National Aeronautics and Space Administration

A Thermal Precipitator for Fire Characterization Research

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Outline

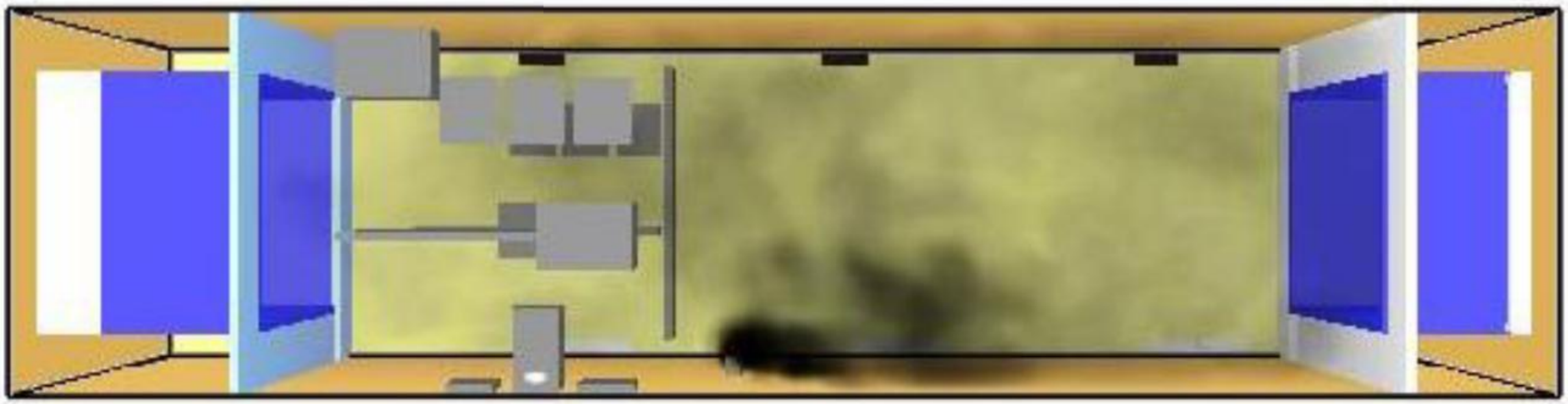
- Motivation – Fire Characterization Research
- Background
- Design goals
- Modeling
- Testing & Hardware
- Results
- Conclusion

Fire Characterization Research

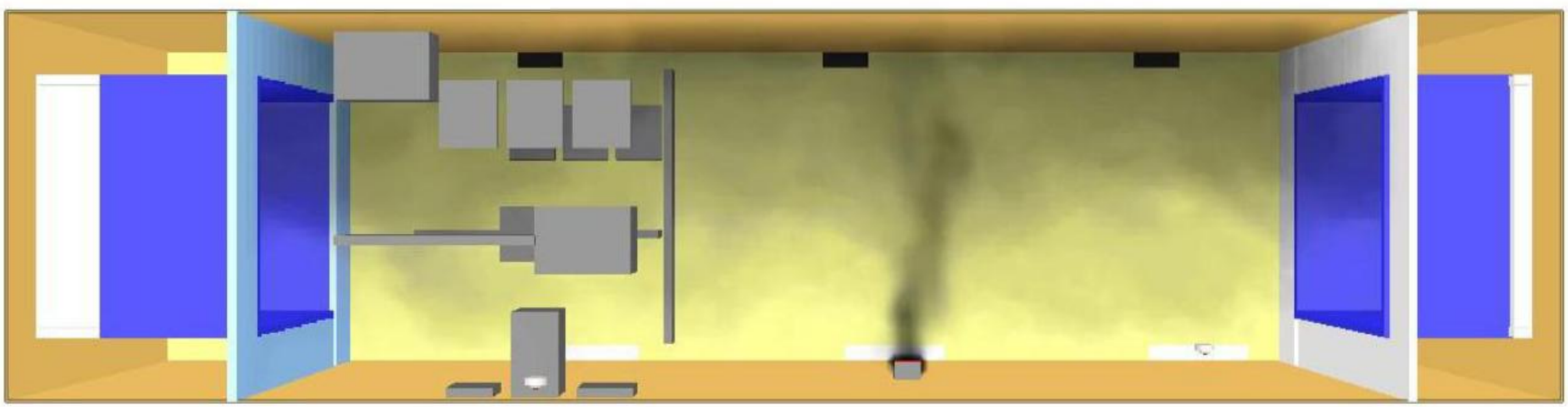
at NASA Glenn Research Center

- Most likely source of a fire on the International Space Station is overheating electronic equipment
- Early detection (before flame develops) allows rapid crew response
- Spacecraft fire safety is unique
  - No natural convection to concentrate smoke at ceiling
  - Smoke generated will disperse slowly through the cabin by forced convection caused by the ventilation flow
    - Approximately 10-15 cm/s but depends on location, stowage, etc.

ISS Destiny Smoke Detection Simulation-25% Soot



Low-gravity



Normal-gravity

Fire Characterization Research

- Next-generation space fire detectors will consist of
  - Aerosol sensors
  - Gas sensors

  } Appropriate alarm thresholds will minimize false alarms
- Multiple small, low-power sensors will allow distributed detectors and more rapid fire response

Fire Characterization Research

- Need: Characterize aerosols and gases produced by overheating common spacecraft materials
- A thermal precipitator was designed to collect smoke aerosol particles for microscopic analysis
- Information on particle morphology, size and agglomerate structure supplements other aerosol and gas data obtained in fire research

Fire Characterization Research

- Test smoke
  - Kapton, Teflon, circuit board, wire insulation, Nomex
  - 300^{o} C to 640^{o} C
  - 1×10^5 to 1×10^6 particles/cm^3
  - 40 to 70 mg/m^3
  - 100 nm < d_p < 1000 nm

Fire Characterization Research

- Goal is to characterize smoke
- Verify a repeatable fire challenge for testing
  - Aerosol instruments
  - Gas sensors
  - Post-fire clean-up equipment
- Multiple NASA smoke test facilities
  - Slightly different burn methods
  - Check fuel preparation consistency

Thermophoresis

- Thermophoretic force, F_{th}, on a particle is the result of a temperature gradient established in the gas medium
  - The force is in the direction of decreasing temperature
- For small particles (large Knudsen number) thermophoresis is explained by kinetic theory of gases
- In the transition and continuum regimes, Navier Stokes equations with slip-corrected boundary conditions have been used

Thermophoresis

- The thermophoretic force on an aerosol particle can be expressed as *(Brock, 1962)*

$$F_{th} = \frac{-6\pi\mu\upsilon d_p C_s \left(\frac{k_a}{k_p} + C_t Kn \right) \frac{\nabla T}{T}}{(1+3C_m Kn)\left(1+2\frac{k_a}{k_p}+2C_t Kn \right)}$$

μ = *viscosity of air*

υ = *kinematic viscosity*

d_p = *particle diameter*

k_p = *particle thermal conductivity*

k_a = *air thermal conductivity*

Kn = *Knudsen number,* $2\lambda / d_p$

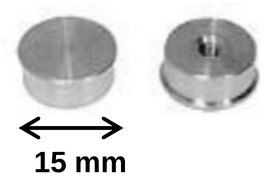
∇T = *Temperature gradient*

T = *Absolute temperature of particle*

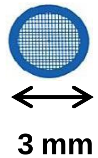
$C_t = 2.18$, $C_m = 1.14$, $C_s = 1.17$, *thermal exchange coefficients* *(Talbot et al., 1980)*

Design

- Develop a portable device for sampling smoke aerosol particles for microscopy
- Collect particles on easily inserted substrates for microscopy
  - Scanning Electron Microscope (SEM) aluminum specimen mount
    - Hitachi stubs with threaded hole



  - Transmission Electron Microscope (TEM) grid
    - Attach to aluminum stub with carbon tape



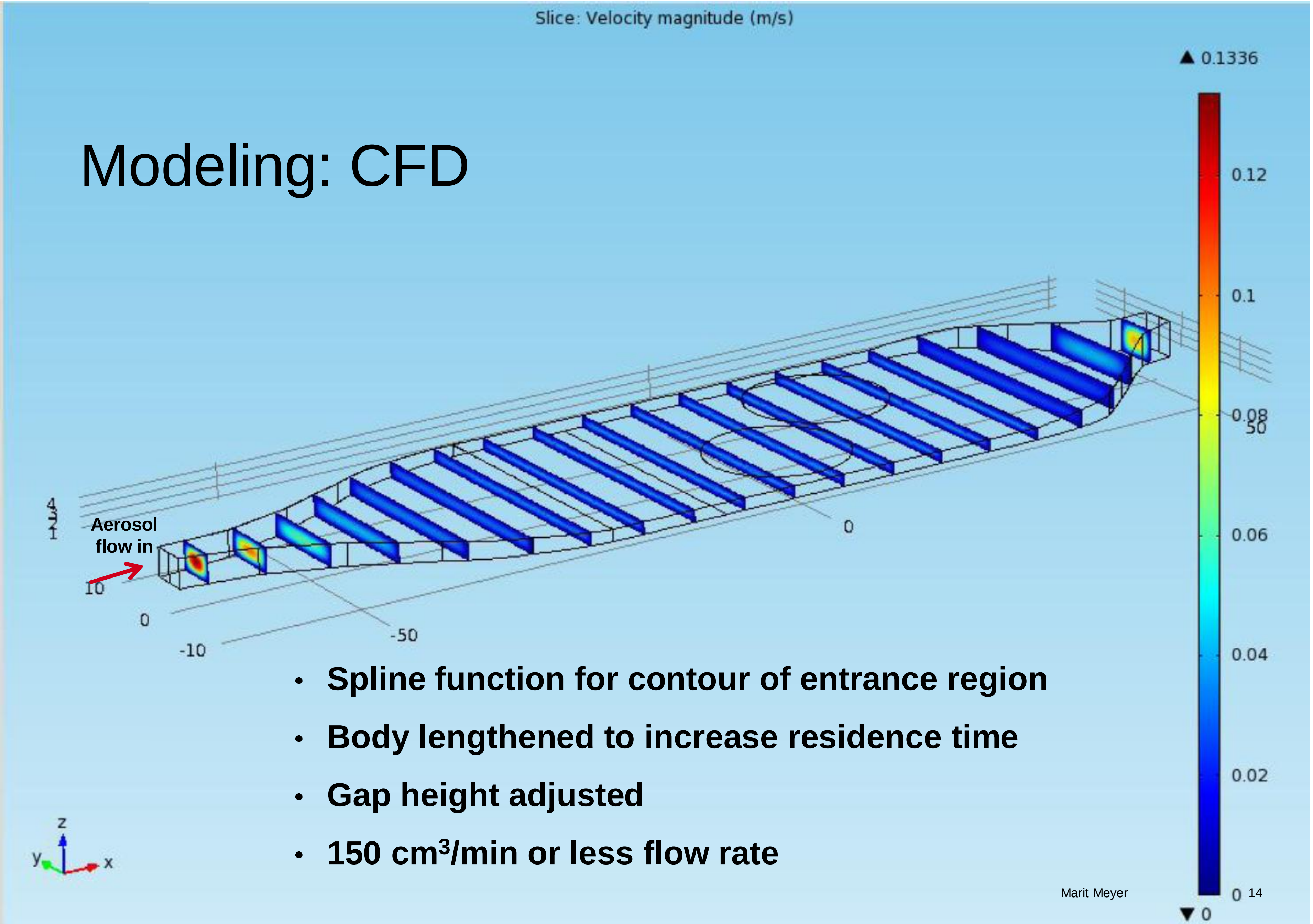
Design

- Reduce aerosol flow from ¼" tubing inlet to very narrow gap
    - Laminar flow
- Highest possible temperature gradient achievable with minimal thermal management (power, size)
    - Thermoelectric coolers (TE)

Design

- Particle residence time in TP is controlled by
  - Flow rate
  - Height of gap
  - Length of body
  - Temperature gradient
- Multiphysics finite element model determined reasonable combination of these variables
  - Computational Fluid dynamics
  - Thermal
  - Particle trajectories

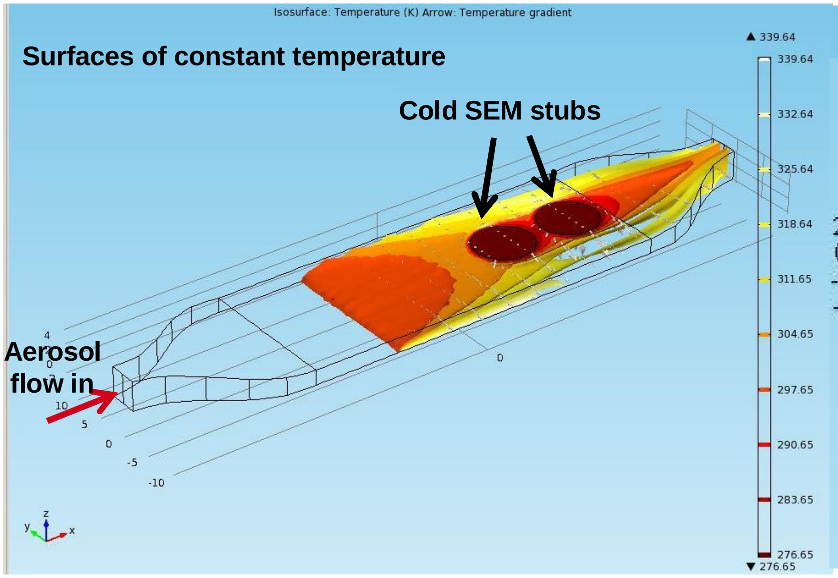
Modeling: CFD

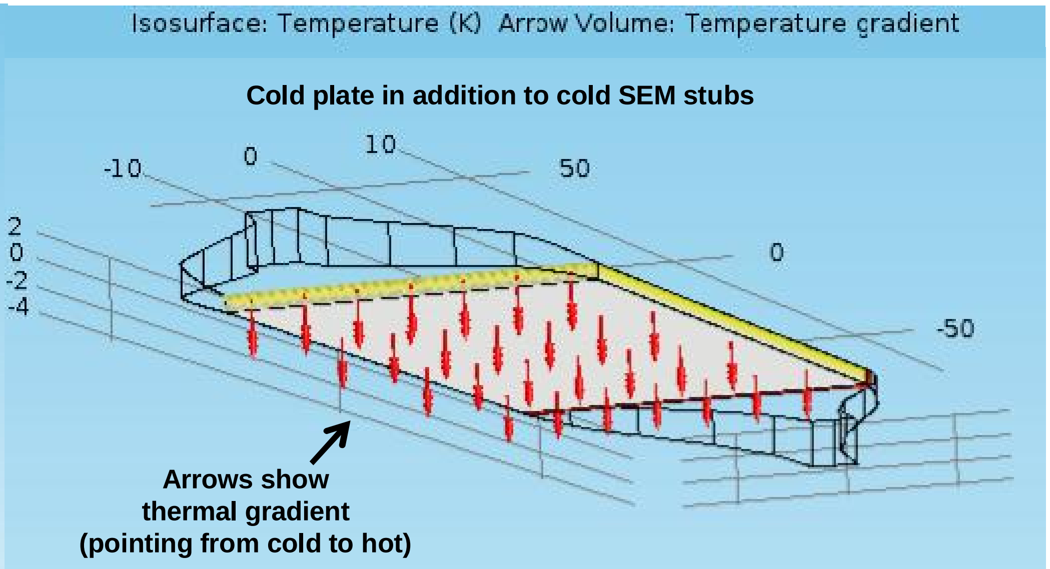


- **Spline function for contour of entrance region**
- **Body lengthened to increase residence time**
- **Gap height adjusted**
- **150 cm^3/min or less flow rate**

Modeling: Thermal

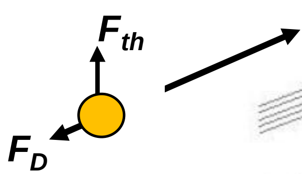
- Design iteration from model results
  - Increased area of constant thermal gradient

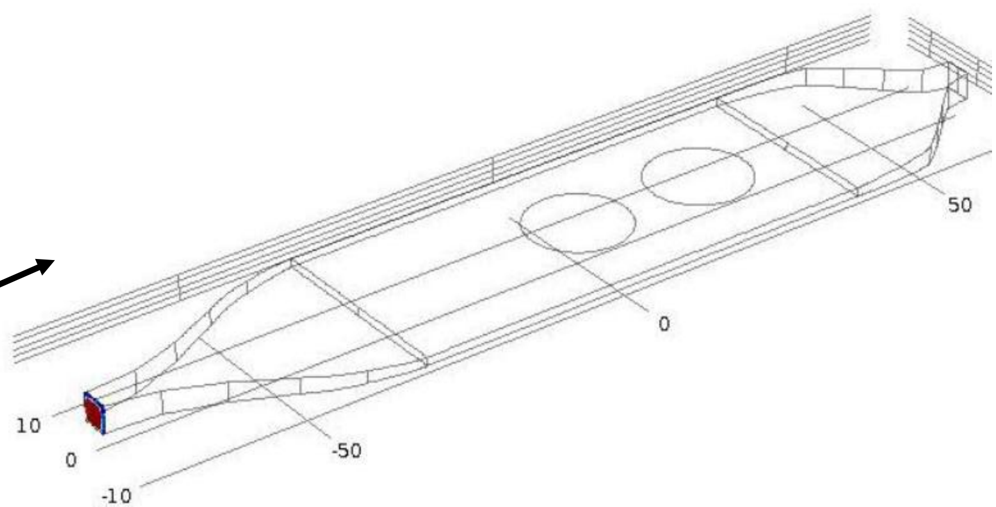




Modeling: Trajectories

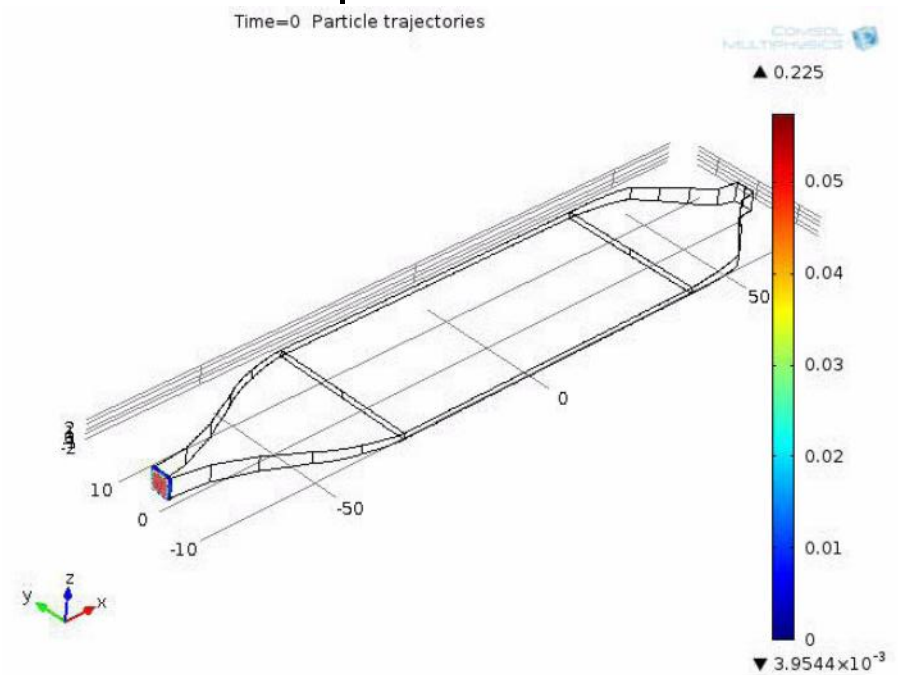
- Particle trajectories based on combined physics in numerical model
  - Slip-corrected Stokes drag and thermophoretic force
  - Average value of particle thermal conductivity 0.19 W/m-K
  - Multiple particle sizes: 100 nm, 500 nm, 1000 nm



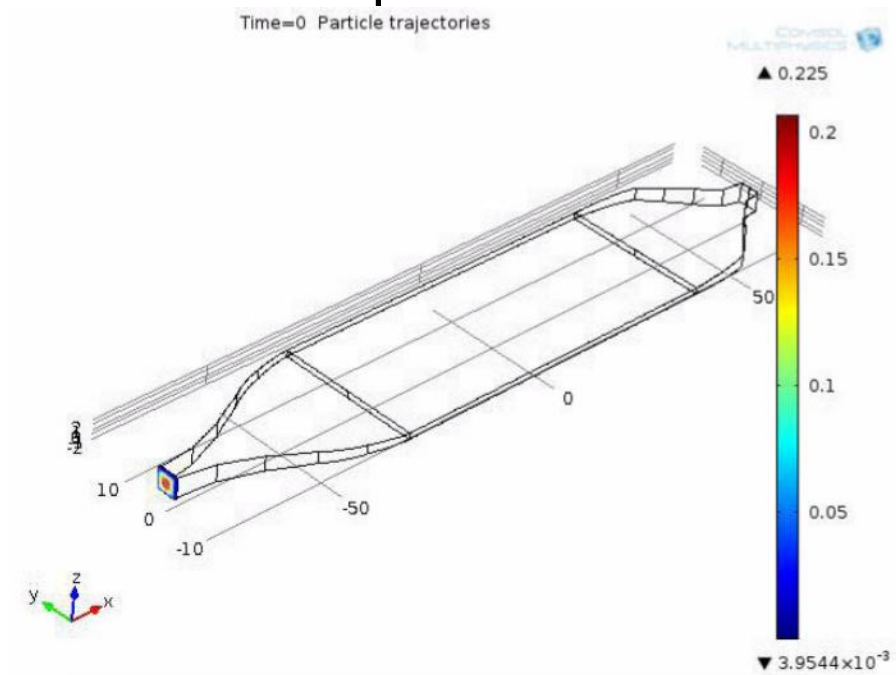


Modeling: Trajectories

100 nm particles



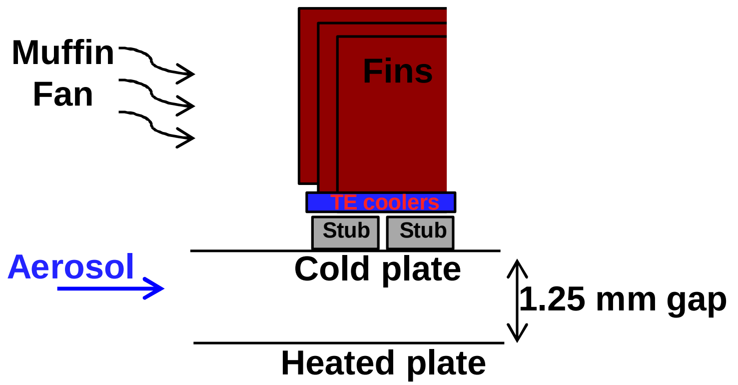
1000 nm particles



- SEM stub locations
- Final flow rate

Hardware

- Thermoelectric (TE) coolers and Kapton heater provided temperature gradient
  - Gap height 1.25 mm
  - No direct temperature control, only ΔT of cooler
  - Efficiency of heat removal from the hot side of the TE cooler established the gradient



Thermal Design Iterations During Testing

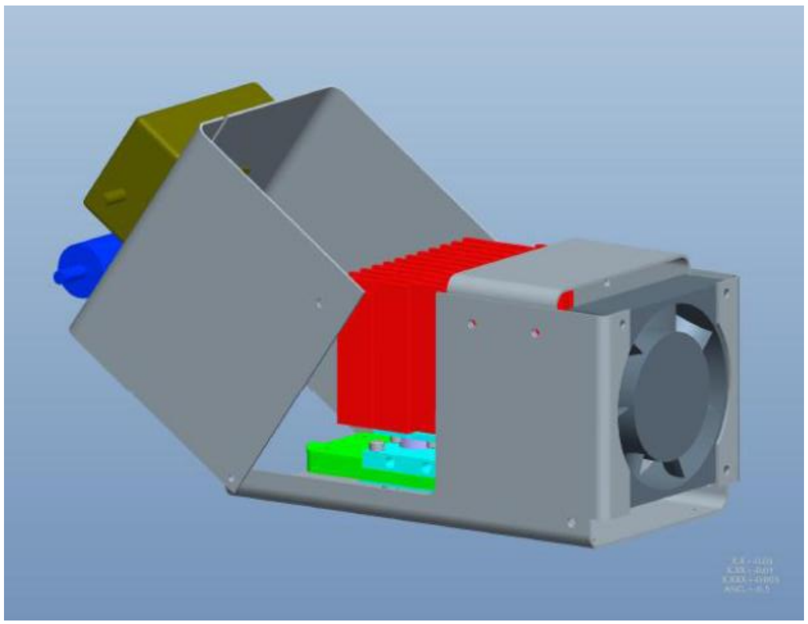
- Permanent thermocouples on cold plate and heated plate
- Improve heat removal from TE cooler
  - Larger fin surface area & larger fan
- Increase contact conductance between stubs, TE coolers and heat sinks
- Add insulation

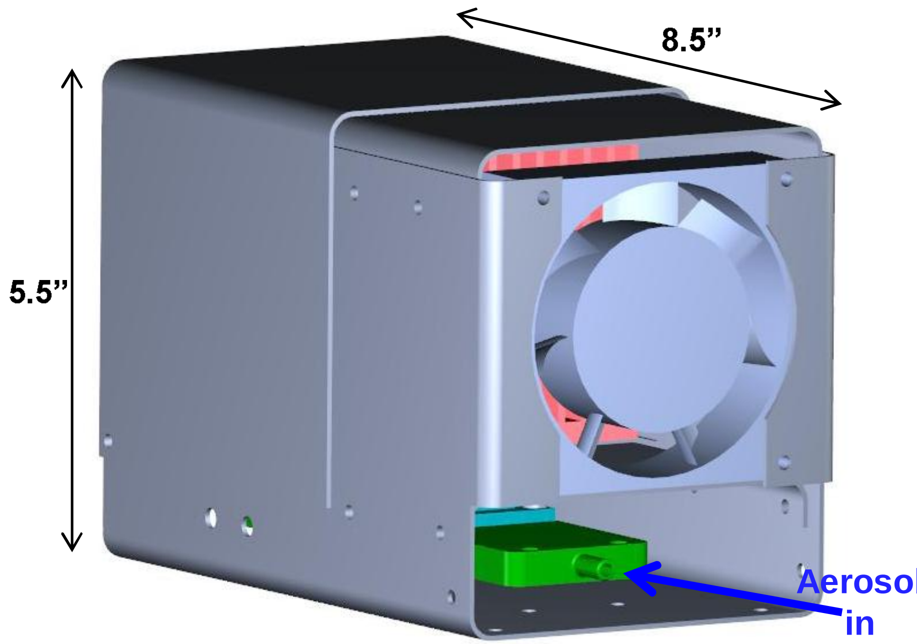
Testing

- Achieved 70º C temperature gradient with 8 to 10 minute warm-up time
  - Heated plate ~ 65º C
  - Cold plate ~ -5º C
- Sampled filtered air with TP for an hour
  - Verified no particles on stubs
- Verified PSL particle collection
  - 1.0, 0.67 µm and 100 nm
- Condensation issues during testing with PSL aerosol generation from aqueous solution
  - Smoke chamber dew point ranges from -9º to -18º C

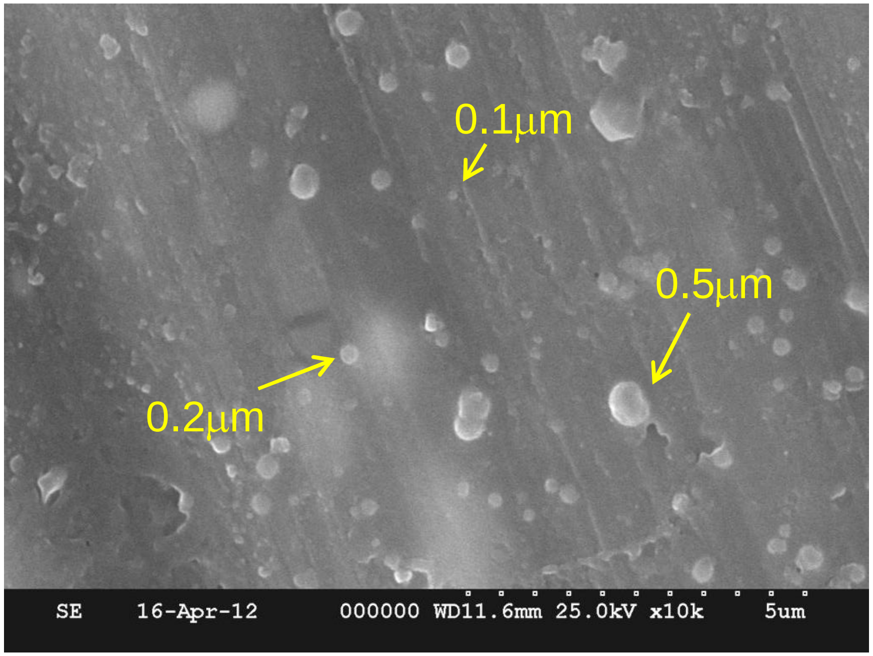
Packaging

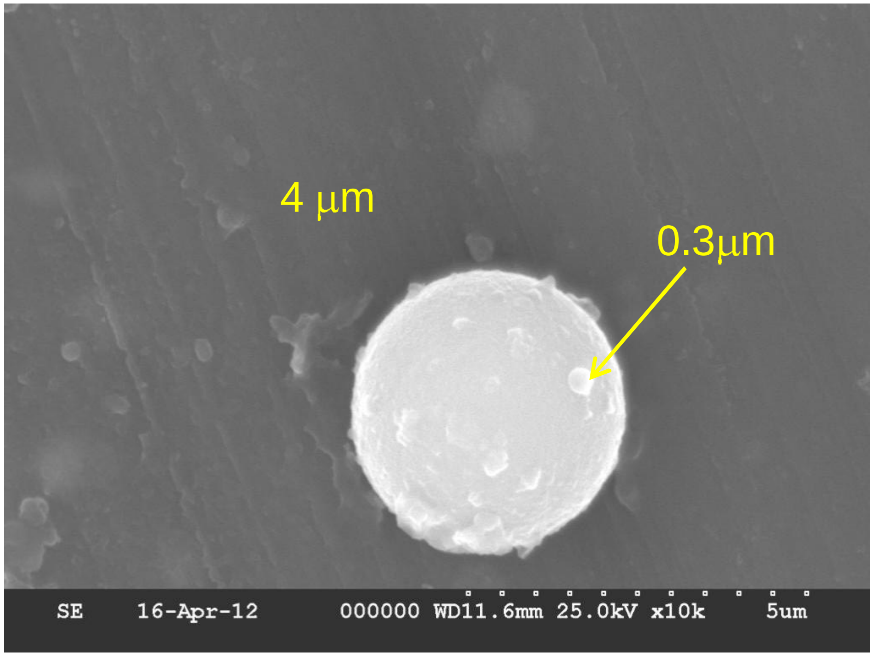
- Aluminum housing positions fan and directs air onto heatsink for heat removal
- Lid opens for access to SEM stubs





Wire Insulation 640º C

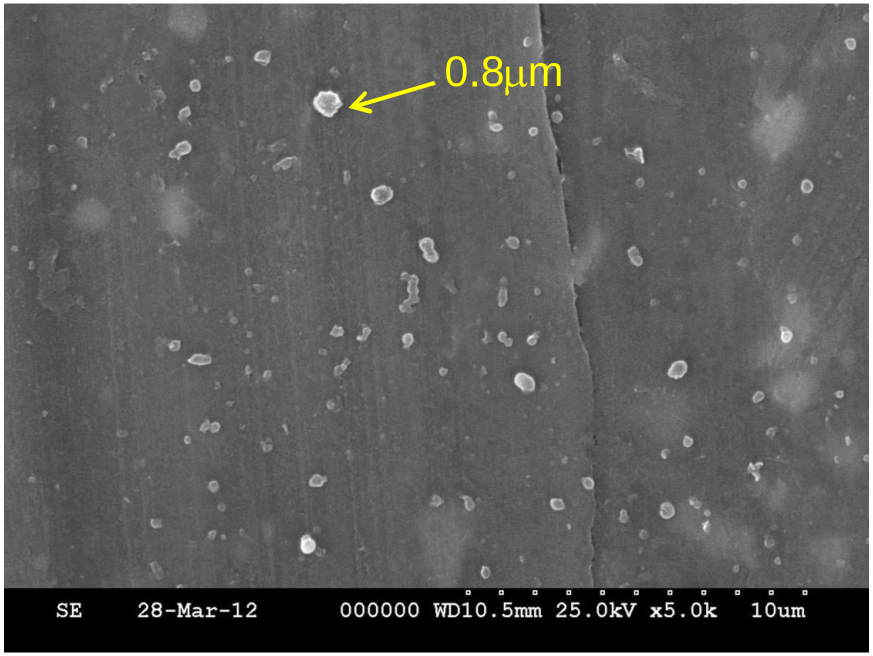




SEM stub 1 μm

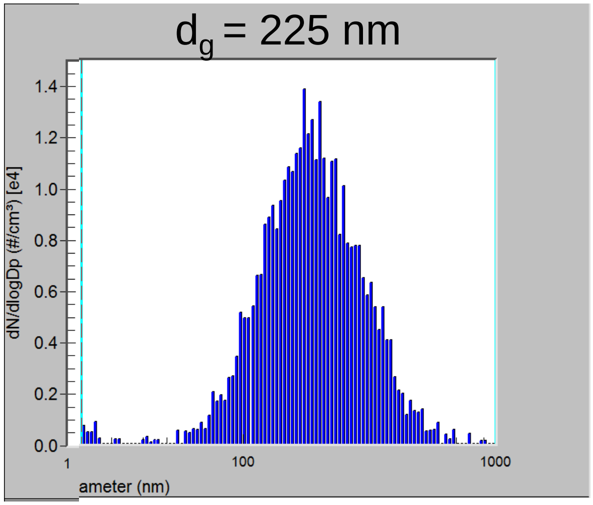
1 μm

Kapton 640º C

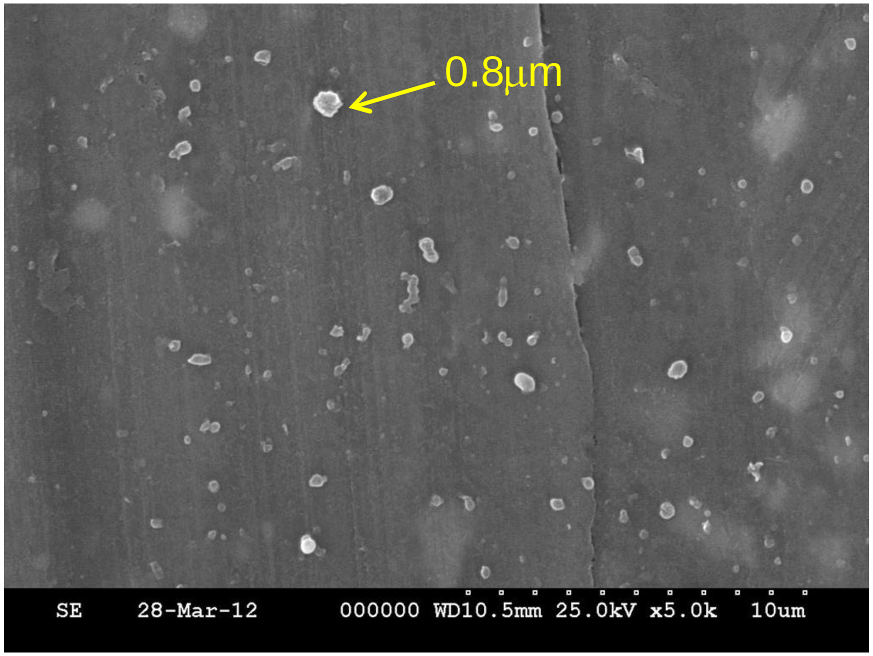


SEM stub

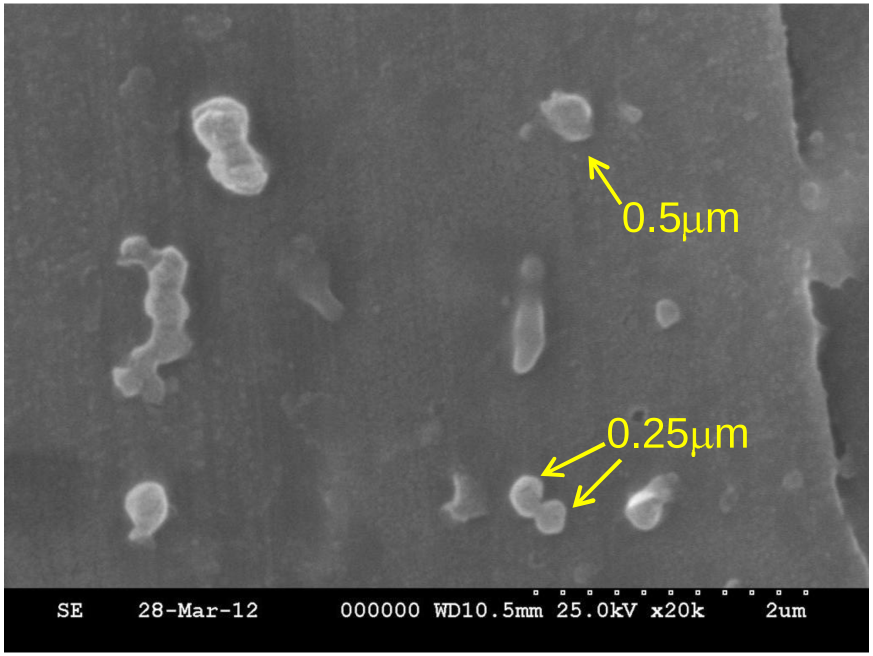
2 μm



Kapton 640^{o} C

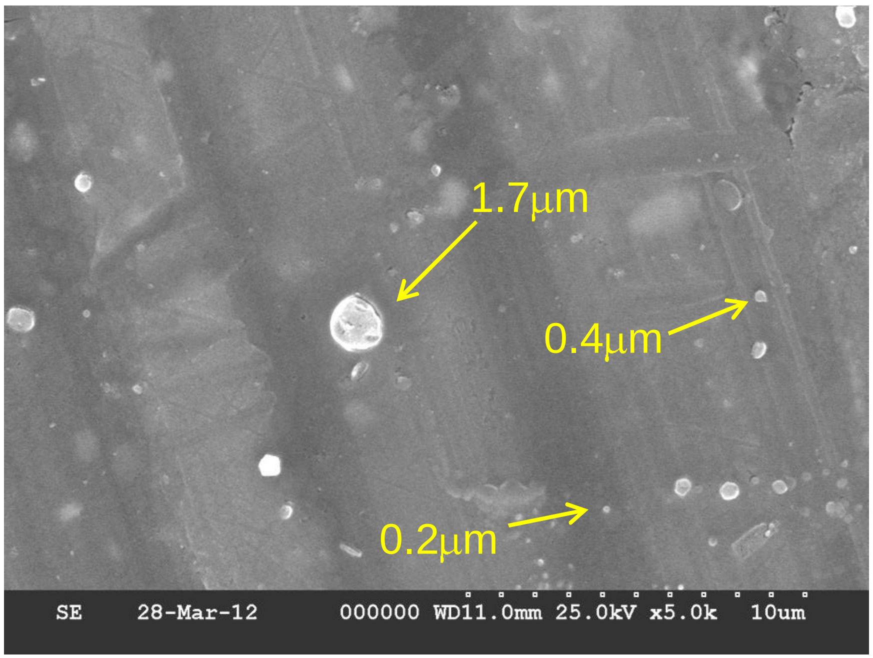


SEM stub 2 µm

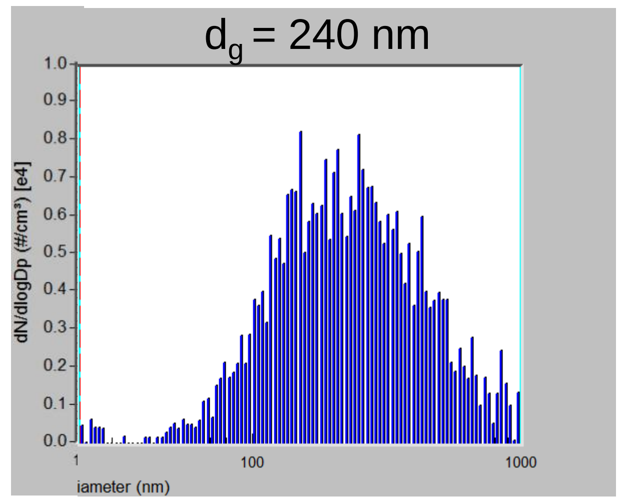


1 µm

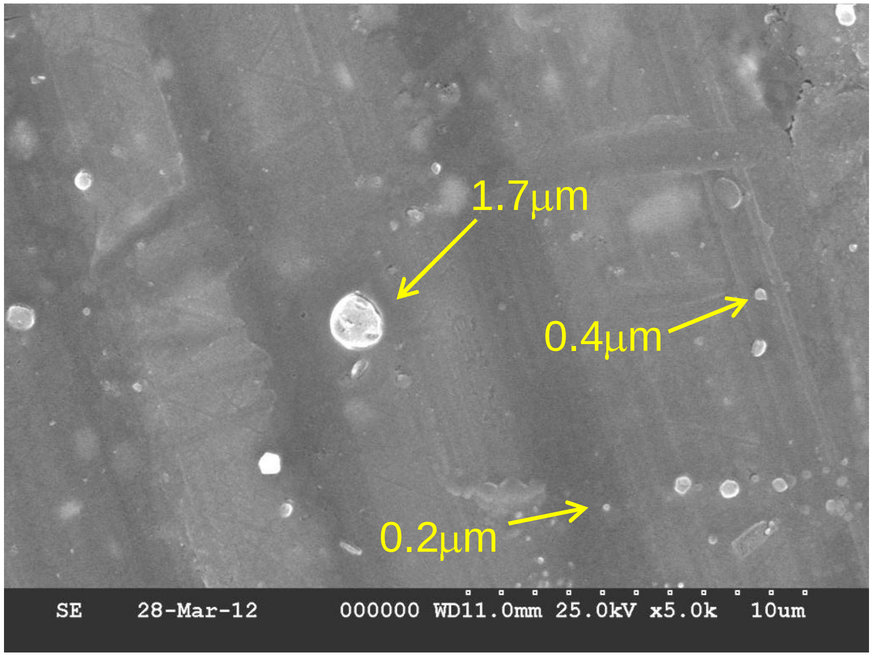
Teflon 640^{o} C



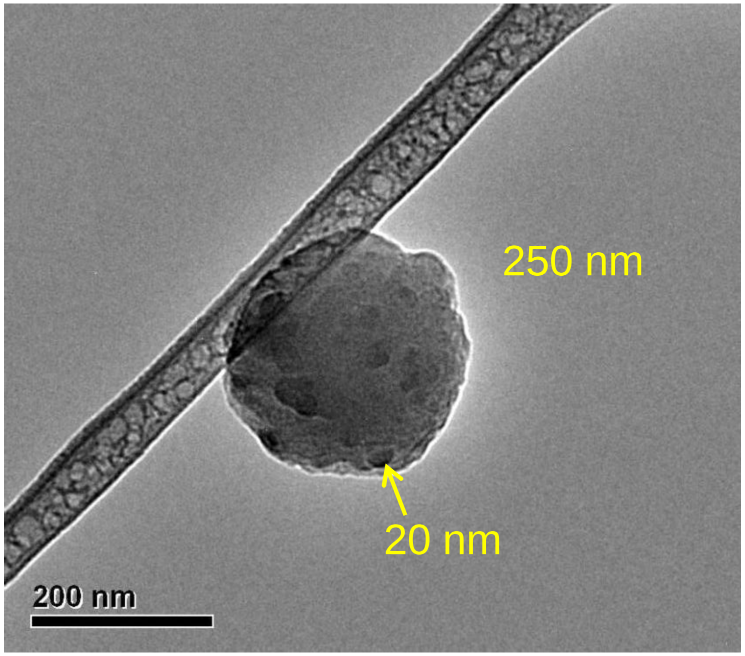
SEM stub — 2 µm



Teflon 640^o C



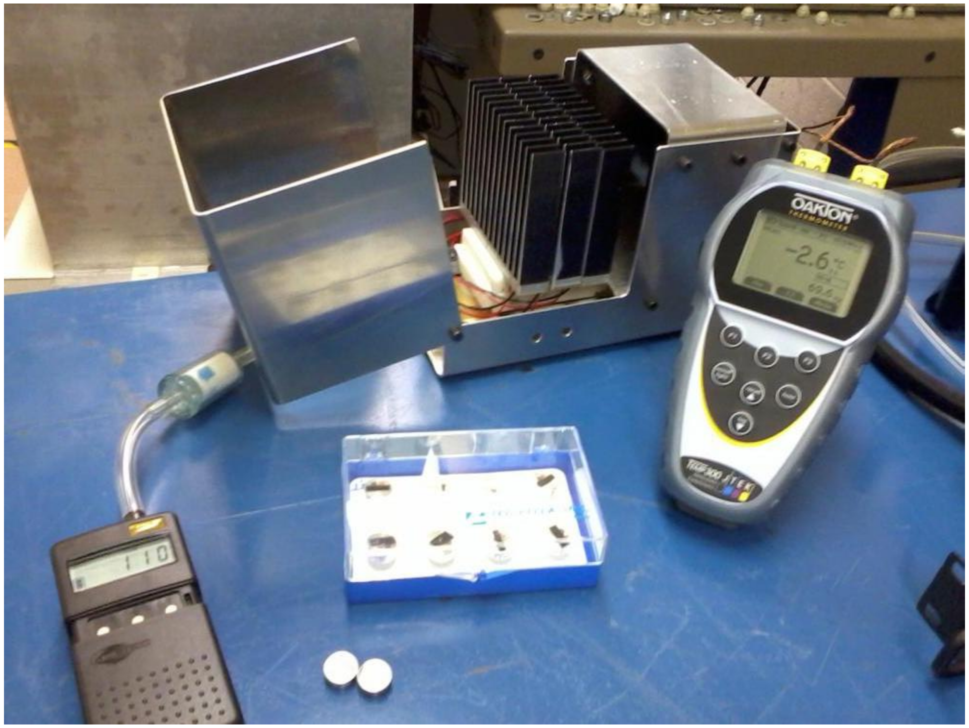
SEM stub — 2 µm



TEM grid

Conclusion

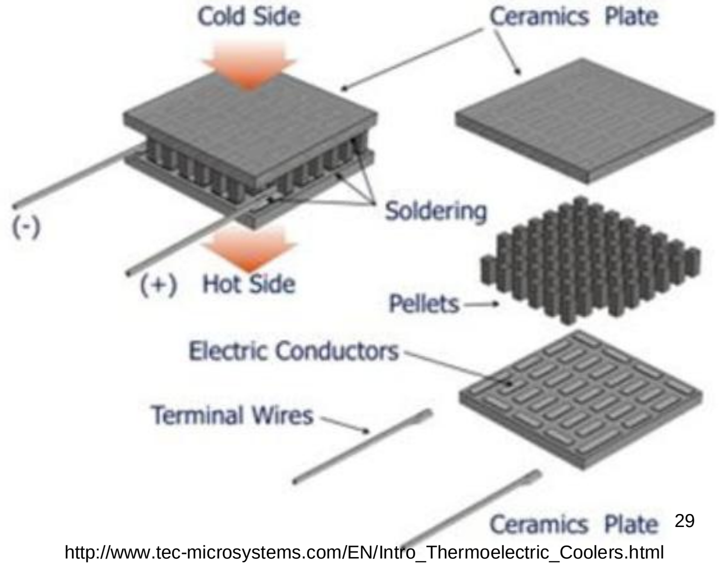
- Thermal precipitator designed, modeled and tested
- Successful particle collection
- Fire characterization research ongoing
  - Aerosol/gas kinetics



Acknowledgment: Daniel Gotti contributed to the mechanical design and did the CAD model for this project

Backup Slide: Thermoelectric Cooler

- Also known as Peltier cooler or heater
- Creates a heat flux between the junction of two different types of materials (N and P-type semiconductor pellets)
- Datasheet gives ΔT_{max} (between each side of cooler), cooling capacity, current and voltage restrictions



http://www.tec-microsystems.com/EN/Intro_Thermoelectric_Coolers.html

Backup Slide

- Carbon tape strip placed in the direction of flow
- TEM and HRTEM grids are attached to carbon tape

Backup Slide