Smoke Generator Standardization
and
The Effects of Environmental Variations

Presented to: International Aircraft Systems Fire Protection Forum

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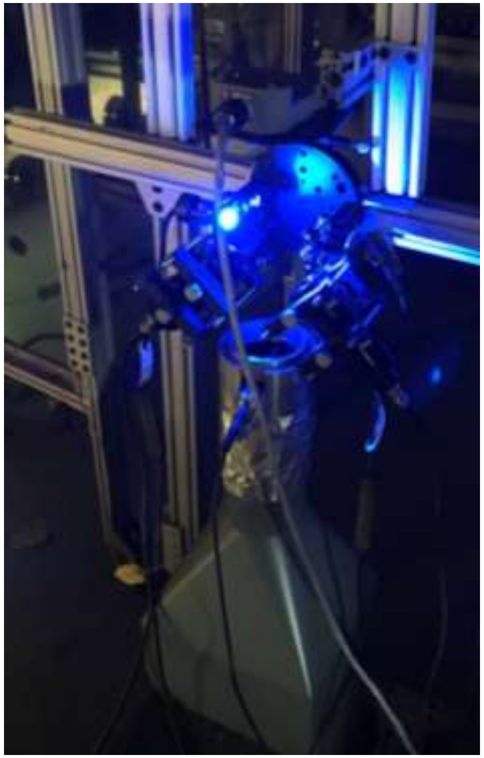
Questions

- Can standardizing smoke generators make smoke detector certification tests more consistent?
- Does ambient environment impact the smoke particle obscuration, diameter, concentration and/or plume buoyancy?
- What parameters should be considered while creating a smoke generator standard?
- What should be the standard reference and should it be based off of an actual fire source?



SGSA and Smoke Plume Buoyancy Cone

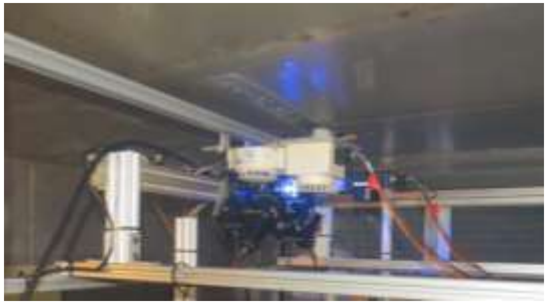
Altitude Chamber

- **8’ length by 6’ width by 6’ height**
- **Controls**
  - Temperature
    - As low as: -100F
  - Pressure
    - As low as: 2psia
- **Tested range**
  - Temperature
    - 50F – 90F
  - Pressure
    - 10psia – 14.7psia

Altitude Chamber

Test Apparatus

- **5 Smoke Detectors**
- **1 Blue and 1 IR light scattering measurement (SGSA)**
  – 3” below ceiling
- **1 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



SGSA and smoke detectors

Thermocouples, anemometers and obscuration meters

Smoke Generators

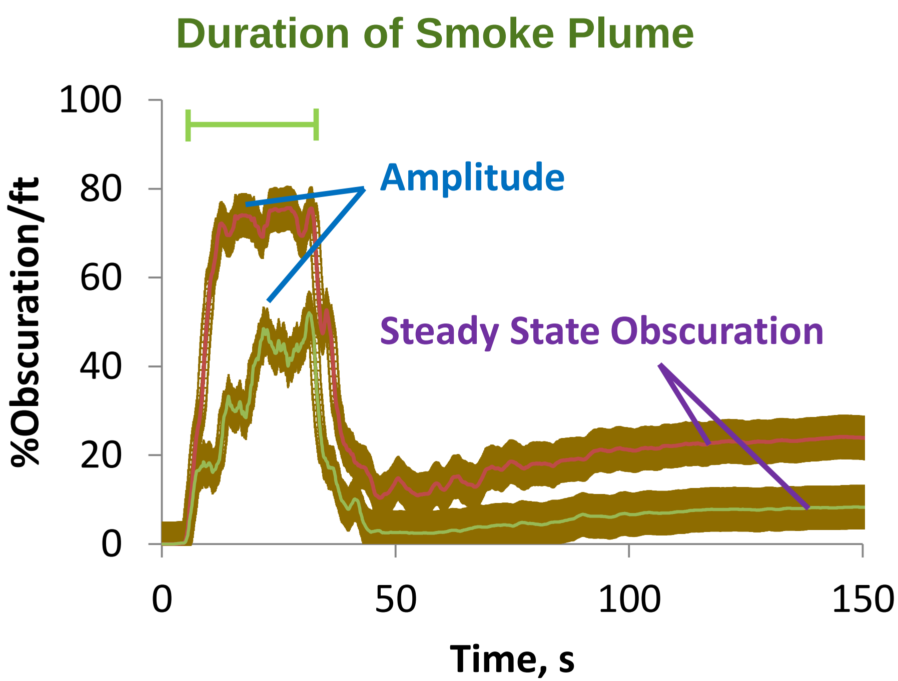
- **Concept Aviator UL**
  - Non-pressurized tank for steady smoke release
  - High user adjustability
    - Oil temperature
    - Heat exchanger temperature
    - Chimney temperature 0-100%
    - Smoke density valve
- **Siemens Cerberus**
  - Pressurized tank for instant smoke release
  - Preset smoke programs with timed bursts of smoke
    - Tested programs 3, 5 and 6
    - Various heat outputs
    - Two possible exit nozzles

Concept Aviator

Siemens Cerberus

Smoke Obscuration

- **Potential Parameters**
  - Amplitude
    - Possible maximum threshold
  - Steady State Obscuration
    - Characterizes total smoke obscuration
      - Dependent on volume
  - Time Dependent Reference Curve
    - Duration of smoke plume
    - Minimum and maximum bounds (± 5%obscuration/ft)
  - Area Under the Curve

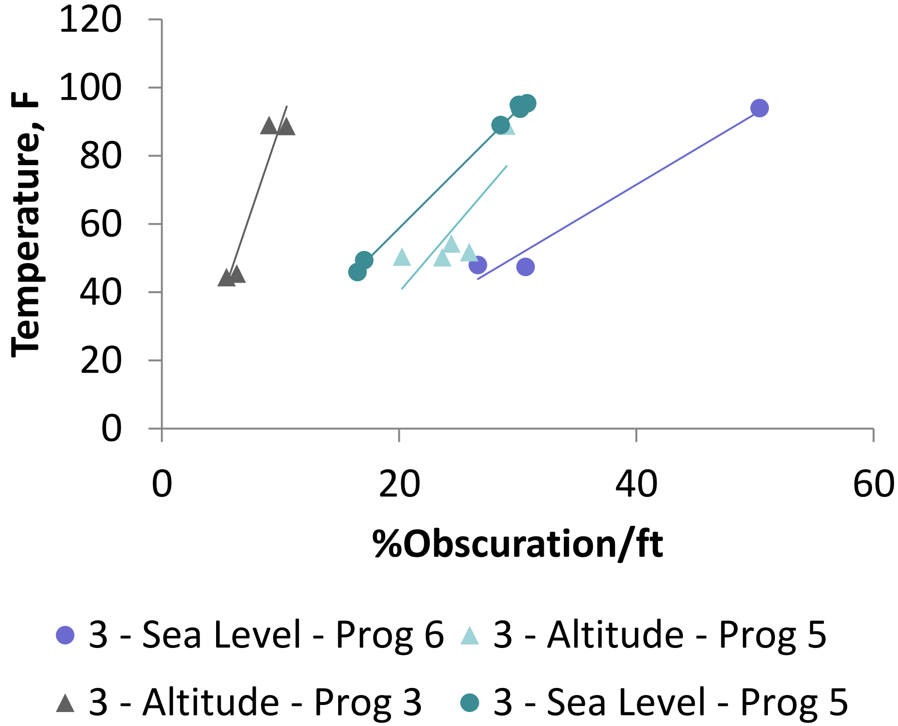


Time vs % Obscuration
Arbitrary Concept Aviator settings

Smoke Obscuration - Temperature

- Positive correlation between the steady state percent obscuration per foot and the ambient temperature
  - within tested range of 50-90F
- Most observable at sea level
  - Varies from:

    17%obscuration/ft at 50F to 30%obscuration/ft at 90F with program 5 at sea level



Steady state percent obscuration per foot vs temperature with various test conditions and settings with Siemens Cerberus

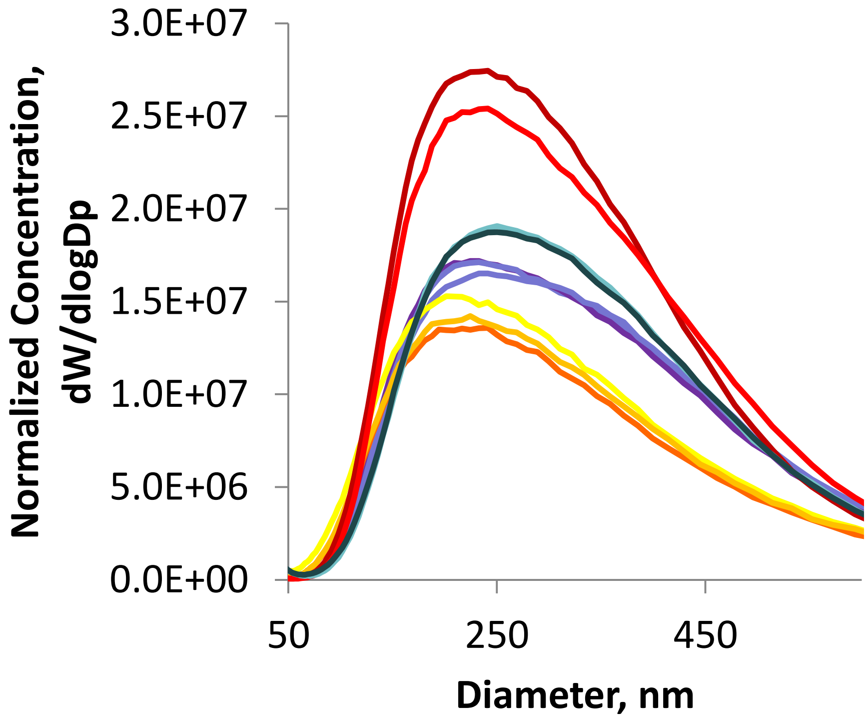
Scanning Mobility Particle Sizer (SMPS)

- **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.

Electrostatic classifier model 3082 with Long DMA, Left
Condensation particle counter model 3756, Right

Particle Characterization

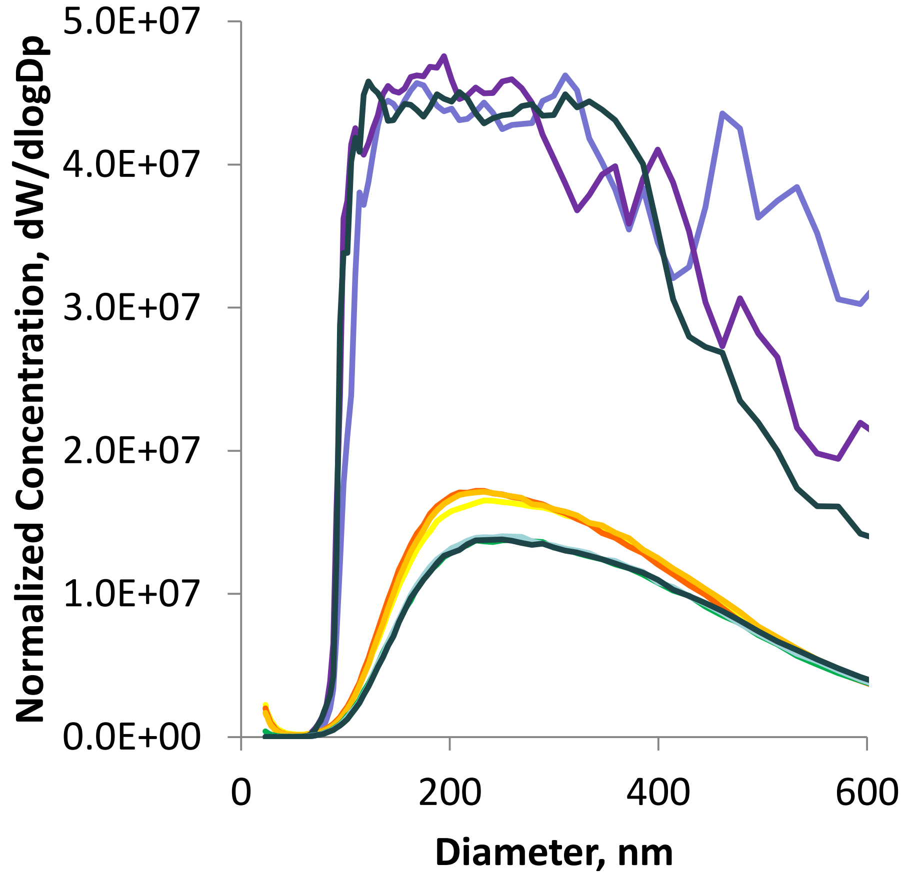
- Particle size and distribution changes with ambient temperature and pressure
  - 8000ft altitude 90F– reds
  - 8000ft altitude 50F – greens
  - Ambient 90F – purples
  - Ambient 50F – yellows



Diameter vs particle concentration
Test samples of 60 seconds starting at 90 seconds after gas release with Siemens Cerberus Program 5

Particle Characterization

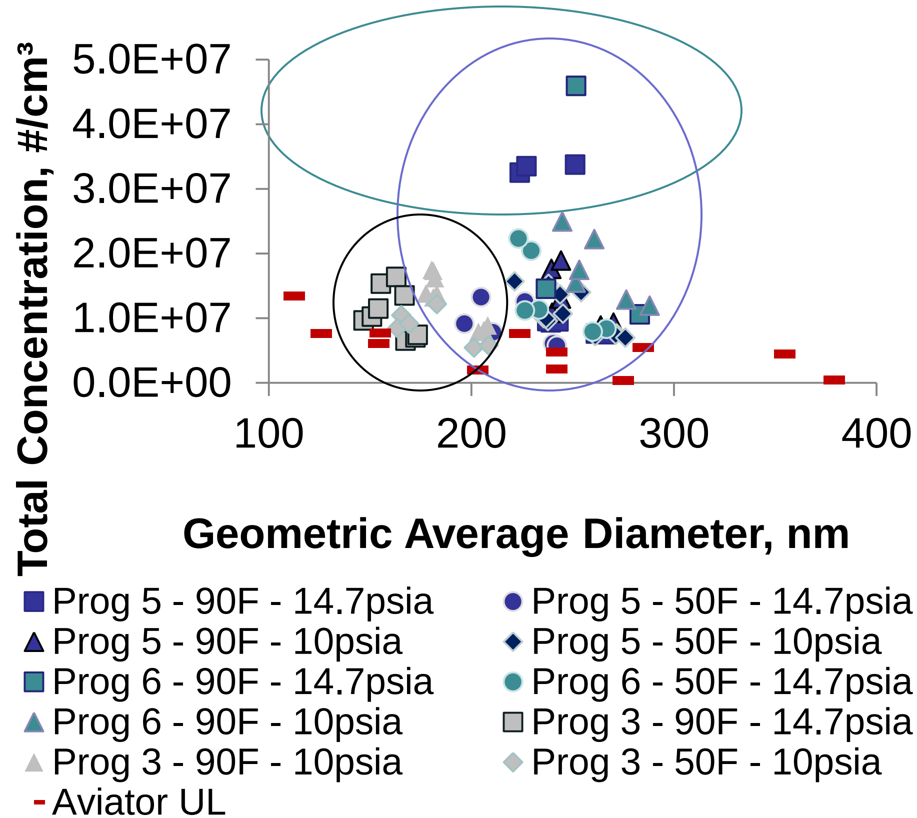
- Particle size and distribution changes with time of measurement
- 60 second data collection starting at:
  1. 10 seconds – purples
     - Upper limits of condensation particle counter
  2. 90 seconds – yellows
  3. 210 seconds – greens



Diameter vs particle concentration
Test samples of 60 seconds starting at 10, 90 and 210 seconds with Siemens Cerberus Program 5

Particle Characterization

- **Siemens Cerberus Diameter**
  - Program 3: **176±18nm**
  - Program 5,6: **246±20nm**
- **Concept Aviator Diameter**
  - Varies by setting
  - Ranges from: **108 – 374nm**
- The **average total concentration** varies mostly by time of collection
  - Wide range: **5.4-46million/cm³**
  - Higher concentrations when measured shortly after gas release



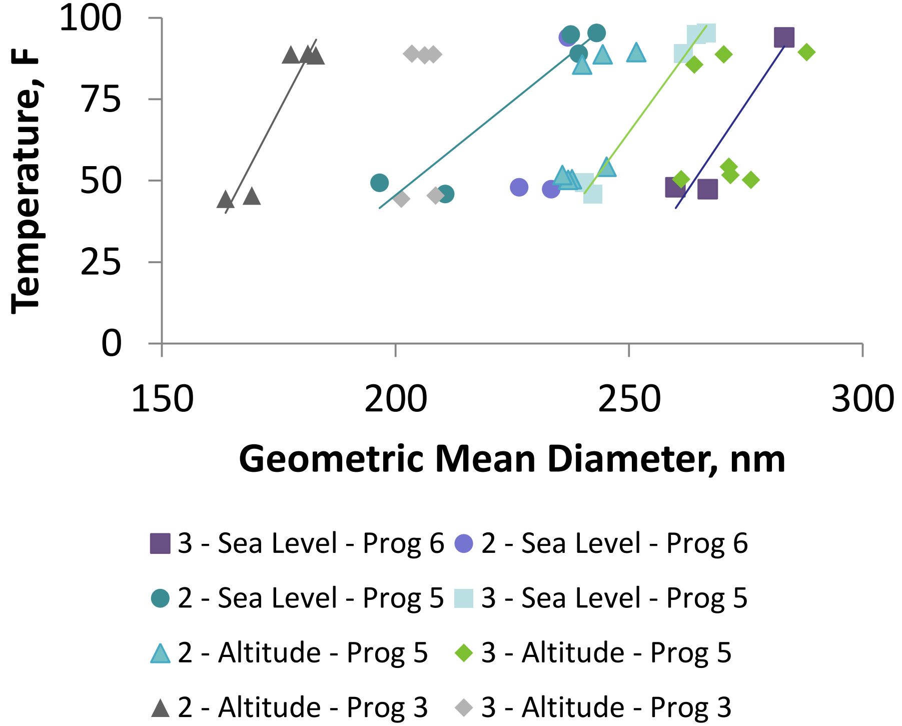
Diameter vs particle concentration
Individual test sample averages of various programs and environmental settings with Siemens Cerberus and Aviator UL

Particle Size - Temperature

- **There is a slight but observable trend**
  - **Increasing the temperature** causes a **slight increase in geometric mean diameter**
  - Varies from:

    196nm at 50F to

    243nm at 90F with program 5 at sea level



Diameter vs temperature
Test samples of 60 seconds with varying sampling starts, programs and environment with Siemens Cerberus

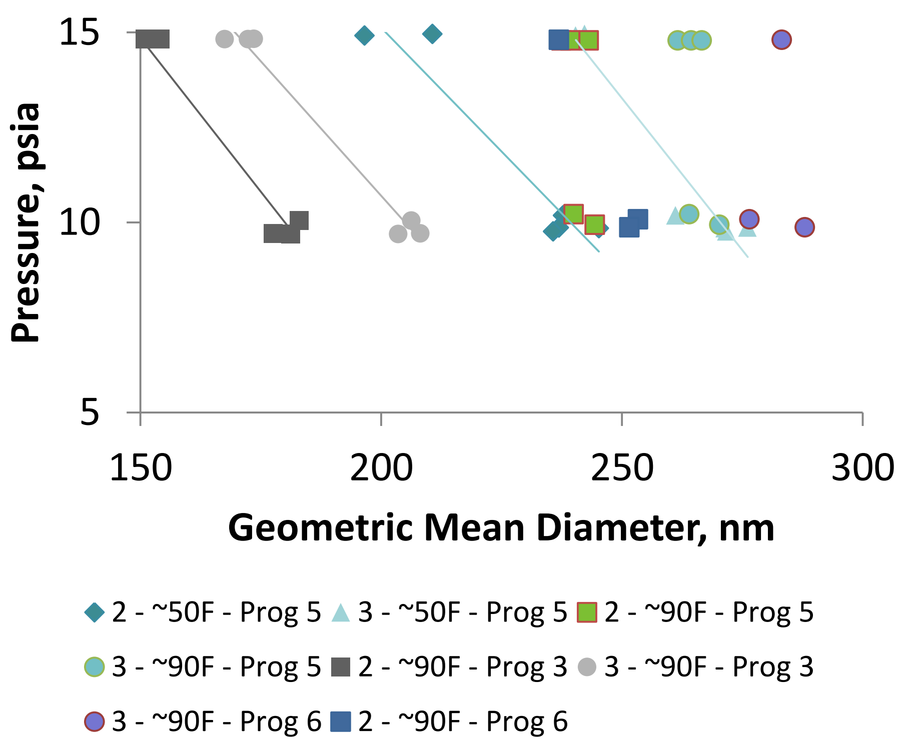
Particle Size - Pressure

- **There is a slight but observable trend**
  - **Increasing the pressure** causes a **slight decrease in geometric mean diameter**
  - Varies from:

    167nm at 14.7psia to

    208nm at 10psia with

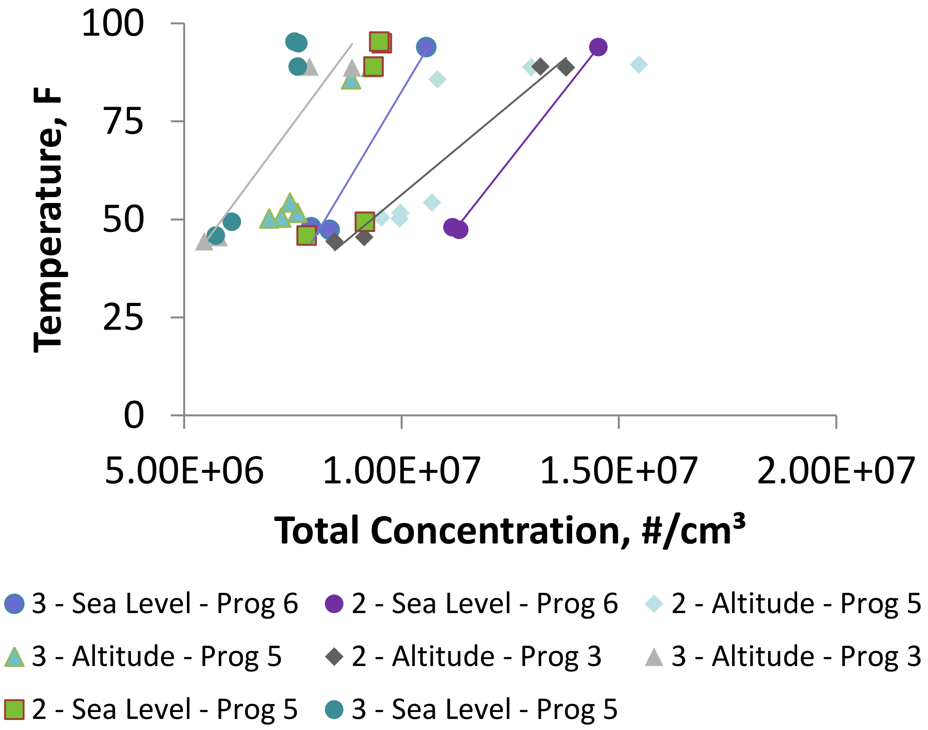
    program 3 at 90F



Diameter vs pressure
Test samples of 60 seconds with varying sampling starts, programs and environment with Siemens Cerberus

Particle Concentration - Temperature

- **There is a slight but observable trend**
  - **Increasing the temperature** causes a **slight increase in particle concentration**
  - Within the tested range, the environmental impact on particle concentration appears insignificant



Total concentration vs temperature
Test samples of 60 seconds with varying sampling starts, programs and environment with Siemens Cerberus

Particle Concentration - Pressure

- **There is a slight but observable trend**
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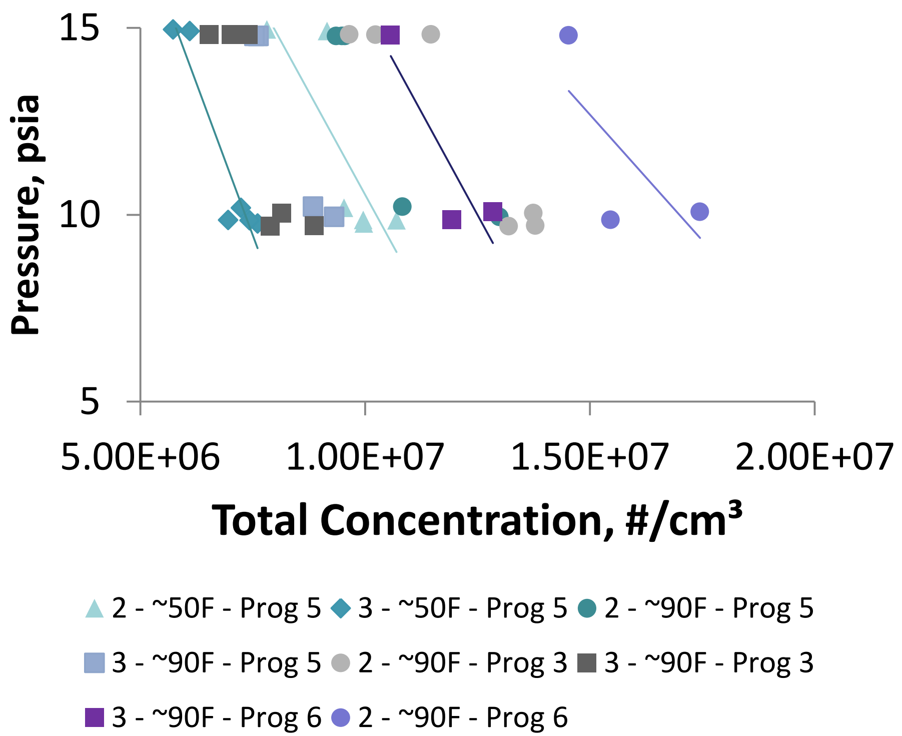


Total concentration vs pressure
Test samples of 60 seconds with varying sampling starts, programs and environment with Siemens Cerberus

Theory
Light Scattering

- **Mie Scattering Theory** governs light scattering by sub-micron particles
- The general solution is found through the application of **Maxwell's equation**
- A simplified approximation of Mie scattering is given by van de Hulst [6]

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

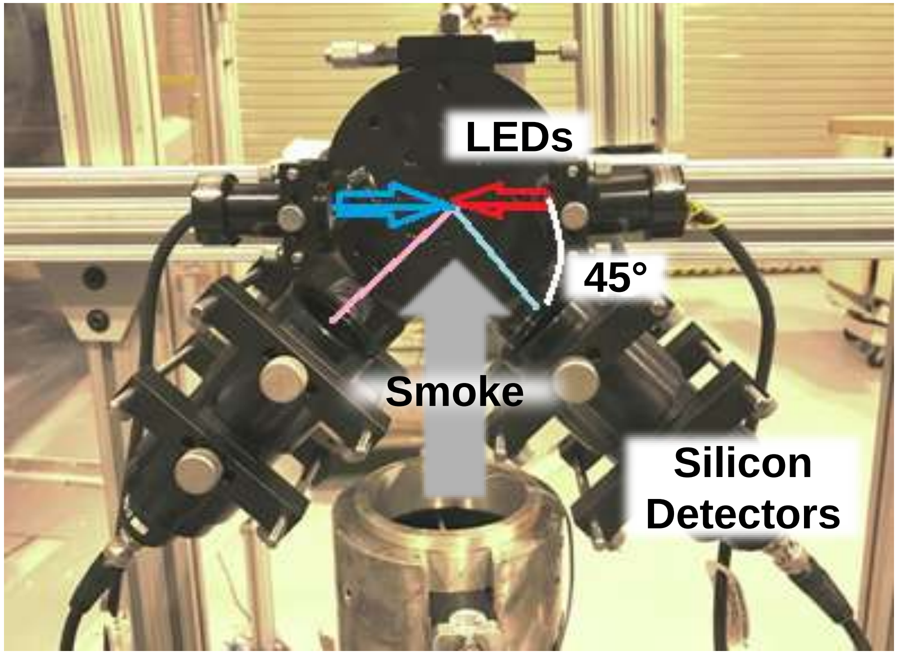
- Where Q is the efficiency factor of scattering

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

- 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**

Smoke Generator Standardization Apparatus (SGSA)

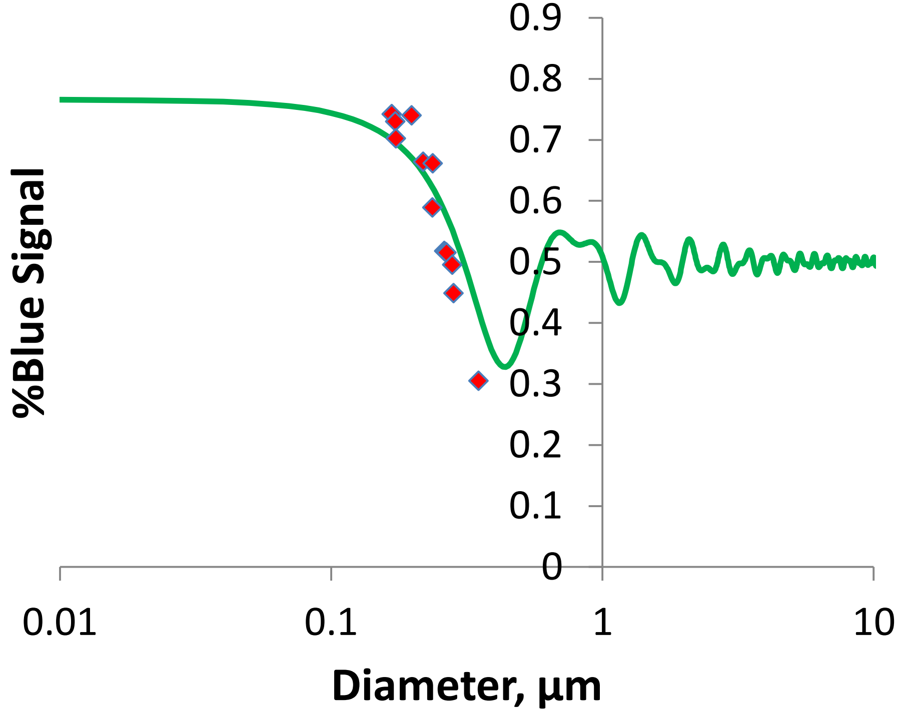
- **Two silicon detectors**
  - photovoltaic effect
- **Two voltage outputs**
  - 470nm light scattered at 45°
  - 850nm light scattered at 45°
- **Measurements used to calculate:**
  - 1. Percent increase Blue response
  - 2. Percent increase IR response
    - Calculate %Blue signal
    - Calculate Blue + IR signal



Smoke Generator Standardization Apparatus (SGSA)

Theory
Blue and IR Light Scattering

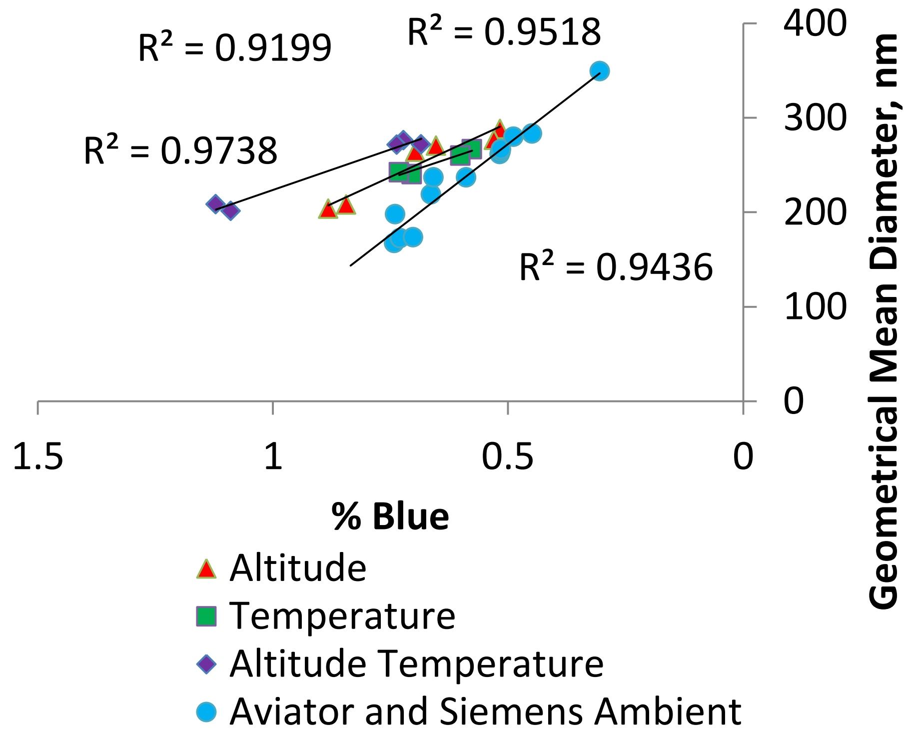
- Green line represents the **theoretical** %Blue correspondence to diameter according to the Mie Scattering Theory
- Red dots annotate **experimental** test results from SGSA and the measured diameter with the SMPS
  - Data from both Siemens Cerberus and Concept Aviator
- **Experimental data agrees with the Mie Scattering Theory!**



Maxwell's Equation plotted using 470nm for Blue and 850nm for IR scattered light, assuming refractive index of 1.65 with Siemens Cerberus and Concept Aviator

Particle Size – SMPS & SGSA

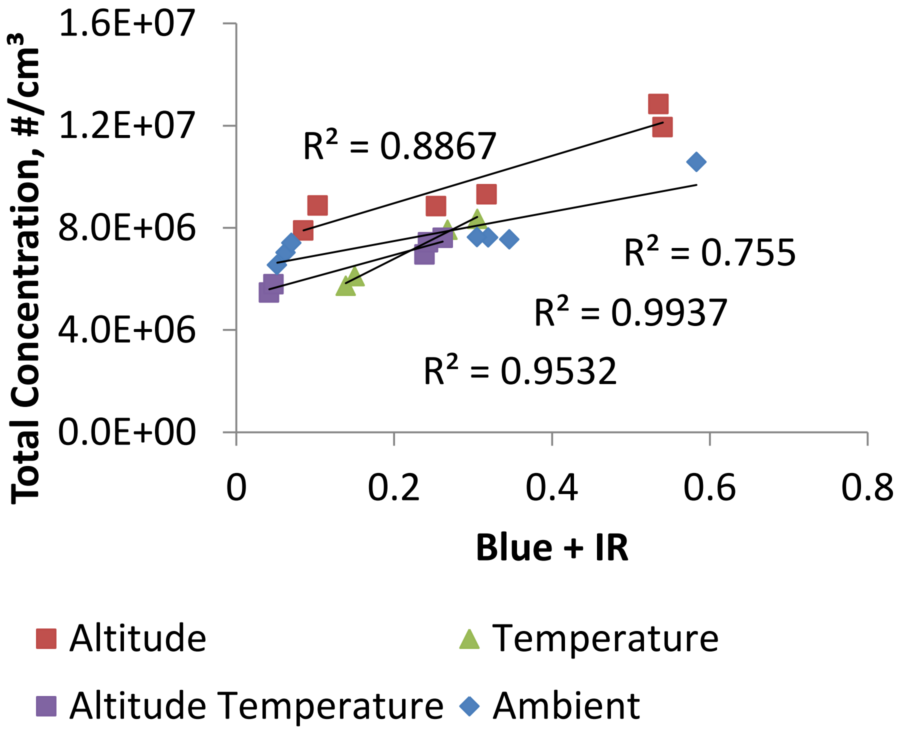
- There is a positive correlation between SMPS particle size and SGSA %Blue signal after grouping the data points by the test environment and start time of data collection
- Altitude
  - ~10psia ~90F
- Altitude Temperature
  - ~10psia ~50F
- Temperature
  - ~14.7psia ~50F
- Ambient
  - ~14.7psia ~90F



%Blue signal vs SMPS diameter
Test samples starting at 210 seconds for 60 seconds with varying programs and environments with Siemens Cerberus (programs 5 and 6) and Aviator UL

Particle Concentration – SMPS & SGSA

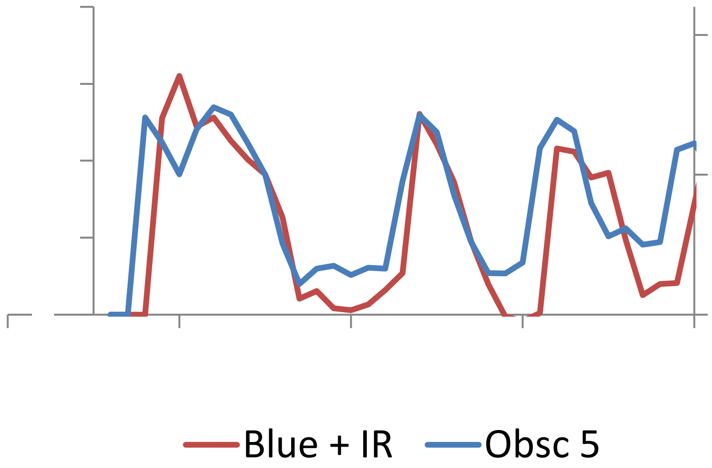
- There is a positive correlation between SMPS concentration and SGSA Blue + IR signal after grouping the data points by the test environment and start time of data collection
- Altitude
  - ~10psia ~90F
- Altitude Temperature
  - ~10psia ~50F
- Temperature
  - ~14.7psia ~50F
- Ambient
  - ~14.7psia ~90F



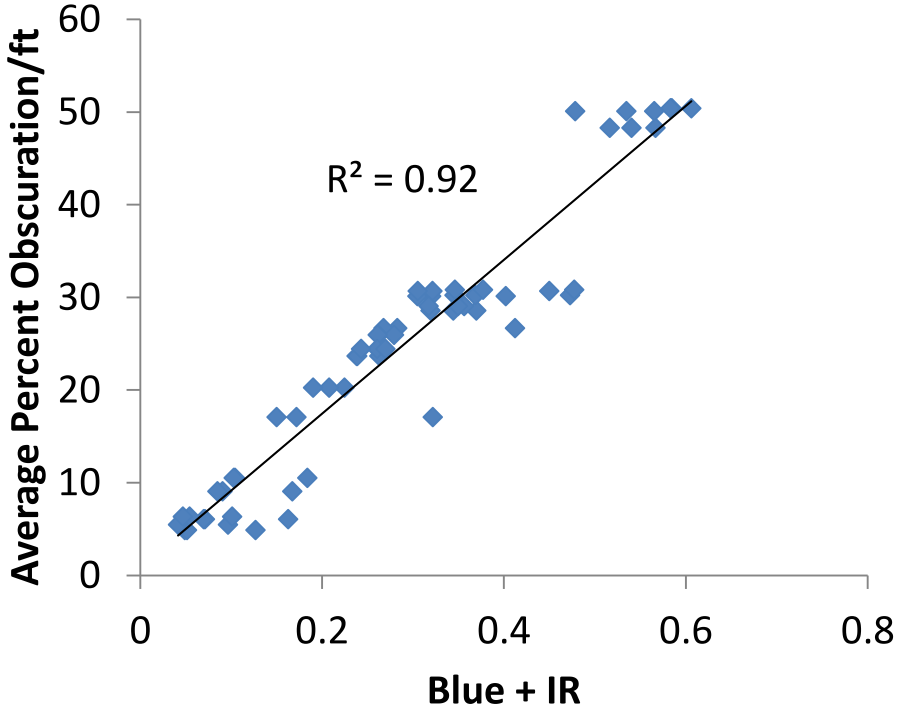
%Blue signal vs SMPS concentration
Test samples starting at 210 seconds for 60 seconds with varying programs and environments with Siemens Cerberus (programs 5 and 6)

Smoke Obscuration and SGSA

- The combined blue and IR signal has a strong correlation with the average steady state percent obscuration



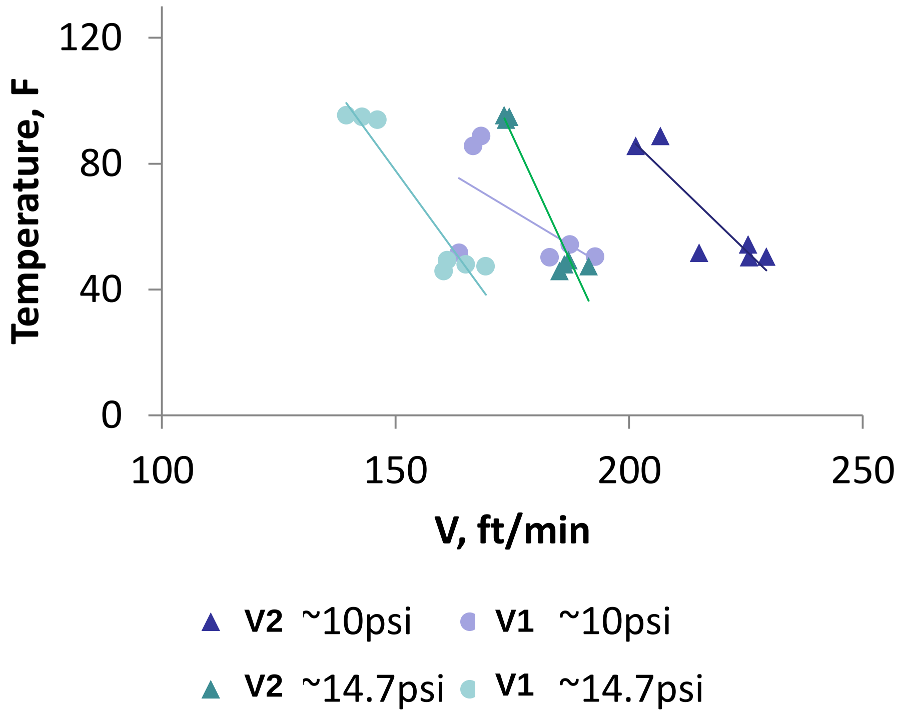
Blue and IR scattered light signal and %obscuration per foot vs time



Blue and IR scattered light signal vs average percent obscuration per foot

Smoke Plume Buoyancy

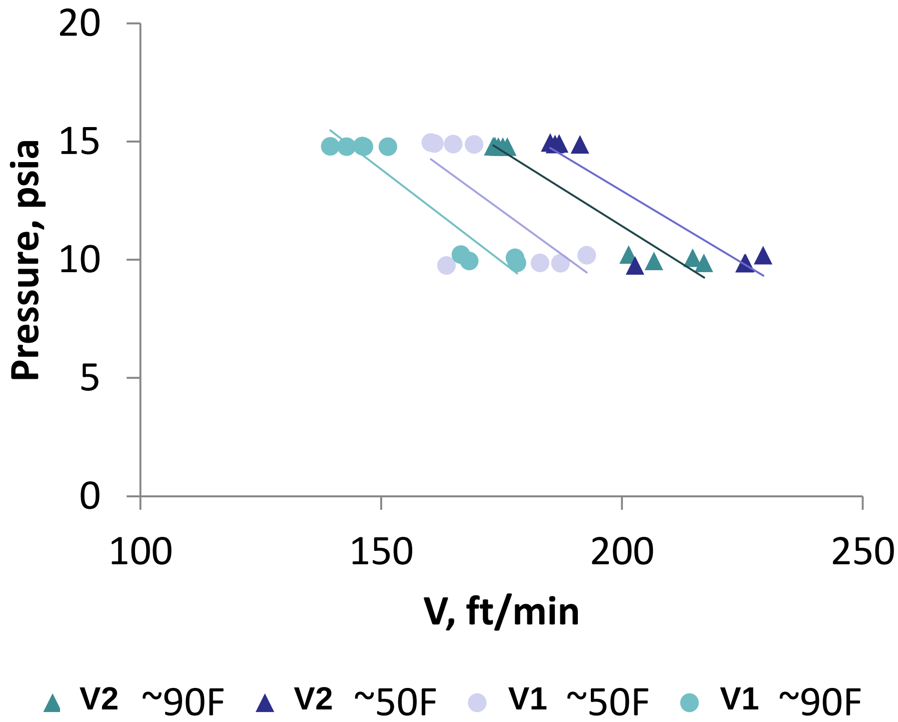
- Decreasing the ambient temperature slightly increases the smoke plume buoyancy
- V1: 10” from generator
- V2: 20” from generator



Velocity vs temperature
Velocity is averaged over 60 seconds with varying pressures, Siemens Cerberus (programs 5 and 6)

Smoke Plume Buoyancy

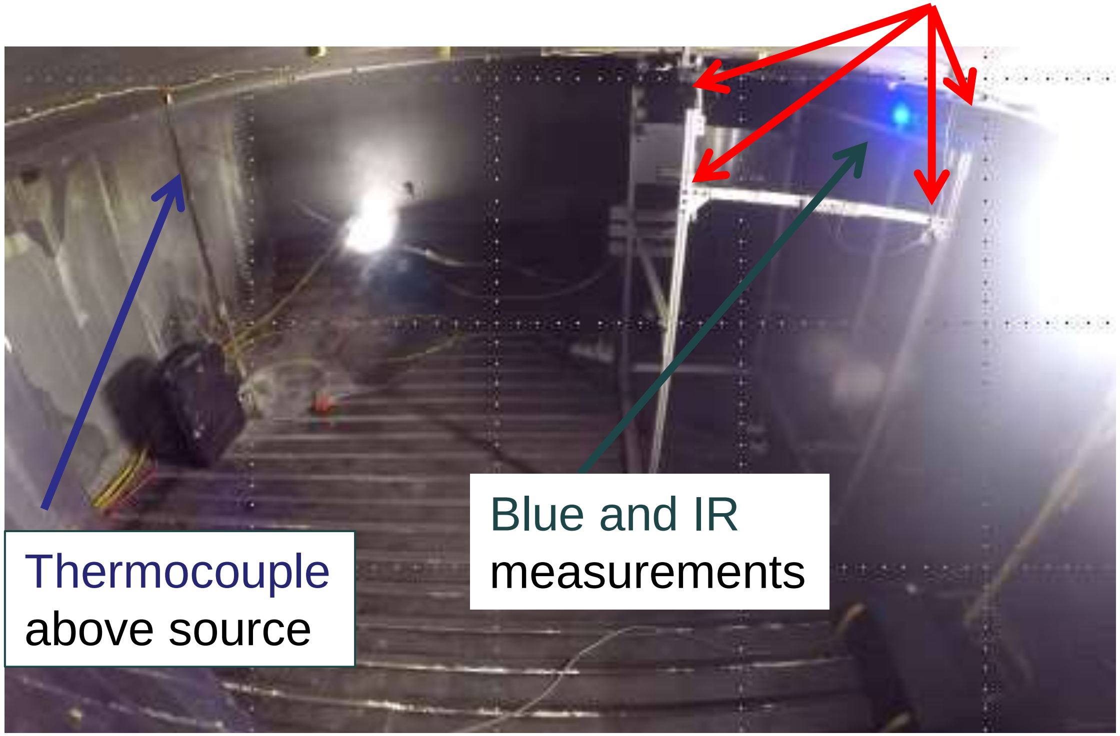
- Decreasing the ambient pressure slightly increases the smoke plume buoyancy
- V1: 10” from generator
- V2: 20” from generator



Velocity vs pressure
Velocity is averaged over 60 seconds with varying temperature, Siemens Cerberus (programs 5 and 6)

UMD Testing

- Testing was conducted inside a partitioned DC-10 cargo compartment
- Thermocouple measurements were taken at eight locations above source
  - Average temperature rise was calculated
- Varying fire loads
  - Smoldering and flaming



Partitioned D-10 Cargo Compartment

Smoke Transport and Fire Growth

- **Smoke transport is buoyancy driven**
- **Correlates to temperature**

- **Incubation period**
  - Period before flaming
  - Representative of smoldering fire
  - Varies and is difficult to quantify

- **Established growth**
  - Representative of growing fire
  - Well studied with the given idealized parabolic equation

$$Q = \alpha(t - t_o)^2$$

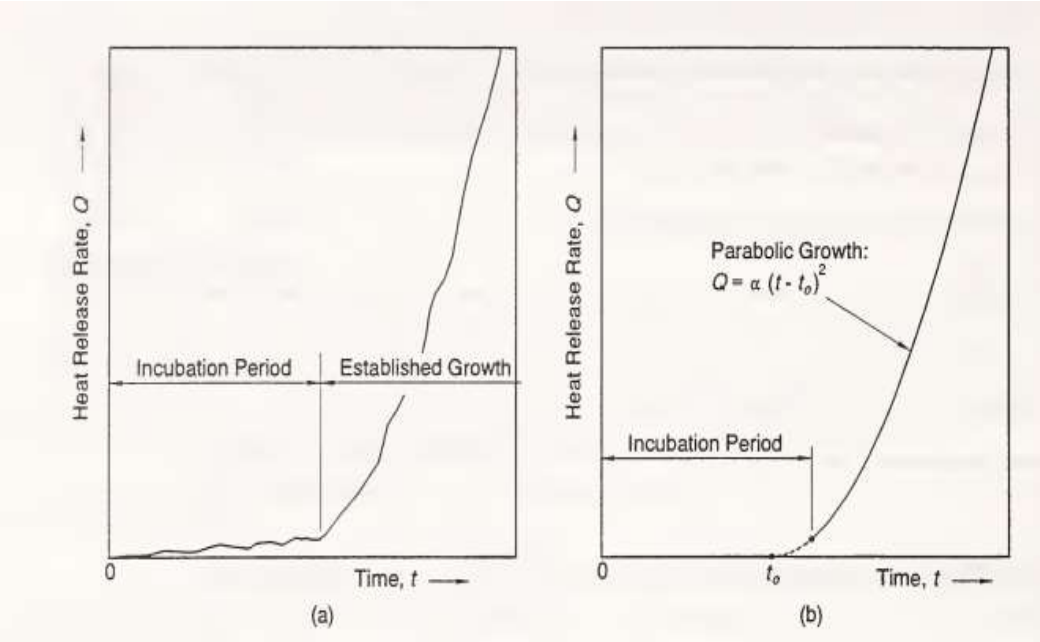
- **Where**

  Q= heat release of fire, kW

  α = fire growth coefficient, kW/s^2

  t= time after ignition, s

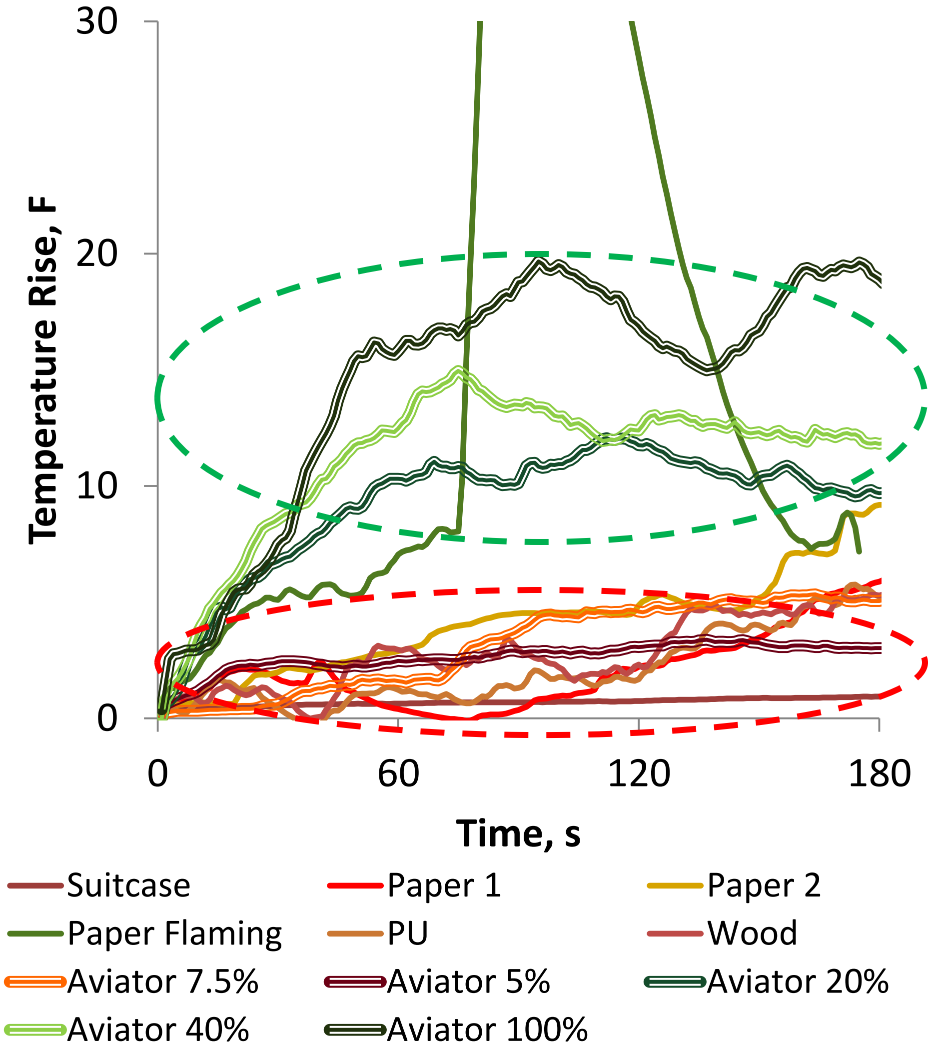
  t_o=effective ignition time, s



Fire growth (a) typical curve, and (b) idealized parabolic curve [9]

Temperature

- Concept Aviator UL has an adjustable chimney heater (~0.9kw) ranging from 0-100%
- The Aviator UL heater setting **above 20%** best emulates the temperature increase from a fire transitioning from incubation period to established growth
- The Aviator UL heater setting **below 7.5%** best emulates the temperature increase from a smoldering fire



Time vs temperature rise
Comparison of temperature rise of various smoke sources and smoke generator heater settings

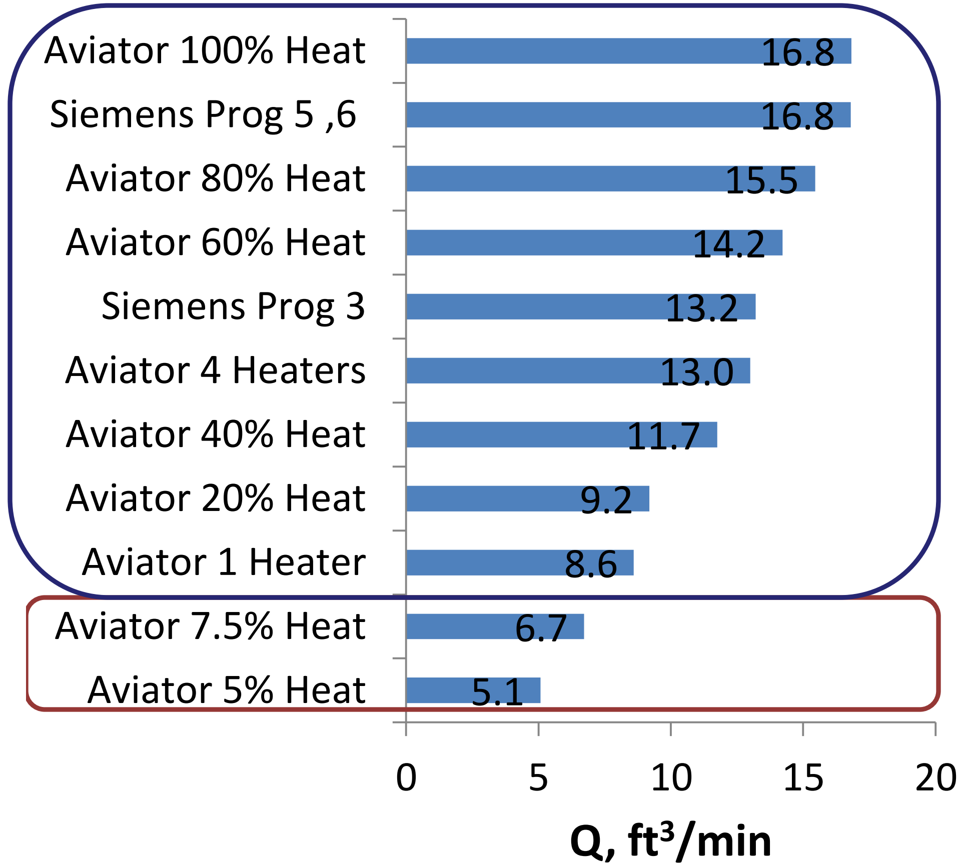
Volumetric Flow Rate

- A cone is connected to the exit of the smoke generator
- On top of the cone is a vane anemometer to measure the volumetric flow rate

Siemens Cerberus with Volumetric Flow Rate Cone

Smoke Plume buoyancy

- Smoke plume velocity increases with smoke generator heat output
- Estimated volumetric flow rate for fire transitioning from incubation period to established growth
- Estimated volumetric flow rate for a smoldering fire



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

Questions and Answers

- **Can standardizing smoke generators make smoke detector certification tests more consistent?**
- Yes:
  - Testing standards can provide an even reference for test methodology and equipment for smoke detection certification

Questions and Answers

- **Does ambient environment impact the smoke particle obscuration, diameter, concentration and/or plume buoyancy?**
- Yes, within the tested range of 50-90F and 10-14.7psia:
  - Percent obscuration per foot varies with temperature
  - The smoke particle diameter, concentration and smoke plume buoyancy varies slightly with ambient environment
- New question: **Is this impact significant?**
  - Depends on the parameters of a smoke generator standard

Questions and Answers

- **What parameters should be considered while creating a smoke generator standard?**
- Smoke detection is dependent on smoke density, particle size, smoke plume buoyance and compartment size
  - **Smoke Density:** It is possible to characterize smoke obscuration by amplitude, steady state obscuration and/or with a time dependent reference curve
    - The combined blue and IR signal has a strong positive correlation with the obscuration meter percent obscuration per foot
  - **Particle Size:** There is a strong negative correlation between the SMPS particle size and the SGSA %blue signal
  - **Smoke Plume Buoyancy:** Volumetric flow rate yields repeatable plume buoyancy and is independent of distance from smoke generator
  - **Test Compartment Volume:** Increasing the volume decreases smoke density

Questions and Answers

- **What should be the standard reference and should it be based off of an actual fire source?**
    - **Smoldering, transitioning or flaming?**
        - Low chimney heater settings appear to better emulate smoldering fires
        - High chimney heater settings appear to better emulate transitioning fires
        - Higher chimney heater settings can better emulate flaming fires
    - **Fire load size?**
        - The Concept Aviator and the Siemens Cerberus have adjustable settings that can greatly alter smoke output
    - **Other?**
    - **Should reference depend on cargo compartment volume?**

Contact Information

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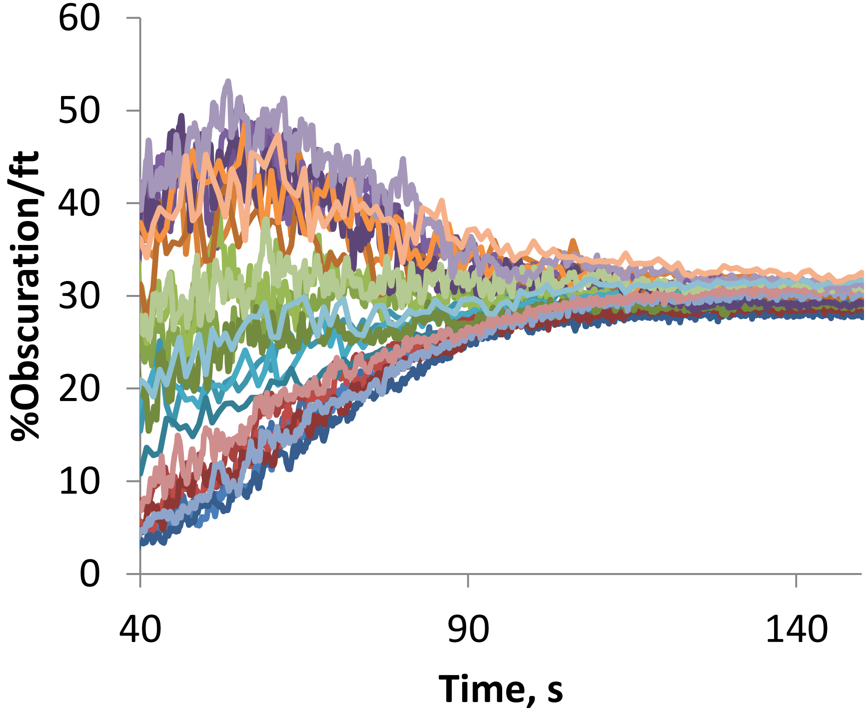
Particle Characterization

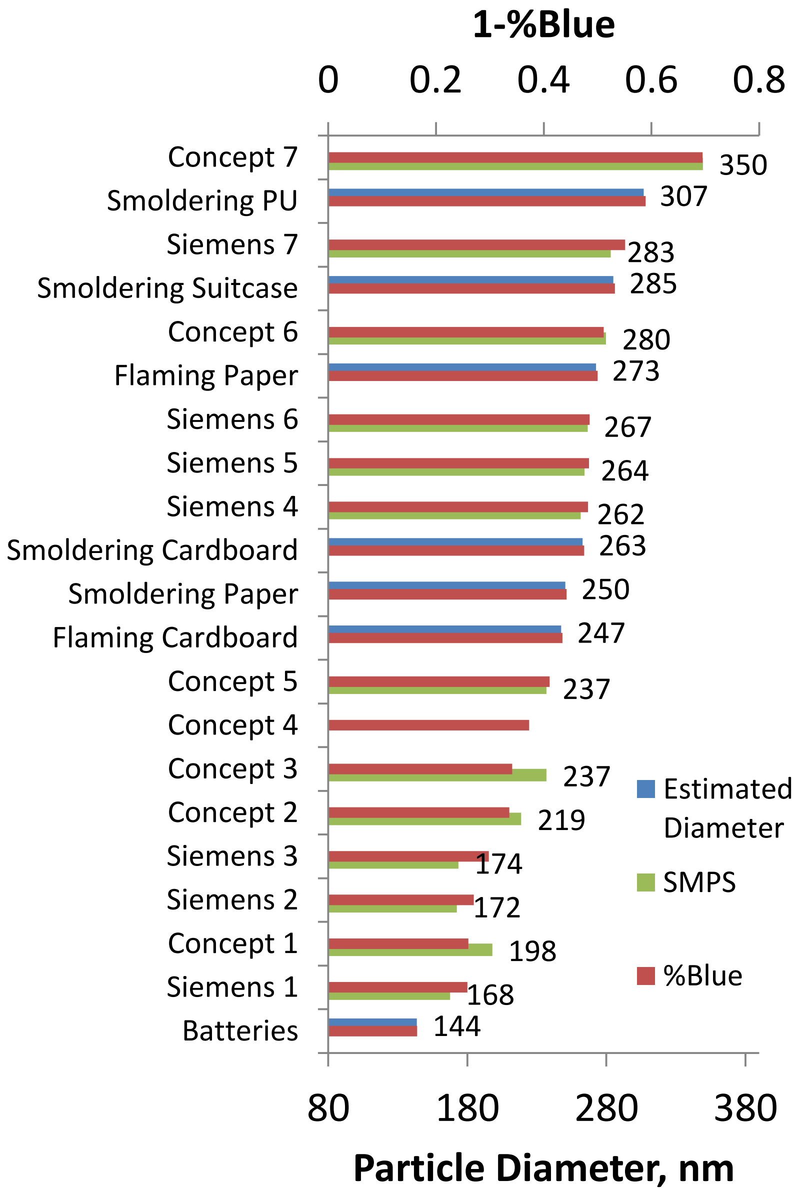
- Repeatability between tests and reproducibility between smoke obscuration meters



Time vs percent obscuration per foot
Five overlapping tests of same setting

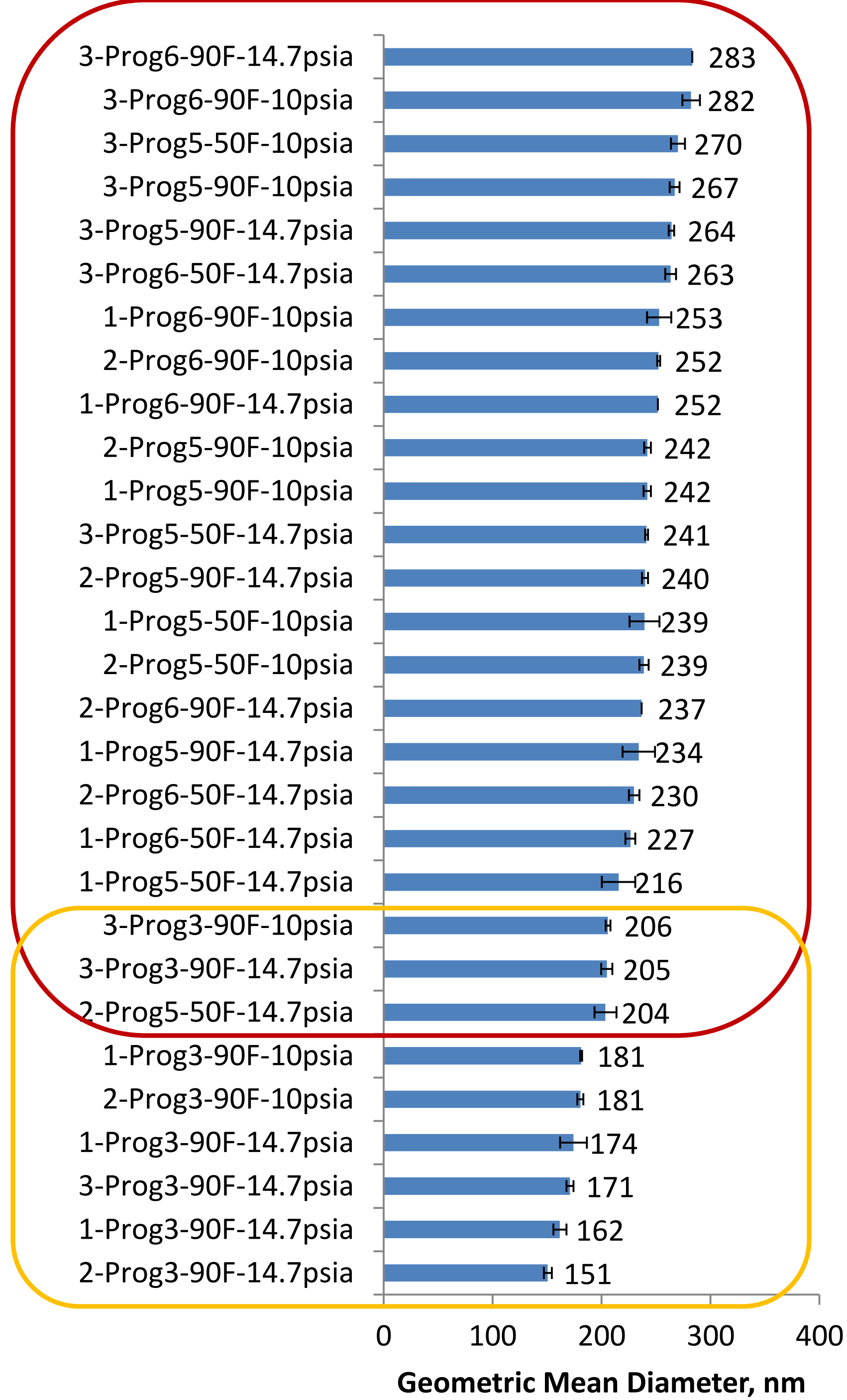
SMPS and SGSA

- There is a strong negative correlation between the SMPS particle size and the SGSA %blue signal
  - For the Concept Aviator and Siemens Cerberus at ambient temperature and pressure
- Possible to estimate actual smoke particle size assuming similar refractive index



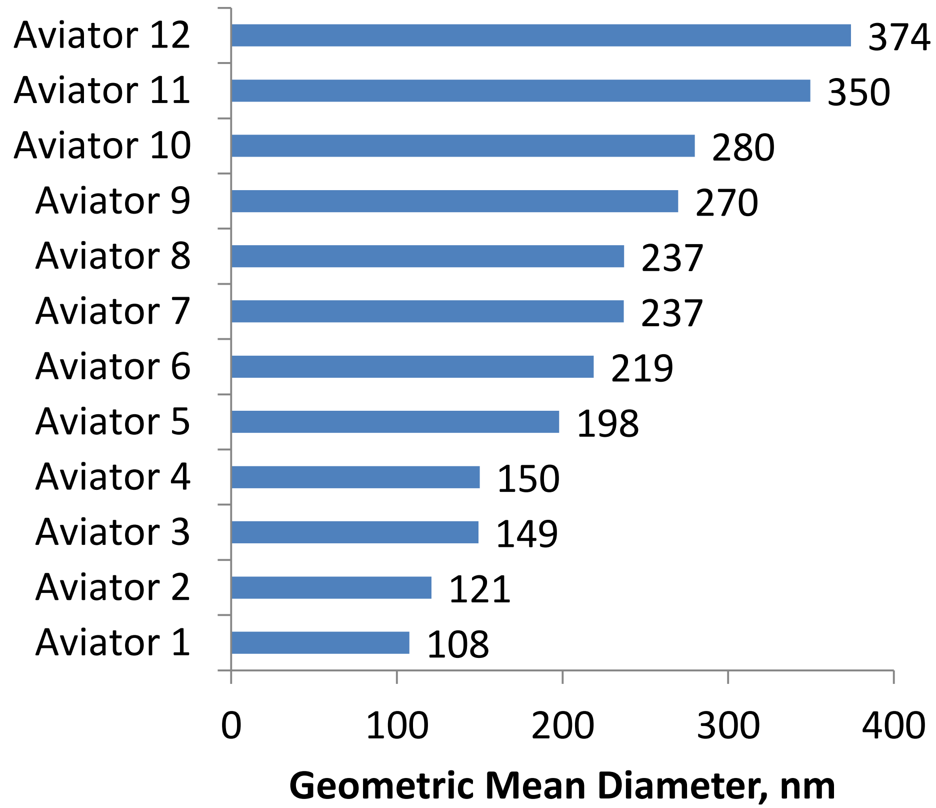
Particle Size Summary

- Particle size increases over time
- Particle size changes depending on program setting and exit nozzle diameter
  - Programs 5 and 6
  - Program 3
  - Larger exit nozzle diameter > large particles
- Increasing the ambient temperature
  - increases the particle size
- Decreasing the ambient pressure
  - increases the particle size



Particle Size – Concept Aviator

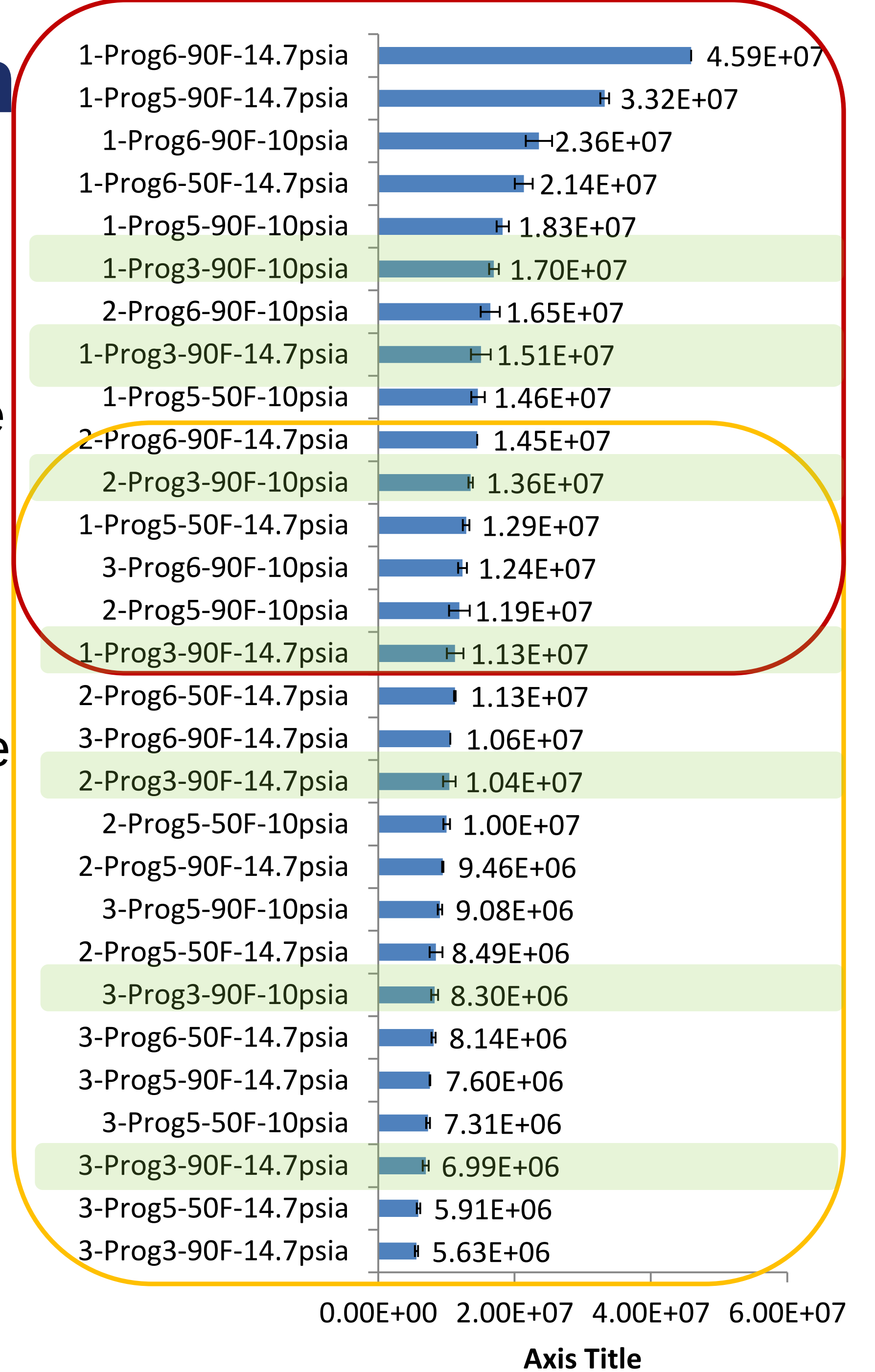
- Concept Aviator particle size varies by setting and ranges from 108 – 374nm
- Can create similar particle diameters and concentrations to Siemens Cerberus
- Depending on:
  - Smoke density valve setting
  - Chimney heater setting
  - Gas propellant pressure



Smoke particle diameter for various Aviator UL smoke generator settings measured by SMPS with Concept Aviator UL

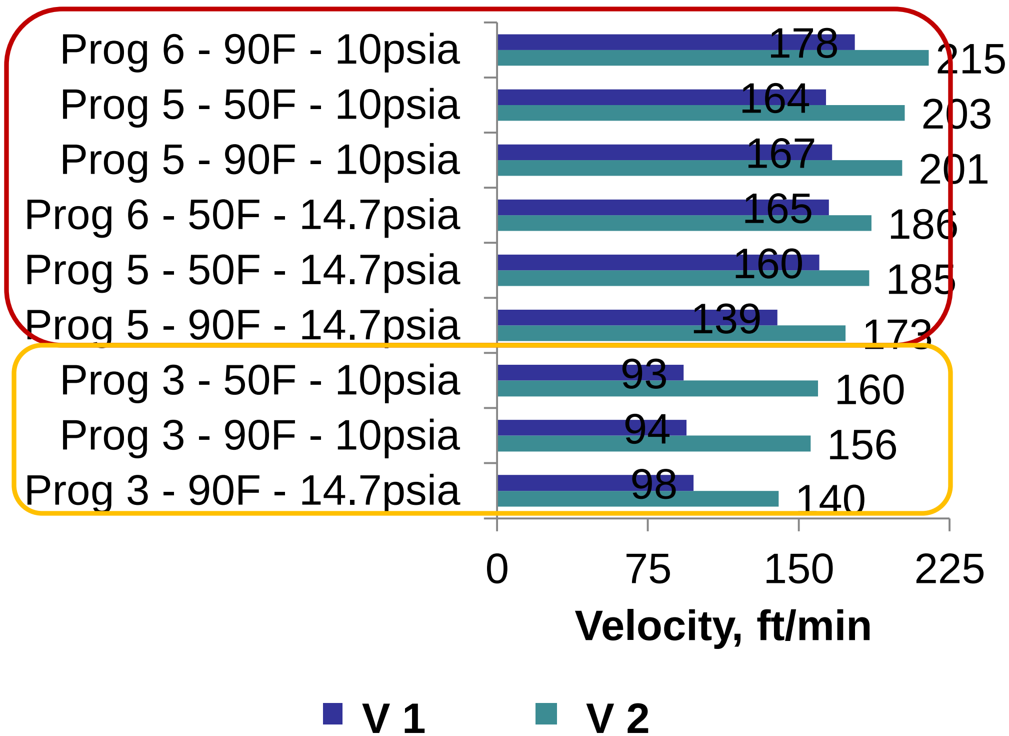
Particle Concentration Summary

- Particle concentration is most dense during initial bursts of smoke
  - From 10-70s
  - From 90-150s and 210-270s
- Particle concentration changes slightly depending on program
- Increasing the ambient temperature
  - increases the particle concentration
- Increasing the ambient pressure
  - decreases the particle concentration



Smoke Plume Buoyancy Summary

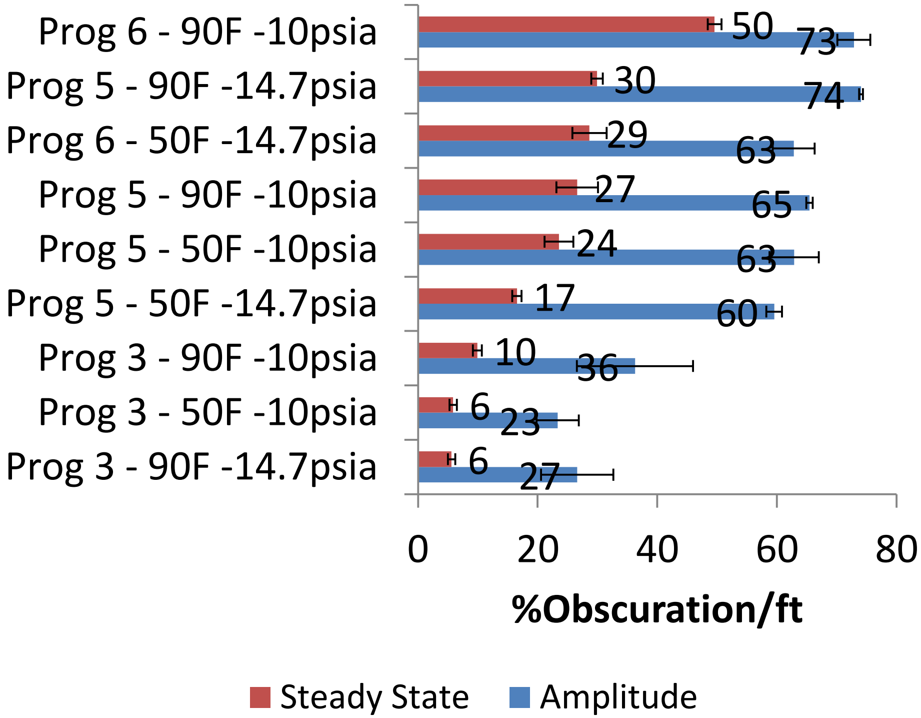
- The smoke plume buoyancy is dependent on the smoke generator heat output
  - Red high heat output
  - Yellow low heat output
- V1 10” from generator
- V2 20” from generator



Velocity comparison at different heights by program, temperature and pressure with Siemens Cerberus

Smoke Obscuration

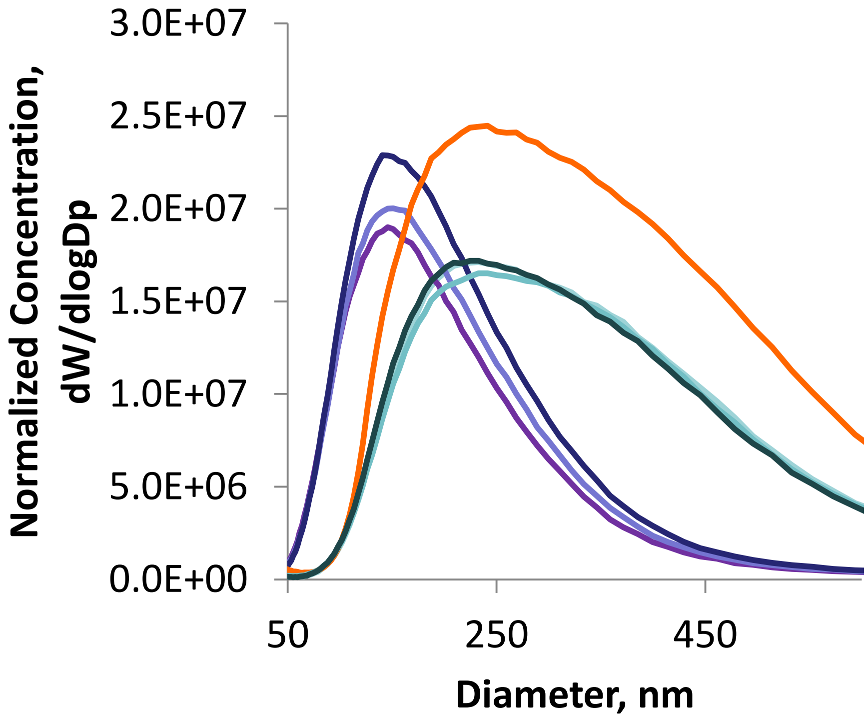
- Less deviation with steady state measurements than amplitude measurements
- Large difference between maximum amplitude and steady state obscuration
- Positive correlation with ambient temperature
- No observable correlation with ambient pressure



Comparison of percent obscuration per foot with various test conditions with Siemens Cerberus

Particle Characterization

- Particle size and distribution changes with program setting
  - Program 6 – oranges
  - Program 5 – greens
  - Program 3 – purples



Diameter vs particle concentration
Test samples of 60 seconds starting at 90 seconds after gas release with Siemens Cerberus