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Characterization of Convective and Particle Losses in High-Temperature Particle Receivers

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SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy
U.S. DEPARTMENT OF ENERGY
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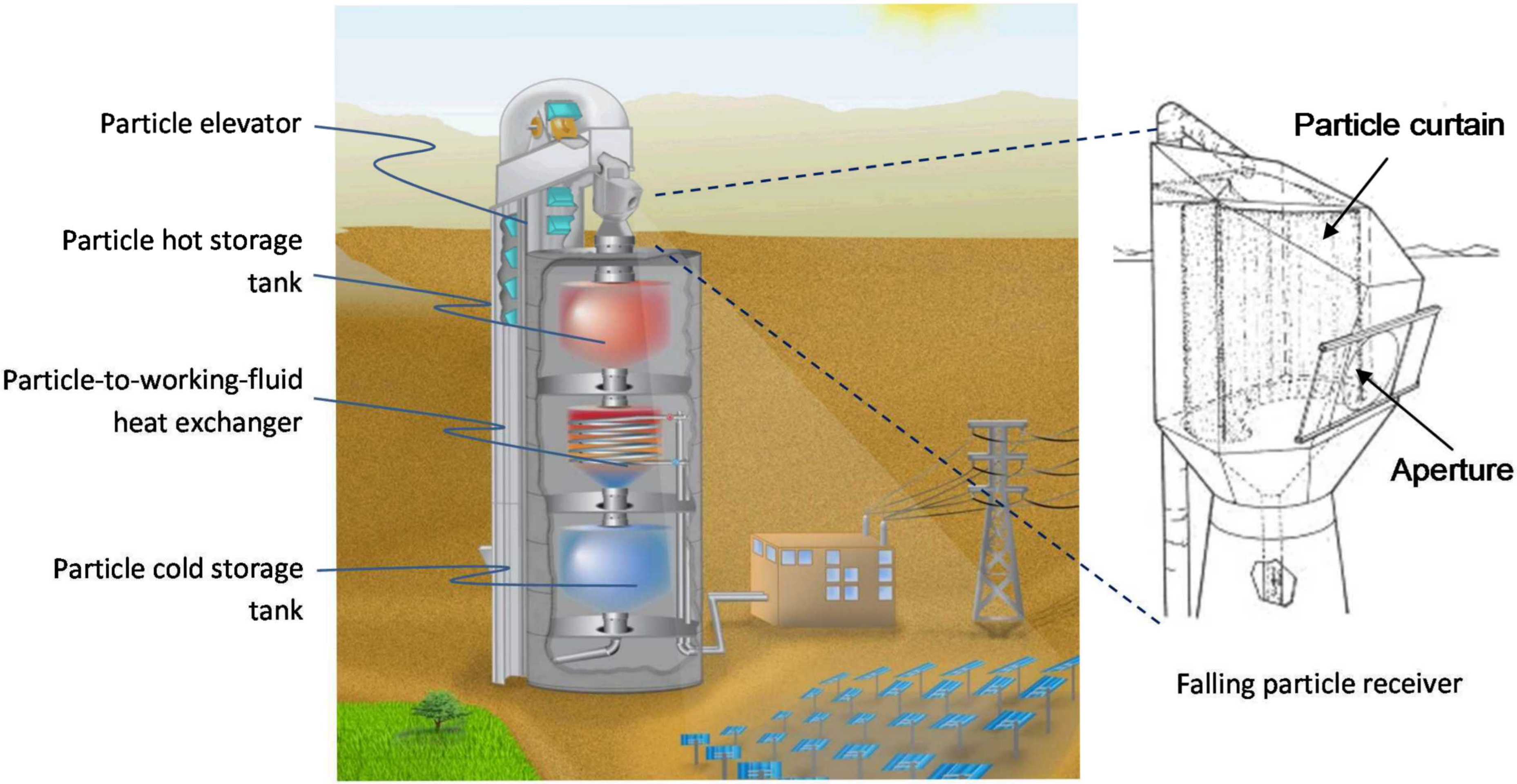
Overview

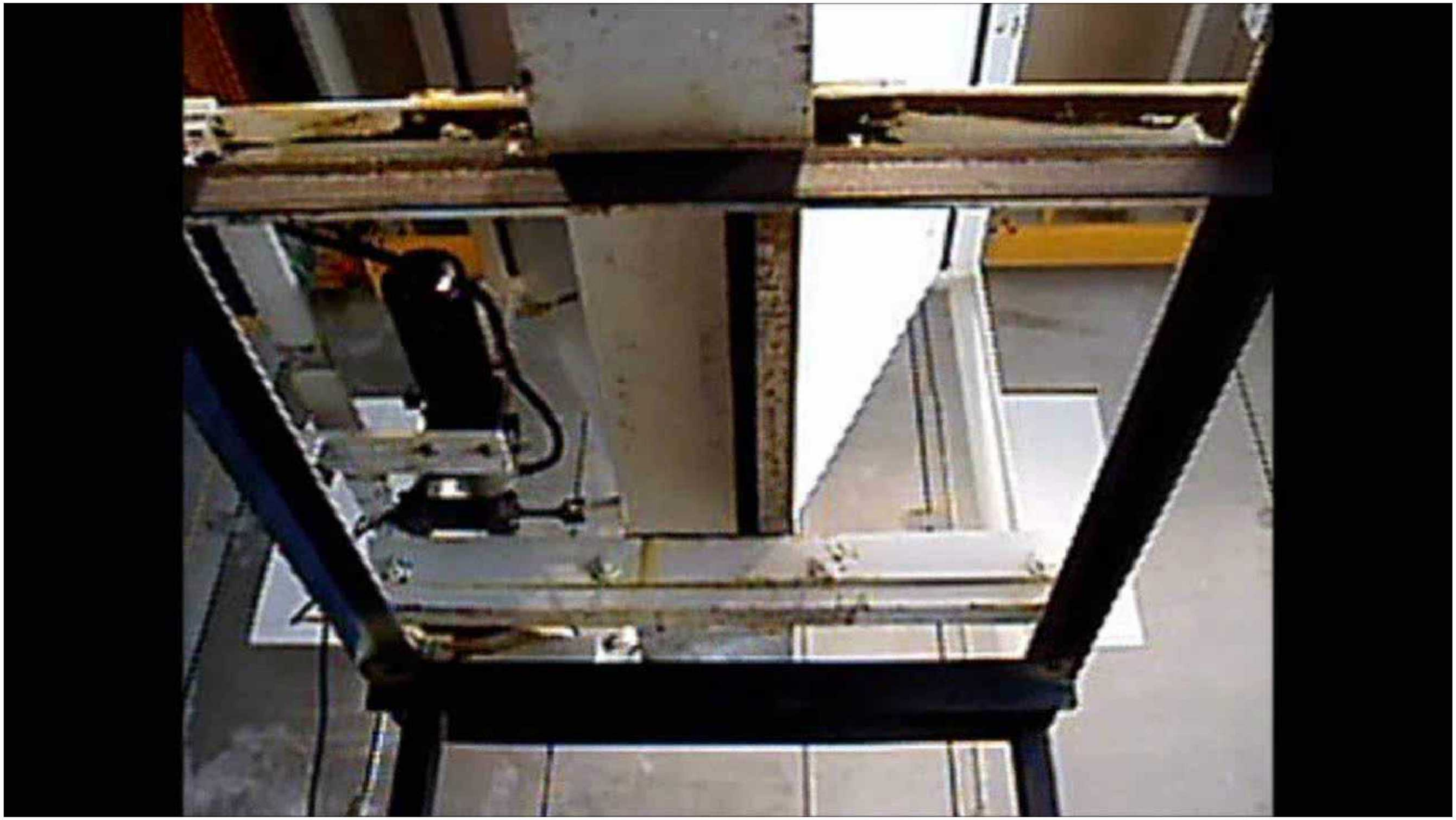
- Introduction and Objectives
- Particle Imaging
- Particle Sampling
- Conclusions

High Temperature Falling Particle Receiver



Goal: Achieve higher temperatures, higher efficiencies, and lower costs

Particle Receiver Designs – Free Falling

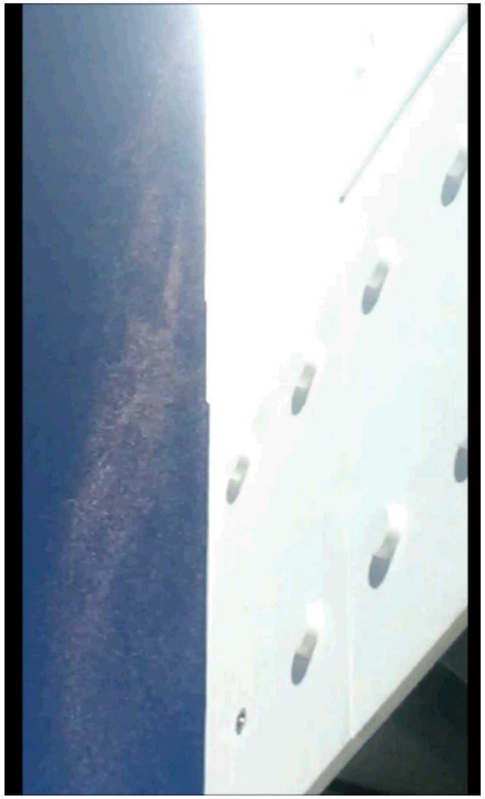


Value Proposition

- Proposed particle receiver system has significant advantages over current state-of-the-art CSP systems
  - Sub-zero to over ~1000 °C operating temperatures
  - No freezing and need for expensive trace heating
  - Use of inert, non-corrosive, inexpensive materials
  - Direct storage (no need for additional heat exchanger)
  - Direct heating of particles (no flux limitations on tubes; immediate temperature response)

Problem Statement

- Particles can escape from the open aperture of a falling particle receiver
  - Inhalation/pollution hazard
  - Loss of particle inventory
- Need to minimize both particle *and* convective heat losses
  - Can imaging of particles be used to estimate convective heat losses?



Nov. 2, 2015
3/8” slot – free fall
280 micron ACCUCAST ID50
10-15 mph south wind
500 – 1000 suns

Project Objectives

- **Task 1**: Develop imaging methods to characterize particle and heat losses emitted from the aperture of a high-temperature particle receiver
- **Task 2**: Quantify particle emissions using standard air monitoring procedures and compare to OSHA standards (15 mg/m^3) and EPA standards (12 μg/m^3)

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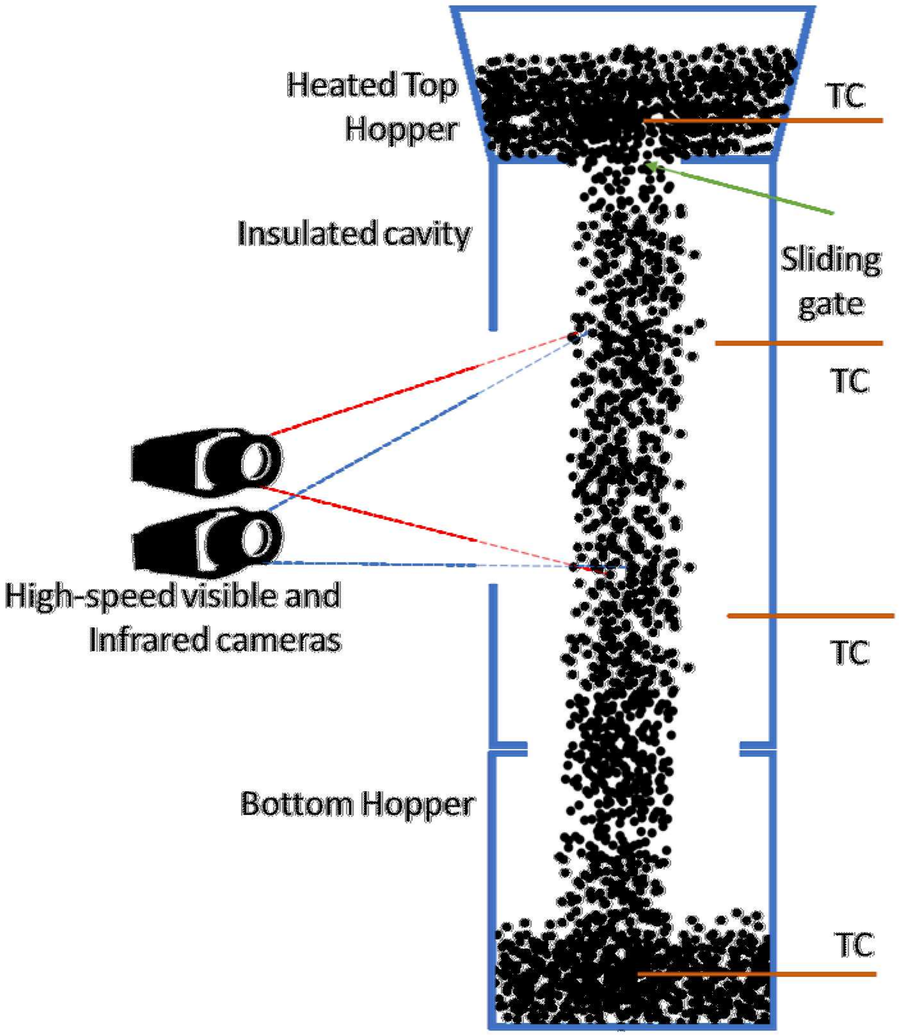
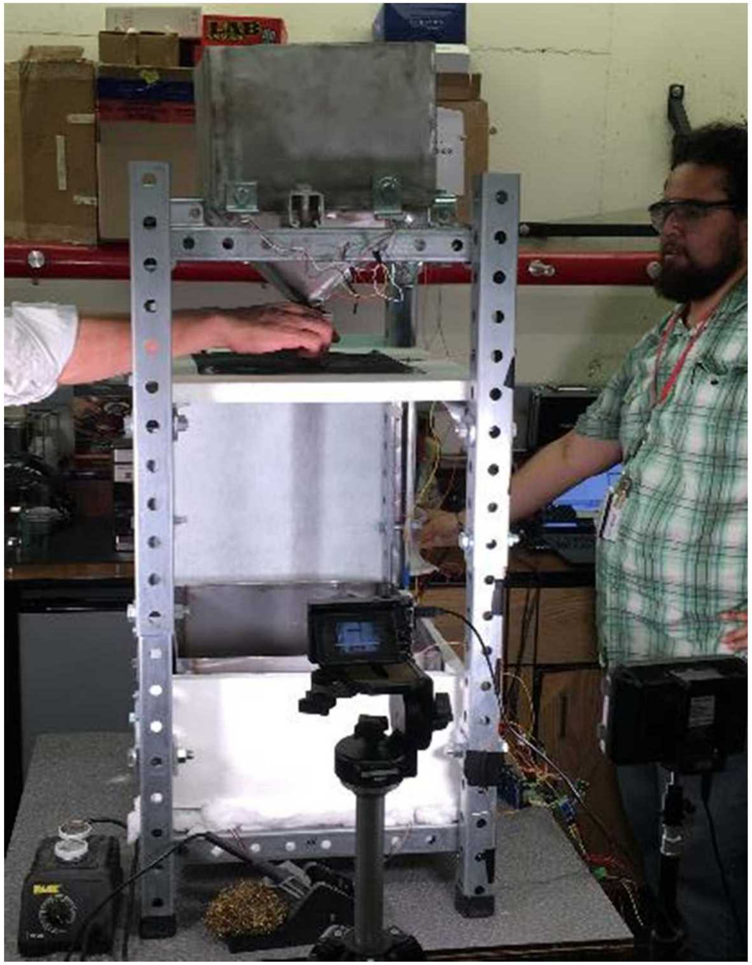
Particle Imaging Approach

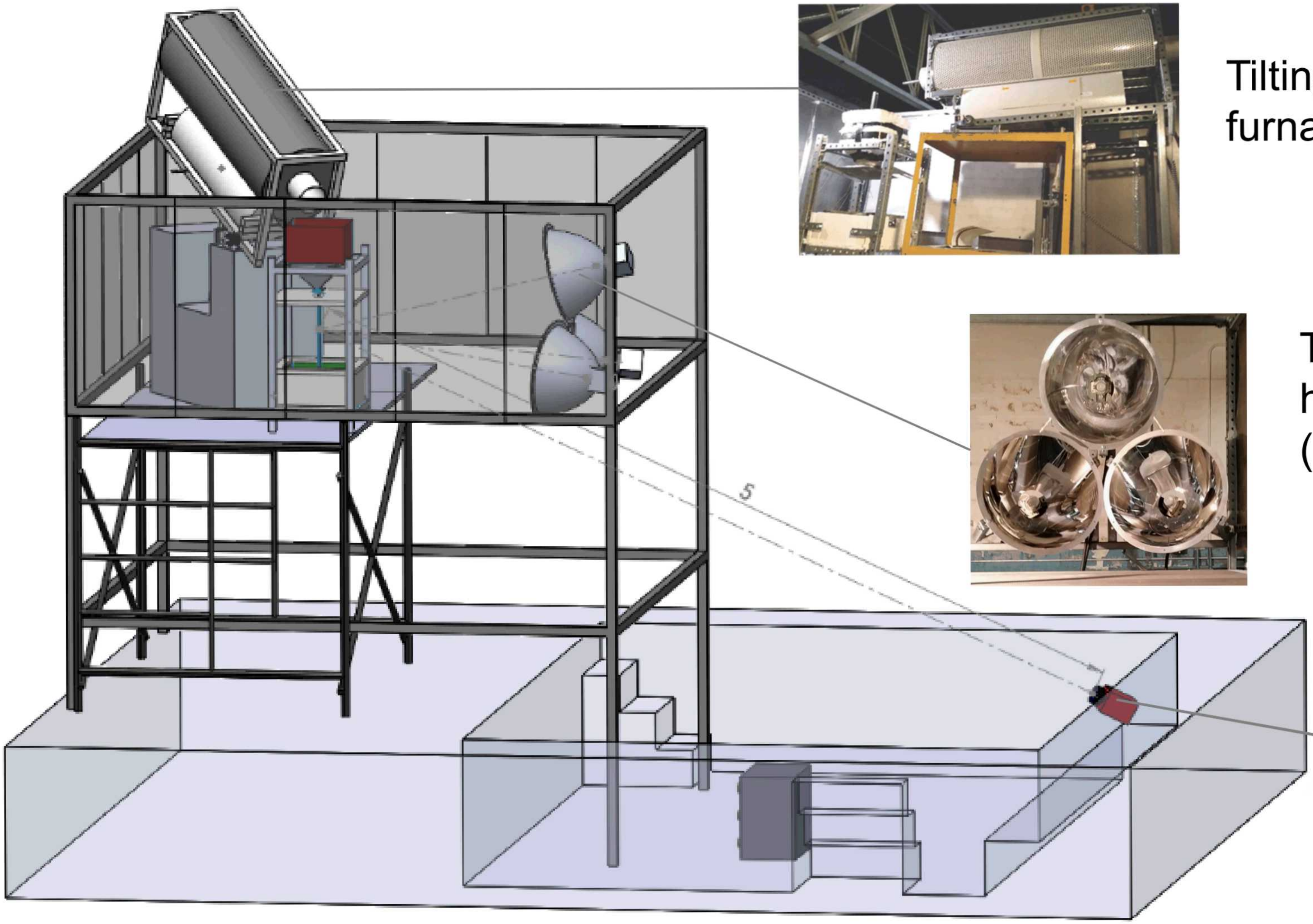


InfraTec ImageIR 8320 HP

Imaging Falling Particles



Test Configuration



Tilting tube furnace

Three metal-halide lamps (12 kW)

IR Camera

Calibration and Testing

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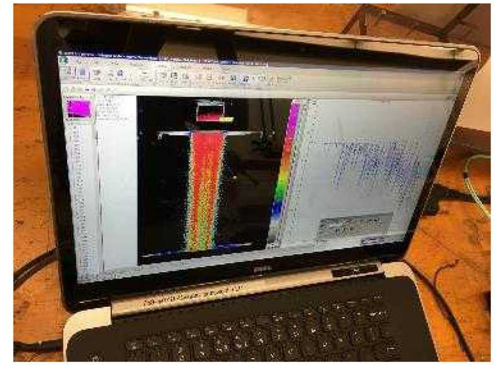
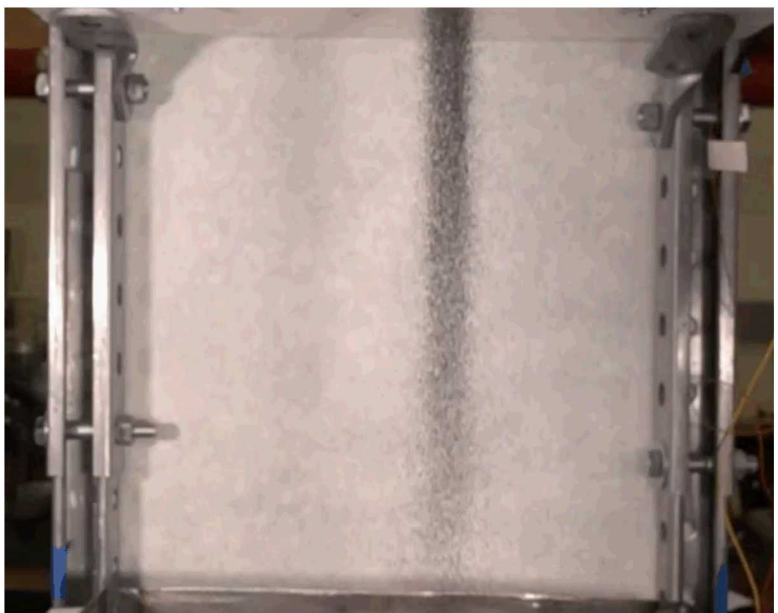
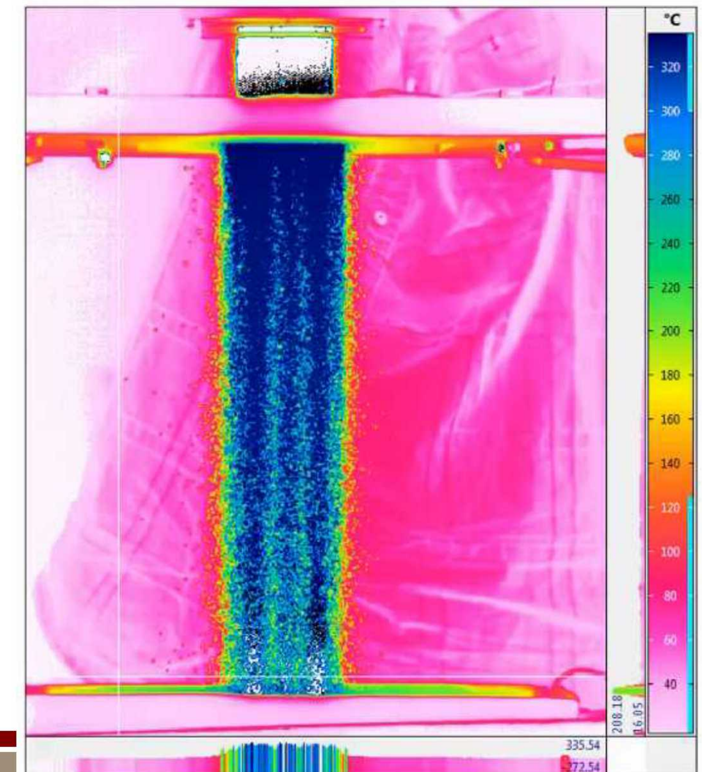
- Videos: High-speed image from visible camera (left) and false-color temperature profile from IR camera (right)







Particle and Heat Loss Estimation

- Model / algorithm development using imaging data
  - Advective heat loss estimated from particle temperatures and velocities
  - Particle loss determined from particle velocity, solids volume fraction, and flow area measured from IR camera

$$Q_{loss} = \dot{m}_p \bar{c}_p \left(T_{p,out} - T_{p,in}\right) + \dot{m}_a \left(h_{a,out}(T_{a,out}) - h_{a,in}(T_{a,in})\right)$$

$$\dot{m}_p = \rho_{b,p} v_p A_{flow,p}$$

where $\rho_{b,p} = \rho_p f_p \qquad f_p = -\dfrac{2d_p \ln\left(\dfrac{I}{I_o}\right)}{3w}$

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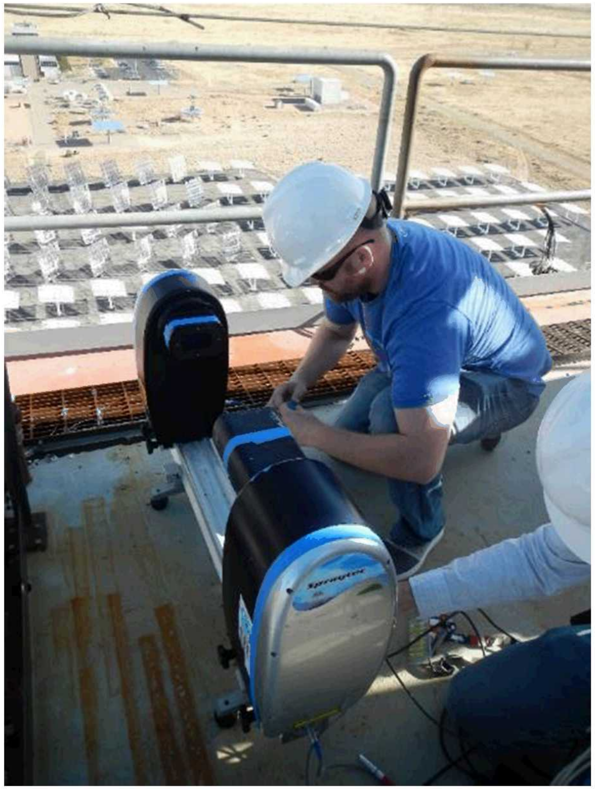
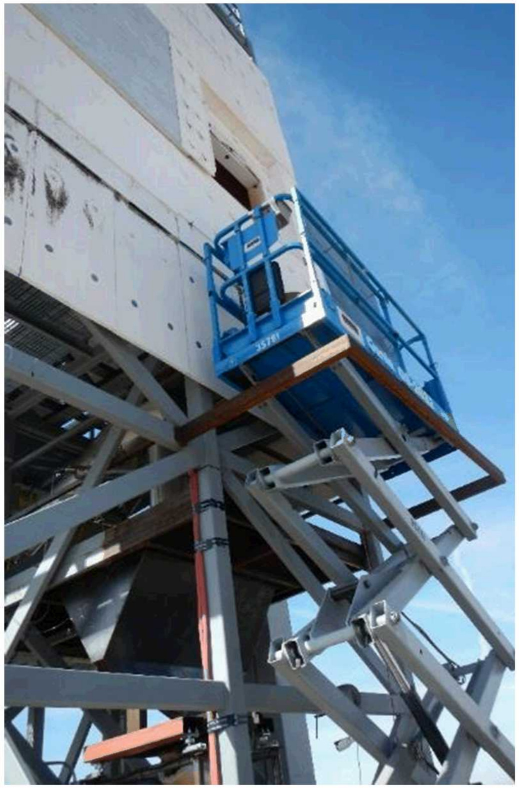
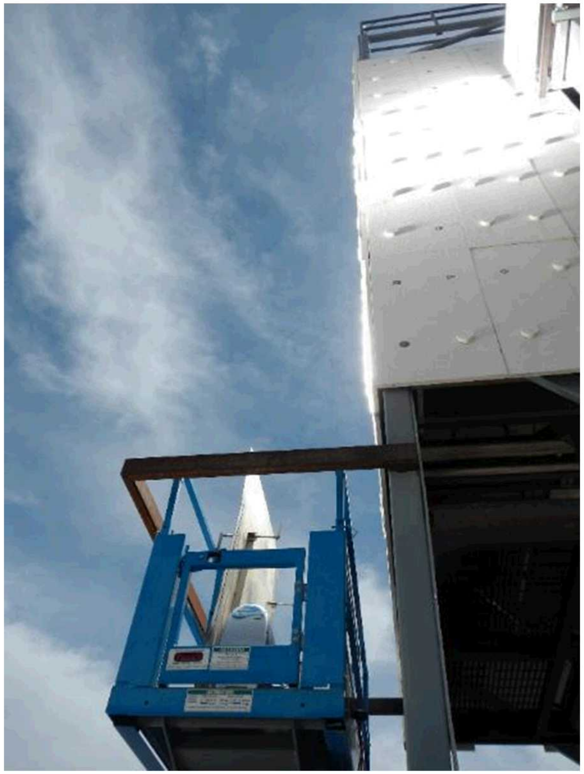
Large Particle Sampling

Malvern Spraytec particle analyzer used to evaluate large particles (tens to hundreds of microns)
April 5, 2018, Sandia National Laboratories

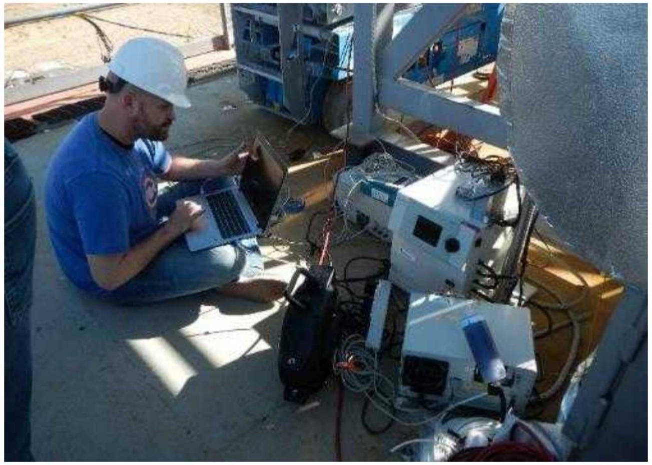






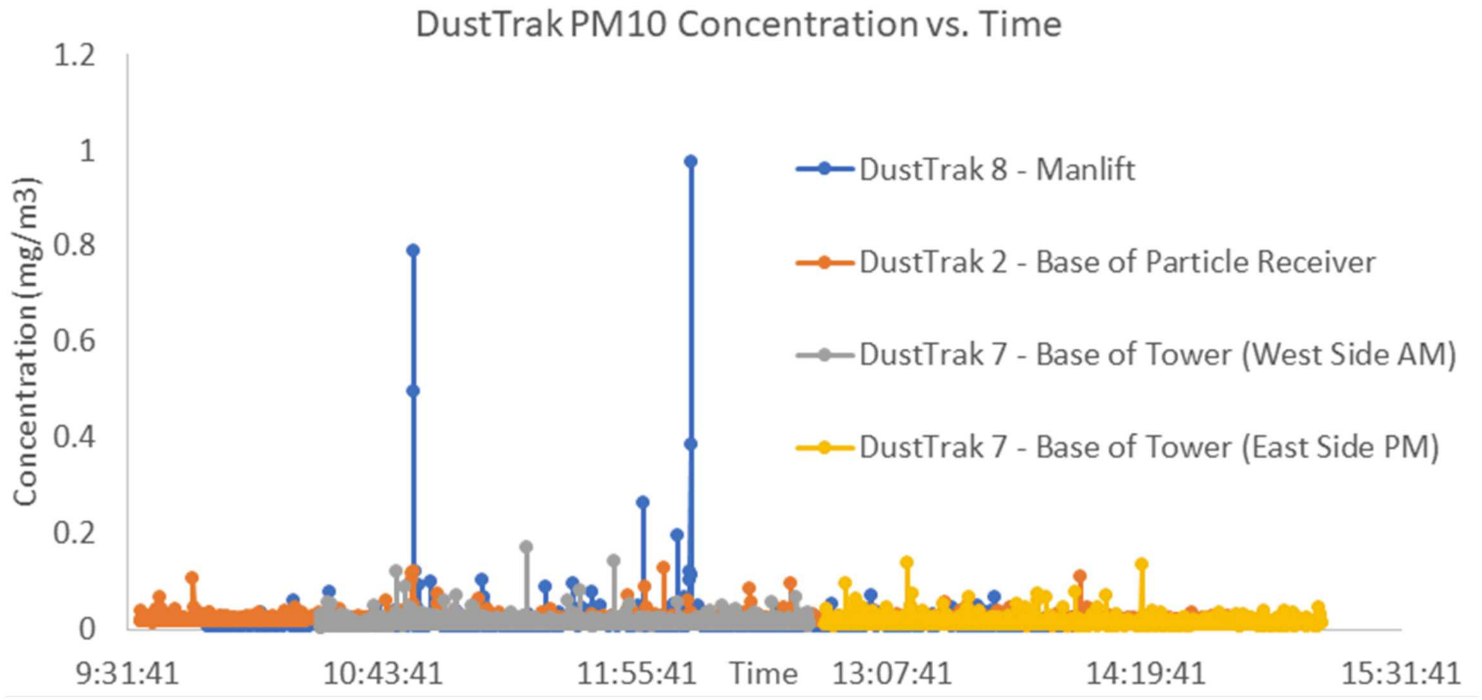
Small Particle Sampling

Used traditional air samplers to evaluate small particle emissions (submicron to micron) at the base and top of the tower



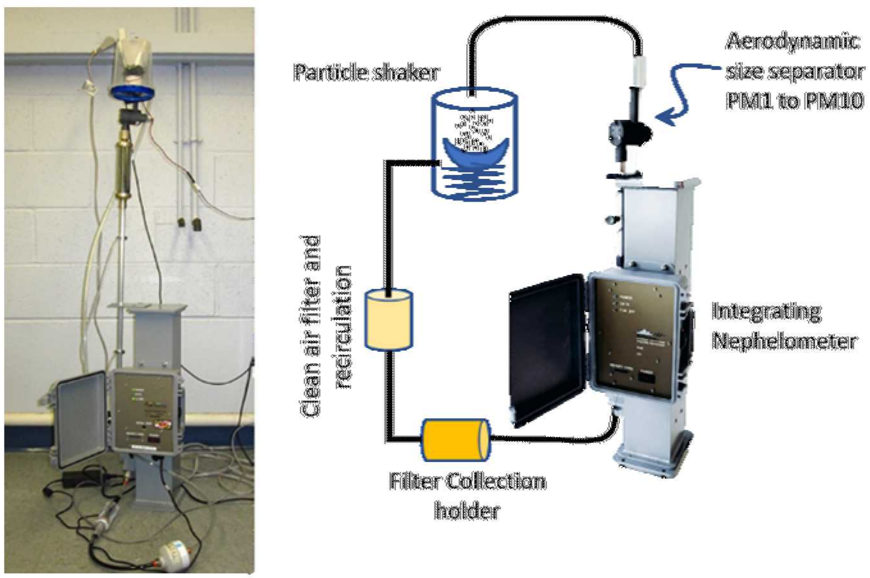
Air Monitoring Results

- Results showed PM10 emissions much lower than OSHA standard (15 mg/m^3)
- Peak particle emissions corresponded to start-up activities
  - Indigenous dust being shaken off equipment?

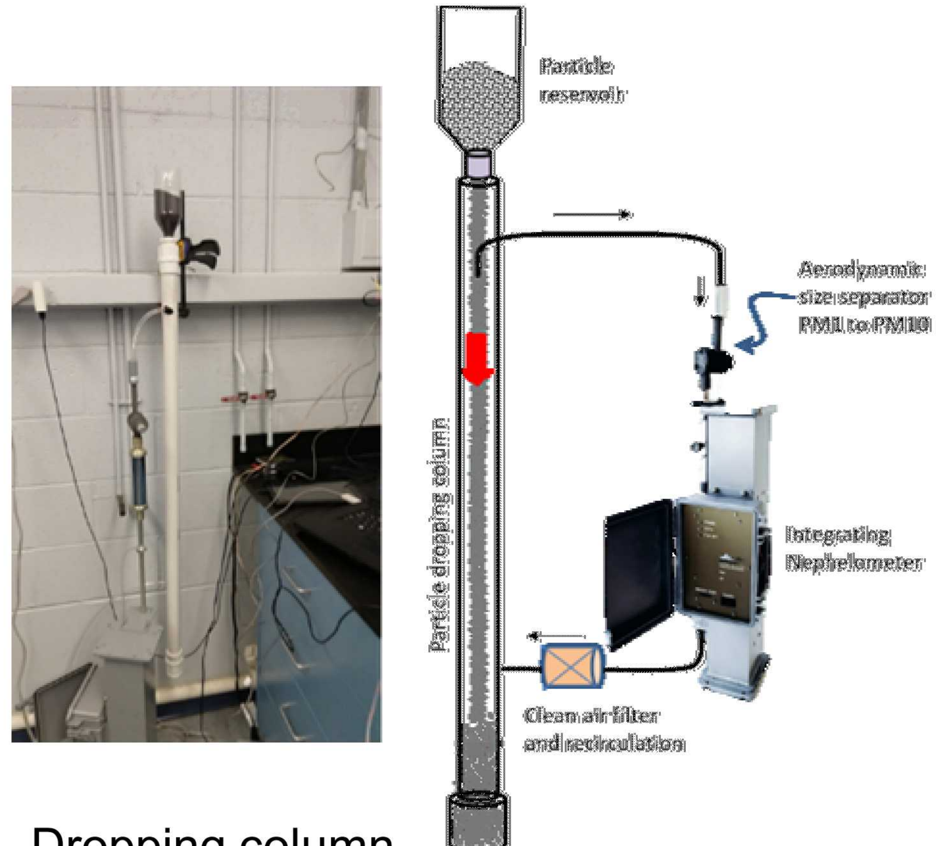


Lab-Scale Particle Fines Generation

- AirPhoton bench-scale testing of small particle generation



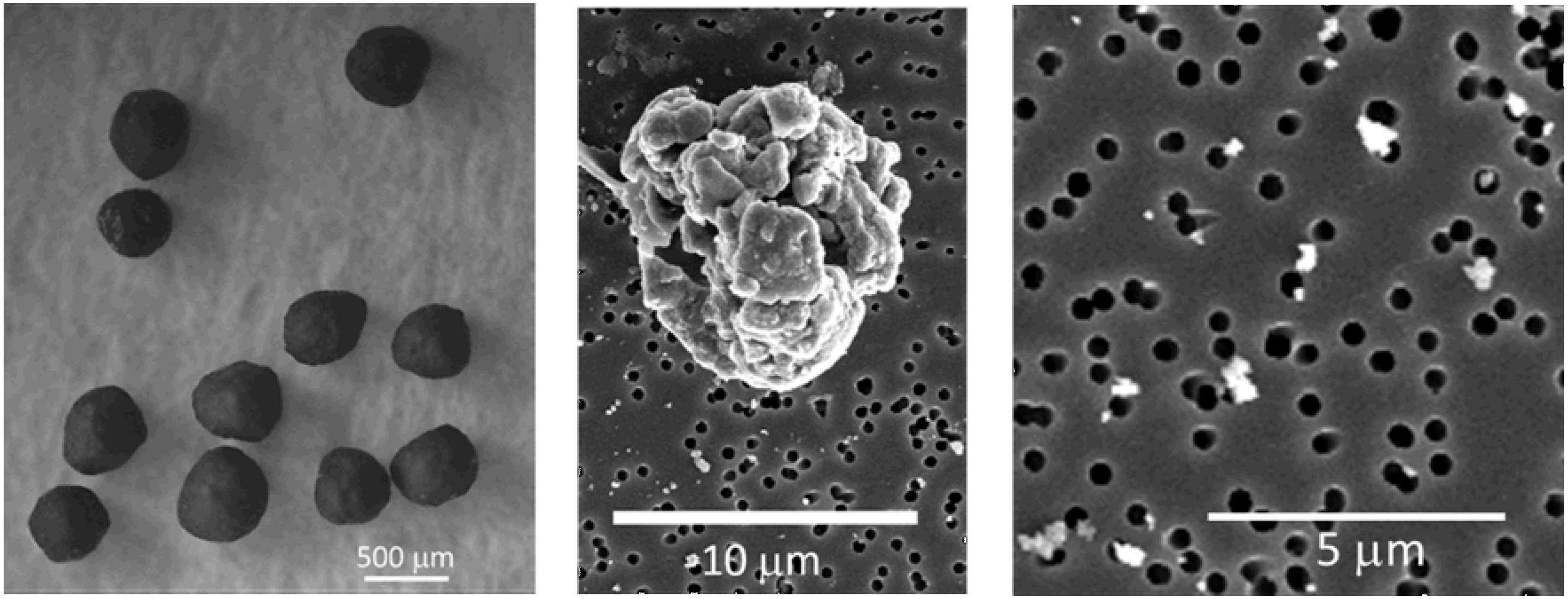
Particle shaker



Dropping column

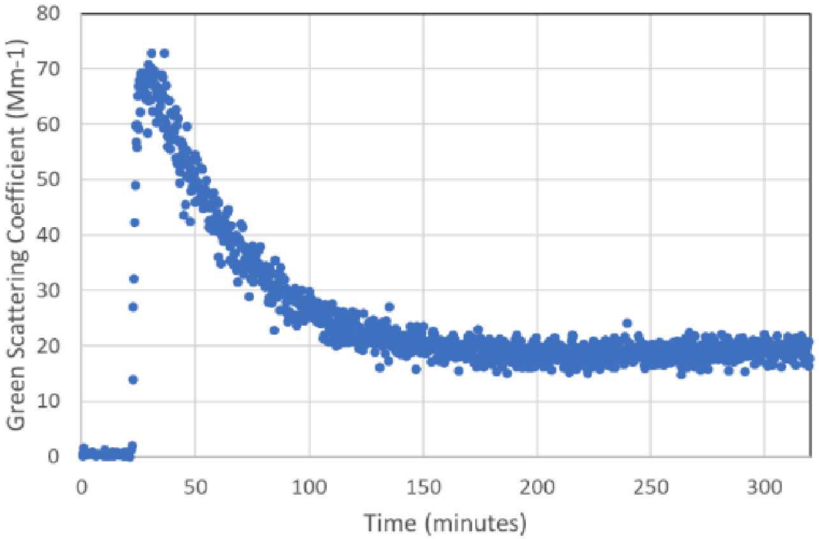
Particle Fines Characterization

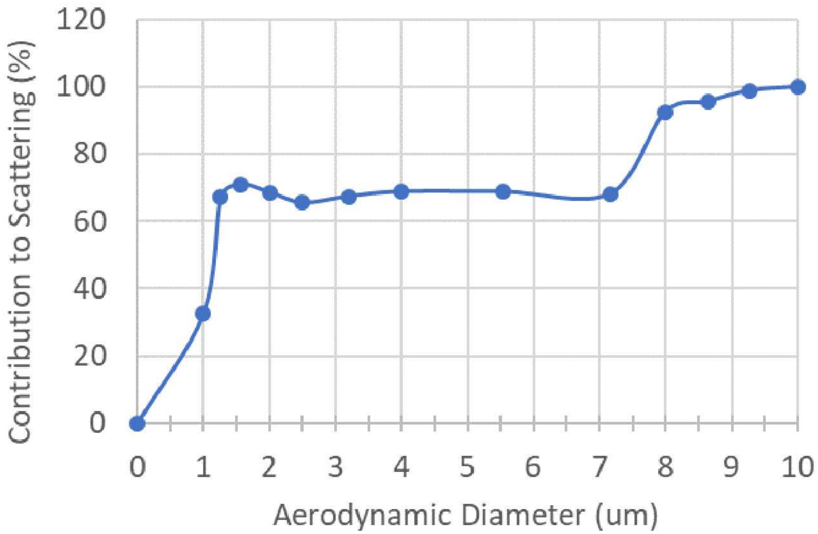
- Optical microscopy (left) showing CARBO HSP parent particles and SEM images (center and right)



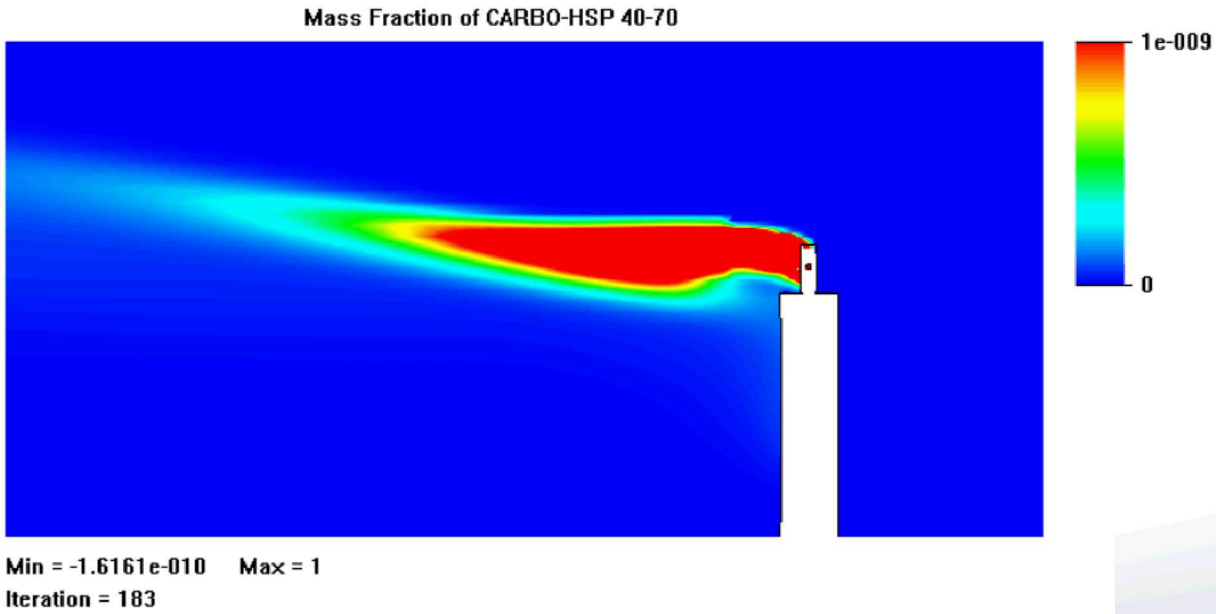
Particle Fines Generation

- Continuous production of small particles (~4 days of continuous shaking)
- Small particles produced
  - < ~1 micron (deagglomeration of pre-existing particles)
  - ~8 – 10 microns (mechanical fracture/abrasion during particle collisions)
  - Small particle generation rate ~1x10^{-5} % of original mass

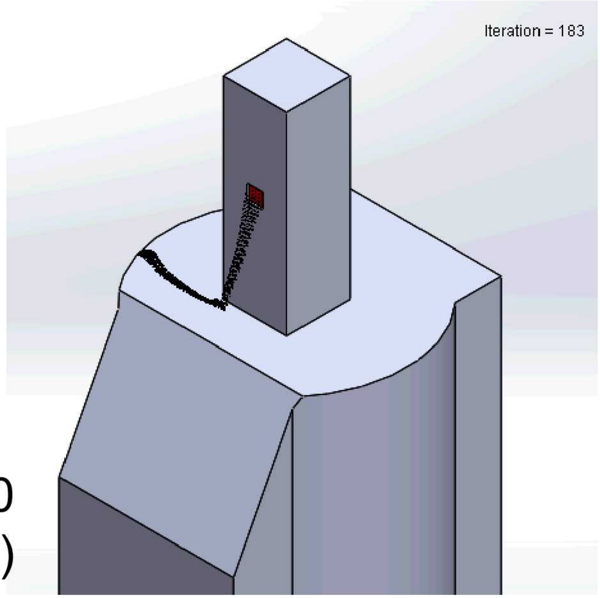




Particle Emission & Dispersion Modeling



Simulation of small particle (~1-10 micron) concentrations



Simulation of large particle (~350 microns)

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Conclusions

- Imaging method has been developed to characterize particle and heat losses from falling particle receiver
  - Lab-scale tests performed to demonstrate method
  - Measured particle velocities and temperatures used to estimate convective and particle losses
- On-sun tests performed to measure particle losses from receiver aperture
  - Measured particle emissions very low relative to OSHA standards (PM10 << 15 mg/m^3)
  - Evaluating particle emissions for EPA standards
- Lab-scale tests characterized particle fines generation
  - Small particle generation rate ~$1x10^{-5}$ % of original mass

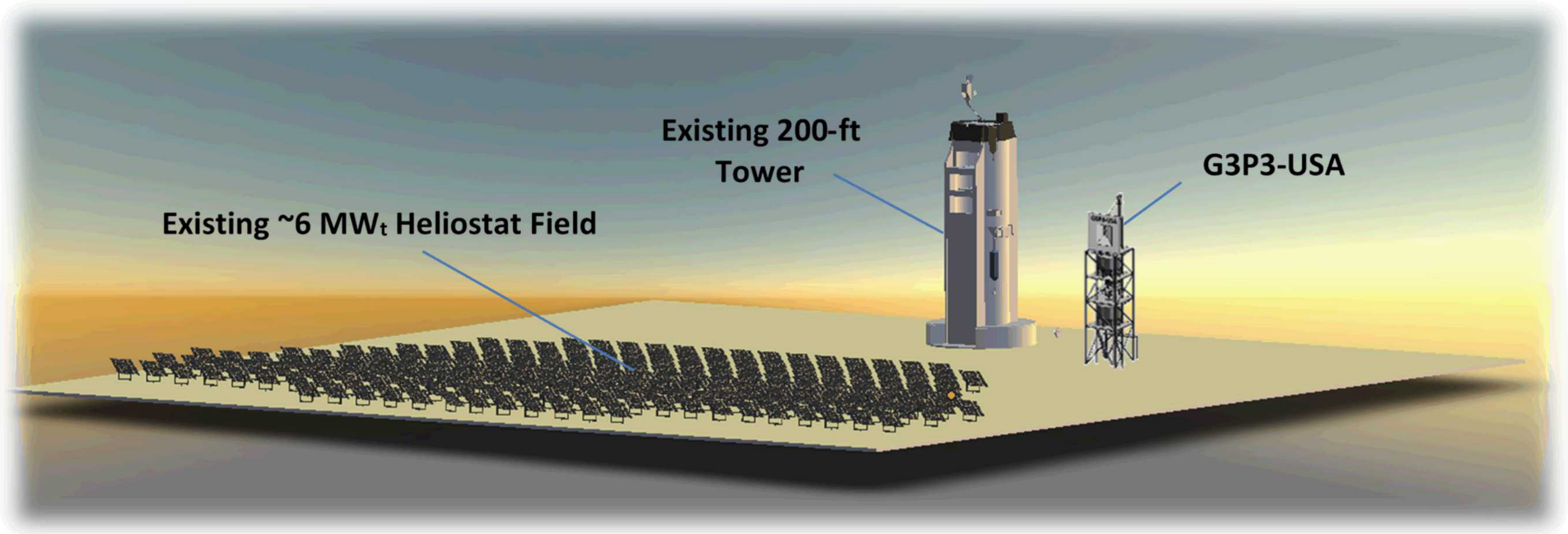
Next Steps

- **Task 1:** Particle Imaging Methods
  - Perform hot-particle flow tests and assess/validate models of particle and heat losses
  - Complete solar simulator and commence high-flux testing
- **Task 2:** Particle Sampling / Air Monitoring
  - Finalize plume dispersion modeling
  - Evaluate particle emissions relative to EPA standards (12 $\mu g/m^3$)

Acknowledgments

- This work is funded in part or whole by the U.S. Department of Energy Solar Energy Technologies Office under Award Number 33869
  - DOE Project Managers: Matthew Bauer, Andru Prescod

Questions?



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BACKUP SLIDES

Particle Velocity Measurements

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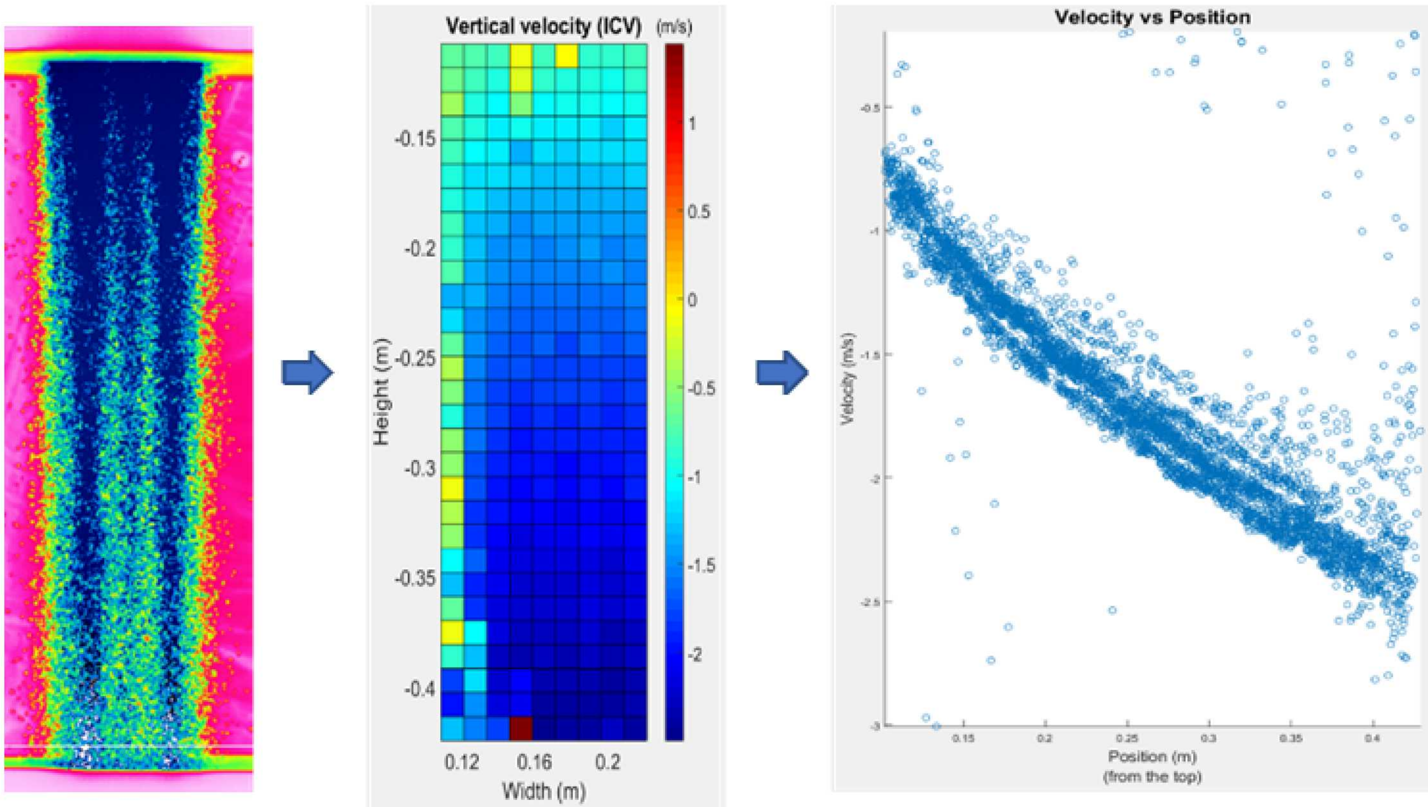
- Extracting velocity data from thermal images using advection corrected correlation image velocimetry ACCIV



Left: false-color instantaneous image of the curtain. Center: Velocity distribution obtained by ICV. Right: Raw velocity data as the function of downstream distance.

Properties of Alternative Particles

Material	Composition	Properties: Density (kg/m^3)	Properties: Specific Heat (J/kg-K)	Advantage	Dis-advantage
Silica sand	SiO_2	2,610	1,000	Stable, abundant, low cost	Low solar absorptivity and conductivity; inhalation risk
Alumina	Al_2O_3	3,960	1,200	Stable	Low absorptivity
Coal ash	SiO_2, Al_2O_3, + minerals	2,100	720 at ambient temperature	Stable, abundant, No/low cost	Identify suitable ash, attrition
Calcined Flint Clay	SiO_2, Al_2O_3, TiO_2,Fe_2O_3	2,600	1,050	Mined abundant	Low absorptivity, attrition
Ceramic particles	75% Al_2O_3, 11%SiO_2, 9%Fe_2O_3, 3%TiO_2	3,300	1,200 (at 700°C)	High solar absorptivity, stable	Relatively higher cost

Mitigate risks of attrition, high cost, and low heat absorption