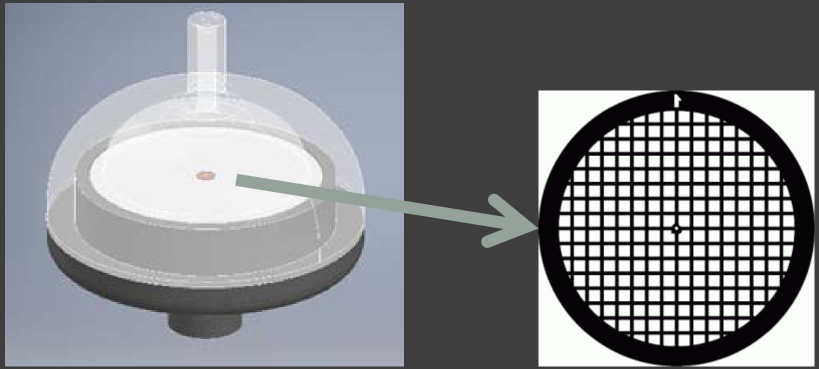
Development of a direct sensing sampler for submicron mining particles including coal, silica and nano-sized diesel particulates

CANDACE TSAI, JÜRGEN BRUNE, DAVID JANES
UNIVERSITY OF CALIFORNIA, LOS ANGELES
COLORADO STATE UNIVERSITY
COLORADO SCHOOL OF MINES
PURDUE UNIVERSITY

Objectives of the Project

- Meet the performance requirements of a personal sampler that can measure the nanometer and submicrometer portion of respirable particles.
- Collected respirable particles without using a cyclone.
- Measure the deposited particles in real time with the capacitive sensor strip.
- Collect submicrometer sized particle with high efficiency.

Sampling Cassette and Design

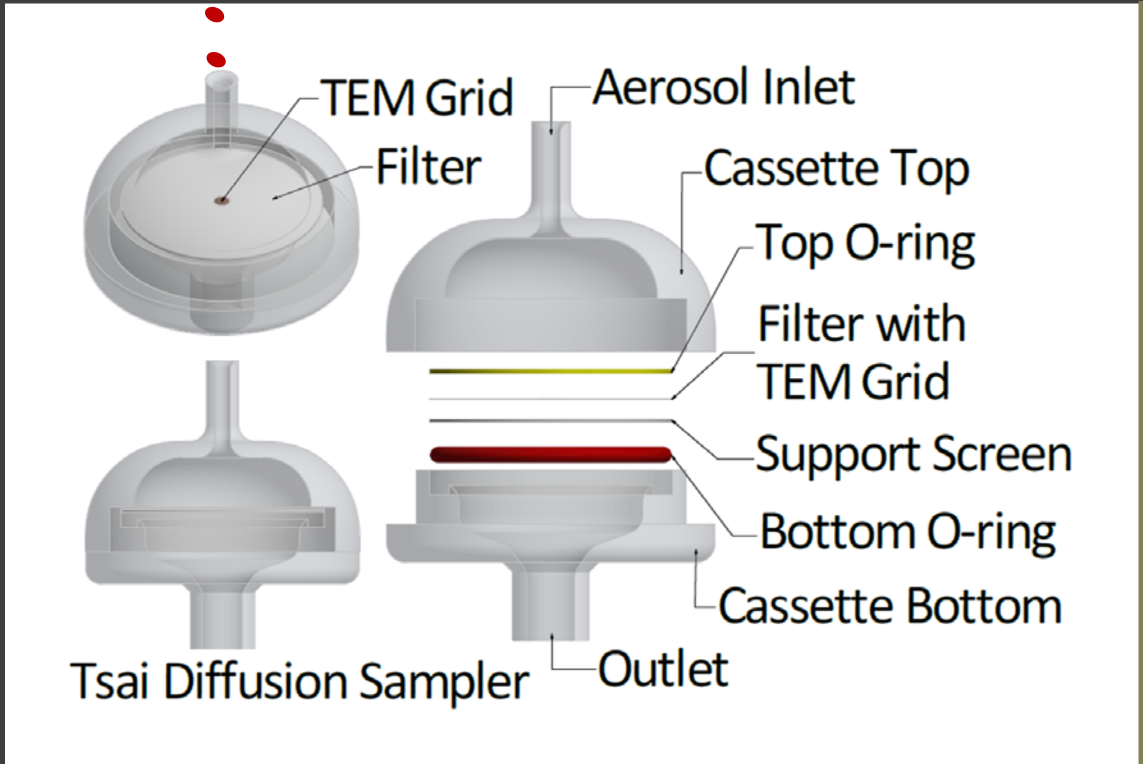


- Sampling substrates: TEM Grid and Polycarbonate Filter
- Grid: Analyzed by Transmission Electron Microscope (TEM)
- Filter: Analyzed by Scanning Electron Microscope (SEM)
- Filed patent: the Tsai Diffusion Sampler (TDS)

Particles on filter (Ref: Twomey 1962, Spurny, Lodge et al. 1969)

$$N_D = \frac{LDP}{R_0^2\, q}$$

$$E_D = 1 - 0.081904\, e^{-3.6568\, N_D} - 0.09752\, e^{-22.3045\, N_D} - 0.03248\, e^{-56.95\, N_D} - 0.0157\, e^{-107.6\, N_D} - \cdots$$



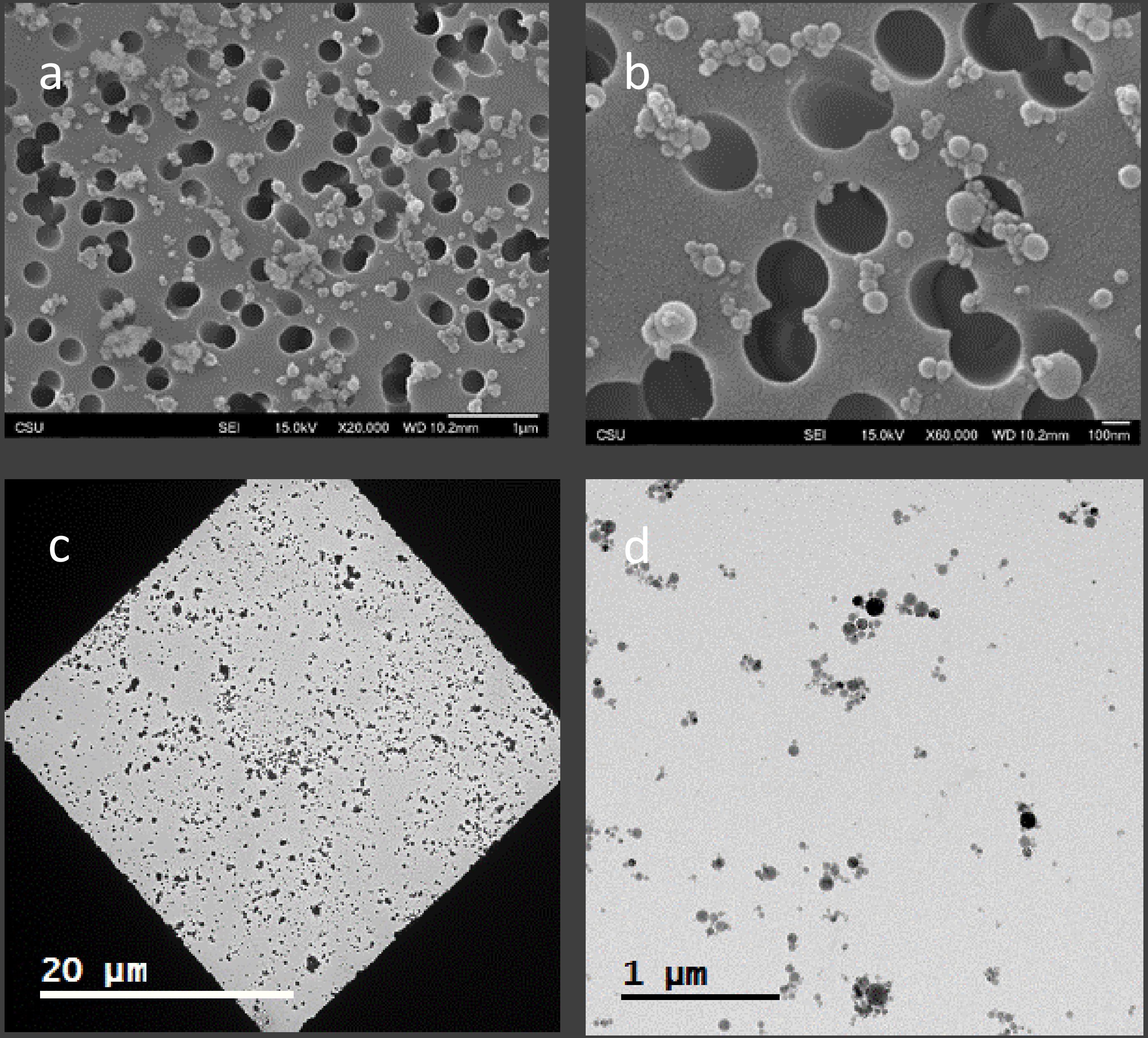
Particles on grid
(Ref: Hinds 1999)

$$D = \frac{kTC_c}{3\pi\eta d_p}$$

$$\sigma = X_{rms} = \sqrt{2Dt}$$

$$Stokes\ number\ (Stk) = \frac{U_0}{d_c}$$

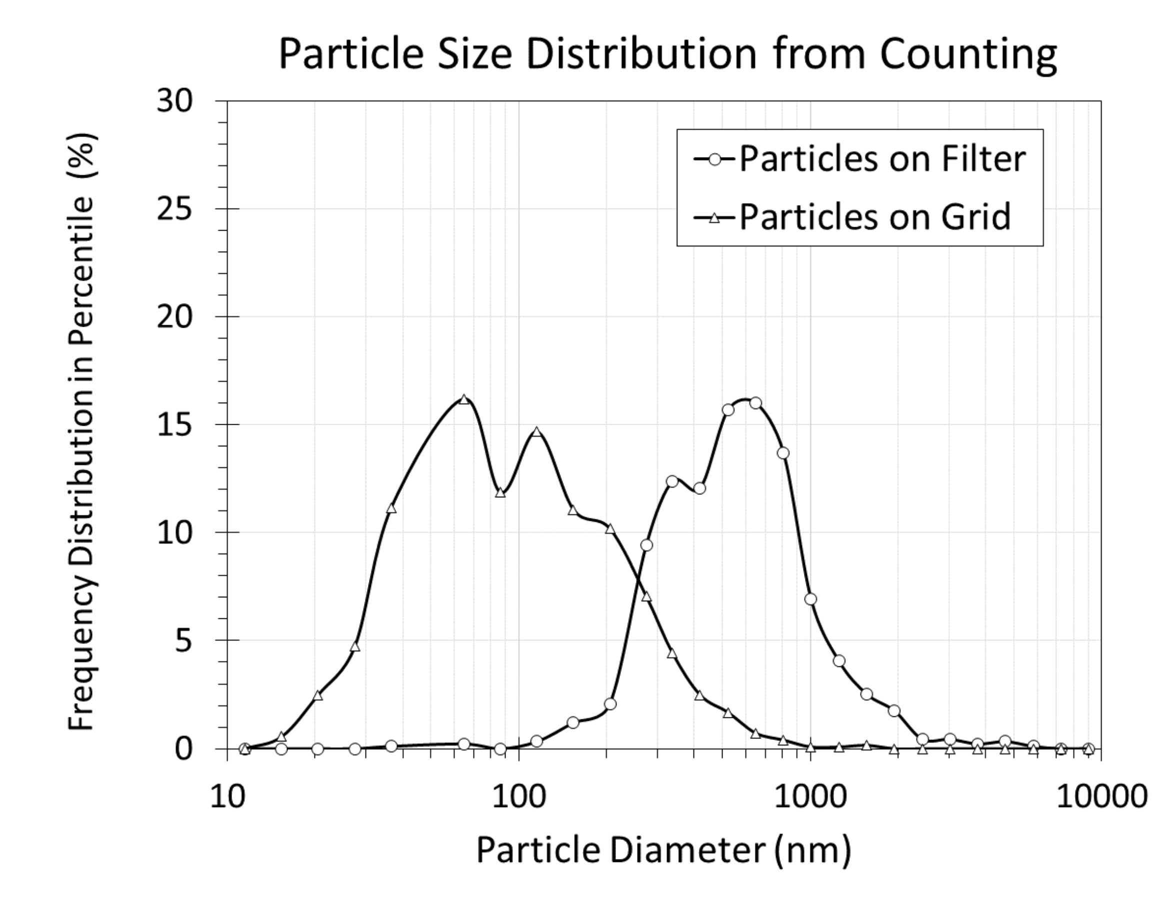
$$\tau = \frac{\rho_p\, d_p^2\, C_C}{18}$$



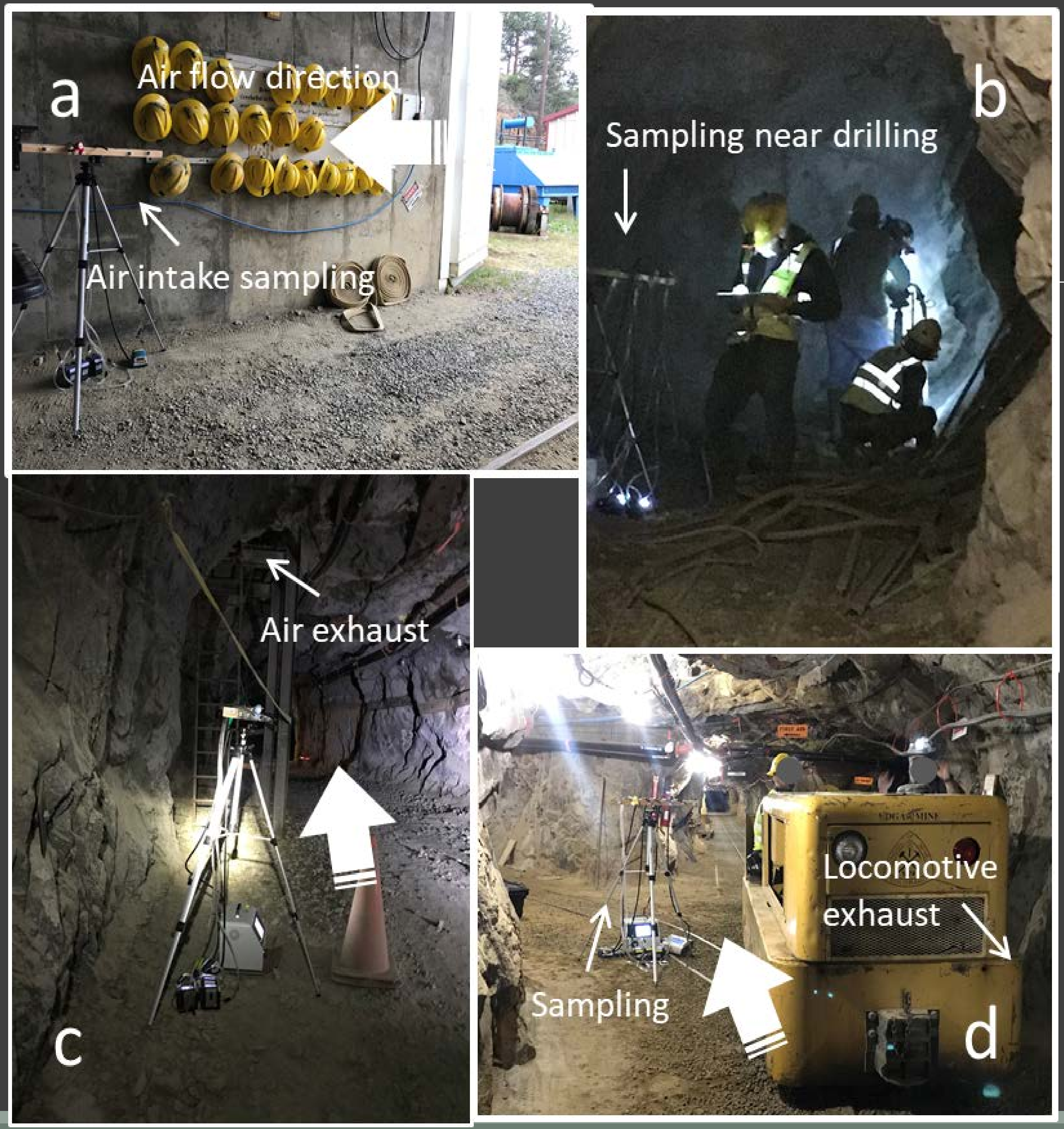
(a) SEM images of particles collected on filter, x20,000
(b) SEM images of particles collected on filter, x60,000
(c) TEM images of particles collected on grid space, x500
(d) TEM images of particles collected on grid space, x5000.

Collected Substrate and Flow Rate		Count Median Diameter CMD (nm)
TEM grid	0.3 L/min	113
	0.9 L/min	187
Filter	0.3 L/min	548
	0.9 L/min	498

Sampling Cassette Specification



- ✓ Size selective entrance: 3.8 µm MMAD
- ✓ Low flowrate and smooth air streamline
- ✓ High collection efficiency >90%
- ✓ Direct detection and analysis: SEM/TEM, sensor



Field Sampling Study

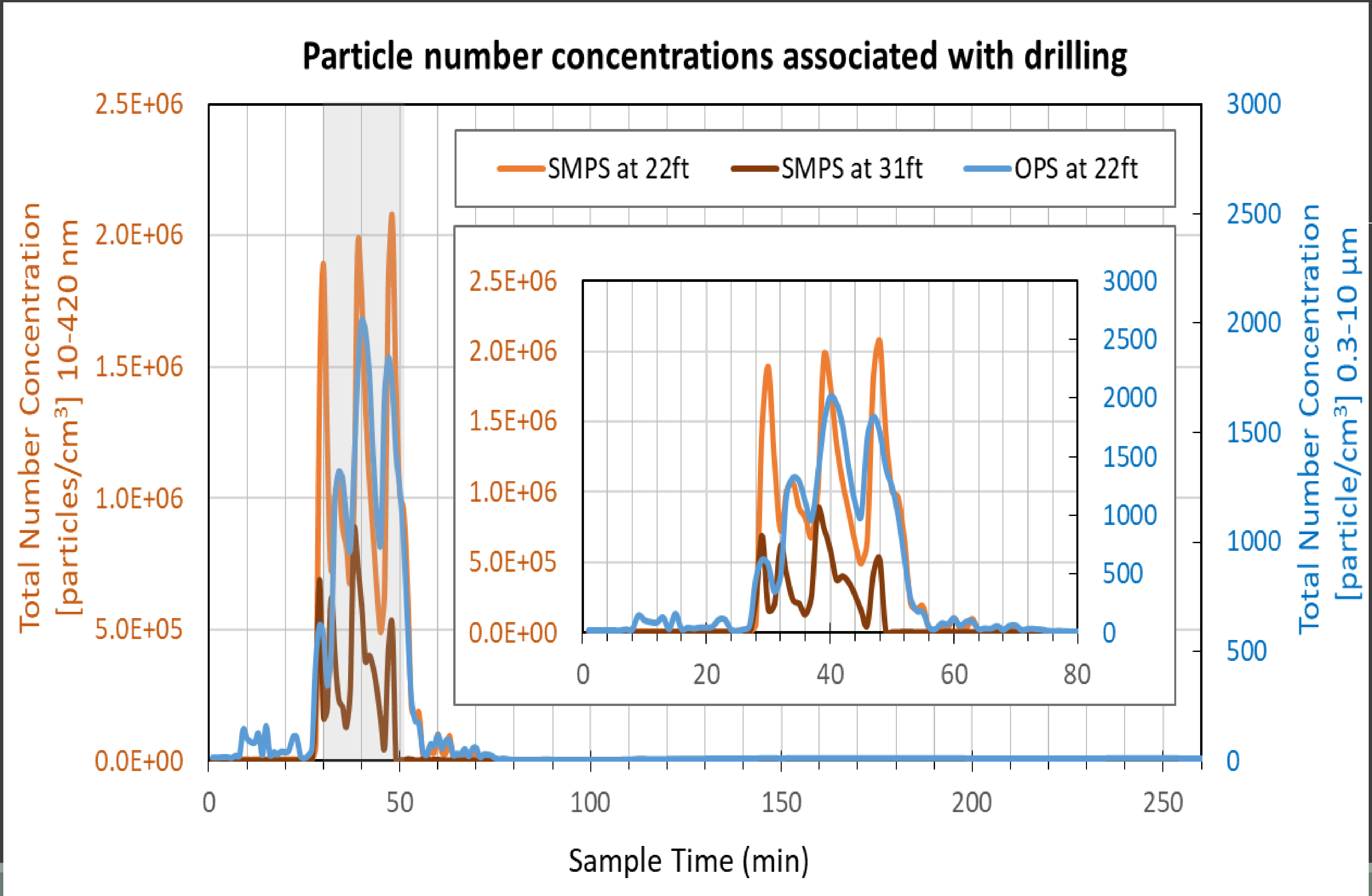
Edgar Mine at Colorado School of Mines

a) Air intake location near the main entrance of the mine.

b) Drilling location, showing drilling at the end of the shaft and the sampling performed at a distance of 6.7 m (22 ft) from the drilling.

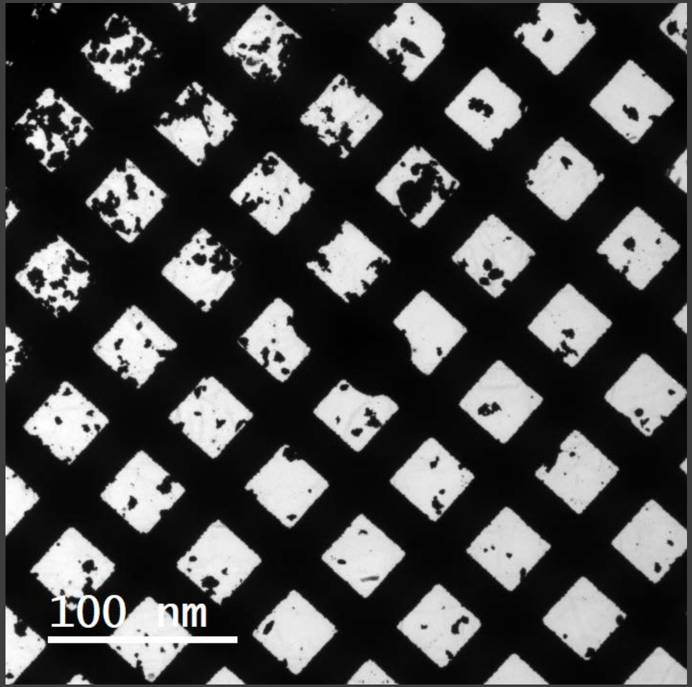
c) Location of the air exhaust for the mine ventilation system.

d) Diesel locomotive and the nearby sampling system.

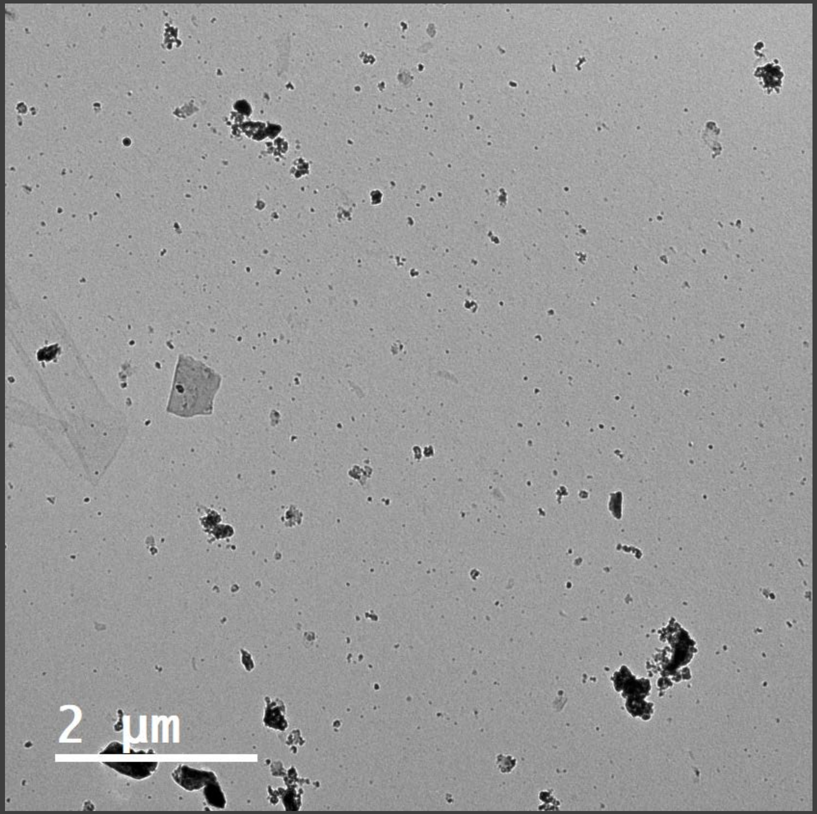


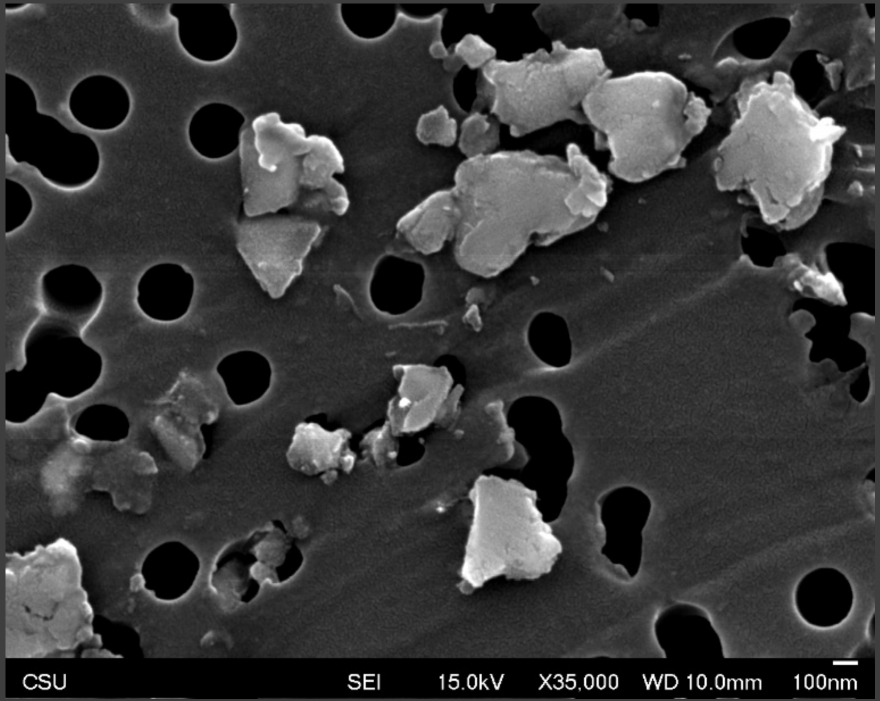
Particle number concentrations associated with drilling
SMPS at 22ft
SMPS at 31ft
OPS at 22ft
Total Number Concentration [particles/cm³] 10-420 nm
Total Number Concentration [particle/cm³] 0.3-10 µm
2.5E+06
2.0E+06
1.5E+06
1.0E+06
5.0E+05
0.0E+00
3000
2500
2000
1500
1000
500
0
0
20
40
60
80
50
100
150
200
250
Sample Time (min)

Particles Emitted from Drilling

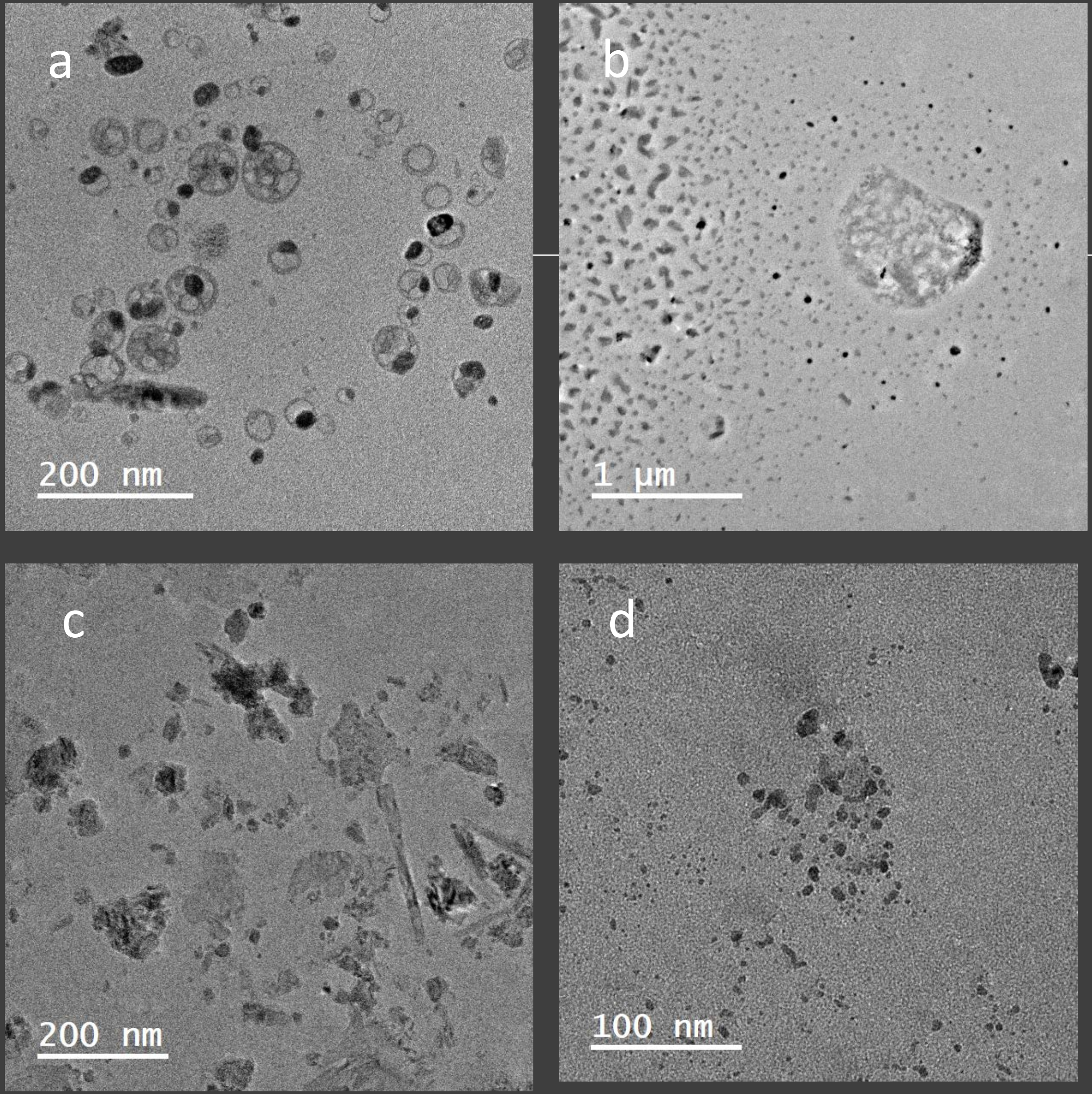


Particles collected on grid





Particles collected on filter
Elements include O, Cu, Ca, Fe, Si, Al, Mg.



Particles Emitted from Drilling

a) Particles with residuals of suspected liquid droplets at a distance of 6.7 m (22 ft)

b) Particles with suspected deagglomeration at a distance of 6.7 m (22 ft)

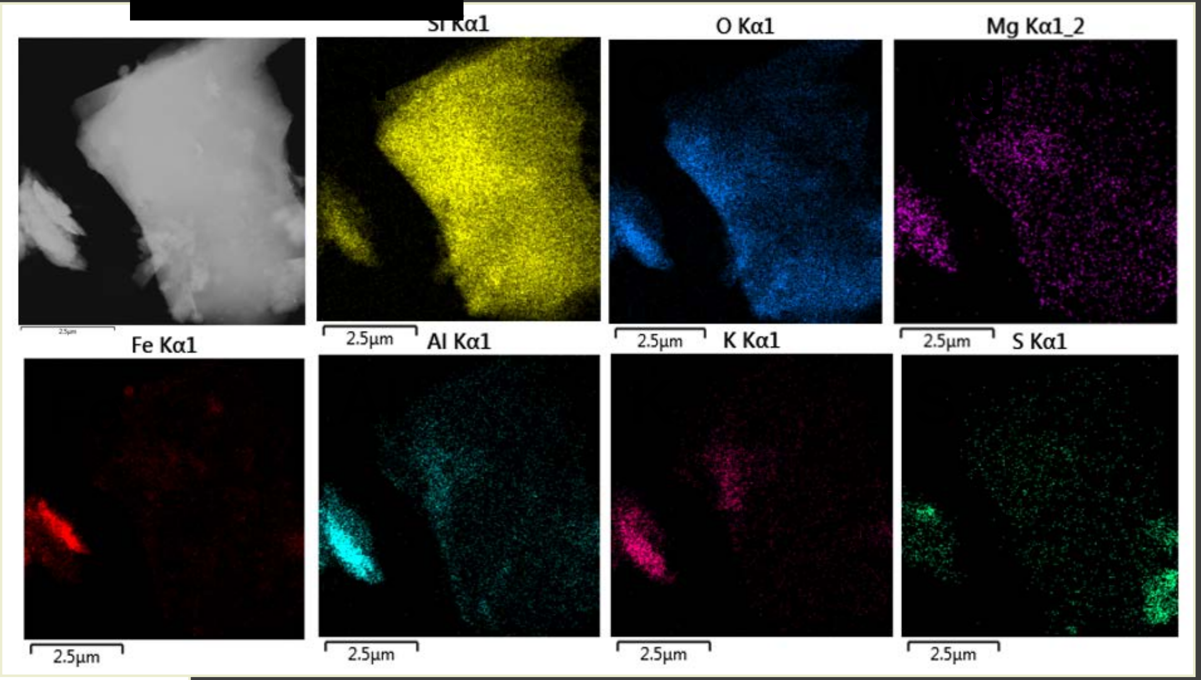
c) Particles at a distance of 9.4 m (31 ft)

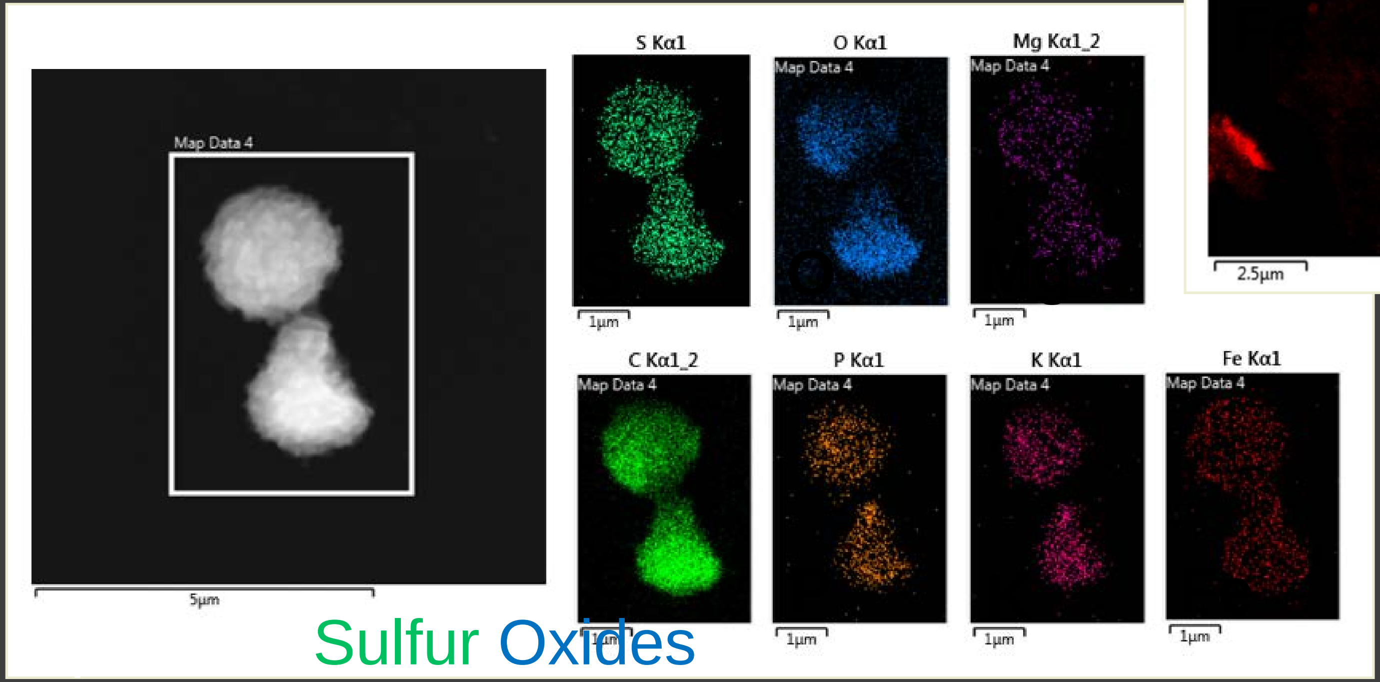
d) Particles at the air exhaust area during drilling.

Tsai et al, 2020

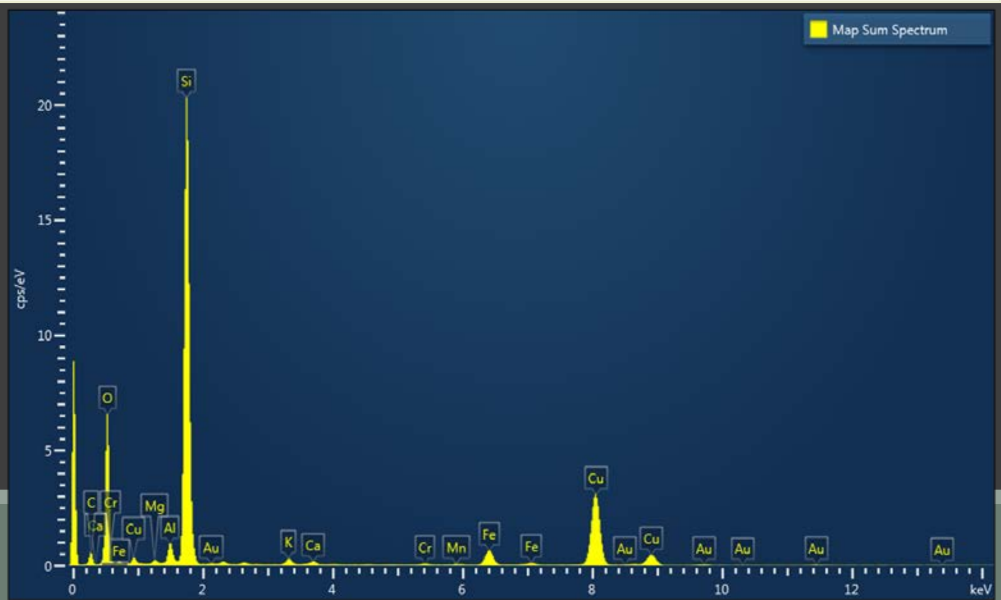
Primarily silicon rich particles, oxides and soot.

Silicon Rich





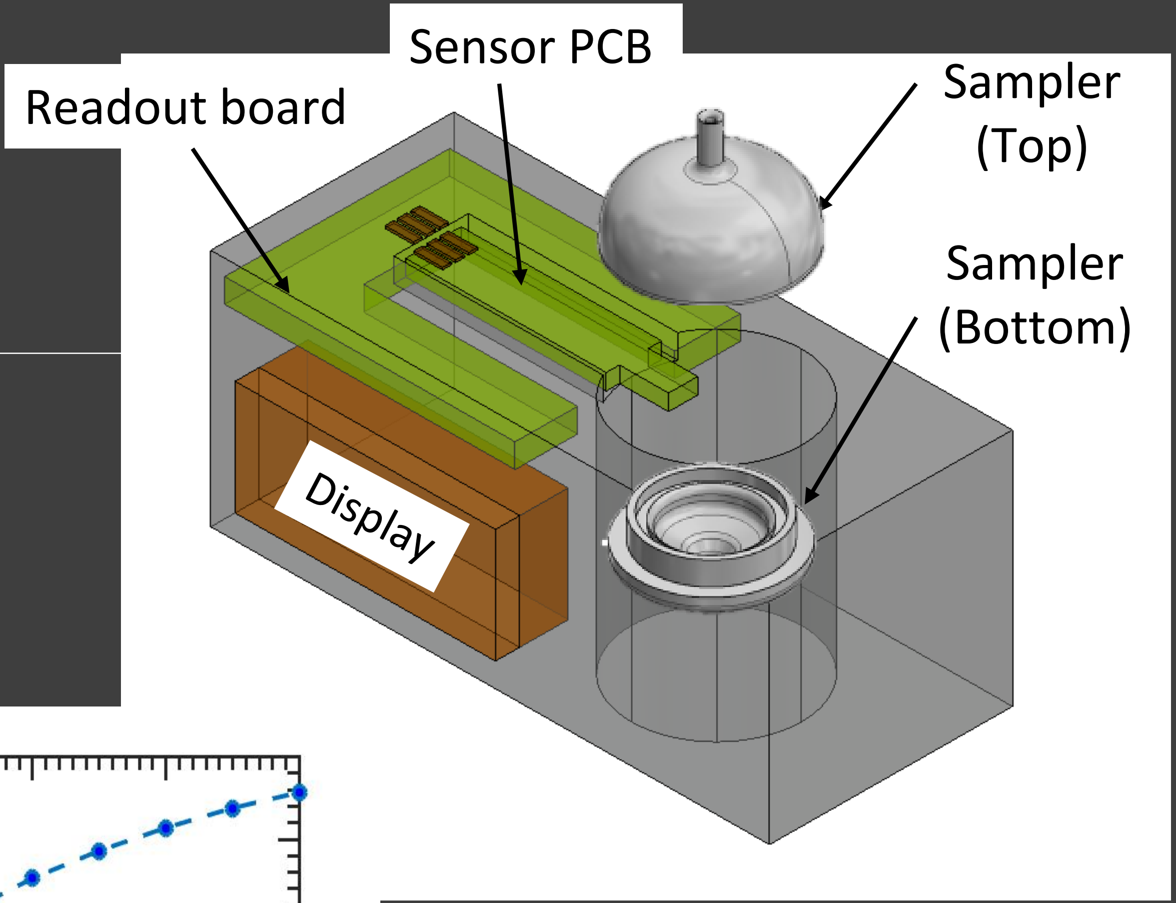
Sulfur Oxides

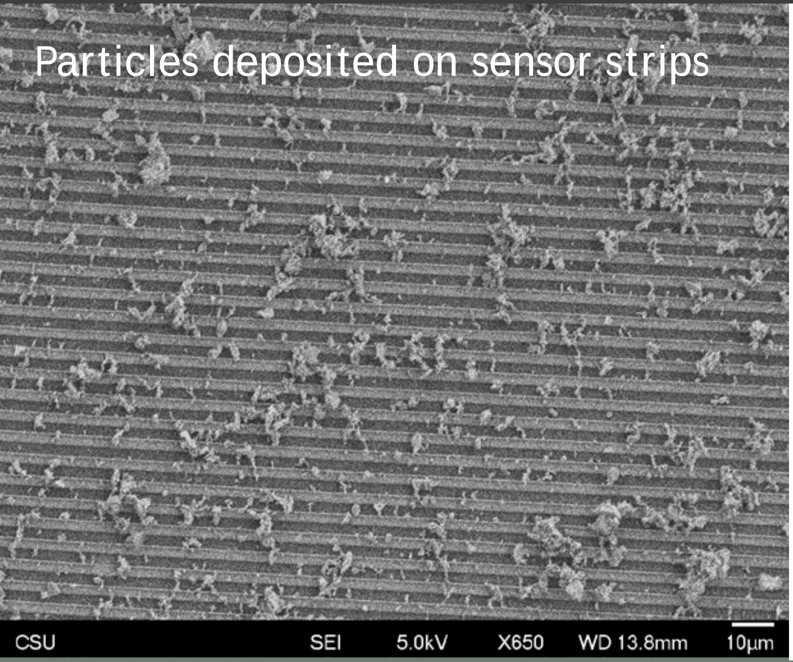


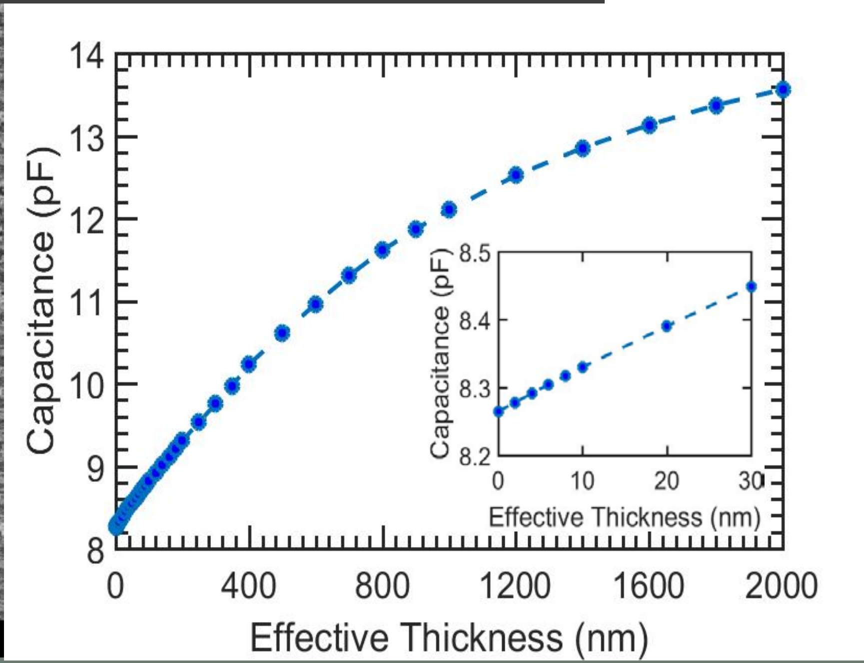
Capacitance Sensor

Rely on a shift in capacitance due to the dielectric loading of particles deposited on the interdigitated capacitor structure.

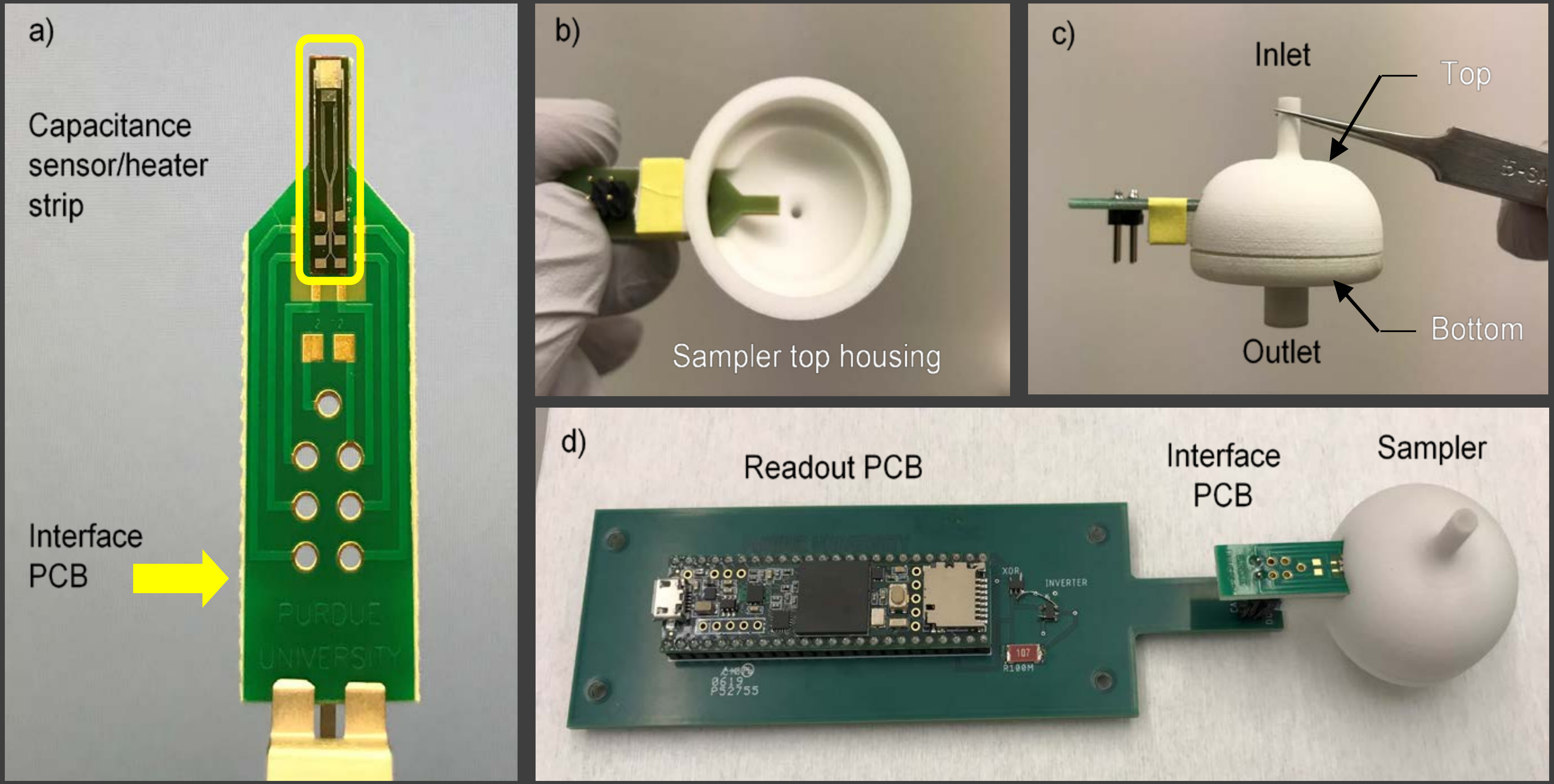
Patent pending







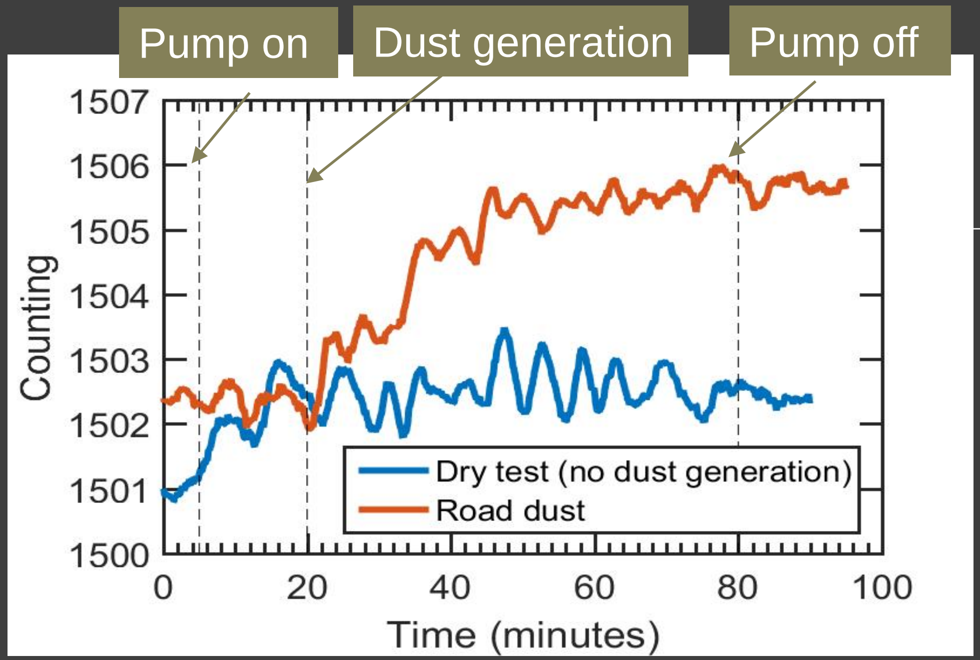
- ✓ Current: Direct sensing
- ✓ Future: Particle differentiation

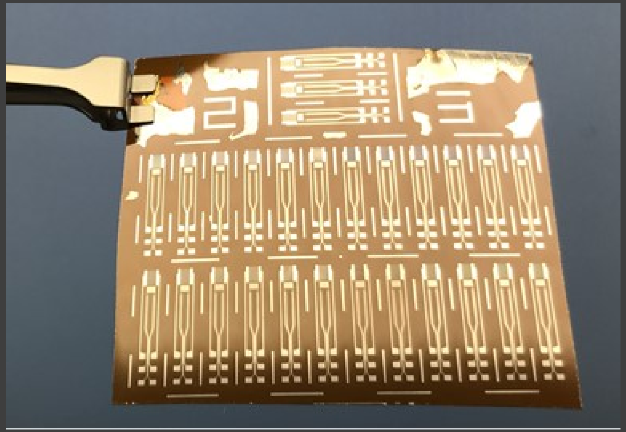


Photographs of a) capacitance sensor/heater strip mounted on interface PCB; b) and c) strip/interface PCB assembly mounted in a modified sampling cassette, showing bottom view of top housing and side view of full sampler, respectively; and d) fully assembled system. The sensor/cassette assembly is electrically connected to the separately designed readout board. The readout board can be re-used.

Capacitance Response to Dust

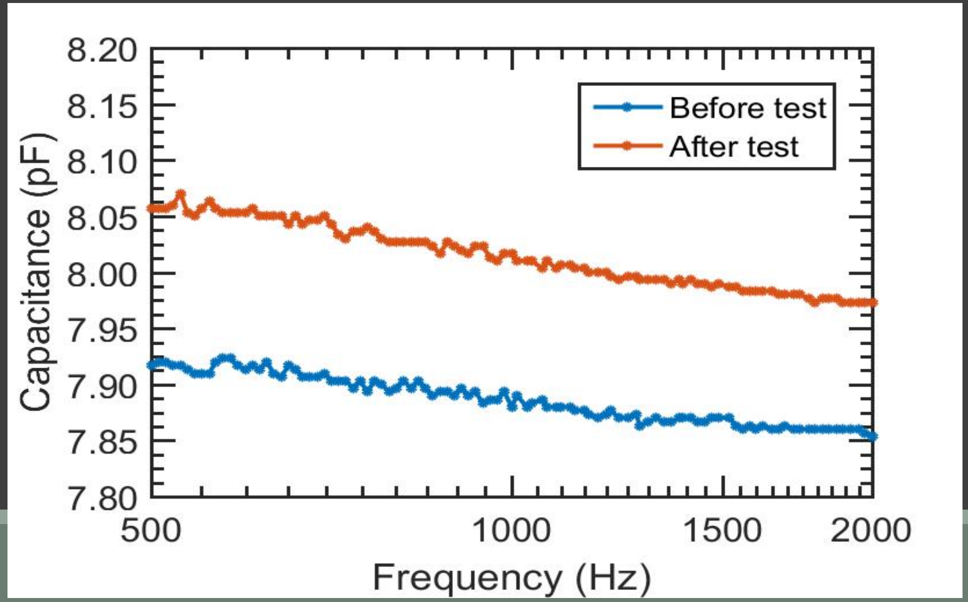
(a)





Array of 24 strips fabricated on Kapton substrate by using scalable micro-fabrication approaches.

(b)

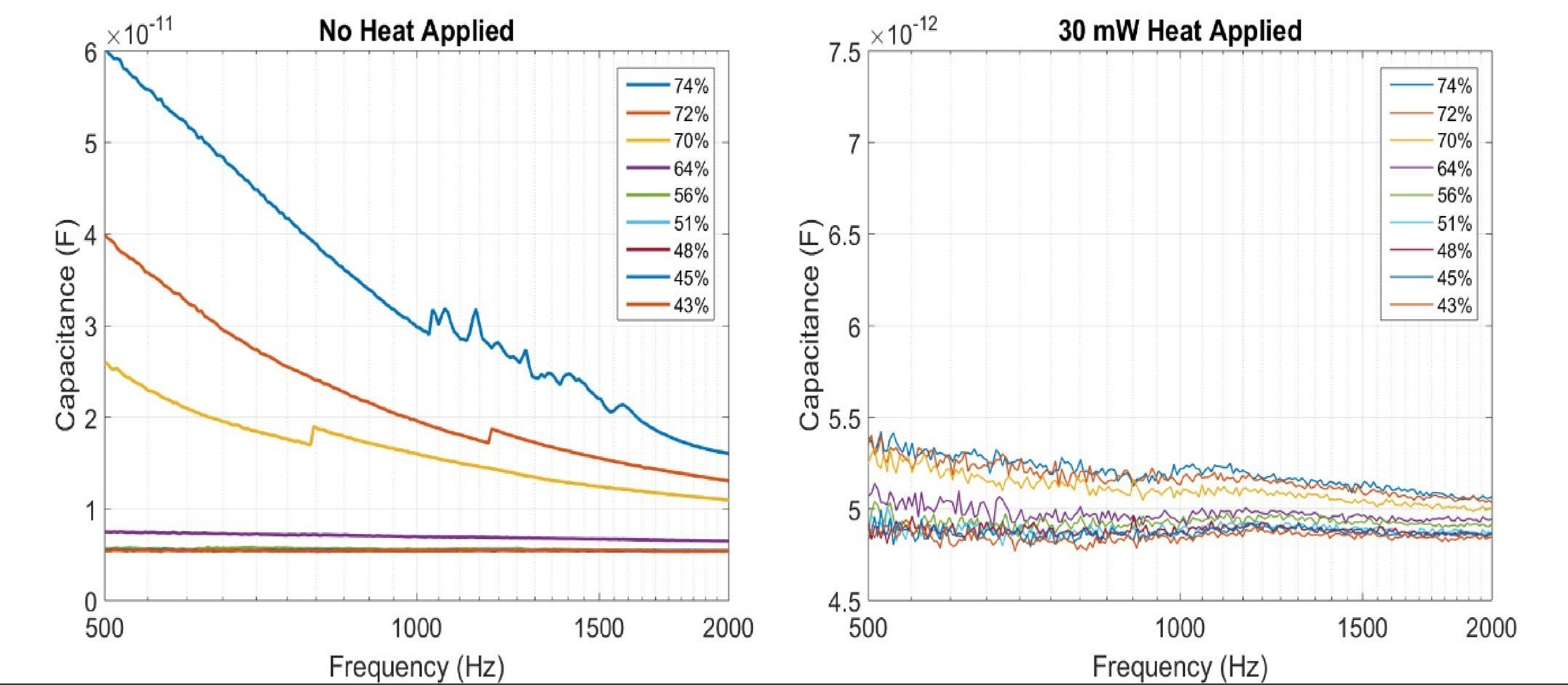


a) Time-response of an integrated sampler, comparing i) test with road dust and ii) a "dry" test, without particle generation. A clear differential response was observed for the case in which particles were generated in the chamber volume.

b) Capacitance shift before/after testing, as measured by a laboratory capacitance meter. The positive shift in capacitance is consistent with increased counting.

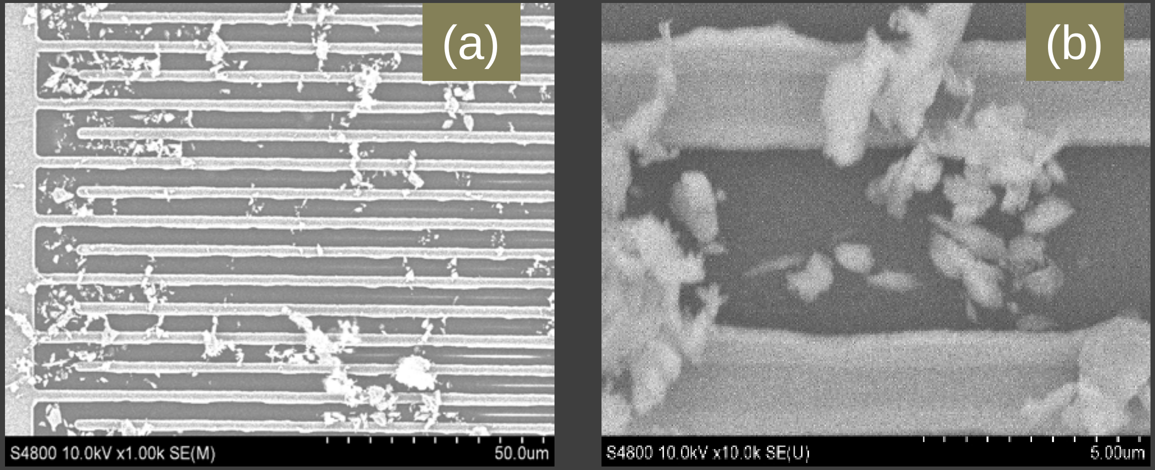
Capacitance Response and Relative Humidity

(a) (b)



Capacitance response at different relative humidity levels a) without a heater and b) with 30 mW heater power. The stability of capacitance markedly improved specifically at higher relative humidity (or dew point).

Particle Deposition on Capacitance Sensor



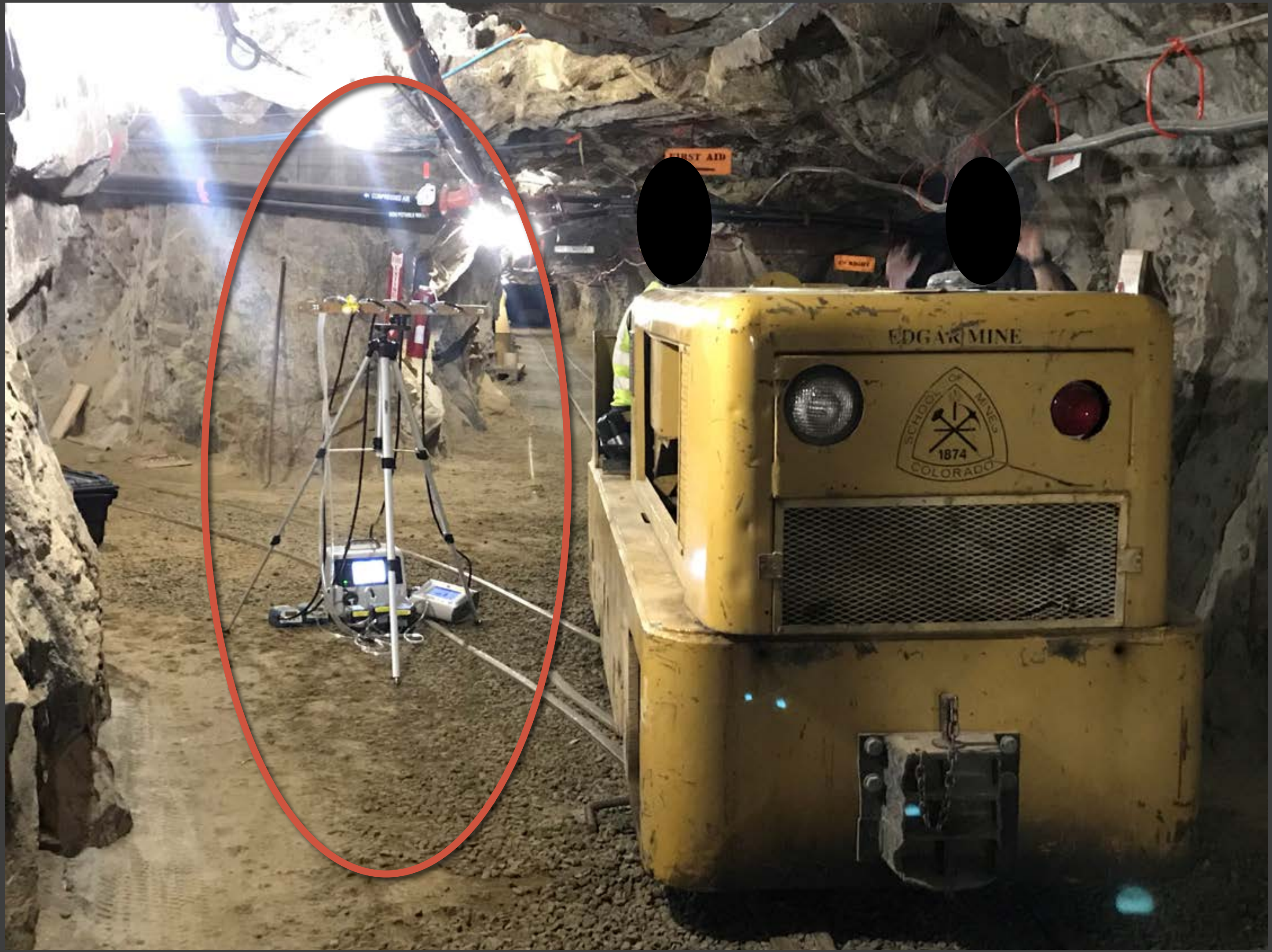
SEM image of a) particles deposited on a capacitance sensor after exposure to comparable particle flux. For reference, the lines and spaces in the image are approximately 3 microns. b) A magnified SEM image showing agglomerates of sub-micron particles.

Post-analysis of particle information using SEM

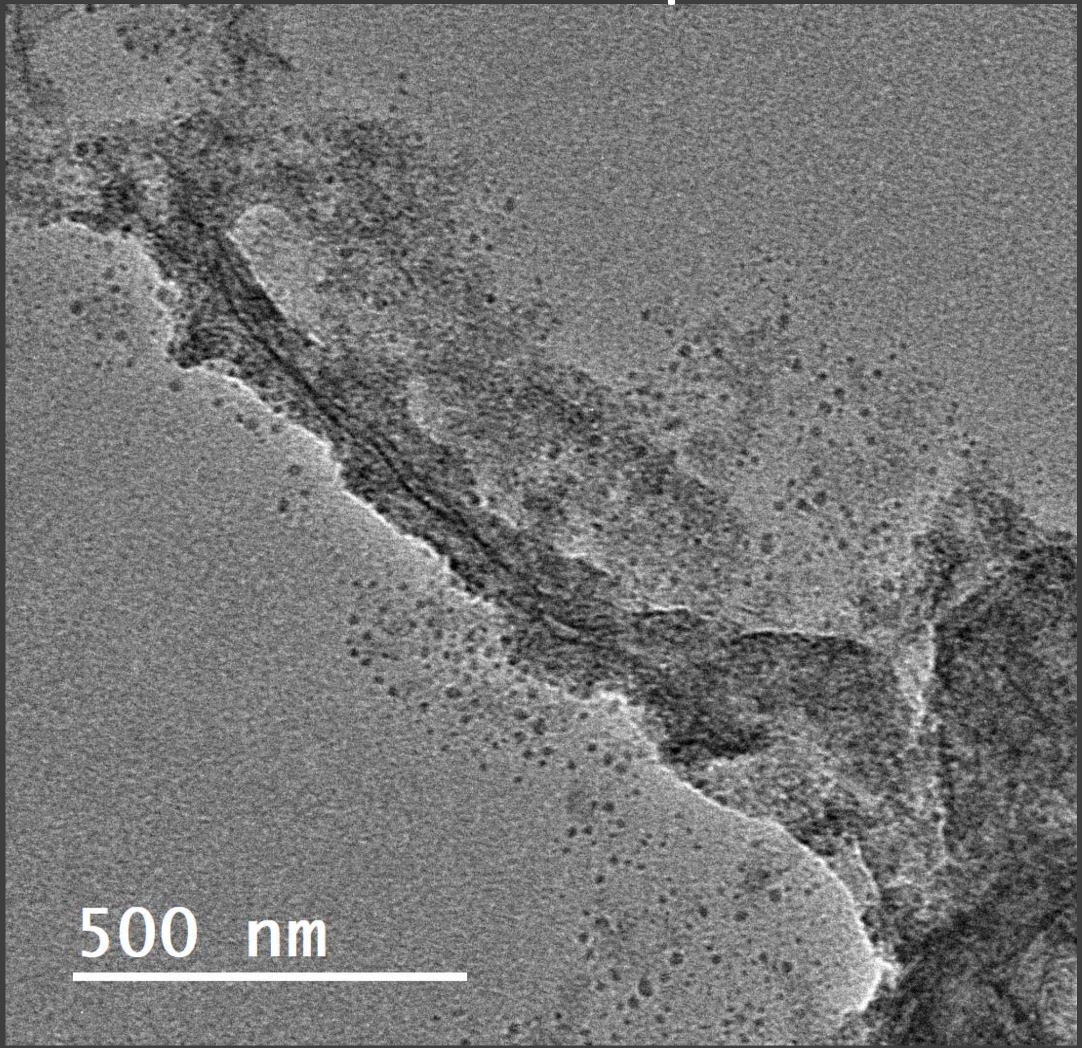
Group	Size range	D_{eff} (µm)	# of Particles	V_{eff} (µm^3)	m_{eff} (g)	Fraction (%)
A	**D ≤ 1 µm**	**0.5**	**10,005**	**6.5×10^{2}**	**1.7×10^{-9}**	**5.7**
B	**1 < D ≤ 2 µm**	**1.5**	**2,728**	**4.8×10^{3}**	**1.3×10^{-8}**	**42.1**
C	2 < D ≤ 3 µm	3	140	2.0×10^{3}	5.3×10^{-9}	17.3
D	3 < D ≤ 4 µm	4	120	4.0×10^{3}	1.1×10^{-8}	34.9
Total			12,993	1.2×10^{4}	3.0×10^{-8}	100

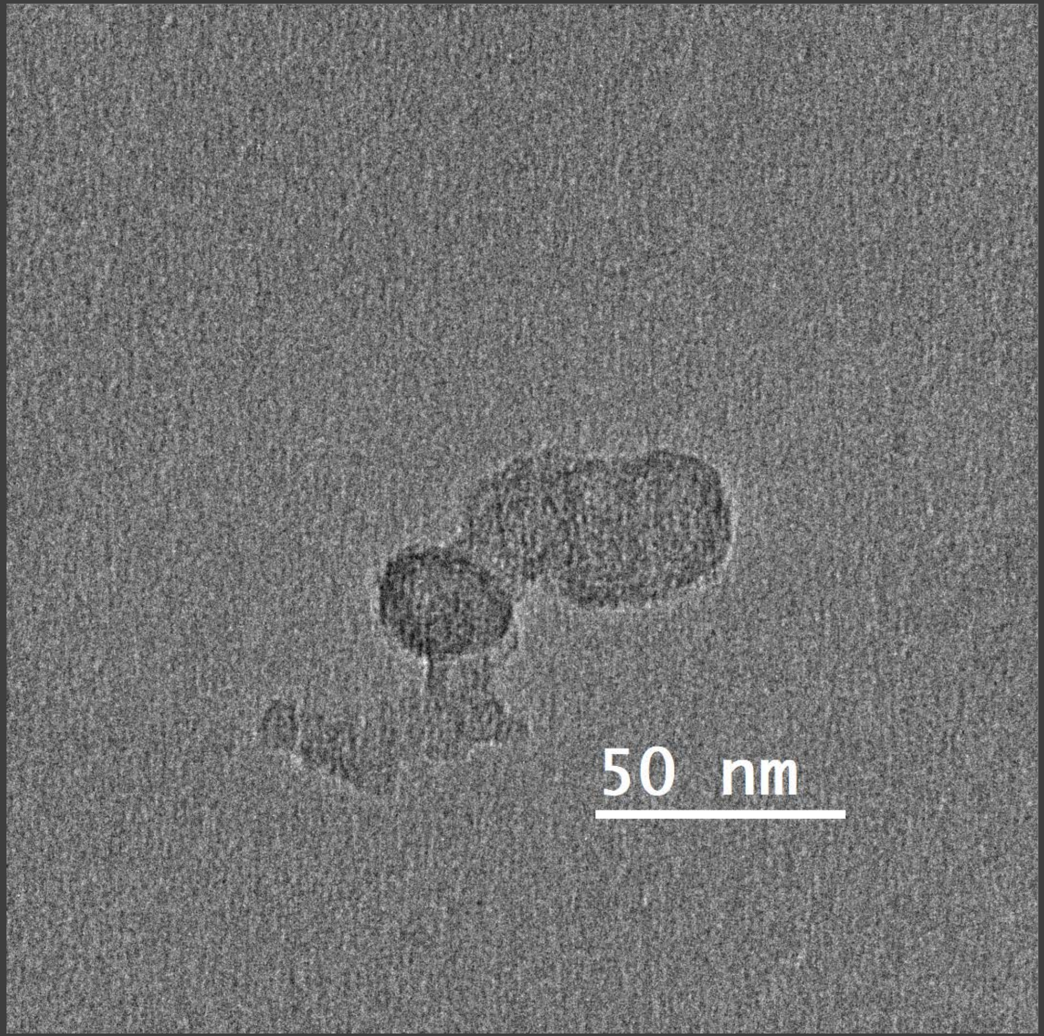
Diesel Exhaust

Monitor emission and collect emitted diesel exhaust using TDS.

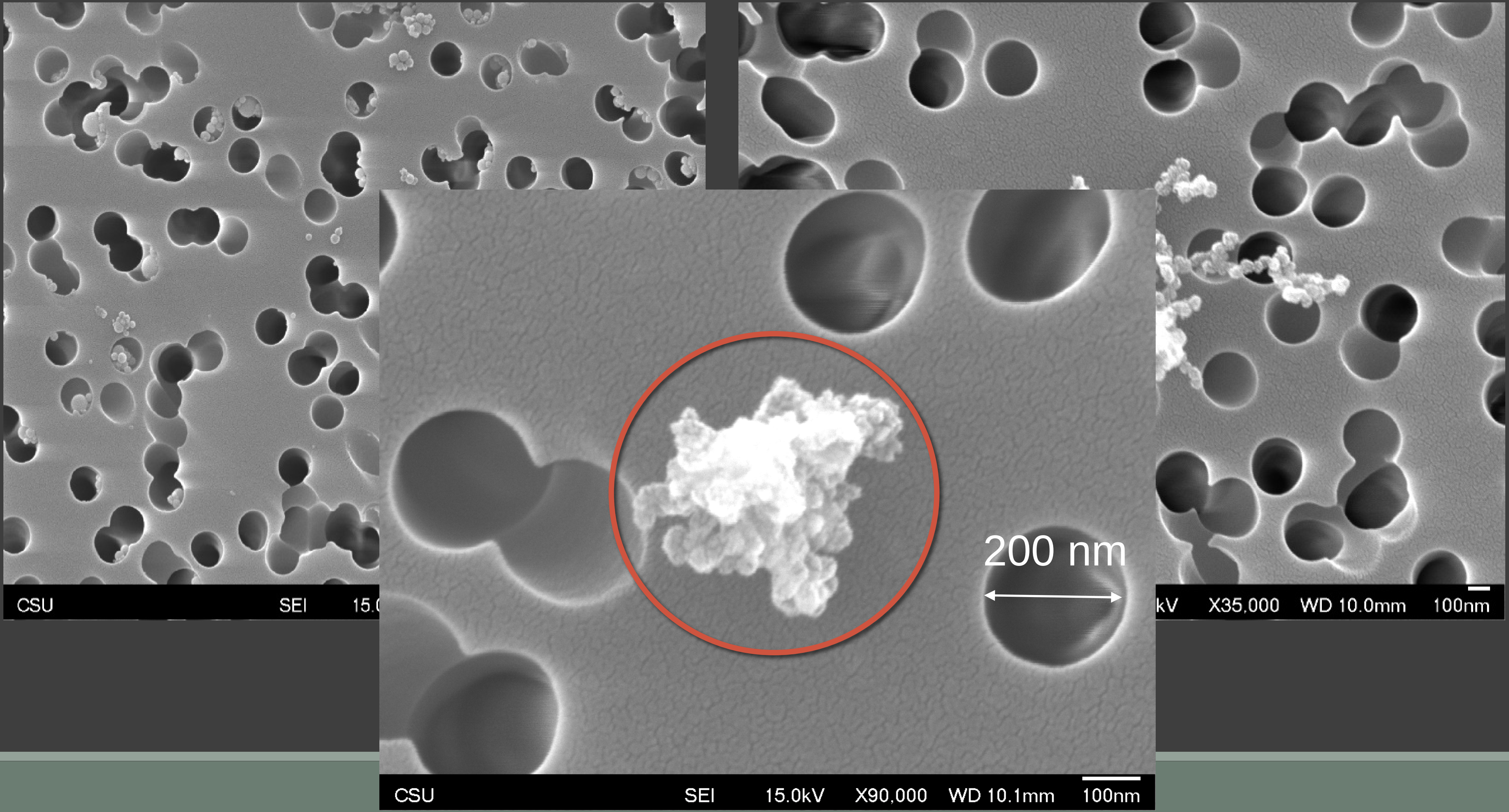


Diesel exhaust particles collected on a TEM grid in TDS





Diesel exhaust particles collected on a polycarbonate filter in TDS



Summary

- ✓ Dust concentration from drilling was found to be lower than 0.6 mg/m^3 (600 μg/m^3) for total respirable particles. Current respirable coal mine dust concentration limit is 1.5 mg/m^3.
- ✓ Exposure to diesel exhaust and emitted particles from drilling in an underground mine involve a high number of sub-micrometer-sized particles with a trace amount of mass. Particles were effectively collected and seen with TDS sampling.
- ✓ The sensor detection was successful from low concentrations to concentrations approximately 10 mg/m^3 or higher.
- ✓ The current generation of our technology uses a micro-USB port for power and data transfer to a computer. In the next generation, wireless communication can be applied through Wi-Fi or Bluetooth, and a commercial battery can be used for power.

Summary

- ✓ Modern sampling technique for quantifying small particles is needed.
- ✓ Protection for miners against exposure to small respirable particles must be prioritized, with a need for studies on the relationship between this exposure and associated effects or diseases.
- ✓ On going project: The effect of coal and mine respirable dust size on lung cells and exposure assessment.

Acknowledgments

This research was funded by the Alpha Foundation Technology Development and Exploratory Research Fund.

Drs. Candace Tsai, Jürgen Brune, David Janes

Participated Students: Doosan Back, Daniel Theisen, Nara Shin

University of California, Los Angeles (UCLA) Candace.umass@gmail.com

1. Tsai, C.S.J.*, Shin, N., Brune, J., Evaluation of sub micrometer sized particles generated from diesel locomotive and drilling within an experimental underground mine, Annals of Work Exposures and Health, July 28, 2020.

2. Back, D., Theisen, D., Seo, W., Tsai, C.S.J.*, Janes, D.*, Development of Interdigitated Capacitive Sensor for Real-time Monitoring of Sub-micron and Nanoscale Particulate Matters in Personal Sampling Device for Mining Environment, IEEE Sensors Journal, May 20, 2020.

3. Tsai, C.S.J.*, Theisen, D., A sampler designed for nanoparticles and respirable particles with direct analysis feature, Journal of Nanoparticle Research, 20:209, 2018.