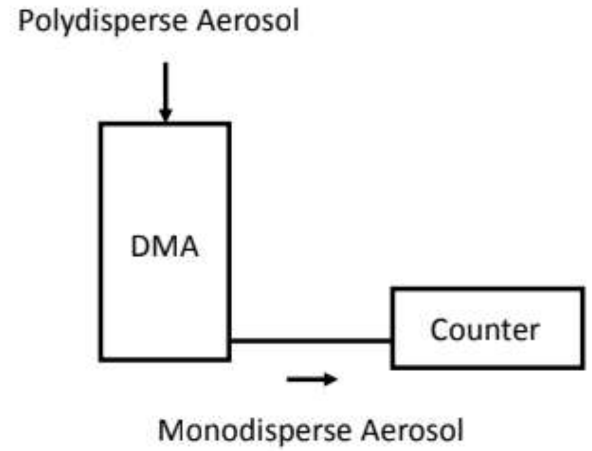
Combustible Materials

European beech wood
QTY10, 1.27cm x 7.6cm x 2.5cm

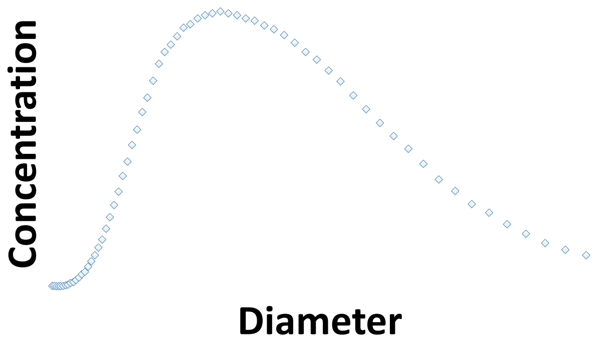
Open cell polyurethane foam
2.5cm x 15.2cm Dia.

Scanning Mobility Particle Sizer (SMPS)

- **How does the SMPS work?**
  - An impactor removes large particles and measures flow.
  - A neutralizer creates a well-characterized charge distribution on the particles.
  - Inside a Differential Mobility Analyzer (DMA), the charged particles experience an electrical field that separates particles based on their electrical mobility and outputs a monodisperse aerosol.
    - Electrical mobility is inversely related to particle size
  - The condensation particle counter (CPC) counts the monodispersed particles as they exit the DMA.



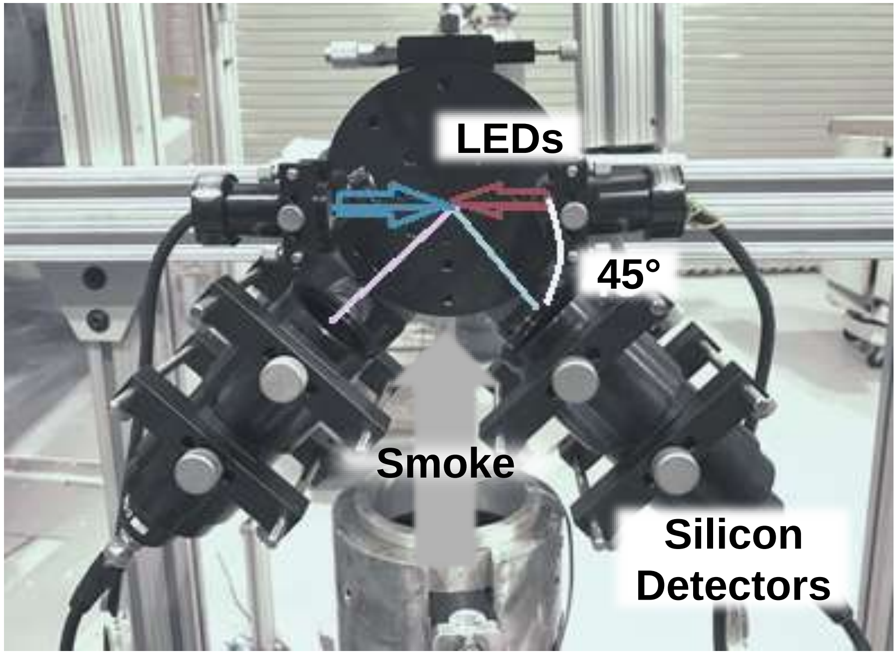
SMPS Simplification



SMPS Output

Electromagnetic Radiation Scattering Measurement (EMRSM)

- **Two LEDs**
  - 470nm blue LED scattered at 45°
  - 850nm IR LED scattered at 45°
- **Two silicon detectors**
  - To measure scattering intensity
- **Measurements used to calculate:**
  - 1. Percent increase Blue response
  - 2. Percent increase IR response
    - Calculate %Blue signal



Electromagnetic Radiation Scattering Measurement (EMRSM)

Mie Scattering Theory

- **Mie Scattering Theory** governs light scattering by sub-micron particles
- A simplified approximation of Mie Scattering Theory is given by van de Hulst [4]

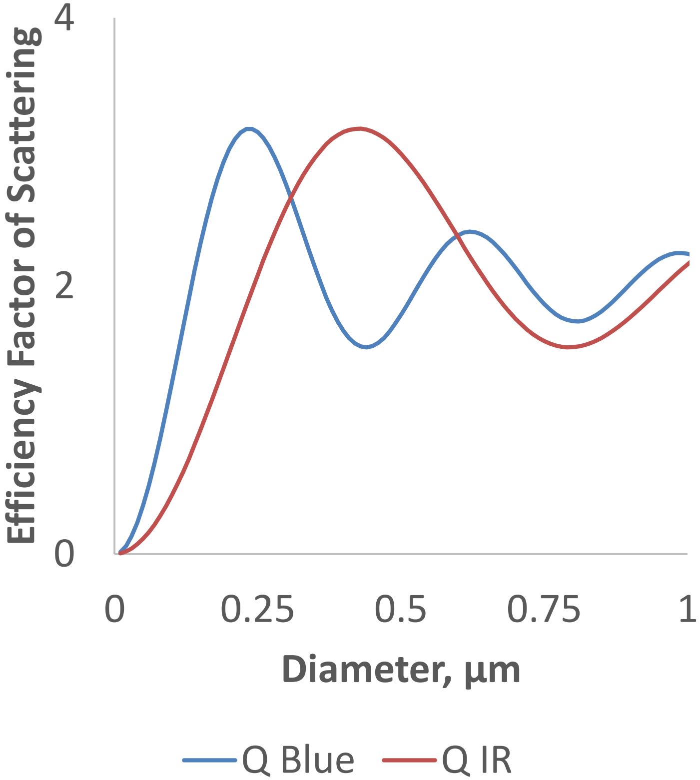
$$Q = 2 - \frac{4}{p}\sin(p) + \frac{4}{p^2}(1 - \cos(p))$$

- Where Q is the efficiency factor of scattering

$$p = \frac{4\pi a(n-1)}{\lambda}$$

This shows that the **scattering intensity** is a function of

n, **<u>Refractive index</u> of the particle**
a, <u>radius</u> of the particle
λ, <u>Wavelength</u> of the incident light



Maxwell's Equation plotted using 470nm and 850nm wavelengths, refractive index 1.5

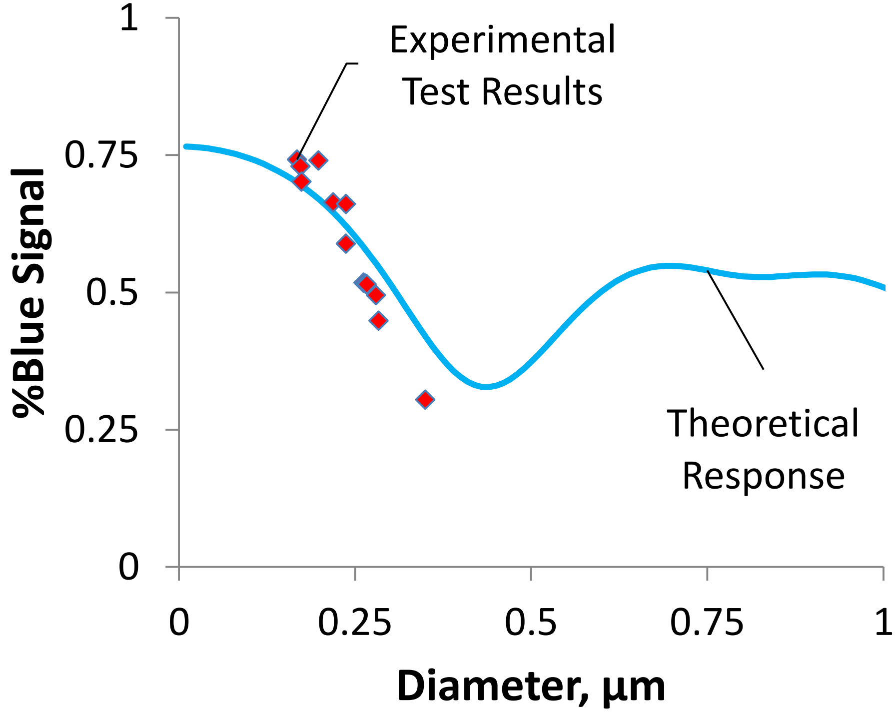
[4] van de Hulst, H. C. (1957). *Light scattering by small particles*. New York: John Wiley and Sons. ISBN 9780486139753.

Mie Scattering Theory Experimental Data

- Blue line represents the Mie Scattering **Theory**

- Red dots represent **experimental** data from EMRSM and the SMPS
  - Data collected from the Siemens Cerberus and Concept Aviator UL

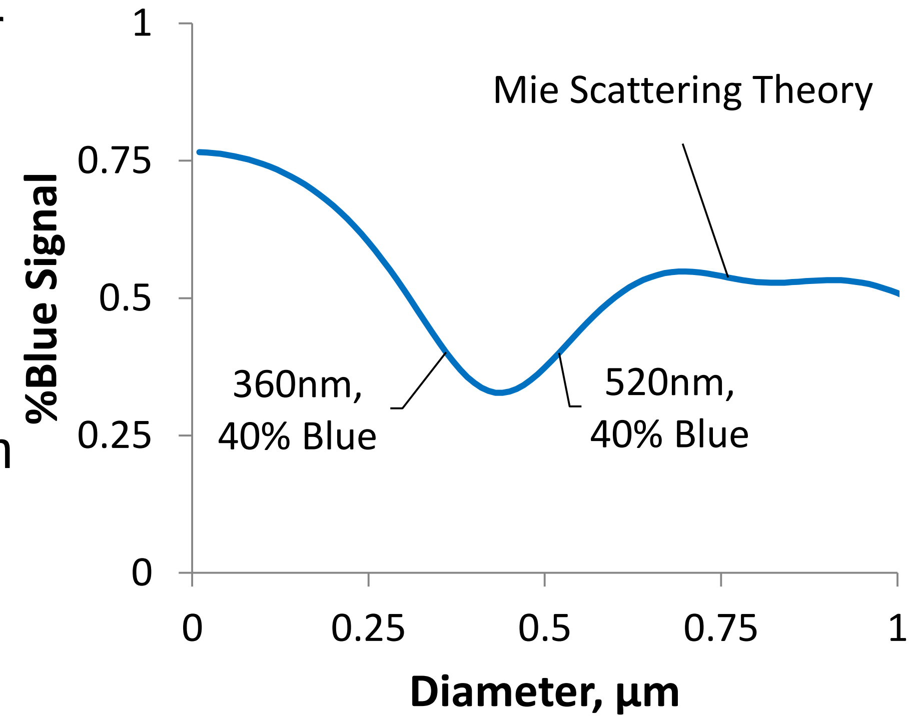
- **Experimental data agrees with the Mie Scattering Theory!**



Maxwell's Equation plotted using 470nm and 850nm wavelengths, assuming refractive index of 1.65 with Siemens Cerberus and Concept Aviator UL

Mie Scattering Theory Potential Issues

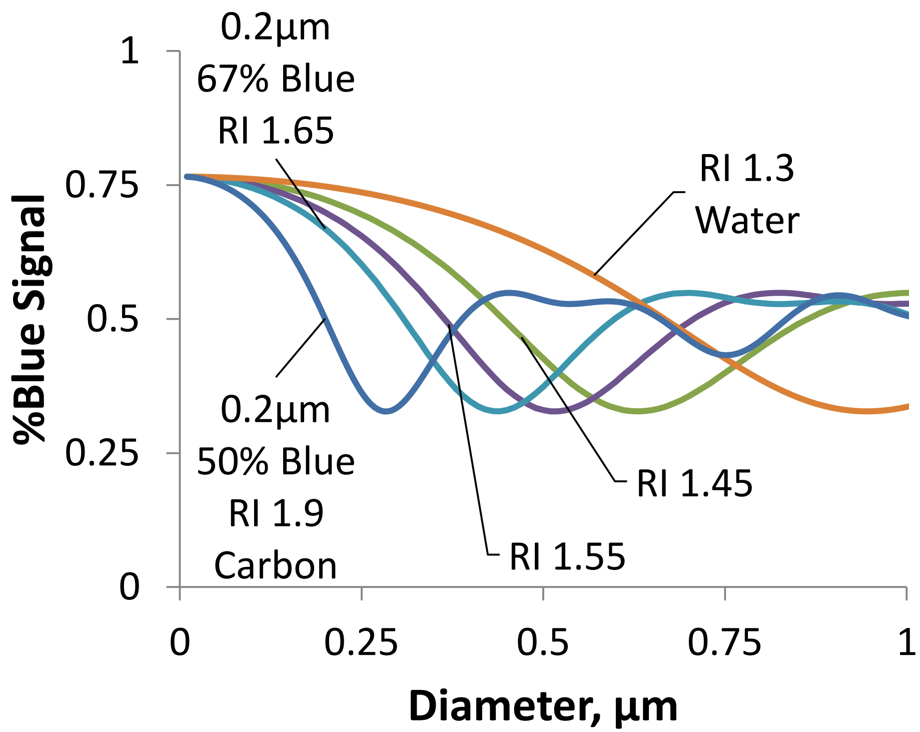
- Maxwell's equation shows a nonlinear correlation between particle diameter and percent blue signal
- Potentially two solutions for a single percent blue data point
  - **Example:** Both 360nm and 520nm equate to 40% blue signal
    - Assuming a refractive index of 1.65



Maxwell's Equation plotted using 470nm and 850nm EM radiation wavelengths, refractive index 1.65

Mie Scattering Theory Potential Issues

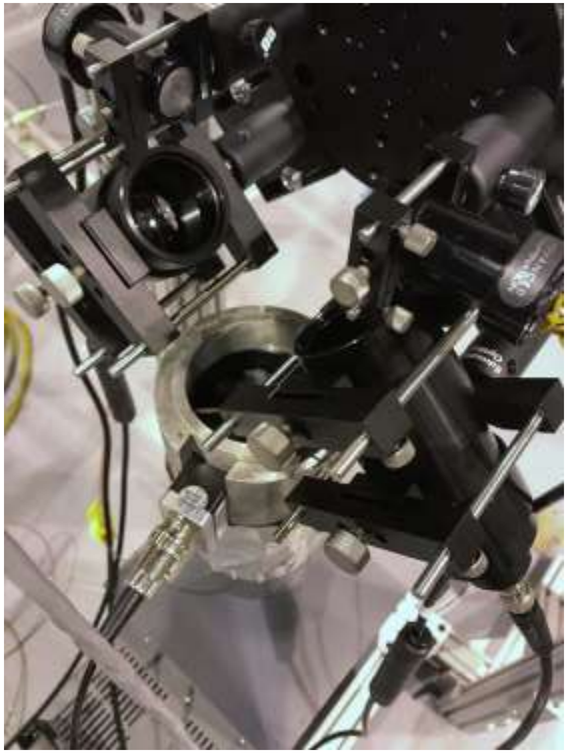
- Variations in refractive indexes can cause a significant difference in the scattering intensity
  - **Example**: A 0.2 micron particle can have multiple solutions depending on refractive index
    - With a refractive index of 1.9 the particle would have 50% blue signal
    - With a refractive index of 1.65 the particle would have 67% blue signal



Maxwell's Equation plotted using 470nm and 850nm wavelengths, various refractive indexes

Section 3
Potential Parameters

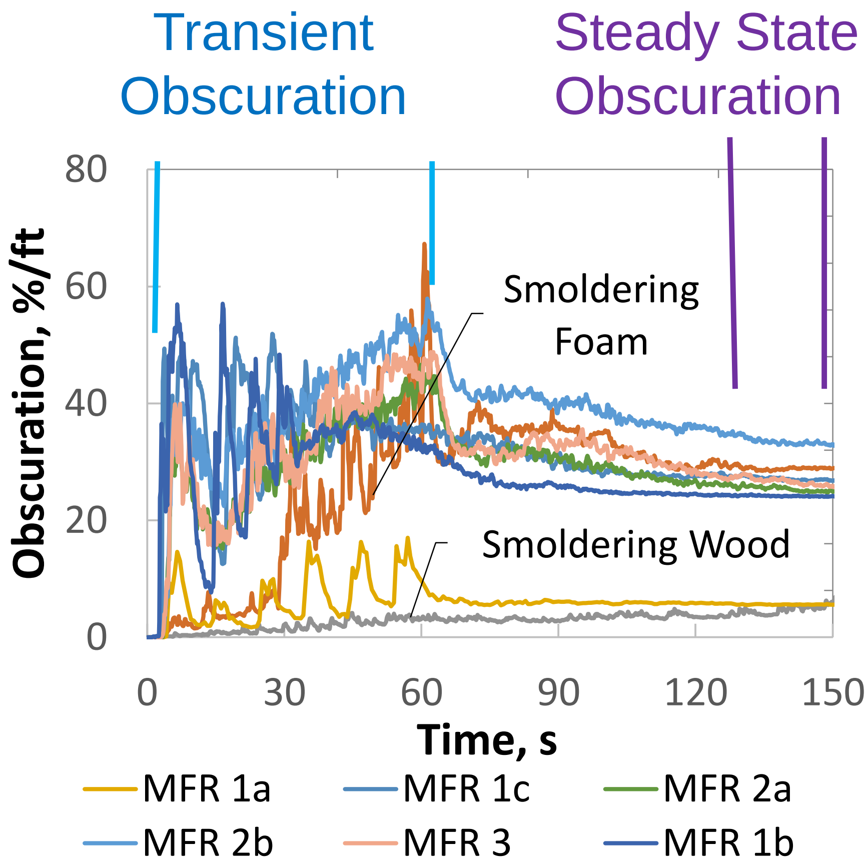
- **Light obscuration**
  - Transient obscuration
  - Steady state obscuration
  - Repeatability
- **Particle size**
  - EMRSM
  - SMPS
- **Smoke transport**
- **Ambient environment**



EMRSM and Vane Anemometer Cone

Light Obscuration

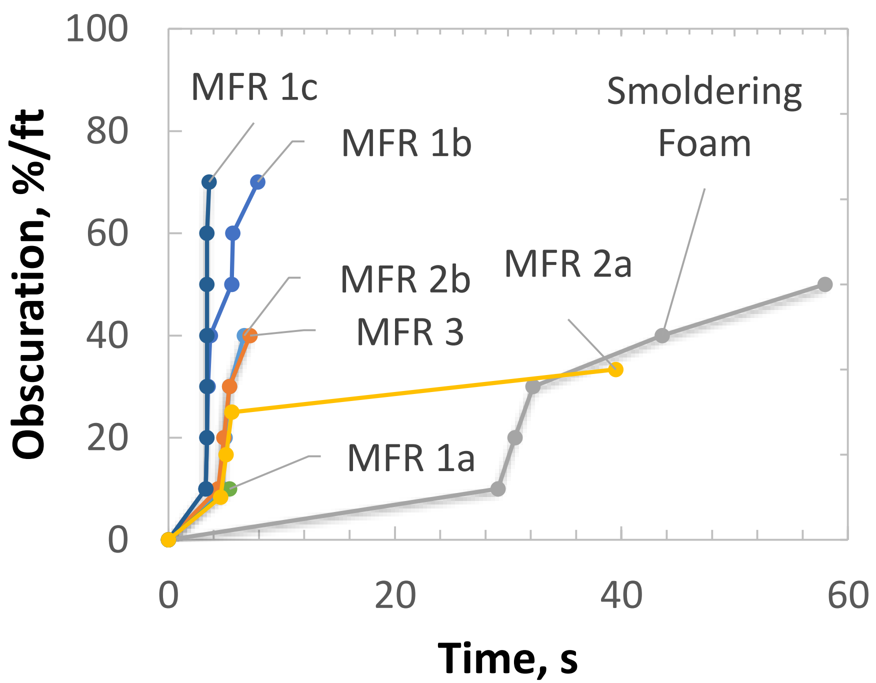
- **Transient Obscuration**
  - Initial 60 seconds
  - Characterizes **rate** of smoke production
- **Steady State Obscuration**
  - After 120 seconds when the smoke fully mixes
  - Characterizes **total** smoke production
- **Repeatability**
  - Relative deviation between tests over a 10 second period



Time vs light obscuration
Various manufacturer smoke generator settings

Transient Obscuration

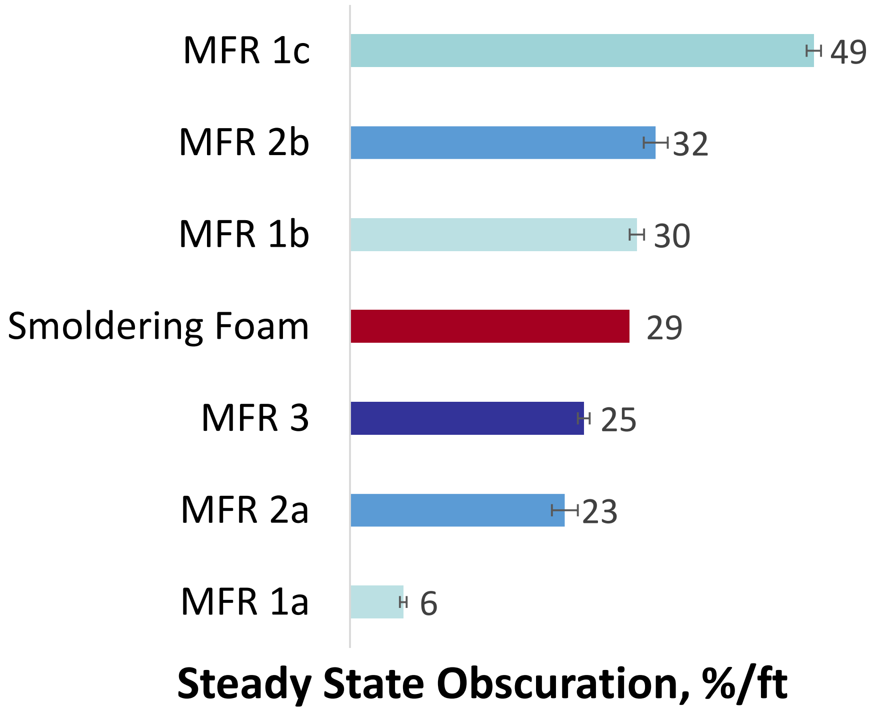
- The data points represent the **time to surpass the marked light obscuration threshold**
- The **steeper the curve**, the **more rapid the smoke production** rate
- The highest point on the curve represents the **maximum light obscuration** reached
- The smoke production rate varies by setup
- Smoldering foam emits smoke at a much slower rate then the tested setups



Time vs light obscuration
Used to determine transient light obscuration

Steady State Obscuration

- The data represents the total smoke production
- The average steady state obscuration is 32 %/ft with a standard deviation of 9 %/ft
  - This shows that there is a large variation between setups



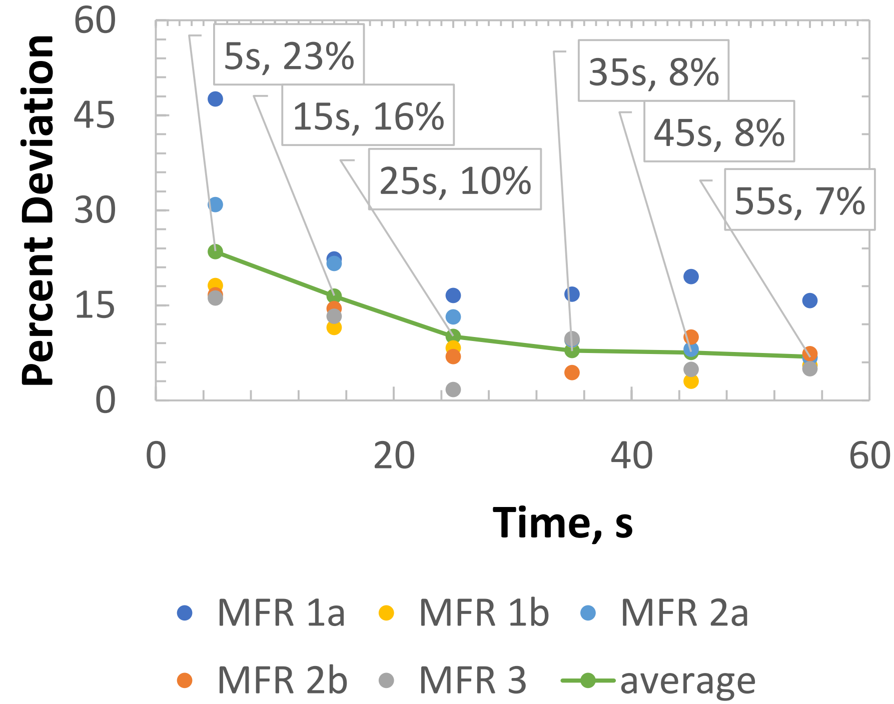
Time vs light obscuration
Used to determine steady state light obscuration

Repeatability

- The percent deviations between a minimum of three tests over 10 second periods are calculated to determine test repeatability

- The initial 10 seconds are the least repeatable and arguably the most significant portion of certification testing

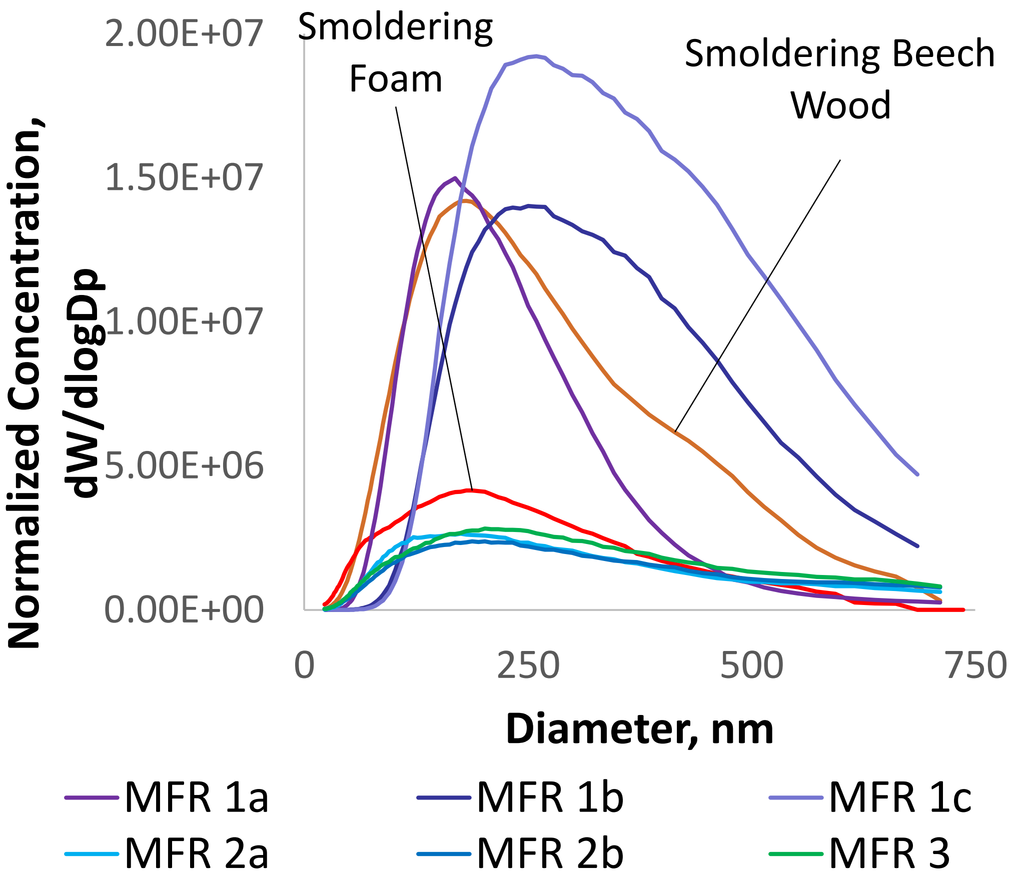
- The first 10 seconds have on average a 23% deviation between tests compared to a 10% deviation during the third 10 seconds



Time vs percent deviation
Used to determine repeatability

Particle Size - SMPS

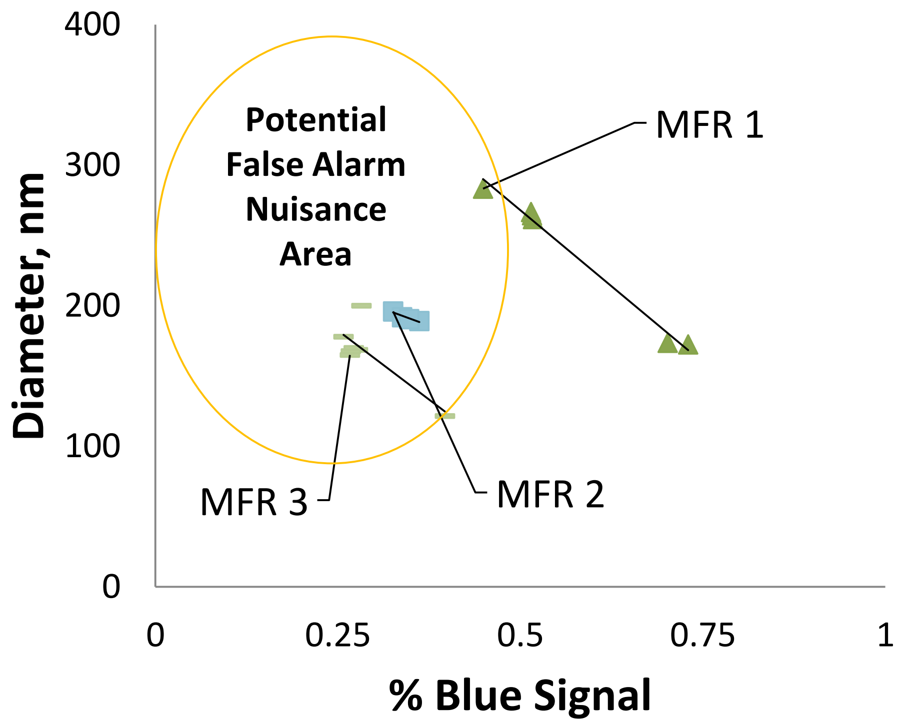
- The average particle diameter ranges from 175 to 250 nm depending on the setup
  - This is similar to the average particle size of smoldering beech wood and smoldering foam – 163 and 181 nm respectively
- MFR 1 has higher particle concentrations then MFR 2 and MFR 3



Diameter vs concentration
SMPS data output of various smoke sources

Particle Size - EMRSM and SMPS

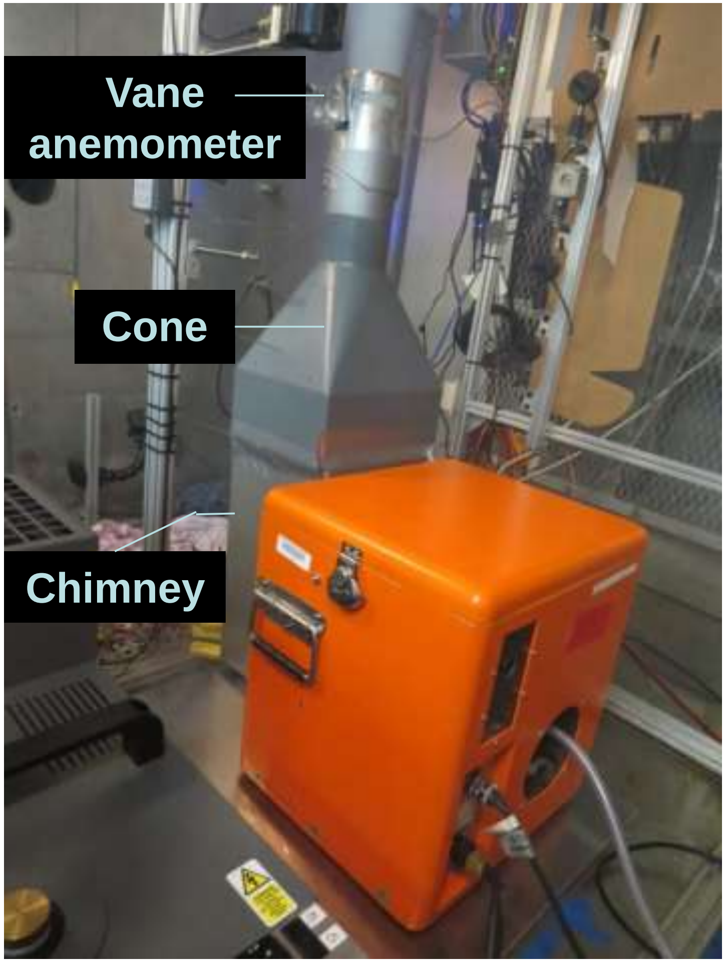
- There is a 13% deviation in particle diameter and a 42% deviation in percent blue signal between the various setups
  - A **similar particle diameter** measurement with a significantly **lower percent blue signal** can be attributed to a **greater refractive index**
- **Low percent blue signal** is typical of **larger particles and smoke alarm nuisances**



EMRSM %blue signal vs SMPS diameter
Shows correlation between SGSA and SMPS for various aircraft manufacturers' smoke generators and settings

Smoke Transport

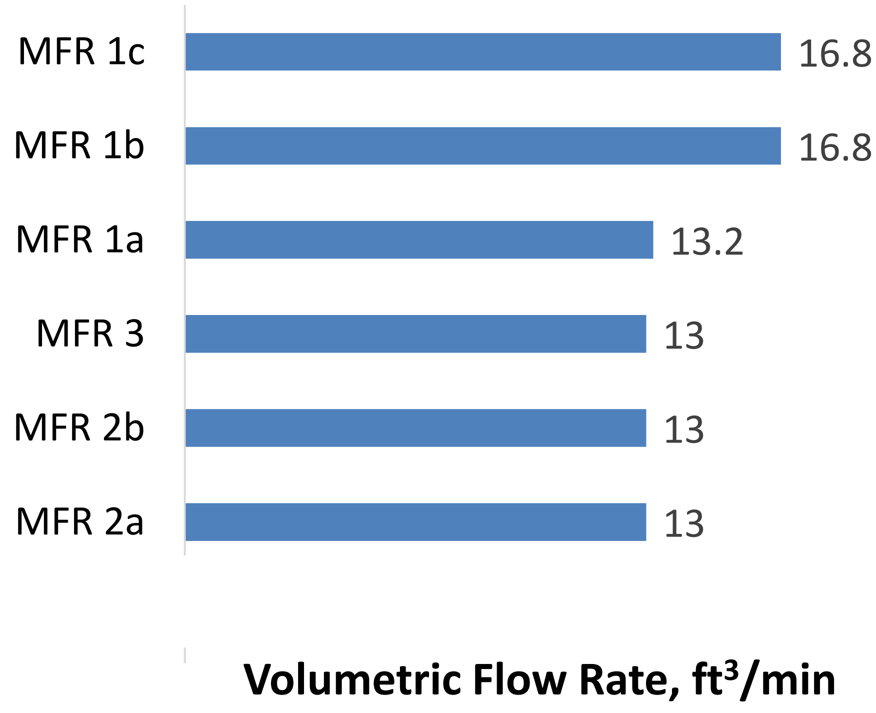
- A cone is connected to the smoke generator's chimney
- Attached to the cone is a vane anemometer to measure the **volumetric flow rate**
- The **volumetric flow rate is directly correlated with chimney heat output**



Siemens Cerberus with Volumetric Flow Rate Cone

Smoke Transport

- Data is representative of smoke transport
- The smoke plume velocity varies by setup
  - Previous large scale testing has shown that **detection time** is **significantly reduced** by **increasing volumetric flow rate**

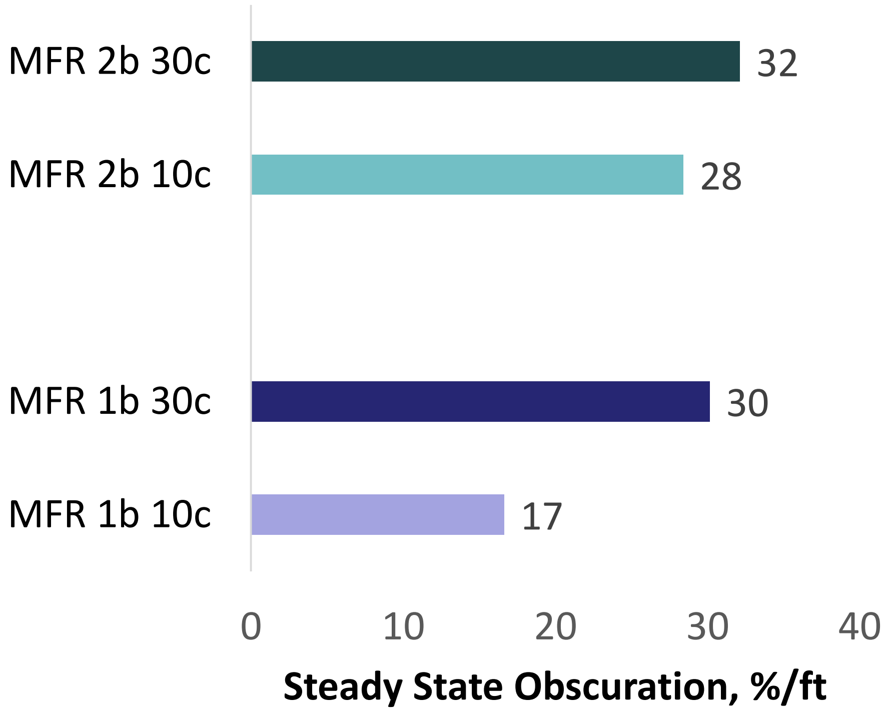


Volumetric flow rate
Comparison volumetric flow rate of various smoke generator settings with Siemens Cerberus and Aviator 440

Ambient Environment and Steady State Obscuration

- **Decreasing the ambient temperature** causes a **decrease in the steady state obscuration** of both MFR 1 and MFR 2

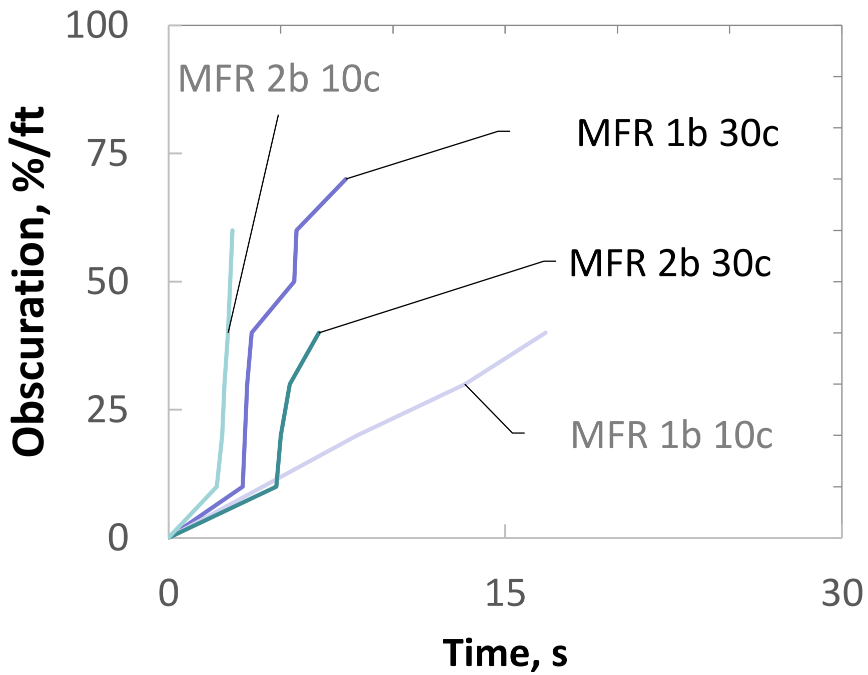
- **Ambient temperature** has a **significantly greater** effect on MFR 1 then MFR 2
  - There is a 57% difference for MFR 1
  - There is a 12% difference for MFR 2



Time vs light obscuration
Used to determine steady state light obscuration

Ambient Environment and Transient Obscuration

- MFR 1 smoke production rate and peak obscuration is greater at a higher ambient temperature
  - Due to its greater total smoke production at higher ambient temperatures
- MFR 2 smoke production rate and peak obscuration is greater at a lower ambient temperature
  - Due to the increased plume velocity caused by the greater temperature difference between chimney and ambient

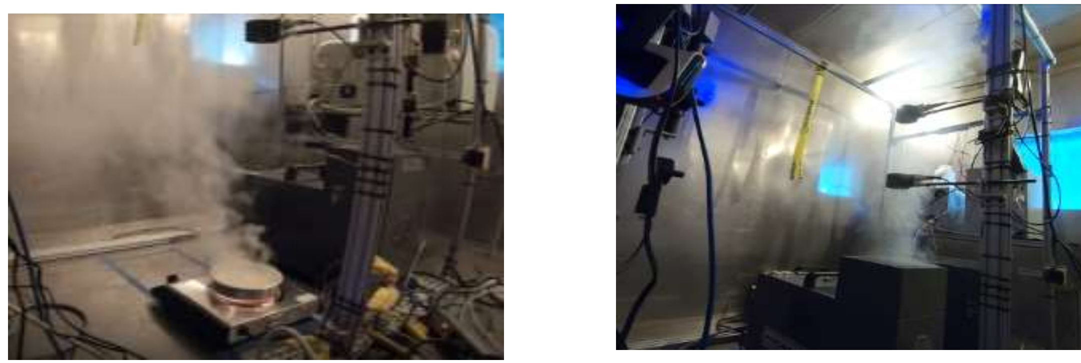


Time vs light obscuration
Used to determine transient light obscuration

Section 4

Simulating Smoldering Smoke

- Strategies for simulating smoldering smoke are assessed
  - Increasing smoke production with time
  - Using less chimney heat

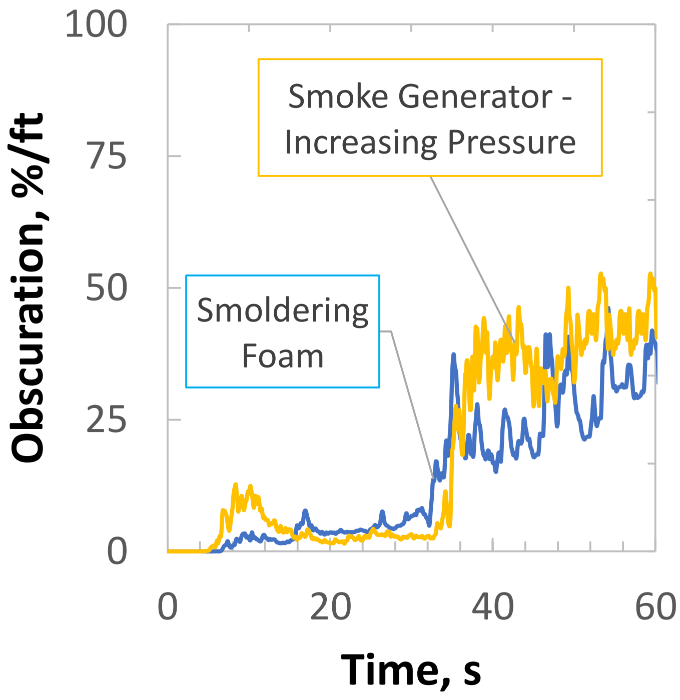


Time: 15 seconds

Time: 45 seconds

Simulating Smoldering Smoke Light Obscuration

- Light obscuration from smoldering foam significantly increases with time
- Increasing the gas propellant pressure on a smoke generator produces similar results



Time vs light obscuration Comparison of smoldering foam and custom smoke generator setting

Stages of Fire

1. Incubation period
   - Representative of smoldering fire
   - **Low** heat release
2. Established growth
   - Representative of growing fire
   - **High** heat release
   - Well studied with the given idealized parabolic equation
   - $Q = \alpha(t - t_o)^2$

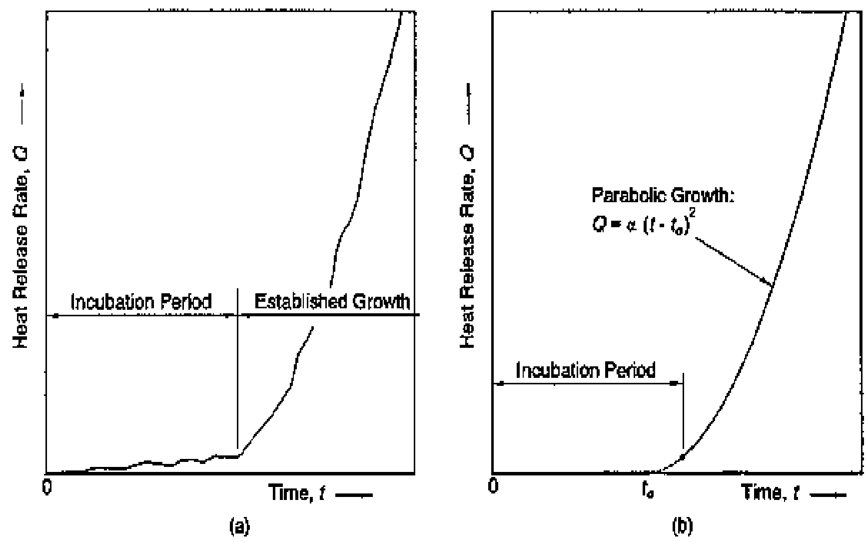
     Q= heat release of fire, kW

     α = fire growth coefficient, kW/s^2

     t= time after ignition, s

     t_o=effective ignition time, s

- Equation shows that the **heat release is low during the smoldering period** and **exponentially increases during established growth period**

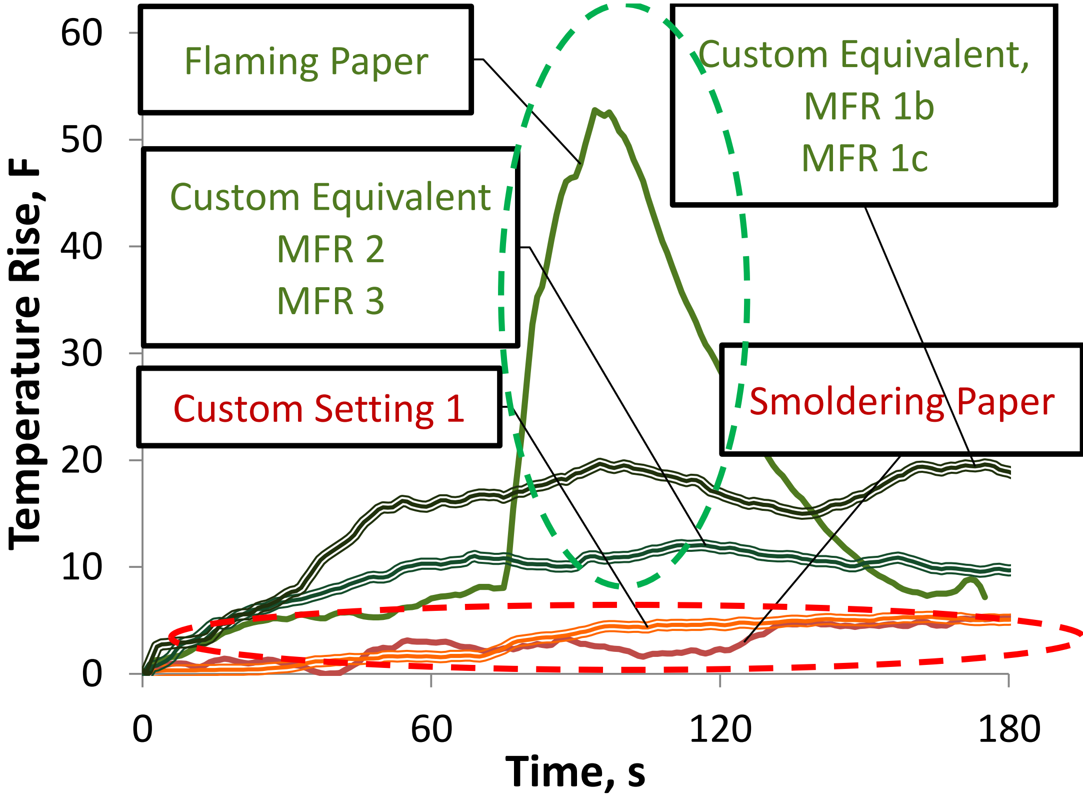


Fire growth (a) typical curve, and (b) idealized parabolic curve [4]

[4] Klote, J. Method of predicting smoke movement in atria with application to smoke management

Simulating Real Fires Temperature

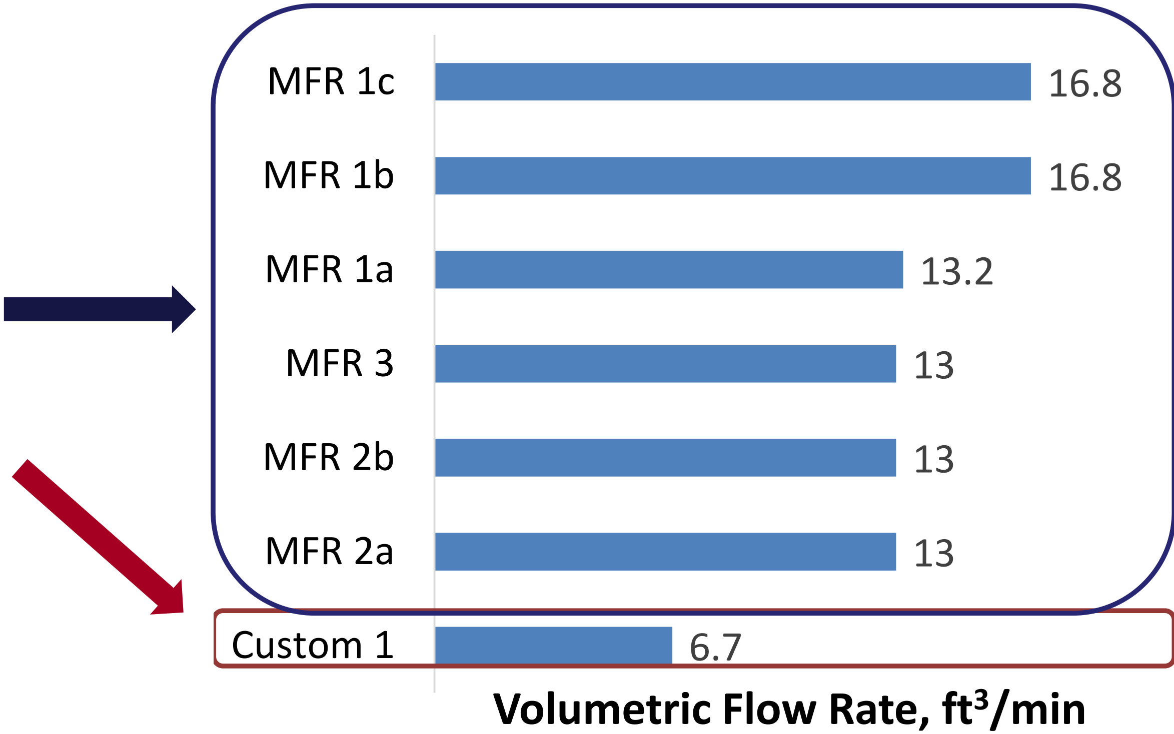
- Encircled in green
  - The common smoke generator setups best simulate the temperature increase from a flaming fire
- Encircled in red
  - A custom low chimney heat smoke generator setting best simulates the temperature increase from a smoldering fire



Time vs temperature rise
Comparison of temperature increase of various smoke sources and smoke generator heater settings. Full scale testing in cargo compartment.

Simulating Smoldering Smoke Smoke Transport

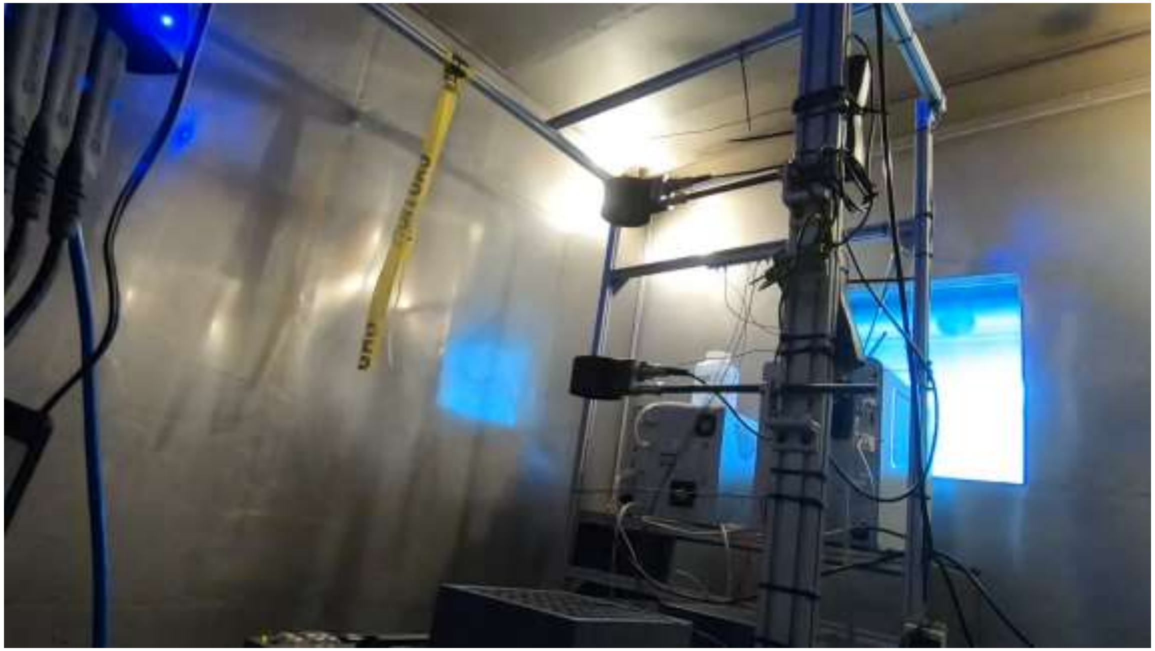
- The corresponding volumetric flowrates from previous slides are shown
- Estimated volumetric flow rate for the **established growth period**
- Estimated volumetric flow rate for a **smoldering fire**
- To be representative of a smoldering fire, the volumetric flow rates should be significantly reduced



Volumetric flow rate
Comparison volumetric flow rate of various smoke generator settings with Siemens Cerberus and Aviator UL

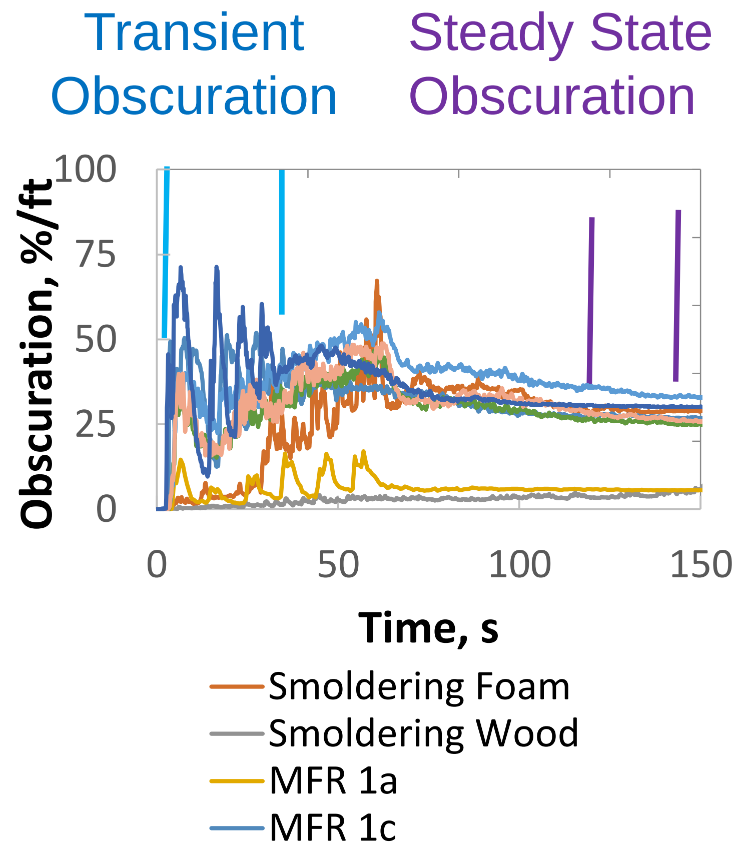
Simulating Smoldering Smoke Chimney Heater Comparison

- There is a visibly observable difference between using high and low chimney heat
- 1^{st} 10 seconds
  - No chimney heat
  - Representative of a smoldering fire
- 2^{nd} 10 seconds
  - High chimney heat
  - Representative of a flaming fire



Section 5 Recommendations

- Open discussion to determine thresholds
  - Light obscuration
    - Transient obscuration
    - Steady state obscuration
    - Repeatability
  - Particle size
    - SMPS
    - EMRSM
  - Smoke transport
    - Volumetric flow rate/heat output
  - Ambient environment
    - Temperature



Time vs light obscuration
Various manufacturer smoke generator settings

Section 6
Future Testing

- Test for a baseline of additional aircraft manufacturers' smoke generators and settings
- Test and compare smoke generators inside cargo compartments while in flight to determine effects of unexpected variables
- Test to determine how volume and dimensions affect smoke generator variables
- Explore smoke generator options to better simulate smoldering fires
  - Using less heat
  - Using pressure controller to steadily increase the smoke output

Contact Information

- Matthew Karp
- Research Engineer
- FAA ANG-E211 Systems Fire Protection
- Phone: 609-485-4538
- Email: Matthew.Karp@FAA.gov
-

Federal Aviation Administration

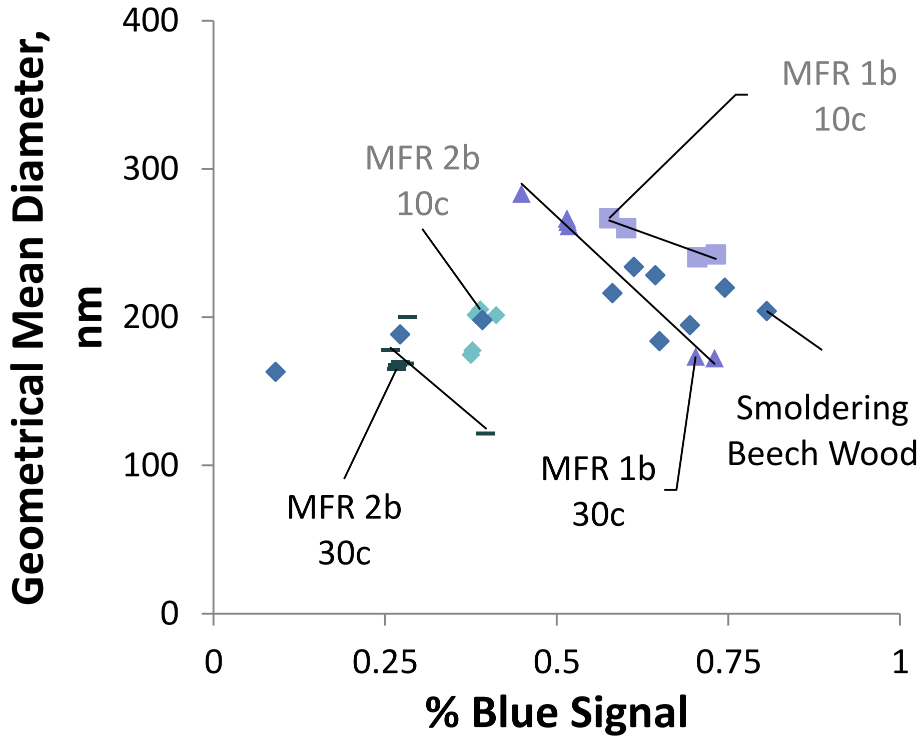
Test Apparatus

- **Blue and IR electromagnetic radiation scattering measurement (EMRSM)**
  - 3” below ceiling
- **SMPS**
  - 3” below ceiling
- **5 Thermocouples**
  - 0”, 5”, 11”, 23” and 35” above smoke generator
- **2 Anemometers**
  - 10” and 20” above smoke generator
- **6 Obscuration Meters**
  - 6”, 12”, 18”, 24”, 36” and 40” above smoke generator

Thermocouples, anemometers, EMERSM and obscuration meters

Ambient Environment and Particle Size

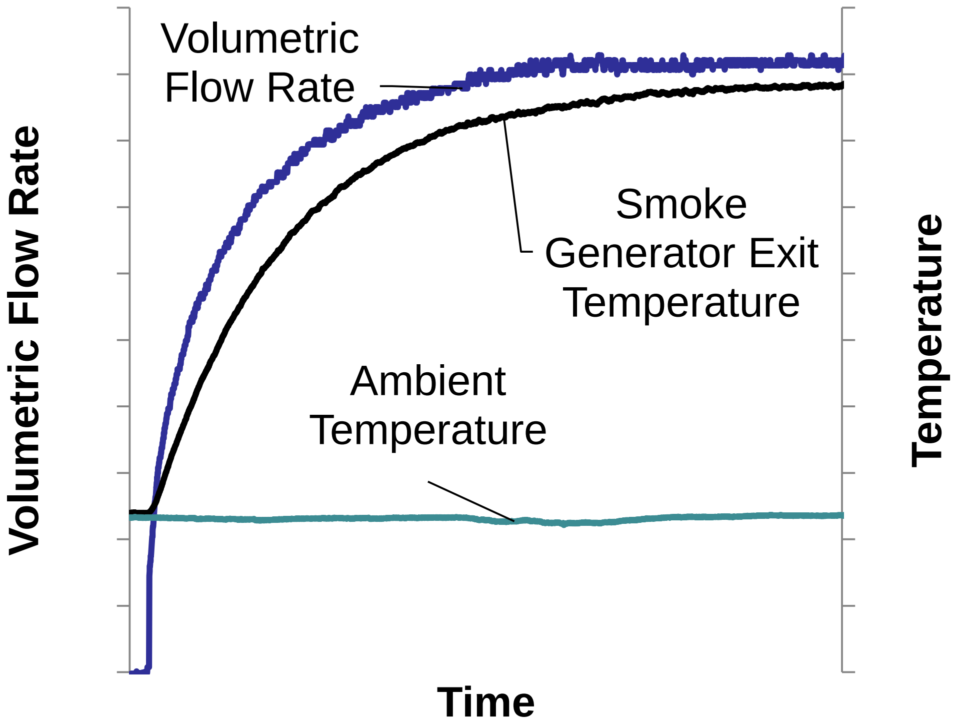
- Decreasing the ambient temperature slightly increases percent blue signal and particle diameter



SGSA %blue signal vs SMPS diameter
Shows correlation between SGSA and SMPS for various aircraft manufacturers' smoke generators and settings

Smoke Transport and Temperature

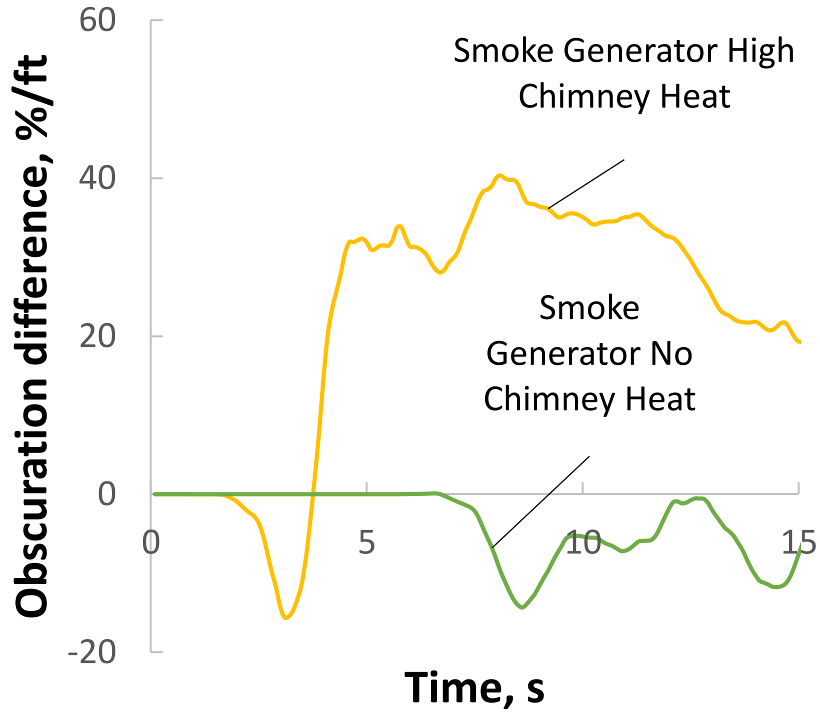
- The smoke transport is buoyancy-driven
- As the exit temperature increases the volumetric flow rate increases



Time vs temperature and volumetric flow rate Demonstrates correlation between temperature and volumetric flow rate

Simulating Smoldering Smoke Smoke Layers

- Smoke from smoldering fires rise towards the ceiling less quickly
  - Creates a less sharp smoke layer interface
- Smoke from flaming fires quickly rise towards the ceiling
  - Creates a sharp smoke layer towards the ceiling
- The absolute difference in light obscuration between 2” and 18” from the ceiling is measured to demonstrates a sharp and less sharp smoke layer interface



Time vs light obscuration difference Comparison of difference in light obscuration by height for high and low chimney heat