Selection and Use of Direct-Reading and Sensor Technologies for Aerosols Monitoring

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National Institute for Occupational Safety and Health (NIOSH)
Centers for Disease Control and Prevention (CDC)

Disclaimers

- The findings and conclusions in this presentation are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC).
- Mention of company names or products does not constitute endorsement.

About Me

- Originally from Italy; moved to the USA in 2007.
- Trained as a Chemical Engineer. Significantly involved in IH/OH for the last ten years
- Since 2014, involved in the activities of the NIOSH Center for Direct Reading and Sensor Technologies. Co-director of the Center since 2019
- AIHA member and contributor of the following working groups:
  - Aerosol Technology Committee (current vice-chair)
  - Real-time Detection Systems Committee
  - CPAG Big Data and Sensor Technologies Working group

NIOSH Center for Direct Reading and Sensor Technologies

www.cdc.gov/niosh/topics/drst/

Mission – to coordinate research and to develop recommendations on the use of 21st century technologies in occupational safety and health

Center Strategic Goals

1. Develop **guidance** documents pertinent to direct reading methods and sensors, including validation and performance characteristics
2. Develop **training** protocols
3. Establish **partnerships** to collaborate in the Center's activities
4. Foster a **national research agenda** for direct reading methods and sensor technologies

John Snawder Director

Emanuele Cauda Director

Pramod Kulkarni Deputy Director

A Snapshot of Center Activities

- Developing new direct-reading methods and sensors
- Sensor Life-Cycle
- Engagement of external stakeholders
- Turning Numbers into Knowledge
- Selection of Sensors for Gases and Vapors
- Selection of Sensors for Particulates
- Framework for Ethical Sensor Use
- Sensor Use in Emergency Response
- NIOSH Manual of Analytical Methods Chapter(s)on DRST

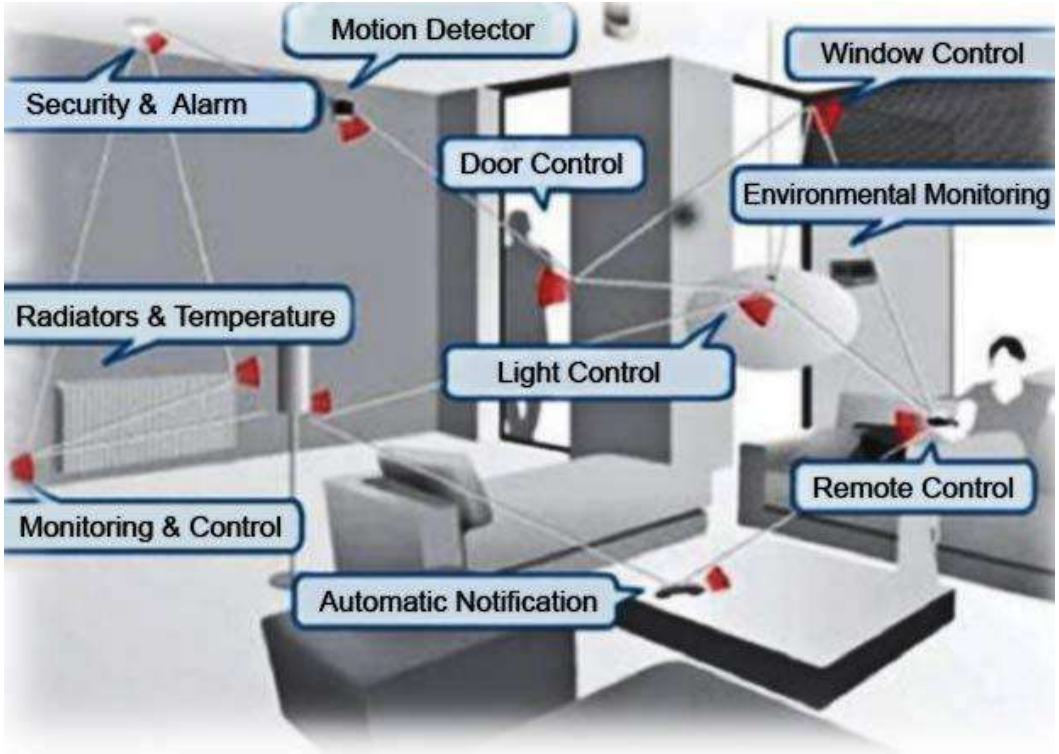
Table of Contents

Notes

- It is not a seminar on aerosol sampling. The focus is on direct-readings and mostly real-time monitors for aerosols.
- It is a condensed selection of material from a 3-hour PDC
- Please add questions in the chat box. I will take a few breaks!

Sensors are everywhere

Smart cities



Smart houses

Smart personal health monitoring

Sensors can be direct-reading methodologies

Is direct-reading adequate or would real-time be better?

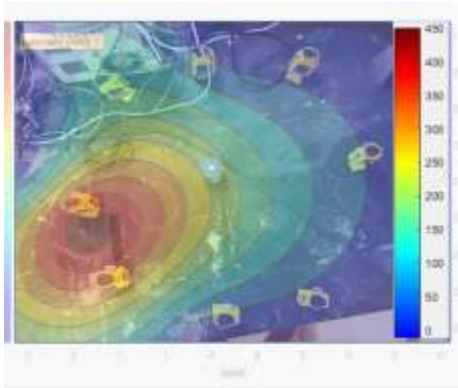
Do we have confidence in the data?
Do we *need* to have more confidence?
Can we afford to pay for more confidence?

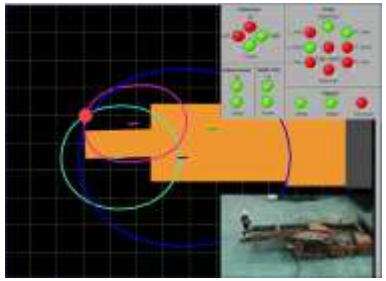
Sensors can be real-time monitors

Do we have confidence in the performance of each real-time monitor?

Real-time monitors and direct-reading methodologies are used widely in occupational environments

….and in health and safety





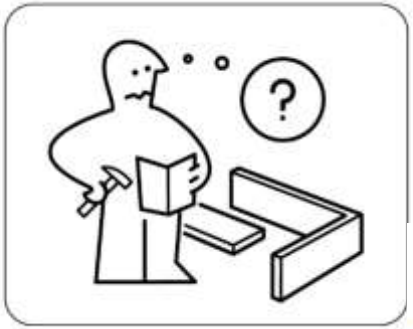
By adopting these technologies, there are benefits …

But with great(er) power comes great(er) responsibility

Right Sensors Used Right

An initiative of the Center to promote the competent development, selection, adoption, and data interpretation of real-time monitors and direct-reading methodologies

Right Sensors – It is much more than picking the right gadget. It is a proper analysis of the specific IH need, the definition of objectives and hypothesis.



Used Right– It is not enough to read (??) a manual of a device. It is the need to understand the capabilities and limitation of the technology and data generated.

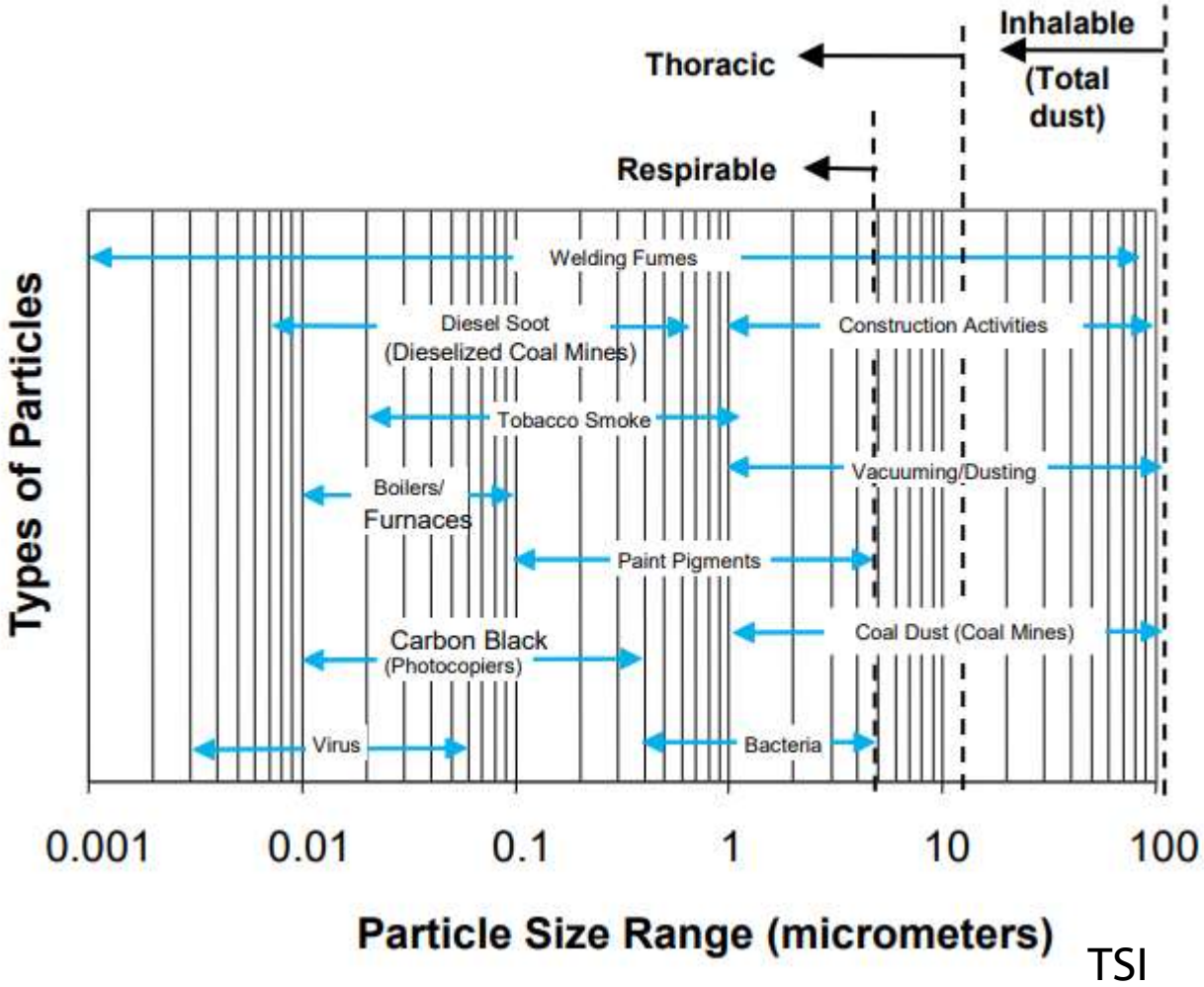
Q: How much of your work focuses on aerosol monitoring? (%)

Define your objective:

Devices or methodologies are only the tools to achieve the objective

Air Quality Index - Particulate Matter	
301 – 500	Hazardous
201 – 300	Very Unhealthy
151 – 200	Unhealthy
101 – 150	Unhealthy for Sensitive Groups
51 – 100	Moderate
0 – 50	Good

1. Generating alarm if particles exceed a threshold
2. Using qualitative surveys to find sources/tasks
3. Evaluating performance of administrative controls
4. Evaluating performance of engineering controls
5. Assessing risk/exposure
6. Monitoring compliance
7. Mapping
8. Training



Aerosol - definition

Tiny particles or droplets suspended in air

(cit. Paul Baron - NIOSH)

TSI

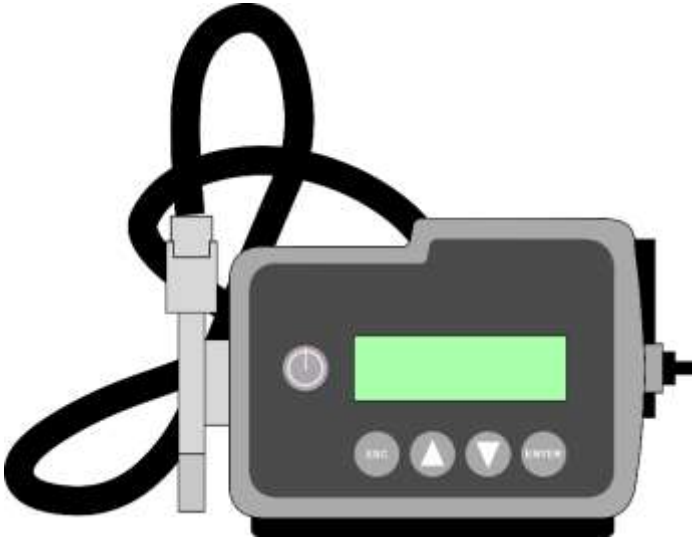
Real-time respirable dust monitors for IH/OH use

- There are several monitors for dust hazards. *Guidance is needed.*

- There is an increased interest in respirable dust monitors because of the OSHA silica rule. *Urgency.*

- While these monitors are familiar tools, they can be easily misused. *Importance of correct practice.*

Components of real-time respirable dust monitors



- *Size selector*
- *Sensing technology*
- *Filter media (optional)*
- *Sampling pump*

Components
of real-time respirable dust monitors

- Size selector
  - Sensing technology
  - Filter media (*optional*)
- Sampling pump

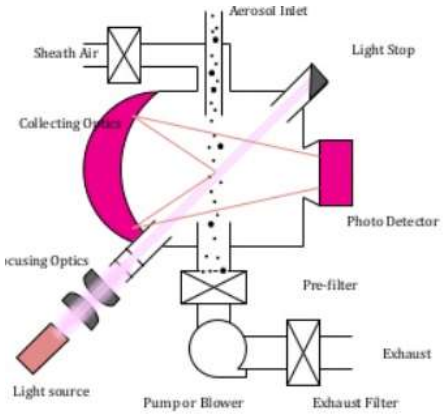
Respirable dust monitoring is possible using a respirable size selector:

- Size selector = a cyclone or an impactor. Better if the performance of the selector has been studied and it is reported.
- Environmental size selectors (PM4) are not respirable size selectors.

- Each size selector works at a precise flow-rate (pump).

- Transfer [selector – monitor] is important: conductive tubing minimizes the dust losses !!!

Components of real-time respirable dust monitors



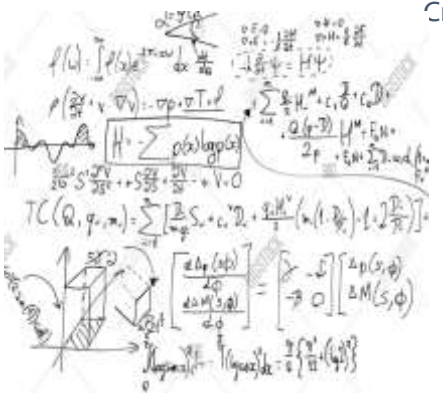
Credits: TSI

- Size selector
- Sensing technology
- Filter media (*optional*)
- Sampling pump

Most dust monitors analyze the respirable dust using interaction between light and dust particles.

Terminology used: *optical particle counters; light scattering monitors, optical dust monitor, photometers.*

These monitors **do count the particles** in the air and through complex equations and modeling provide



Respirable dust mass concentration

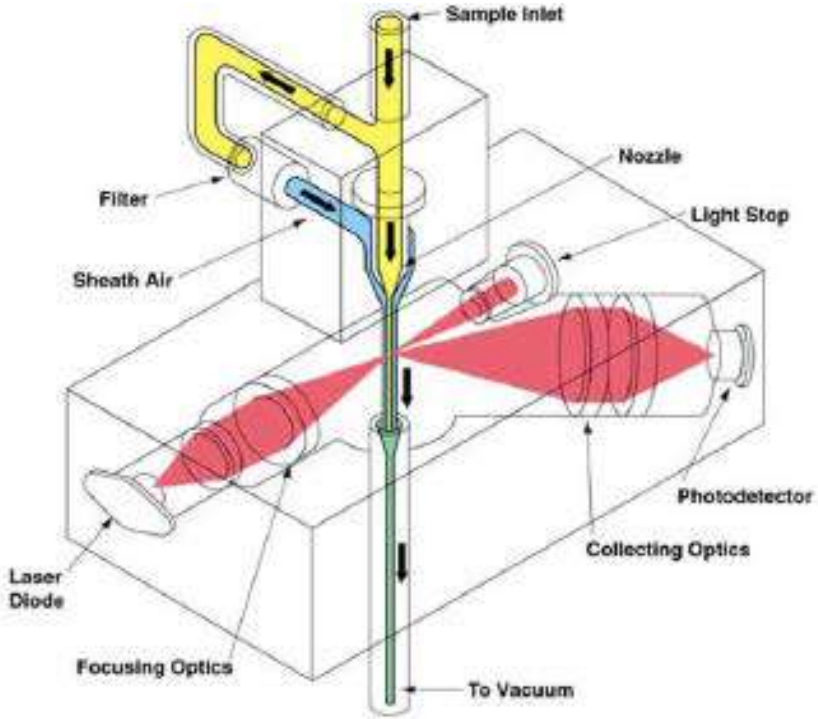
Optical particle counters vs. Photometers/Nephelometers

What's the difference?

Photometers

Optical-based measurement depends on

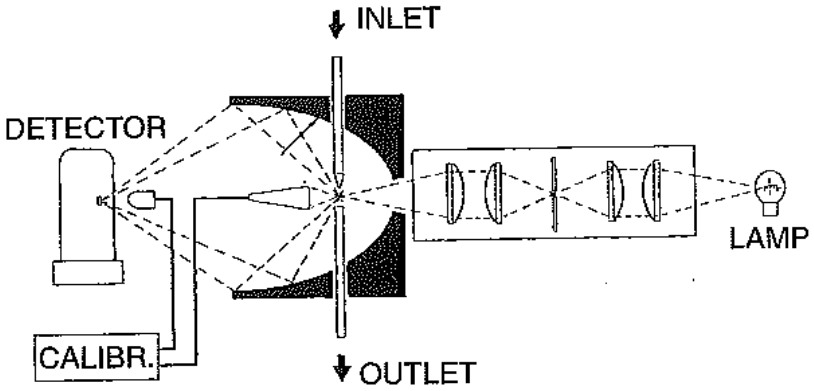
- Optical properties of dust
- Size of dust
- Shape of dust



Optical particle counters

Photometers

Nephelometers



- Still affected by particles' properties
- Can be capable of "counting" single particles and "estimate" size of particles – what if too many particles??
- Still not a direct mass measurement

From Aerosol Measurement: principles, techniques, and applications – Kulkarni, Baron, Willeke. 3rd edition. Wiley Publisher

Optical particle counters vs. Photometers/Nephelometers

What's the difference? (summary)

- If a monitor does count particles (in any way) ….it does not measure mass concentration as a direct measurement
- Technology evolves constantly but not that fast
- Ask questions to manufacturers
- Read manual/specs
- Ask more questions to manufacturers/institutions
- Ask questions

Components of real-time respirable dust monitors

- Size selector
- Sensing technology
- Filter media (*optional*)
- Sampling pump

Main uses of the optional filter:

1) To calibrate the real-time respirable dust monitor in the field with a specific dust
2) For additional specific analysis – crystalline silica, welding fumes, others….
3) A specific filter media should be used for a specific analysis

Field-calibration of real-time respirable dust monitors

- Why do we need to field-calibrate real-time time respirable dust monitors?
- What is the objective of calibrating a real-time respirable dust monitor in the field?
- What are the constraints/variables/limitations associated with this practice?

Need for field-calibration

- Real-time respirable dust monitors are *factory-calibrated* with a standard material.
- The response of a real-time dust monitor is affected by the dust monitored.
- The factory calibration does not assure an accurate measurement of the dust in workplace.

Objective of field-calibration

The field-calibration of a real-time respirable dust monitor should be considered when we are interested in the actual concentration data and not only in the relative levels within a session and between sessions.

Do we have an alternative to the field-calibration? Correction factor - *Collection of a true respirable dust sample for each session….*

TSI SidePak AM520

No internal filter

Thermo Scientific pDR 1500

Internal filter

Best-practice for field-calibration?

- **What do we need?**
  - A real-time respirable dust monitor with right components and setup
  - A reference measurement
  - A dusty environment

- **How many reference samples should be collected?**
  - If external samples, more than one
- **How many sessions should be considered?**
  - The field-calibration should be done with more than one independent testing
- **What do we do with the data?**
- **How do we know the field-calibration is effective?**

Best-practice for field-calibration

For how long should we be sampling?

Use the power of the real-time respirable dust monitor!!!

Analytical techniques Limit of quantifications	
LOQ gravimetric analysis	100 µg

Imput from operator	
AVG concentration reading from real time monitor	500 µg/m3
Flow rate real time monitor	1.7 lpm
Safe margin multiplier	*2*

Minimum sampling time	
For accurate gravimetric analysis	235 minutes
respirable dust mass collected on filter	200 µg

Best-practice for field-calibration

Independent test

Traditional samplers (3)

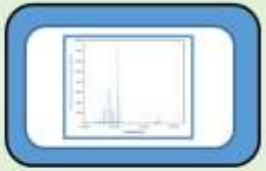
Concentration – 200 mg/m³

Concentration – 220 mg/m³

Concentration – 235 mg/m³

[AVG Concentration 1] – 218 mg/m³

Real-time respirable dust monitor



[AVG concentration 2] – 150 mg/m³

$$\text{Correction factor} = \frac{[\text{AVG concentration 1}]}{[\text{AVG concentration 2}]} = 1.45$$

Users attempting field-calibration

	Run	X4 (internal pDR filter)	pDR-1500		Correction factor using X4	
pDR1500	1	3.37	1.76		0.52	
	2	3.82	2.121		0.56	
	3	5.95	3.545		0.60	
				AVERAGE	0.56	Corrected pDR1500 (mg/m3)
	4	4.1	2.419			4.34
					How much off from X4 in run 4	-5.78%

Note the variability in the correction factors detected.
Is the difference from the standard analysis small enough?

thesynergist | February 2019

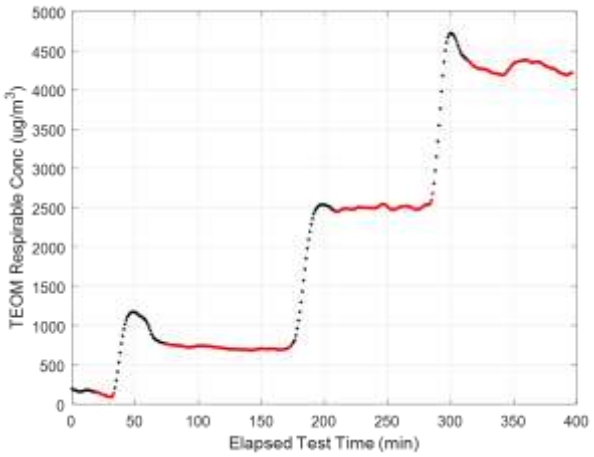
https://synergist.aiha.org/201902-quartz-busters

Users attempting field-calibration

			Respirable Dust mg/m3					
AM520		Run	X1	AM520			Correction factor using X1	
		1	2.73	3.36			1.23	
		2	2.54	4.37			1.72	
		3	5.39	7.28			1.35	
						AVERAGE	1.43	Corrected AM520 (mg/m3)
		4	3.37	4.87				3.40
							How much off from X1 in run 4	-0.78%

Note the variability in the correction factors detected
Is the difference from the standard analysis small enough?

Calm air chamber used to assess real-time respirable dust monitors
Evaluation of correction factors with different dust material



Patts, J. R., D. P. Tuchman, E. N. Rubinstein, E. G. Cauda, A. B. J. M. Cecala, Metallurgy and Exploration (2019). "Performance Comparison of Real-Time Light Scattering Dust Monitors Across Dust Types and Humidity Levels." **36**(4): 741-749.

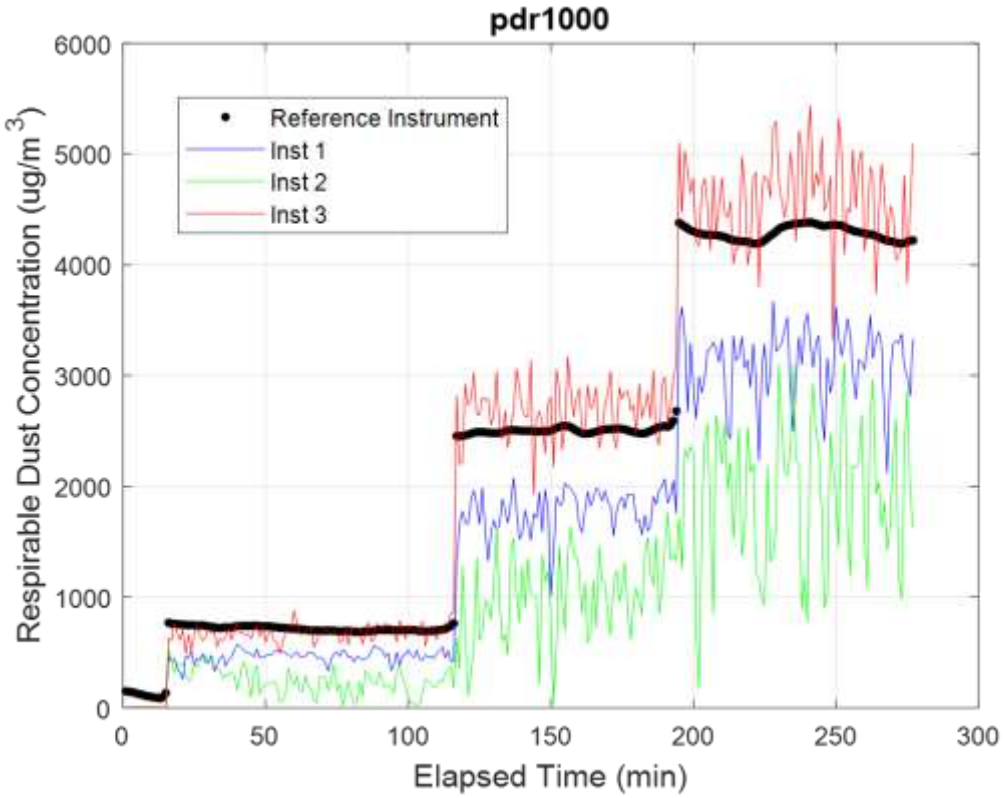
Calm air chamber used to assess real-time respirable dust monitors

Evaluation of correction factors with different dust material

No size selector for respirable dust

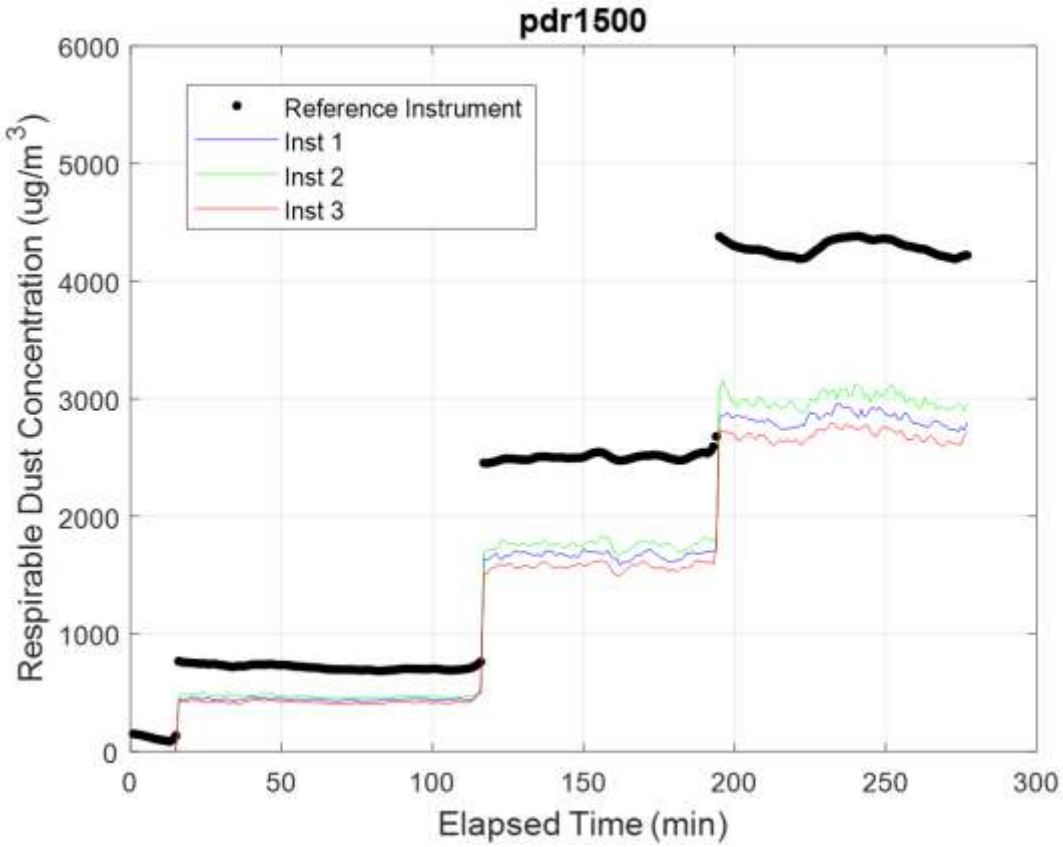
Calm air chamber used to assess real-time respirable dust monitors

Evaluation of correction factors with different dust material



Calm air chamber used to assess real-time respirable dust monitors

Evaluation of correction factors with different dust material



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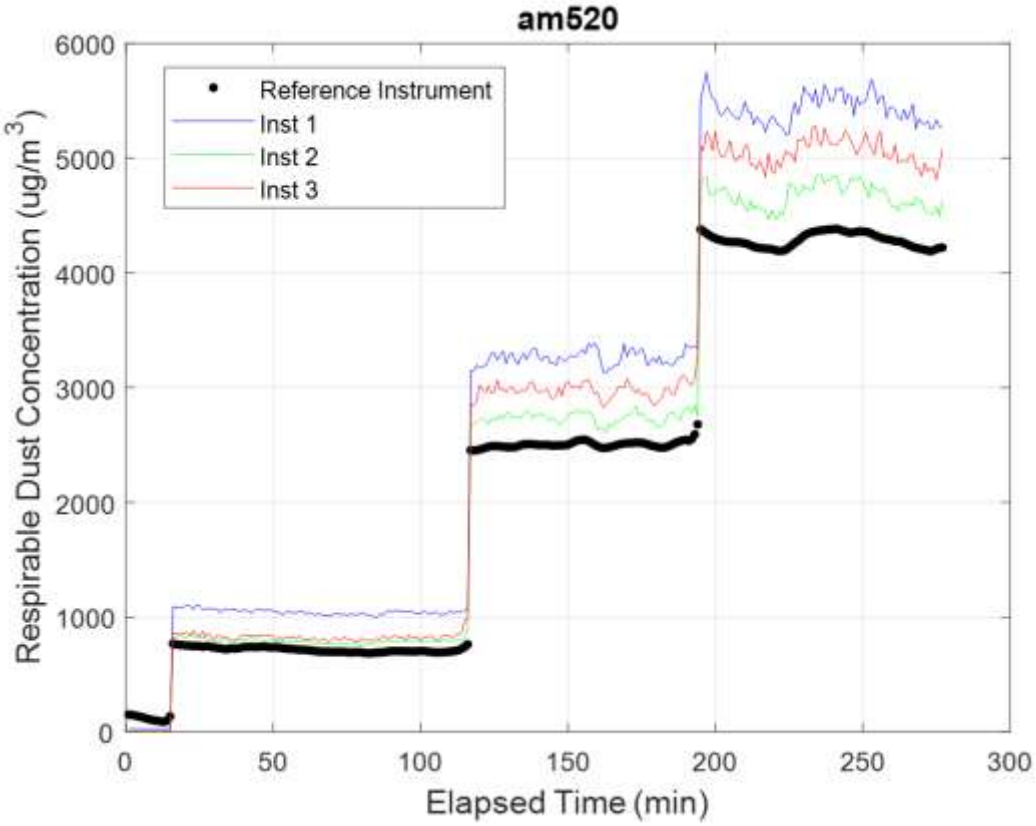
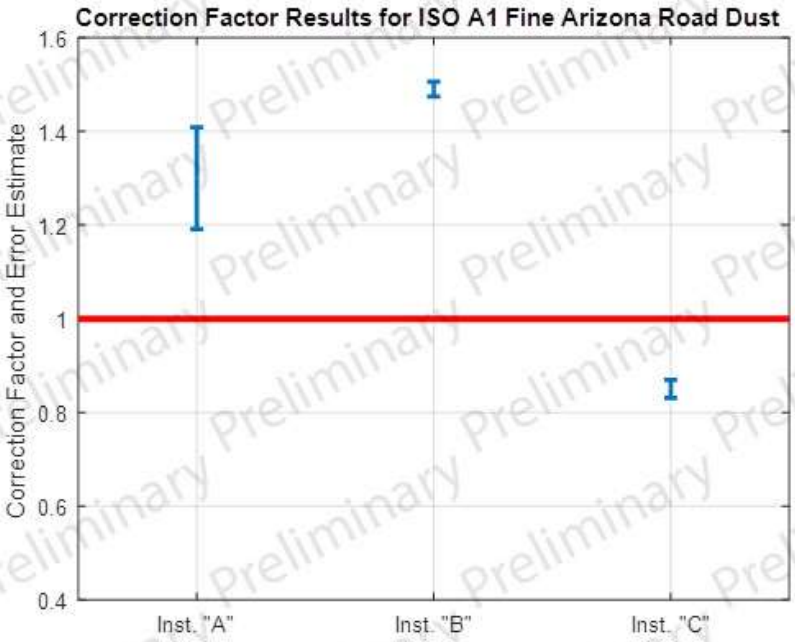


Calm air chamber used to assess real-time respirable dust monitors

Evaluation of correction factors with different dust material



- The correction factor is the value that should be applied to the monitor data in order to calibrate it for the specific dust.
- For one of the monitors, the correction factor is more a “correction factor range” even for one single dust.

Calm air chamber used to assess real-time respirable dust monitors
Evaluation of correction factors with different dust material

	PTI ARD Fine	PTI ARD Course	Sand mine dust	Metal mine dust	Silica	Limestone mine dust
pDr1000	1.46	1.49	1.70	2.05	1.46	1.43
pDr1500	1.52	1.58	1.67	1.87	1.52	1.39
AM520	0.83	0.92	0.99	1.17	0.89	0.77

Even for factory-calibrated respirable dust monitors, the response to different dusts can be quite different

A true mass measurement

Real-time personal dust monitor

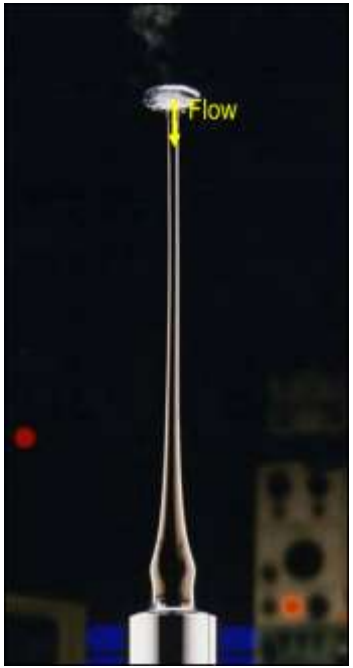
Four main elements

- Dust inlet
- Respirable cyclone
- Tapered Element Oscillating Microbalance (TEOM)
- Controlled pump and acquisition system

A true mass measurement

PDM3700 real-time personal dust monitor

- Filter cartridge mounted on the end of the tapered element collects particles as sample stream flows through hollow tube
- Tapered element always oscillates at its harmonic frequency -- like a tuning fork
- Frequency changes in *direct* relation to the mass collected on the filter
- Gravimetric-equivalent mass measurement
- Measurement principle does *not* respond to other particle characteristics such as optical properties, composition or size distribution



Cons?

- Cost, cost, cost – how many units can you afford?

- Size and weight

Other Real-Time Aerosol Monitoring Options?

Condensation particle counter

- Both portable and handheld
- Sensitive to very small particles – down to few nanometer
- Not suitable for large particles
- They provide particle number concentration
- They don't have a size-selective device – they count everything
- **<u>Applications</u>** – spot-checking, leakages, and for nanoparticles monitoring

Other Real-Time Aerosol Monitoring Options?

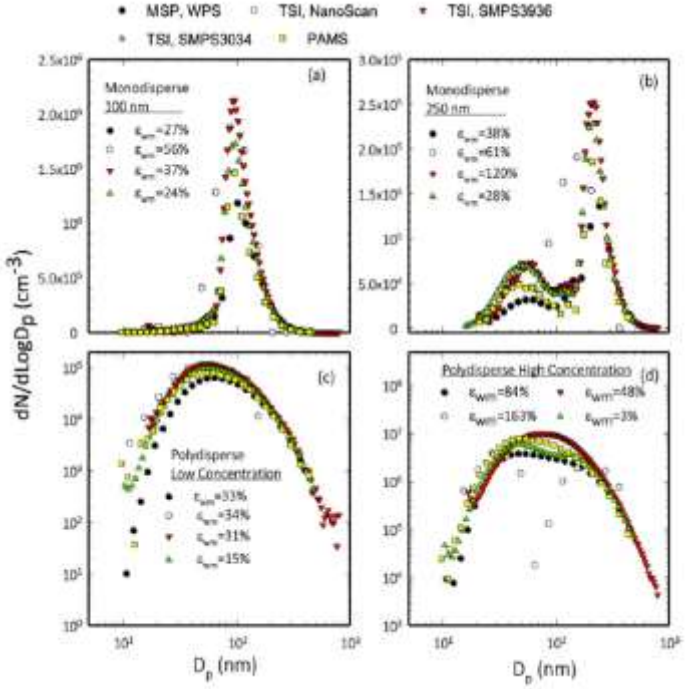
Aerosol particle counters and size distribution monitoring

- Can we measure the size distribution **and** concentration of particles in an occupational environment?? YES !!!
- We can measure large particles (up to 20 um) and very small particles (down to a few nanometers)
- Portable instruments are becoming more and more available for field monitoring

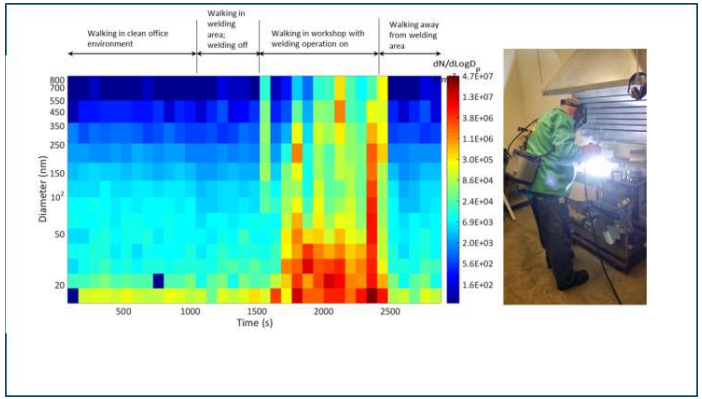
What is the cost?

Aerosol Mobility Spectrometer for Personal monitoring

Collaboration NIOSH – Kanomax (R2P)



Overall Size: 22.5 x 22.5 x 15 cm
Weight: 4.5 kg



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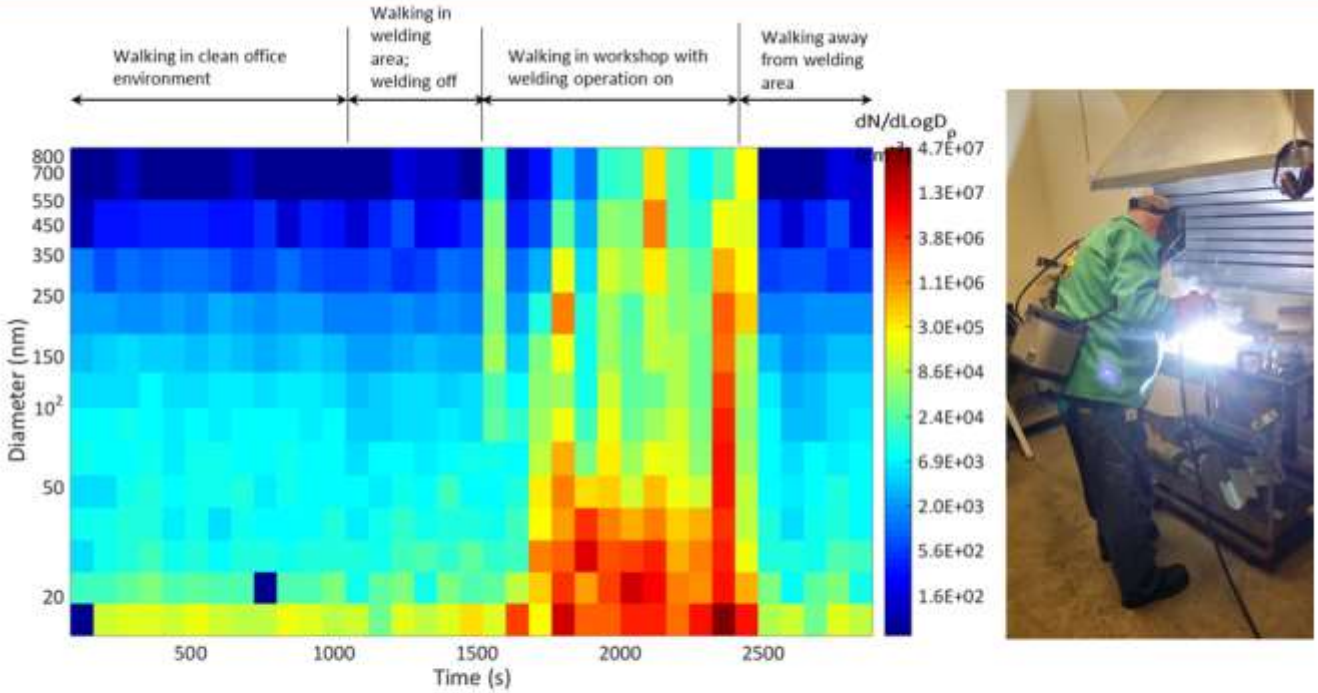
Other Real-Time Aerosol Monitoring Options?

*Aerosol size distribution **personal** monitoring?*



Aerosol Measurement

Combining real-time monitors and post analysis

CPC #/cm^3
(10 or 20 nm – 1 µm)

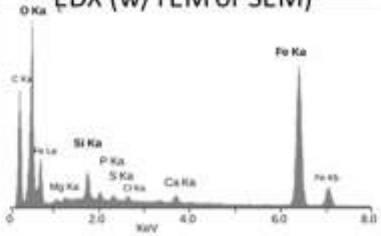
FMPS size and #/cm^3
(5.6 – 560 nm)

APS size and #/cm^3
(0.5 – 20 µm)

Cassette and filter

TEM

EDX (w/TEM or SEM)



SEM

Perkin Elmer

ICP-MS

Other Aerosol Monitoring Options?

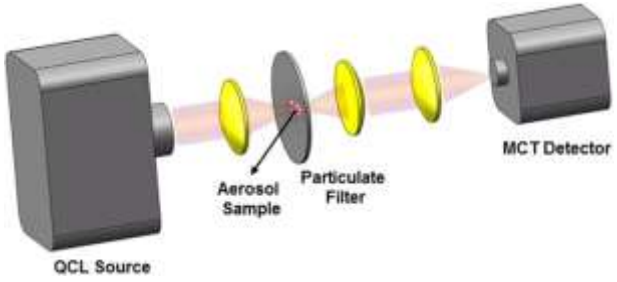
Nanoparticles – many options for monitoring

Metric	Qualification
Mass	A standard approach for OELs (e.g., NIOSH CNT and TiO_2 CIBs)
Surface Area	Relevant for low solubility particles
Surface Chemistry	Relevant for effects observed in toxicological studies
Particle Number	Relevant for fibers and number of cells affected
Particle Size	Influences respiratory deposition and translocation
Particle Shape	Issues including toxicity of fibers versus spheres

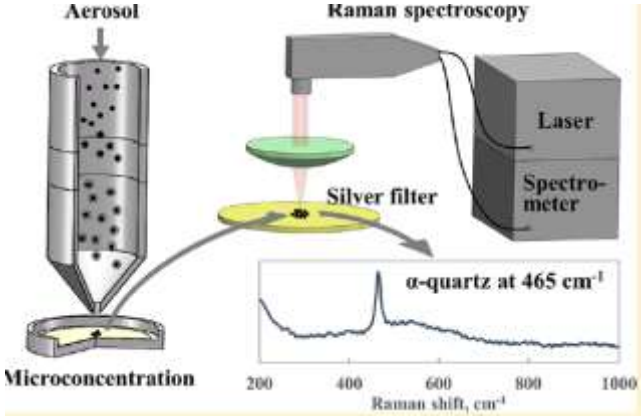
Occupational Exposures: Which Metrics to Use?

Quantum Cascade Laser-IR & Raman

Three sampling methods : (i) conventional aerosol filter collection, (ii) focused spot sample collection directly from the aerosol phase, and (iii) dried spot obtained from deposition of liquid suspensions.



QCL-IR



Raman

For both technologies the low sensitivity indicated the possibility for near-real-time monitoring

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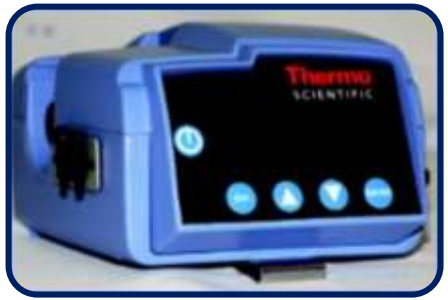
Direct-Reading Methodologies: Field-based Silica monitoring

Collect samples using gravimetric dust samplers → Analyze samples with a portable FTIR unit → Process the FTIR data with NIOSH FAST software → (optional) Verify field analysis with laboratory tests

FAST
Field Analysis of Silica Tool

Lauren Chubb lchubb@cdc.gov

Direct-Reading Methodologies: Field-Based Silica Monitoring



<u>Outcomes:</u>

- Real time respirable dust monitoring – can approximate silica if % is known
- End-of-shift average respirable crystalline silica concentration – confirm that earlier estimate was (or wasn't) accurate

One single monitor
Very accurate
Very expensive

Multiple monitors
Less accurate
One unit inexpensive

Low-Cost Aerosol Monitors

What are they? Devices for area monitoring only (for now?)

Other names? Consumer aerosol monitors; Air quality monitors

What do they measure? PM2.5, PM10 - not exactly IH measures

What's inside the box? light scattering sensors or Optical Particle Counters

How accurate are they? It depends on the sensor inside (*and the math model*)

Cost? Less than $1000 (plus cloud service)

Strength? The possibility to use multiple units at the same time

Low-Cost Aerosol Monitors

(TSI) BlueSky™ Air Quality Monitor

Applied Particle Technology

Strong Aerosol Science background

(Quant-AQ)ModulAIR-PM

(SGS Galson)SMARTSense

Integration with other sensors (gas/vapor)

IQAir

Dylos

Originally communities monitors

Awair

Aircasting

Low-Cost Aerosol Monitors

Can these devices be helpful for industrial hygiene?

Our NIOSH Center is working with the Netherlands Organization for Applied Scientific Research (TNO) and UK Health and Safety Executive (HSE) to explore potential and limitations of these technologies.

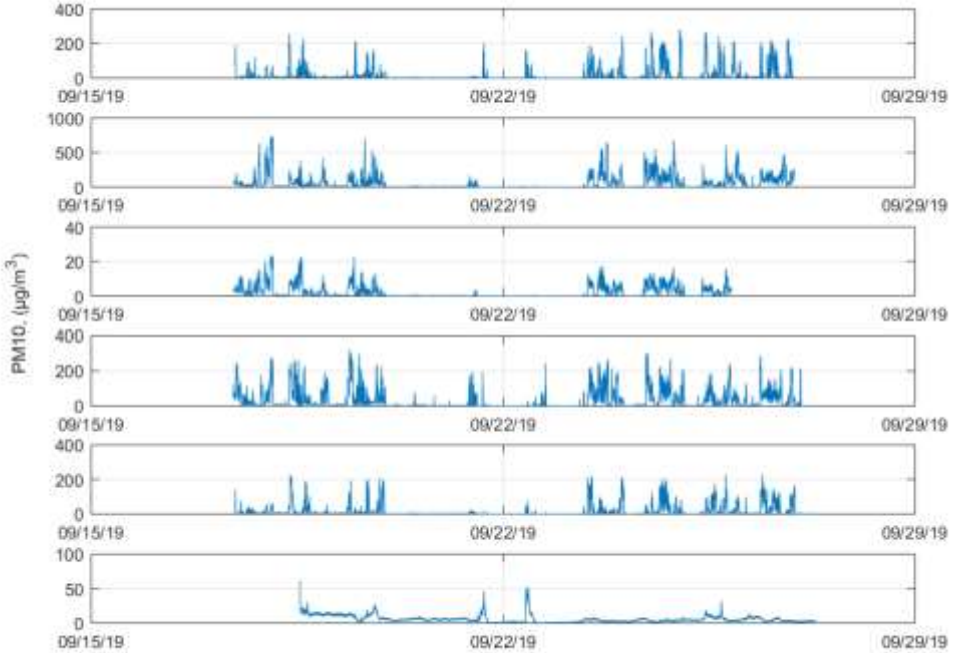
Lab and field testing

AIHA is interested in exploring these technologies for industrial hygiene.

- CPAG - Big Data & Sensor Technology
- Aerosol Technology Committee: *creation of a FACT Sheet on Consumer Aerosol Monitors*

Low-Cost Aerosol Monitors

Possible application - mapping



Research question: Can an array of low-cost aerosol monitors be used to adjust an industrial process if needed to secure healthy conditions for the workers – *Process control*

Justin Patts ***jpatts@cdc.gov***


BREAK
TIME !!

How can we transition from data collection to generation of new knowledge?

Definition of the objective/goal for conducting a session with a real-time respirable dust monitor

Understanding the functionality of each component of the monitor

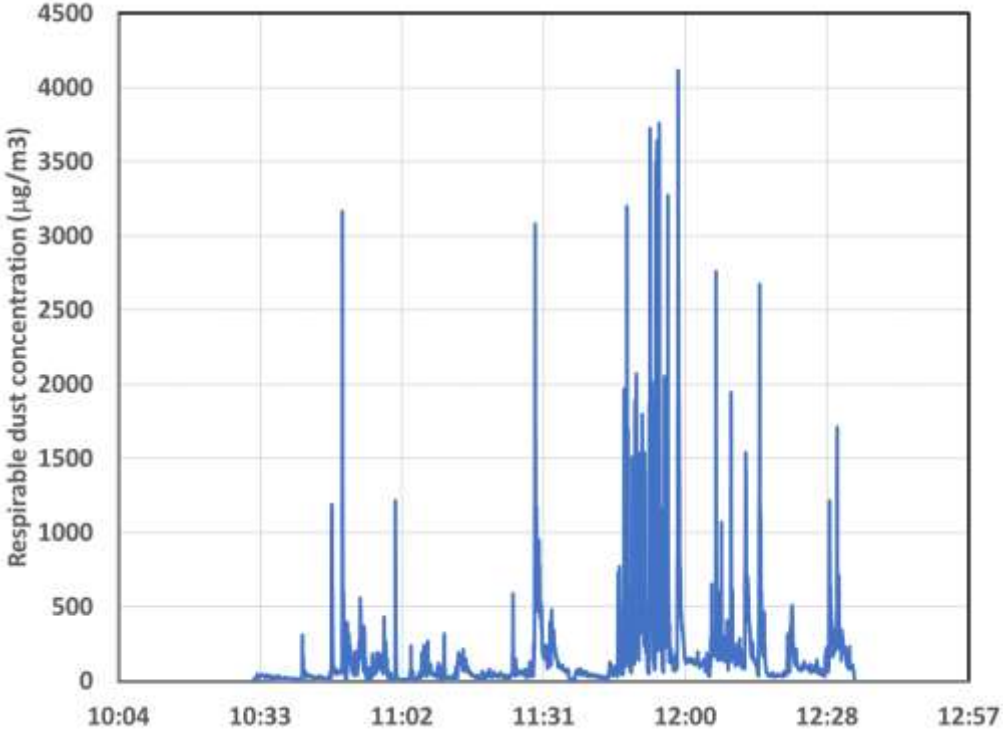
Competence on the capabilities and limitations of the monitor and data

Data

Information

Knowledge

Applications for a Single Session



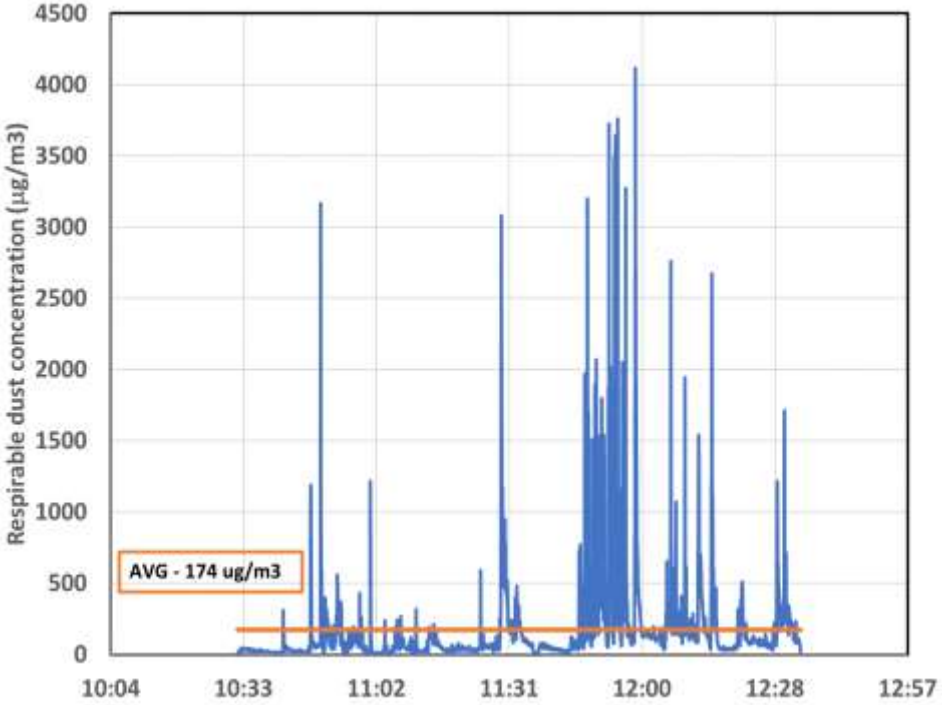
Application #1

Objective – Average concentration for a single session. (Direct-reading)

Benefit – Obtaining average concentration value at the end of the session

Limitation – The information might not be accurate. Is the monitor calibrated for that dust and that environment?

Actual AVG – 265 μg/m3 (from internal filter)

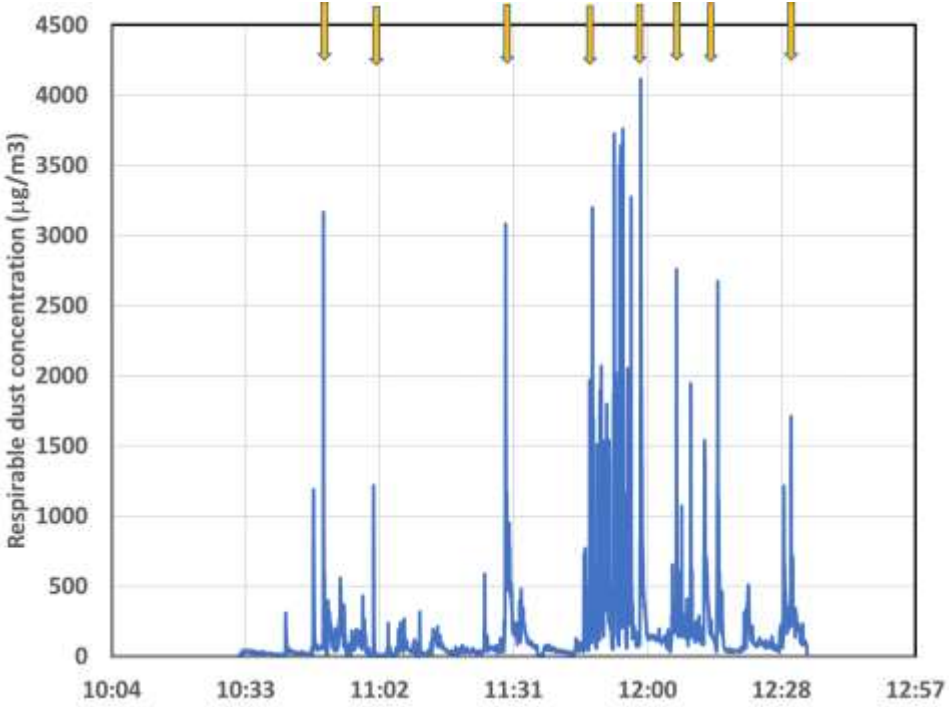


Application #2

Objective – Identification of high concentration events

Application – Are the events clustered together? Can we compare the intensity of each event?

Limitation – The accuracy of the intensity of each event is uncertain. Relative comparison is possible

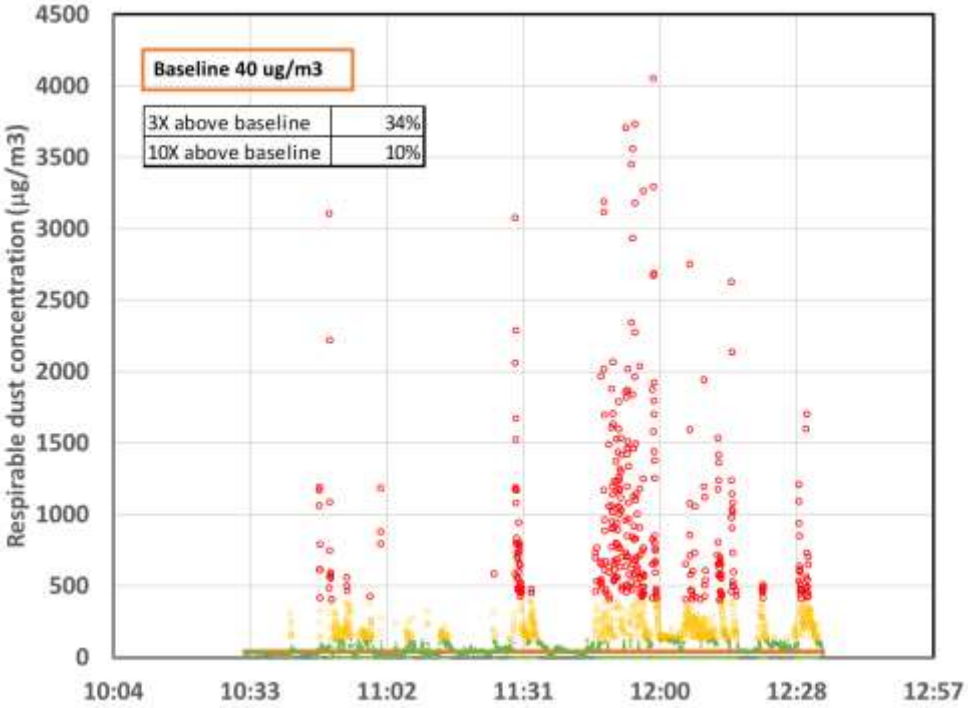


Application #3

Objective – Percent of time above baseline

Awareness – Since the instrument was not calibrated in advance and silica unknown….we cannot compare it with any OEL

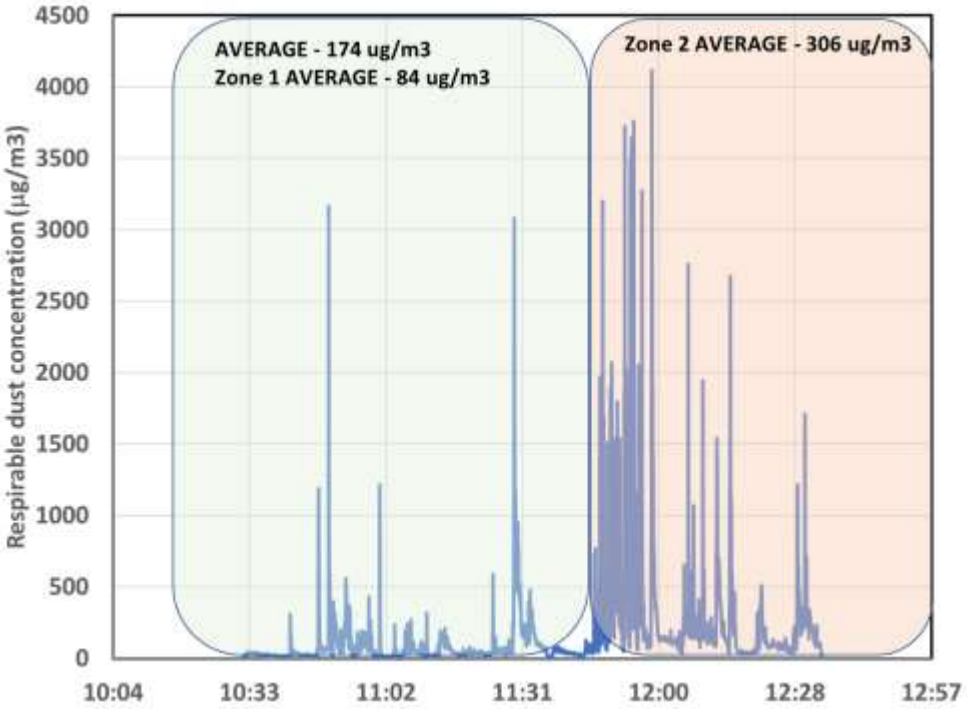
Identification of baseline is subjective



Application #4

Objective – Identification of different "tasks" or distinct periods within the sampling event

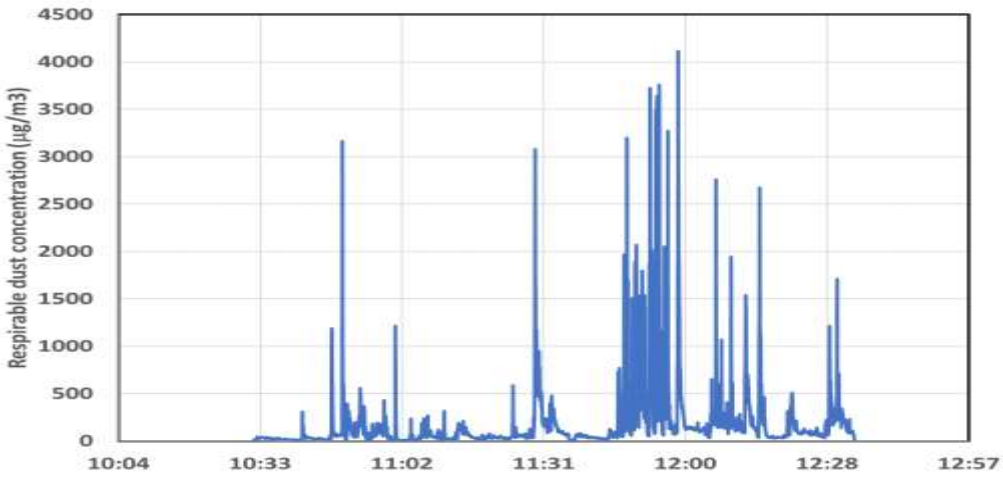
Awareness – The identification and selection of the split is very subjective, and it depends on the overall goal of monitoring

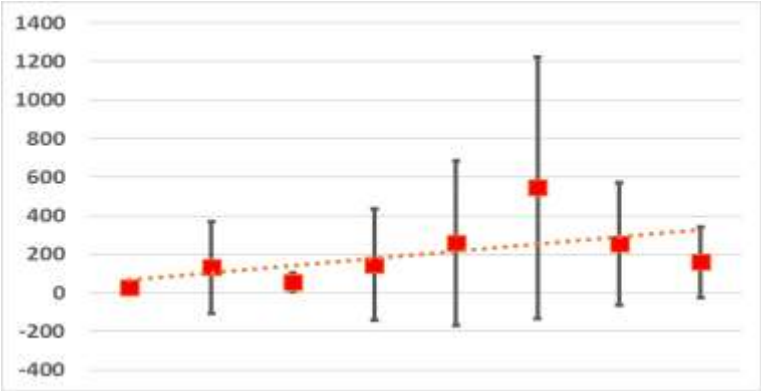


Application #5

Objective – Analysis of the average and variability in time

- Does the average change in time?
- Are there periods of higher variability?
- Is there a temporal trend?

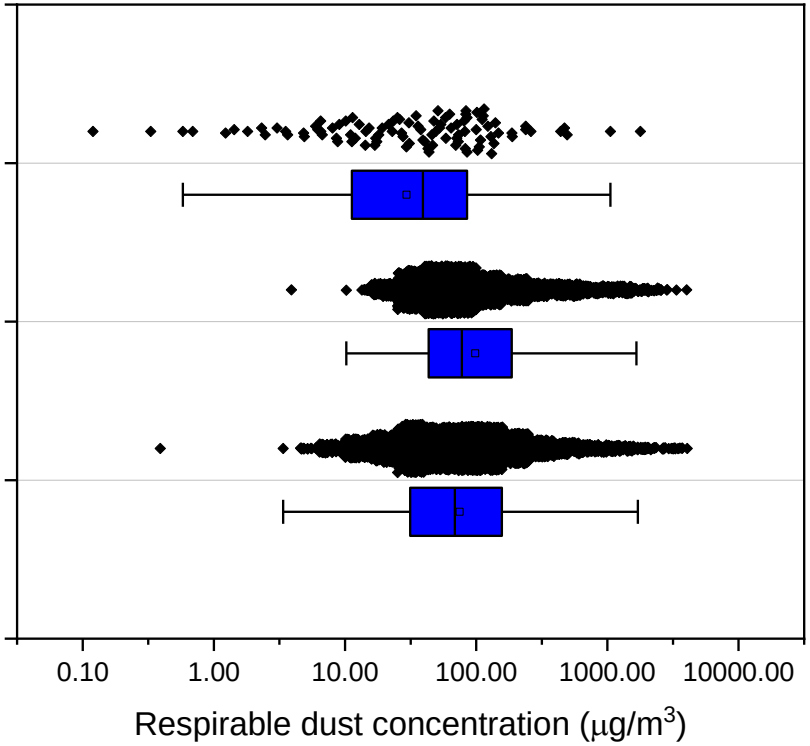




Application #6

Objective – Comparison with other sessions

- Does one session show more variability in concentration than another?
- Are the data from one session normally or log-normally distributed (like in this case)
- Should geometric mean (GM) consider more than AM? What about geometric STDEV?



Case study
Let's bring real-time respirable dust monitors out in the field

Small sand-stone quarry

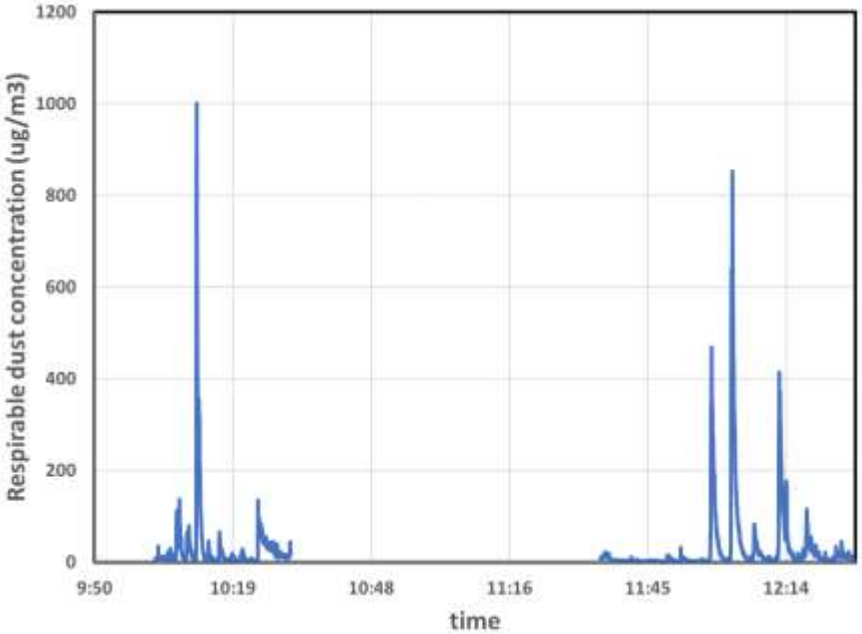
Case study

Let's bring real-time respirable dust monitors out in the field

26 sessions – 3 hours each

Analysis of a Single Session

Real-time monitor inside the enclosed cab of a haulage truck



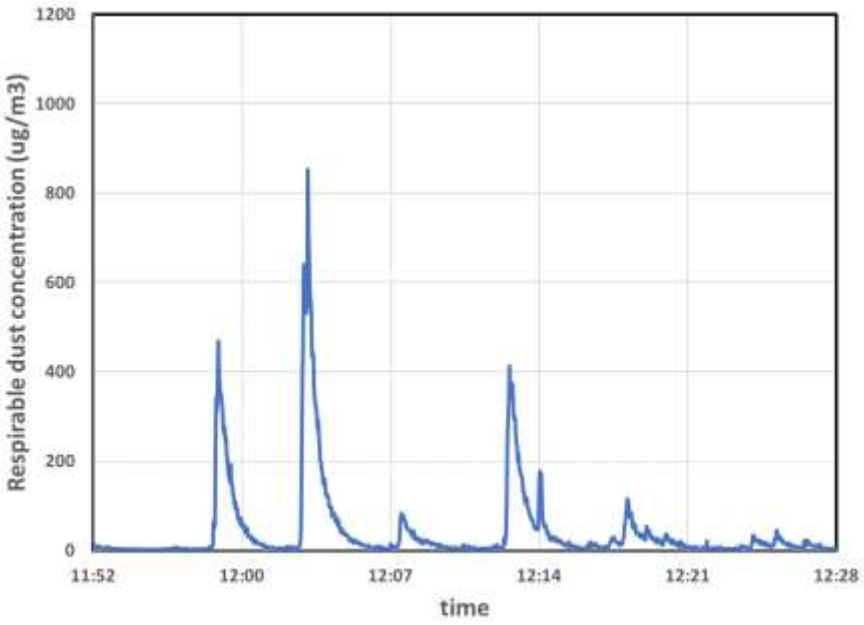
Sub session 1
AVG conc – 29.4 ug/m3

Sub session 2
AVG conc – 28.3 ug/m3

What else can we see by reviewing the real-time monitoring data?

Analysis of a Single Session – *Let's zoom in*

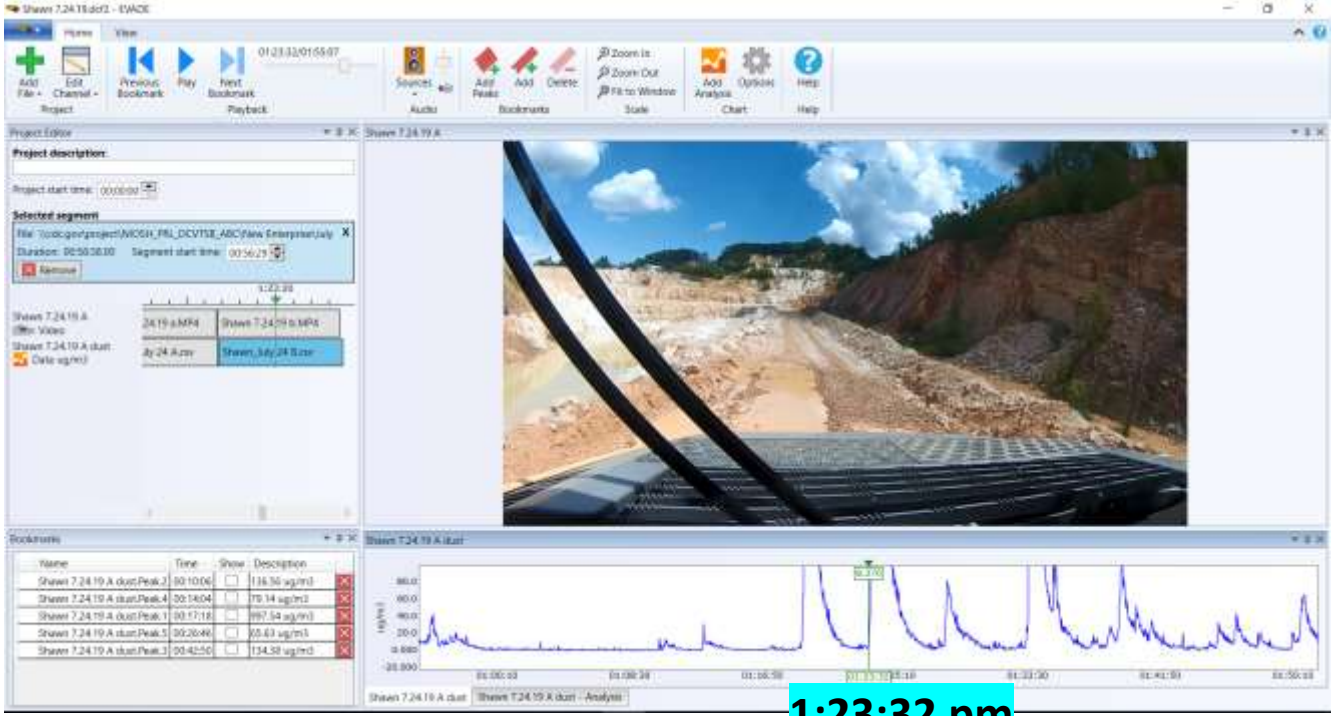
Real-time monitor inside the enclosed cab of a haulage truck



Can we tell what happened in those moments?

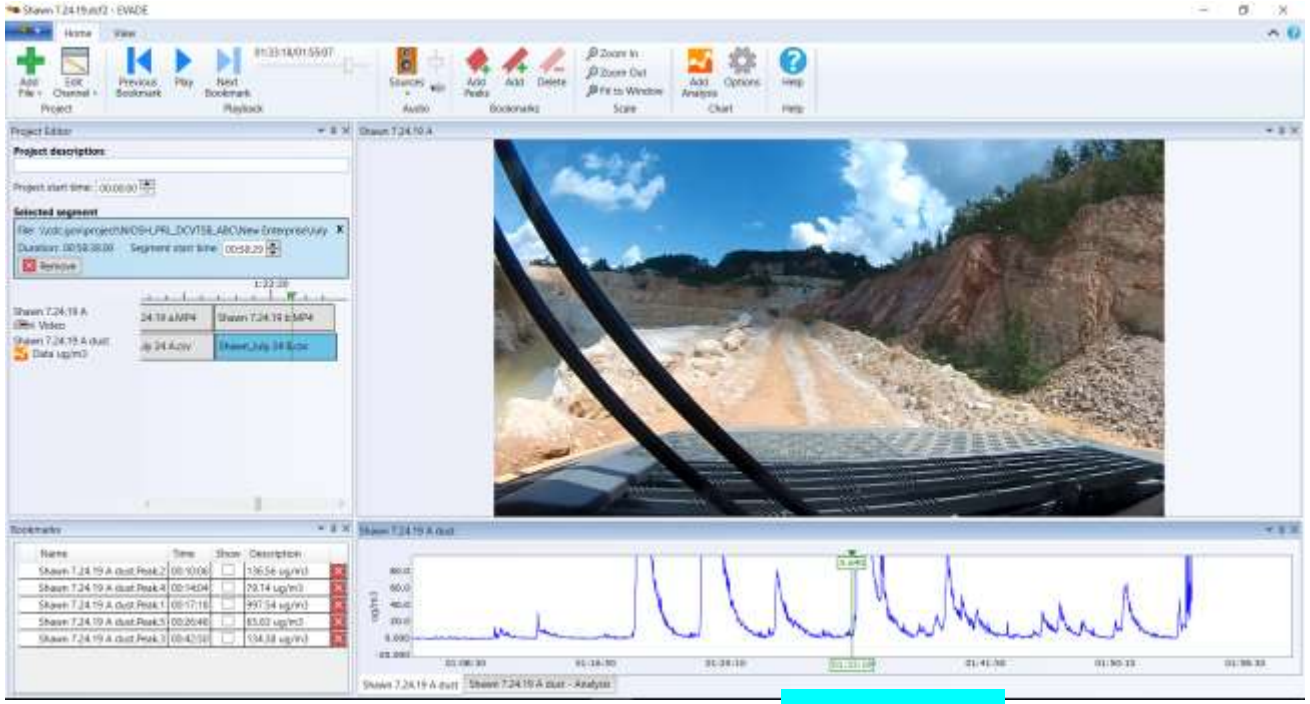
Analysis of a Single Session – *with EVADE you can*

Real-time monitor inside the enclosed cab of a haulage truck



Analysis of a Single Session – *with EVADE you can*

Real-time monitor inside the enclosed cab of a haulage truck



1:33:32 pm

Helmet-CAM
Exposure Monitoring Tool

Evaluation tool to identify "sources of exposure" and to assess "control technology effectiveness"

- Video of tasks performed by worker along with respirable dust exposure monitoring
- Particularly suitable for mobile workers with multiple tasks
- NIOSH designed software "EVADE" merges video and dust data in easy-to-use synchronized format
- ***Goal*** **-** develop control technologies to minimize areas of elevated exposures

Justin Patts jpatts@cdc.gov

Helmet-CAM
Exposure Monitoring Tool

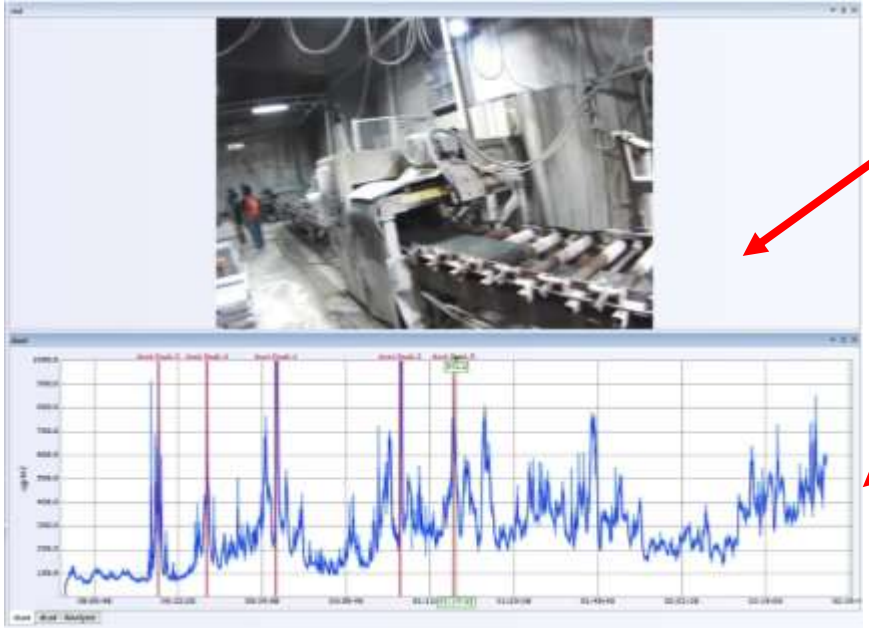
Helmet-CAM
Exposure Monitoring Tool




Backpack/2 Types of Safety Belts/Safety Vest

Helmet-CAM

Software: *Enhanced Video Analysis of Dust Exposures (EVADE)*



POV VIDEO

SYNCED EXPOSURE DATA

NIOSH designed the EVADE software
http://www.cdc.gov/niosh/mining/Works/coversheet1867.html

EVADE 2.0 – *the second generation*

- Still extremely easy to use but more powerful !

- Beyond dust exposure. EVADE 2.0 can interface with several real-time instruments (dust, DPM, noise, organic compounds).

- Multiple channels. Multiple video channels and multiple logged data channels can now be created in a single project.

- Share a project. A file can now be shared and transferred to another computer (corporate office?) where it can be viewed complete with all video and logged data.

- Basic data analyses. Simple analysis functions such as Max, Min, Mean, Derivative, and others are now available.

Analysis of a Single Session –*with EVADE you can*

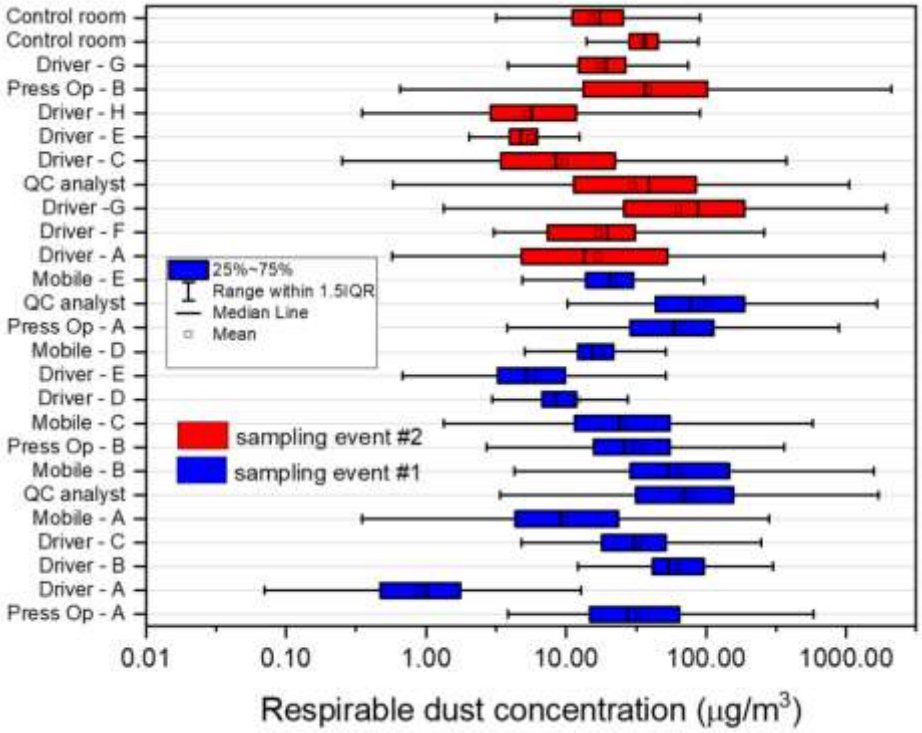
Real-time monitor inside the enclosed cab of a haulage truck

Dusty drilling activity done by contractors in the same area where the truck was passing by

Conclusion

- The protection from the cab was not perfect
- The contractor should use water while drilling to minimize dust emission
- Sometimes you need to consider the entire environment…..

Analysis of Multiple Sessions



26 sessions collected in 2 sampling events – Winter/Summer
What can we see?

	Arithmetic mean (ug/m3)	Concetration from gravimetric analysis (ug/m3)	Ratio
Press Op - A	97.3	117.2	1.2
Driver - A	0.4	< 128	
Driver - B	75.7	219.0	2.9
Driver - C	48.0	< 128	
Mobile - A	18.3	< 84	
QC analyst	174.4	265.2	1.5
Mobile - B	113.0	144.0	1.3
Press Op - B	62.3	< 340	
Mobile - C	51.7	459.2	8.9
Driver - D	75.1	218.8	2.9
Driver - E	13.3	< 120	
Mobile - D	23.9	213.8	8.9
Press Op - A	165.1	287.1	1.7
QC analyst	208.9	647.9	3.1
Mobile - E	27.3	166.1	6.1
Driver - A	7.1	< 131	
Driver - F	24.3	< 121	
Driver -G	67.2	294.0	4.4
QC analyst	54.8	266.0	4.9
Driver - C	28.9	< 243	
Driver - E	7.2	< 106	
Driver - H	8.5	< 130	
Press Op - B	116.9	< 114	
Driver - G	19.8	< 79	
Control room	38.2	670.9	17.5
Control room	19.2	< 51	

What about the correction factors?

What can we observe from the data in the table?

- About the possibility to correct the measurement
- About the stability of the ratios (correction factors)?

Real-Time Monitoring as a Risk Communication Tool

Final Considerations

- Sensors, real-time monitors, and direct-reading methodologies can be important tools as industrial hygienists and occupational health and safety professionals. They will have an important role in Industrial/Occupational Hygiene 4.0
- The entire IH/OH community should embrace the "**Right Sensors Used Right**" mindset and responsibilities
- It is paramount to define the objective of any activity which involves a sensor.
- You need to know the aerosol you want to monitor. Aerosol is big category and the selection and adoption of monitoring technology change with the type of aerosol.
- We need still better technologies, better data management and processing systems, proper communication of finding and ethical evaluation
- It essential to remember the smartest sensor is still the industrial/occupational hygienist !!!

Thanks

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For more information, contact CDC
1-800-CDC-INFO (232-4636)
TTY: 1-888-232-6348 www.cdc.gov

	Photometer		Optical Particle Counter	
	Single Channel	Multi-channel	Portable	Handheld
Indoor Air Quality - Conventional Studies	Good	Excellent	Poor	Good
Indoor Air Quality - UF Particle Studies	Poor	Poor	N/A	N/A
Industrial Workplace Monitoring	Excellent	Excellent	N/A	N/A
Outdoor Environmental Monitoring	Good	Excellent	N/A	Good
Emissions Monitoring	Excellent	Excellent	N/A	N/A
Respirator Fit-testing	Good	Good	N/A	N/A
Filter Testing	Good	Good	Good	Excellent
Clean Room Monitoring	Poor	Poor	Excellent	Poor
Pharmaceutical & Semiconductor Clean Room	Poor	Poor	Excellent	Poor
Research and Development	Fair	Good	Good	Fair
Cost Comparison	$	$$	$$	$

Avula, S. and G. Olson (2012). "Advantages of Real-time Measurements in Industrial Hygiene - Real-time Dust Monitoring." AIHA Synergist.