ALPHA FOUNDATION FOR THE IMPROVEMENT OF MINE SAFETY AND HEALTH

Final Technical Report

Project Title:	Integrating real-time personal dust exposure monitoring with location tracking
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1 EXECUTIVE SUMMARY

Personal dust monitoring (PDM) devices record real-time dust exposure levels, but miners' working locations are not tracked along with their associated dust exposure levels. To better predict hazardous exposure levels and to implement dust exposure controls, excessive dust exposure sources must be identified through location monitoring. The objective of this project was to improve the functionality of the PDM by adding geolocation information to the respirable dust exposure monitoring data.

Researchers experimented with a PDM device in the Edgar Experimental Mine to demonstrate the capabilities of the proposed system. For this part of the projet, the location information was initially recorded manually. For a key finding, researchers developed an algorithm to extract minute-by-minute dust exposure data from the Thermo -Fisher PDM3700 unit used in this project. With this algorithm, the PDM data was pre-processed to generate dust concentration values at one-minute intervals. To create a heat map, researchers interpolated the PDM dust concentration values over the data collection route using spline interpolation. The spline interpolation method produced a raster surface corresponding to different color codes based on the recorded dust concentration. After initial tests in the Colorado School of Mines Edgar Experimental Mine, researchers tested the heat map generation part of the system in an active underground coal mine. However, even though this mine was equipped with an Radio Frequency Identification and Detection (RFID) based miner tracking system, due to privacy restrictions, it was not possible to extract location-time data from this system so locations and times had to be collected manually again. To overcome this deficiency and prove the concept, researchers developed a custom miner tracking system. This system uses an algorithm that combines passive RFID localization with Inertial Motion Unit (IMU) sensing and a map matching technique. Researchers then combined tracking information with the PDM data at the Edgar Experimental Mine. The results of the final test show that the combined PDM + RFID/IMU prototype was successful at collecting dust exposure data to generate heat maps to be utilized in implementing mitigation measures for excessive dust exposure. Integrating location with dust exposure information provides miners and mine operators an additional tool that will allow them to identify where the dust overexposures occurred.

In addition, researchers used three different approaches to measure and collect airborne dust for particle analysis and identification of nanometer-sized particles in mine dust. The particle size information is helpful in determining how quickly a given particle will settle to the ground and how long a particle may be carried in the mine ventilation air stream.

The output of this project is a proof-of-concept that is able to accurately identify locations where overexposures to respirable dust occur and visualize them in an easily interpretable way. The study demonstrated that data from any miner tracking system can be used to combine with minute-by-minute PDM exposure data, as long as the tracking system permits the extraction of time and location information. Miners' access to the information provided by the system can increase their awareness of dust overexposures and its effects on health and safety. It can also increase their ability to effectively communicate the dust overexposure sources to the supervisors. Also, the data provided by the developed system can help mine management to take more effective dust control measures.

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2 PROBLEM STATEMENT AND OBJECTIVES

Mine workers continue to suffer from overexposures to respirable dust, with debilitating health consequences that eventually lead to death. Colinet et al. (2010) found the prevalence of coal workers' pneumoconiosis (CWP) to be increasing between 2000 and 2006, showing CWP in almost 8% of underground coal miners who had >25 years of experience. The National Academies (2018) report on "Monitoring and Sampling Approaches to Assess Underground Coal Mine Dust Exposures" documents that, since 2002 and especially since 2010, there have been significant increases in the prevalence of CWP in U.S. miners who have 15 or more years on tenure in underground coal mining. The report urges developing new technologies that enable area monitoring in addition to real-time personal exposure monitoring. CWP is a debilitating, often fatal disease. The U.S. industry currently uses the Thermo Scientific™ PDM3700 personal dust monitor that provides an end-of-shift (EOS) exposure value for the wearer that is used for exposure monitoring and enforcement of dust exposure regulations. In addition to only evaluating EOS exposures, miners' working locations are not tracked so it is difficult to identify locations and times where dust overexposures might have occurred during the shift. As all underground coal mines in the U.S. are equipped with miner tracking systems, combining the PDM with tracking data would enable mine operators to track down sources of dust and use this information to install and maintain dust control systems.

The project objective is to expand and improve the functionality of the PDM by adding geolocation information to the respirable dust exposure monitoring data. This was done as a proof-of-concept. Researchers were able to extract minute-by-minute dust concentration data from the PDM, to combine this time series of dust exposure data with the time series of location data, and to display the information in the form of heat maps that identify dust hotspots.

Full integration of the location sensor – either a GPS unit, RFID or any other miner tracking unit – will be left to a commercial manufacturer. Researchers will use the PDM3700 by Thermo Scientific™. The PDM is well established in the U.S. coal industry and permissible for use in face areas of gassy underground mines.

Integrating location with dust exposure information will improve not only the awareness of respiratory health and dust exposure risks at mining sites to protect miners' health, but also it will provide both miners and mine operators with additional information that will allow them to track where overexposures occurred. Offeror will accomplish this by presenting respirable dust exposure data in a user-friendly, spatial-temporal graphic environment.

The ultimate goal, although not attainable nor intended under the proposed proof-of-concept, is full integration of location sensing into the PDM. With this, mine operators can evaluate the spatial distribution of dust exposure hazards. Through an AI model, operators can then establish administrative and engineering controls to mitigate respirable dust exposures.

The specific aims of the research included the following tasks:

1. Combine a PDM with a location tracking unit to collect dust exposure data and testing the assembly in a surface laboratory environment.
2. Develop a mapping tool to visualize dust exposure locations to improve miners' and management awareness of overexposures to respirable dust.
3. Combine a PDM with an underground miner location tracking system, most likely RFID, and testing the assembly in a laboratory environment.
4. Field-test the PDM + Tracking prototype in Offeror's underground Edgar Experimental Mine using multiple measurement tools.
5. Create an AI model and software using the localization algorithms to extract and combine the time series of dust exposure data, operational environments, and miner activities from the PDM with location information from the tracking system, and to manage the data effectively.
6. Field-test the PDM + Tracking solution in an operating underground coal mine using multiple measurement tools.
7. Quarterly and annual progress reports to the Alpha Foundation. Reporting and publishing the findings of the research in peer-reviewed scientific and technical journals.

In addition to meeting these objectives, the project team also conducted particle analyses of the respirable dust found in the two test mines.

Further, researchers in the Colorado School of Mines Electrical Engineering Department developed an RFID-based miner tracking system and tested it in the Edgar Mine in combination with PDM dust recordings.

3 RESEARCH APPROACH

To meet the project objectives, researchers needed to develop the ability to extract minute-by-minute dust exposure data from the PDM and produce a time series of this data. The time series from the PDM would then be matched with a time series of PDM locations obtrained from a miner tracking device. Fundamentally, any miner tracking device will work with this approach, including recording manually determined locations and times. In this project, researchers used Geographic Positioning Systems (GPS), Radio-Frequency Identification (RFID) and manual tracking.

The PDM3700 reports dust concentrations in 1-minute intervals. Since a miner can easily walk several hundred feet in one minute, precise localization is not necessary for the approach to be successful. For design purposes, researchers determined that a location accuracy of $\pm$20 feet is sufficient to localize sources of dust.

The following steps illustrate the research methodology implemented in this project:

Step 1: Trial runs combining the PDM with a GPS locator

Researchers arranged a PDM3700 unit with a handheld GPS unit to initially prove the dust location and mapping concept. This step is discussed in Section 4.1

Step 2. Dust data collection at the Edgar Experimental Mine.

Researchers generated clouds of mine dust by releasing compressed air from the mine supply lines to produce dust events at pre-arranged times. The clouds were diluted and eventually carried away by arranging the ventilation system accordingly. Researchers also recorded dust particle sizes and size distributions as this determines how far a given dust particle is carried in the ventilation air stream before it settles to the ground.

Step 3. Pre-Processing of PDM Data

PDM Data were downloaded by downloading the PDM data to a PC using the manufacturer’s software. The software produces an output file in MS Excel format. Typically, the PDM only produces 30-minute average dust exposures anlong with a projection of the end-of-shift (EOS) dust exposure that must be recorded for compliance purposes. However, the PDM also produces minute-by-minute oscillating frequencies of the Tapered-Element, Oscillating Microbalance (TEOM) that senses the instantaneous dust loading. From this, researchers developed a pre-processing algorithm to generate dust exposure levels for each minute. PDM Data Processing is discussed in Section 4.3

Step 4. To develop a tool to generate heat maps of dust exposures (Task 2), researchers developed a data interpolation and visualization tool using the spline method. Details of the data interpolation are discussed in Section 4.4.

Step 5. Testing the visualization tool in an active mine.

Researchers tested the methodology and data visualization at the West Elk Mine in Colorado, an underground longwall coal operation, discussed in Section 4.5.

Step 6. Dust Particle Analysis.

Researchers also collected and analyzed mine dust particles from the Edgar Experimental Mine as well as From the West Elk Coal Mine to identify particle size distributions – this is discussed in Section 4.6.

Step 7. Developing and testing an RFID based location tracking system.

Because extracting location data from a commercial miner tracking system proved to be difficult due to confidentiality concerns, the research team designed, built and tested its own RFID-based tracking system and tested in inside the Edgar Experimental Mine. Detailes are provided in Section 4.7.

4 RESEARCH FINDINGS AND ACCOMPLISHMENTS

4.1. Initial PDM experiment with location tracking and data visualization at the surface

Researchers experimented with PDM and GPS around the Colorado School of Mines campus. The PDM records a single data point per minute and generates a time-series of location data, similar to a miner tracking system. Researchers acquired a Garmin Montana 610 GPS unit and configured it to deliver location readings at 1-minute, fixed time intervals. Figure 1 shows a sample of the time – location series along with a map sketch:

Time	Position		
16:34:00	N39° 45.016' W105° 13.274'		
16:35:00	N39° 45.015' W105° 13.275'		
16:36:00	N39° 45.013' W105° 13.277'		
16:37:00	N39° 45.013' W105° 13.278'		
16:38:00	N39° 45.013' W105° 13.281'		
16:39:00	N39° 45.014' W105° 13.285'		
16:40:00	N39° 45.014' W105° 13.291'		
16:41:00	N39° 45.001' W105° 13.295'		
16:42:00	N39° 44.998' W105° 13.296'		
16:43:00	N39° 45.015' W105° 13.294'		

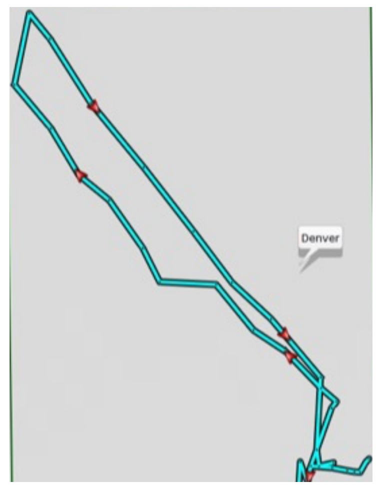


Figure 1: Sample time and location data from GPS with map sketch (not to scale)

This experiment was conducted to confirm that any series of time and location data was suitable to match with PDM exposure data to generate a location-time series of dust exposures. Coordinates acquired from GPS were interpolated to obtain the location information at the time PDM records the data. PDM readings with location are given in Figure 2 where blue to red color indicates dust exposure level C(i) in mg/m^3. Note that the higher dust exposures were recorded near a building construction site on the campus which was clearly identifiable with higher dust concentrations. Researchers also noted that the PDM was capable of recording dust levels in the range of 0.02 to 0.1 mg/m^3, i.e. much lower than typical respirable dust concentrations in an underground mine atmosphere.

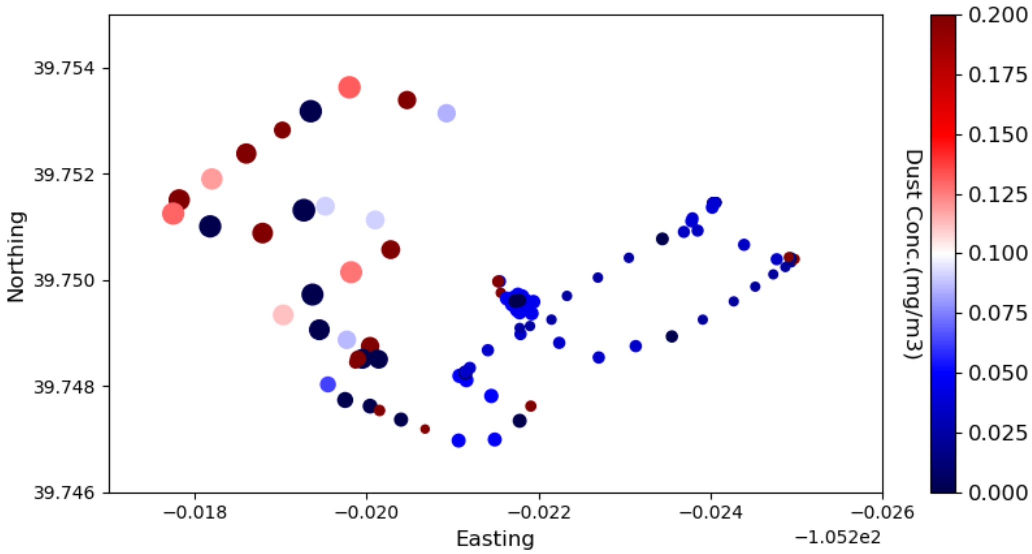


Figure 2. Dust concentration values with location tracking walking along campus roads.

Size of the points indicates the cumulative dust concentration values. As a second trial, a three-dimensional visualization of the same data is generated using the cumulative dust concentration values (Figure 3.). The surface is created with the triangulation of existing data points. Locations with high cumulative dust concentration values correspond to triangles with higher elevation in the graph. These locations are near the active construction site and clearly document higher exposure levels.

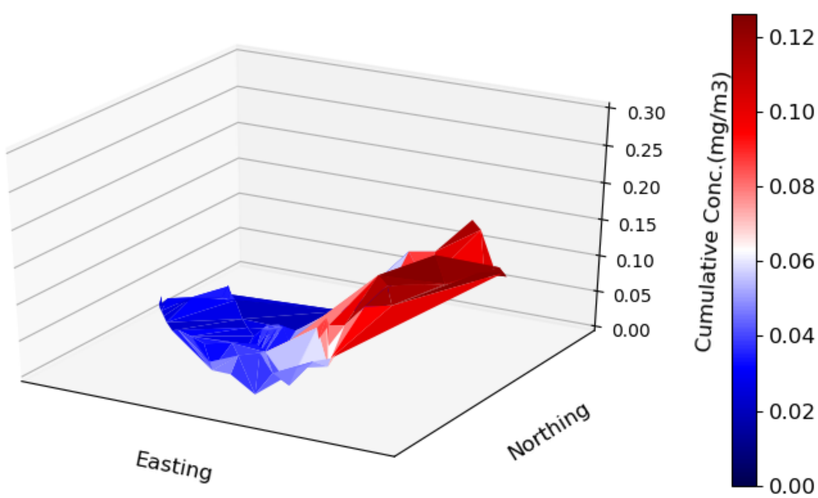


Figure 3. Initial 3-D visualization of cumulative dust concentration values

This initial experiment with GPS and the PDM at surface locations confirmed that it is possible to “marry” the time series of location data extracted from the GPS unit with the time series of dust concentration data retrieved from the PDM. Researchers have refined the data visualization in the form of heat maps, as shown in the following sections.

4.2. Mine dust data collection experiments at Edgar Mine

The NIOSH Dust Control Handbook (Cecala, 2019) defines mine dust as small solid particles created by the breaking up of the larger particles. When suspended in air, these particles will become hazardous to workers' health depending on their size. Particles ranging from 2 to 60 µm remain suspended in the air for longer periods and may be inhaled by miners working underground. Dust particles <10 µm are considered "respirable". ISO 7708-1995 and the American Conference of Governmental Industrial Hygienists (ACGIH) determined the respirable criterion for dust with D_{50} = 4 µm. Furthermore, based on 30 CFR §70.100, the Mine Safety and Health Administration (MSHA) mandates a permissible exposure limit for respirable dust of 1.5 mg/m^3, averaged over an 8-hr shift, to prevent adverse health effects among miners. MSHA requires measurement of respirable dust by an approved continuous personal dust monitor (CPDM) for all underground miners exposed to respirable dust.

Currently, there is one available commercial instrument that has been approved as a CPDM, Thermo Scientific^{TM} PDM3700, which incorporates a real-time particulate monitor to measure respirable dust mass concentration, end-of-shift exposure, and accumulated exposure in real-time (Halterman, 2018). It uses a tapered element oscillating microbalance (TEOM) to measure continuously the mass of collected particles. Airflow enters the PDM through a cyclone, drawn into a heated flow tube to be heated, then flows into mass transducer where the particulate matter is deposited onto the TEOM. After this, the air flows through temperature, relative humidity, and differential pressure sensors, and finally, through the pump to exit the system (Thermo Scientific, 2016). The PDM3700 maintains a constant volumetric flow rate of ~2 L/min and reports the sample volumes in volumetric terms based on ambient temperature as measured near the cyclone.

Researchers experimented with PDM3700 in the Edgar Experimental Mine to demonstrate the capabilities of the proposed system. Since the geolocation and tracking capability of the system was still in the development stage at that time, location information was collected manually. We marked the locations and the times while the PDM recorded dust data from intentional dust releases in the mine. The dust is created artificially by blowing compressed air in mine entries. The reason behind this is that since the Edgar Mine is not an operating mine, dust levels are usually low. The locations where the PDM recorded dust readings in the Edgar Mine were acquired by matching the time readings of the PDM and manual location tracking. The route of PDM data collection locations in the Edgar Mine is shown in Figure 4.

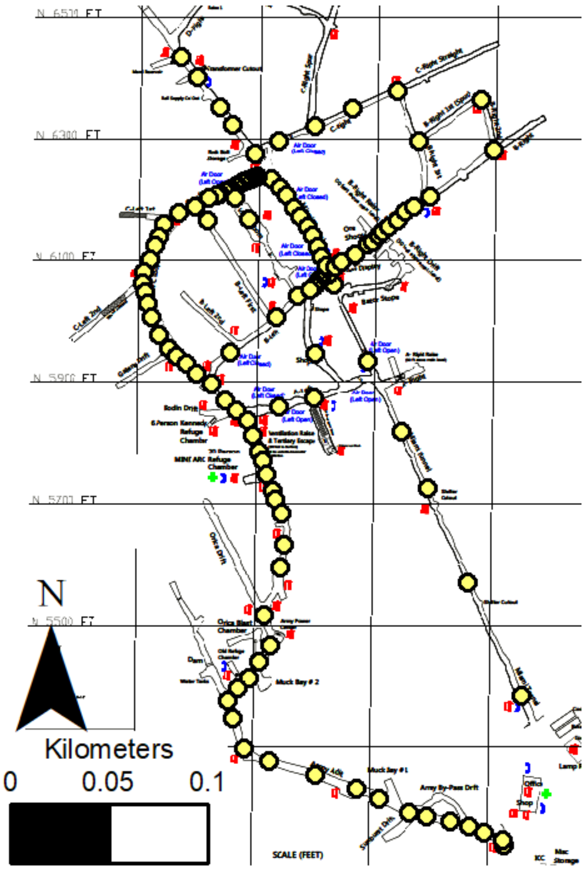


Figure 4. Data collection route at Edgar Mine

4.3. Pre-Processing of PDM Data

The PDM outputs are in the form of the previous 30-min average dust concentration, cumulative mass concentration to that point in time, and an estimated end-of-shift (EOS) projected concentration exposure. These output modes are not suitable for the purposes of this research, since the objective is to precisely identify the locations where the high dust exposure occurs. In order to detect high-exposure locations in a way that accounts for the mobility of the personnel, the dust concentration values per minute needed to be calculated. In this section, the pre-processing of the PDM data to obtain dust concentration per minute values is explained.

The PDM3700 samples, analyzes, and calculates the mass-based concentration of the respirable dust. The illuminated data display on the top of PDM3700 continuously shows the previous 30-min average dust concentration (as default setting), cumulative mass concentration to that point in time, and an estimated end-of-shift (EOS) projected concentration exposure (MASS1 TOTAL).

Figure 5 shows a sample PDM output. The 30-minute averages and MASS1 TOTAL EOS projections are updated in the PDM each minute. These values are also shown in the display at the top of the PDM unit so that the wearer is made aware of his/her current dust exposure and EOS projection if the exposure continues. NIOSH developers viewed the 30-minute average and the EOS projection as more useful information than instantaneous dust readings. Also, the PDM applies internal corrections, for example, if dust mass is lost from the TEOM due to a bump of the unit. Finally, the TEOM will not update MASS1 TOTAL unless the change in TEOM frequency is significant with respect to the accuracy of the TEOM, 0.01 mg.

Time	STATUS COI	AIR HEATER	TE HEATER I	TE HEATER '	AMBIENT P	DIFFERENTI	FLOW RATE	AMBIENT TI	BATTERY VC	MASS FREQ	MASS1 TOT	30 Min Con	Cum1 Conc	Shift Conc
8/1/19 07:33		29.74371	21.70549	46.04703	595.8821	-39.001	2.199668	28.60796	1.806641	296.3792	0.02169	0.313273	0.247675	0.020566
8/1/19 07:34		29.74371	21.70549	46.04703	596.3624	-39.0865	2.199668	28.60796	1.806641	296.3787	0.02169	0.302289	0.247675	0.020566
8/1/19 07:35		29.74371	21.70549	46.04703	596.6954	-39.4516	2.199668	28.7619	1.806641	296.3781	0.02169	0.302289	0.247675	0.020566
8/1/19 07:36		28.5101	20.68512	46.04703	594.4265	-39.4516	2.199668	28.7619	1.906738	296.3783	0.02169	0.302289	0.247675	0.020566
8/1/19 07:37		28.5101	20.68512	46.04703	593.212	-39.816	2.199668	28.91183	1.767578	296.3777	0.02169	0.289077	0.247675	0.020566
8/1/19 07:38		28.5101	19.45487	46.04703	593.2733	-40.0869	2.199668	28.91183	1.90918	296.3775	0.02169	0.289077	0.247675	0.020566
8/1/19 07:39		27.31726	19.45487	46.04703	593.8743	-40.6113	2.199668	29.08212	1.90918	296.3764	0.02169	0.276343	0.247675	0.020566
8/1/19 07:40		27.31726	19.45487	46.04703	594.0901	-41.4089	2.199668	29.08212	1.90918	296.3751	0.02169	0.276343	0.266519	0.020566
8/1/19 07:41		27.31726	19.45487	46.04703	594.6779	-42.238	2.199668	29.25606	1.90918	296.3741	0.02169	0.276343	0.266519	0.020566
8/1/19 07:42		27.31726	18.12956	46.04703	594.9503	-43.0406	2.199668	29.25606	1.90918	296.3733	0.02169	0.276343	0.277367	0.020566
8/1/19 07:43		26.19326	18.12956	46.04703	595.274	-43.8606	2.199668	29.42237	1.90918	296.3726	0.02169	0.276343	0.277367	0.020566
8/1/19 07:44		26.19326	18.12956	46.04703	595.1159	-44.9092	2.199668	29.42237	1.90918	296.3713	0.02169	0.276343	0.291169	0.020566
8/1/19 07:45		26.19326	18.12956	46.04703	595.4066	-45.5352	2.199668	29.58893	1.90918	296.3705	0.02169	0.276343	0.291169	0.020566
8/1/19 07:46		26.19326	18.12956	46.04703	595.5311	-45.9717	2.199668	29.58893	1.90918	296.372	0.02169	0.276343	0.269882	0.020566

Figure 5: Sample PDM output data with key columns highlighted

To relate dust exposures to locations and to identify locations of high exposure requires better precision that the 30-minute averages. For example, a miner may walk a mile of belt entries or return airways in 30 minutes, where the raw PDM data will not provide sufficient information about exposure locations. This also became clear when researchers walked the belt line in the West Elk mine, see Section 4.5 Therefore, researchers developed an algorithm to compute dust concentrations per 1-minute interval, as follows:

The dust mass calculation is based on the change in frequency of the TEOM. 1-min mass concentrations are determined by dividing the mass collected on the PDM3700 filter by the sampling volume (sampling time multiplied by the pump flow rate; Equation 1).

$$Respirable\ dust\ conc.(mg/m^3) = \frac{Net\ dust\ weight\ (mg)}{Sample\ time\ (\text{min})\cdot pump\ flow\ rate(l/min)} \times \frac{1{,}000\ l}{1m^3} \qquad \text{(Eq. 1)}$$

Thermo Scientific provided researchers with a deeper understanding of how the PDM records data and calculates cumulative dust concentration (Cum1 Conc), shift concentration (Shift Conc), and 30-minute average values. Calculation of minute-by-minute dust values requires the calibration constant (K_0) (Equation 2). K_0 is a unit-specific system constant in the PDM that cannot be changed by the user.

$$K_0 = \frac{MASS1\ TOTAL_{final}}{\left[\left(\frac{1}{Mass\ frequency_{final}^2}\right) - \left(\frac{1}{Mass\ frequency_{initial}^2}\right)\right]} \qquad \text{(Eq.2)}$$

The K_0 value is used in the re-calculation of the MASS1 TOTAL values. Since our re-calculation considers the small changes in Mass Frequency values, more sensitive MASS1 TOTAL values are obtained (Equation 3).

$$MASS1\ TOTAL_{i+1} = K_0\left[\frac{1}{Mass\ frequency_{i+1}^2} - \frac{1}{Mass\ frequency_i^2}\right] \quad \text{(Eq. 3)}$$

Due to internal inaccuracies with the mass frequency values, erroneous values of MASS1 TOTAL are sometimes obtained such as decreasing or negative values. However, these values should not be possible since MASS1 TOTAL represents the amount of dust collected on top of the filter. Therefore, theoretically, MASS1 TOTAL values can only remain constant or increase during a shift. For that reason, MASS1 TOTAL values are only updated if the result of Equation 3 is larger than that for the previous minute.

Since MASS1 TOTAL values are calculated each minute, dust concentration per minute can be calculated with the following Equation 4;

$$Dust\ Concentration\ Per\ Minute\ (\frac{mg}{m^3}) = \frac{MASS1\ TOTAL_i - MASS1\ TOTAL_{i-1}}{Flow\ Rate}\ x\ 1000 \quad \text{(Eq. 4)}$$

Calculation of other useful dust concentration values is given in Equations 5-7.

$$30Min\ Concentration\ (\frac{mg}{m^3}) = \frac{\sum_i^{i+30} MASS1\ TOTAL_i - MASS1\ TOTAL_{i-1}}{\sum_i^{i+30} Flow\ Rate}\ x\ 1000 \quad \text{(Eq. 5)}$$

$$Cumulative\ Concentration\ (\frac{mg}{m^3}) = \frac{MASS1\ TOTAL_i}{\sum_1^i Flow\ Rate}\ X1000 \quad \text{(Eq. 6)}$$

$$Shift\ Concentration\ \left(\frac{mg}{m^3}\right) = \frac{MASS1\ TOTAL_i}{\sum_1^{final} Flow\ Rate}\ x\ 1000 \quad \text{(Eq. 7)}$$

Dust concentration values from the PDM are shown in Figure 6. 30-Min average values are obtained from the PDM, while the concentration per minute values were calculated using Equation 3.

The first three compressed air blows did not create much measurable dust because the mine floor was too wet. Therefore, the PDM was moved to a different location. The fourth compressed air blow in the new location created significantly more measurable dust. At t = 170 minutes, the mine exhaust fan was started to clear the dust from the entries. The dust concentration declined sharply after the area was ventilated. This test illustrates the relationship between the 30-min average concentration and the instantaneous concentration per minute values in relation to the timing of high and low dust concentrations generated.

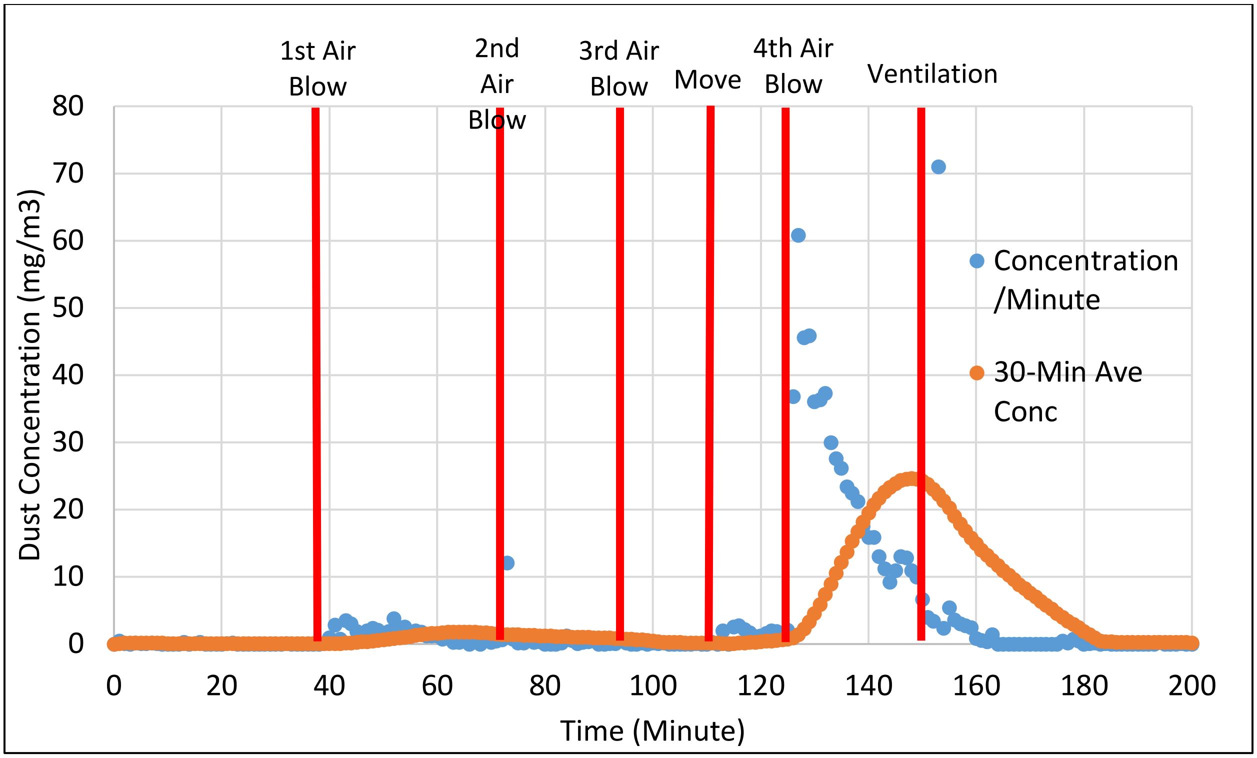


Figure 6. PDM Output, blue dots for instantaneous and orange dots for 30-min average dust concentrations. Red vertical bars mark instances of dust releases.

4.4. Spline Data Interpolation

To create a heat map, researchers interpolated the PDM dust concentration values over the data collection route using spline interpolation. Spline estimates values using a mathematical function that minimizes the overall surface curvature. This results in a smooth surface that passes exactly through the input points (Childs, 2004).

A standard spline interpolation produces a raster surface over a specific geographic space. However, dust concentration events should be analyzed in terms of areas inside the network structure since, in underground mines, dust clouds can only occur along the network of mine entries. Therefore, the interpolation of dust concentration values should be limited to the grid of cells that belong to the Edgar Mine drifts. This approach prevents the interpolation calculations outside the mine entries. In this study, the Edgar Mine drift network is obtained by creating a polygon feature that follows the data collection route (Fig. 7).

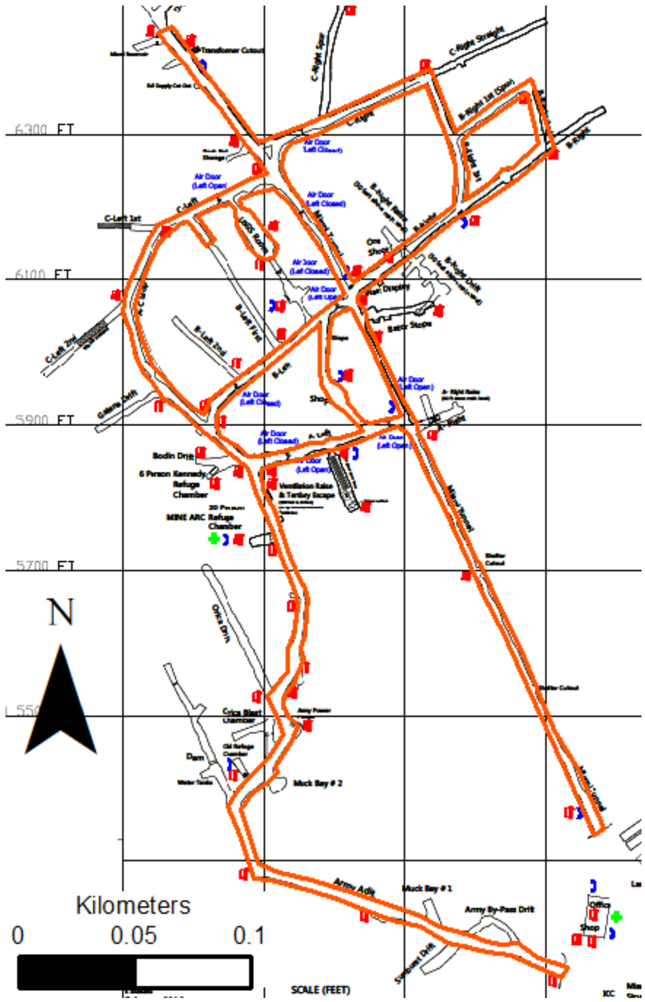


Figure 7. Edgar Mine drift areas used in spline interpolation of dust concentration data

In this study, researchers used the “Spatial Analyst” toolbox available in ESRI’s ArcGIS software to apply spline interpolation on dust concentration values (ESRI, 2019). In spline interpolation, the choice of output cell size is important since this parameter controls how smooth the results will be. For this study, after obtaining interpolation results for several cell sizes, a cell size of 0.15 m resulted in the most effective smoothing of dust concentration values. Figure 8 shows the result of spline interpolation. These results represent the end of shift dust exposure of a person if s/he stays in that location for a full 8-hour shift.

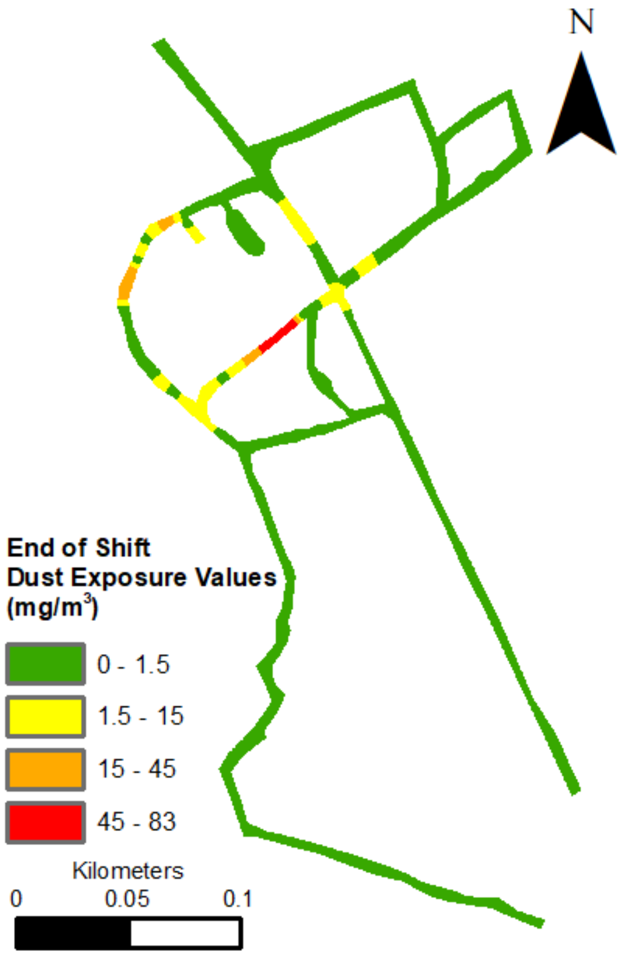


Figure 8. Heat Map generated using spline interpolation of respirable dust data. Note that dust concentrations were intentionally exaggerated for testing purposes. No persons were exposed to these high dust concentrations.

The result of the spline indicates low dust concentration for most of the Edgar Mine. Several locations exhibit dust concentrations above 1.5 mg/m^3. Location mapping documents several distinct areas with high dust concentrations. In comparison, the PDM-only, time-series data in Figure 6 only reveals a single peak of dust concentrations.

4.5. Testing the Dust Visualization Tool in an Active Coal Mine

Researchers tested the heat map generation part of the dust exposure monitoring system in West Elk Mine located in Somerset, CO. The West Elk Mine is an active underground coal mine. The researcher visited the mine on May 6th, 2021. The dust concentration values were collected with two PDM devices. The PDM data was collected on a pre-determined path inside the mine (Figure 9). Although locations were being tracked with a reverse-RFID miner tracking system, the system does not permit extracting the time-location data for confidentiality reasons. Researchers tracked locations manually by recording the distances walked for each minute of the test.

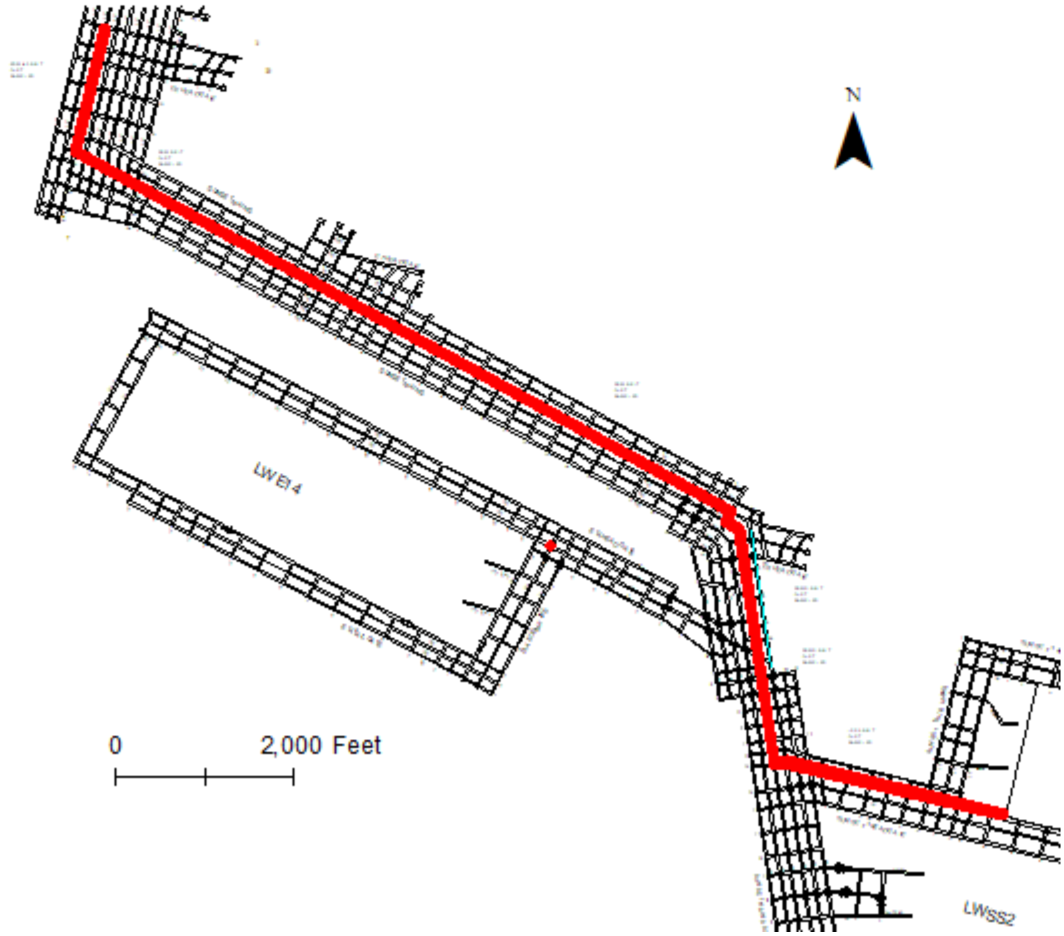


Figure 9. Data collection route at West Elk Mine

Two people carried the PDM devices A and B. They walked on the pre-determined path west to east along the belt conveyor heading, maintaining a ~200 ft distance between them. PDM data was analyzed and processed in the same manner as the data collected in Edgar Experimental Mine. The comparison of the dust concentration values collected by the two PDMs are shown in Figure 10.

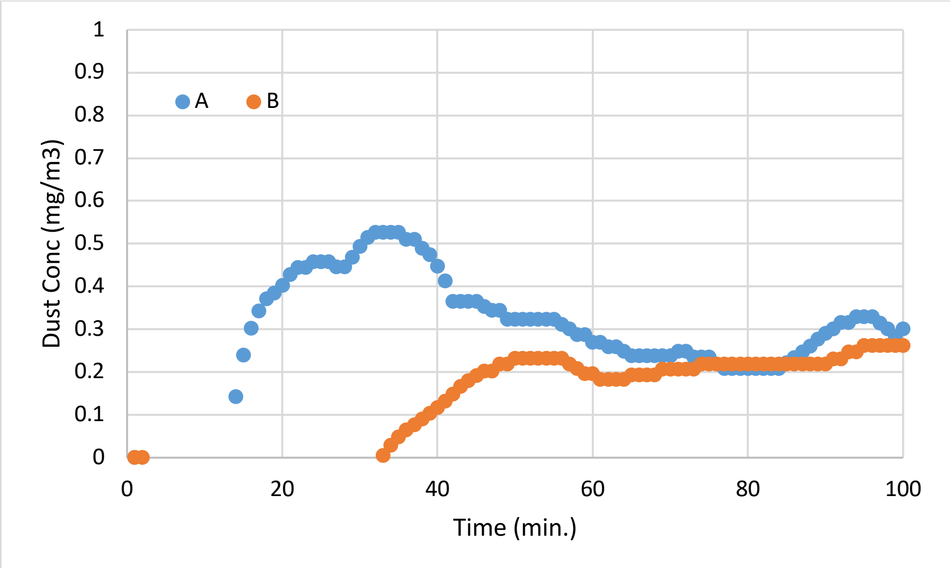


Figure 10. 30-min average dust concentrations at West Elk Mine

30-min average dust concentration value is the average dust concentration recorded by the PDM within the last 30 minutes. PDM A was always ~200 ft in front of the PDM B. Even though the distance between the devices was not large, different dust concentration trends were recorded by the two devices because miners kicked up dust that was carried in the ventilation airstream. Therefore, PDM A recorded much higher dust concentration values than PDM B and PDM A data were used to generate the heat map.

The PDM output was converted to dust concentrations per minute using Equation 4. Figures 11 and 12 show the dust concentration per minute values.

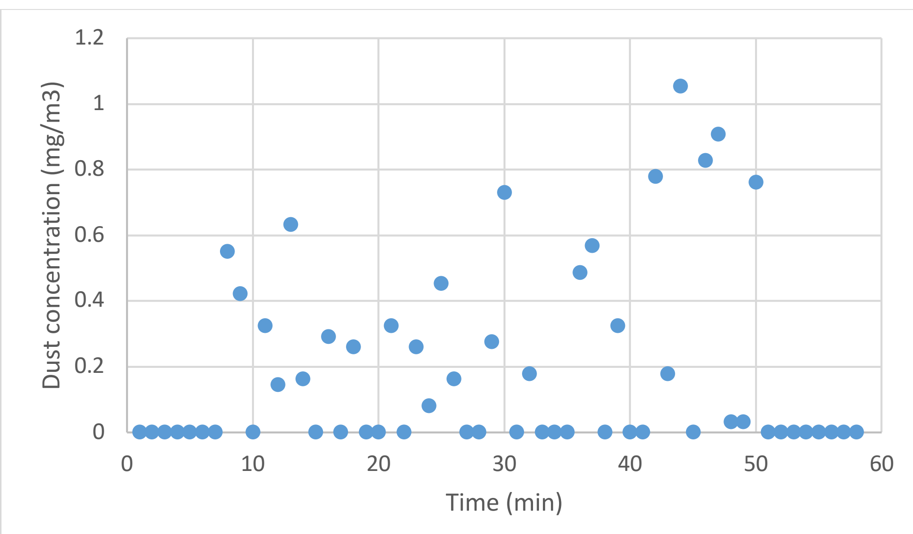


Figure 11. Dust concentration, PDM-A, per-minute values, at West Elk Mine

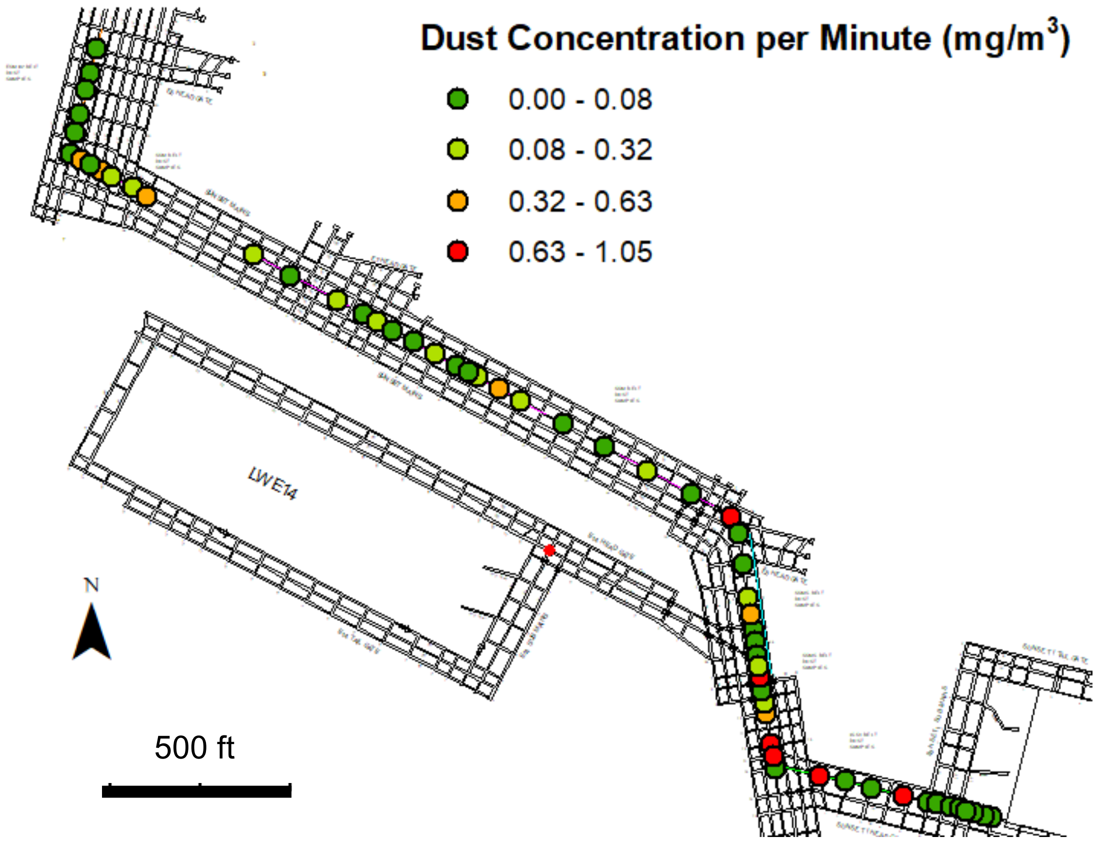


Figure 12. Dust concentration per PDM A, per-minute-interval ranges, at West Elk Mine

Figures 11 and 12 show that the dust concentration values are usually low in West Elk Mine. Instantaneous concentrations approached ~1 mg/m^3 several times as the researchers got closer to the face. It is evident from the location recordings that dust concentrations increase near the belt transfer points and downwind from the transfers. Note that mine ventilation airflow in this belt heading was from west to east, i.e. towards the face. Using the dust concentration per minute values, researchers generated the heat map in Figure 13 using the spline interpolation tool.

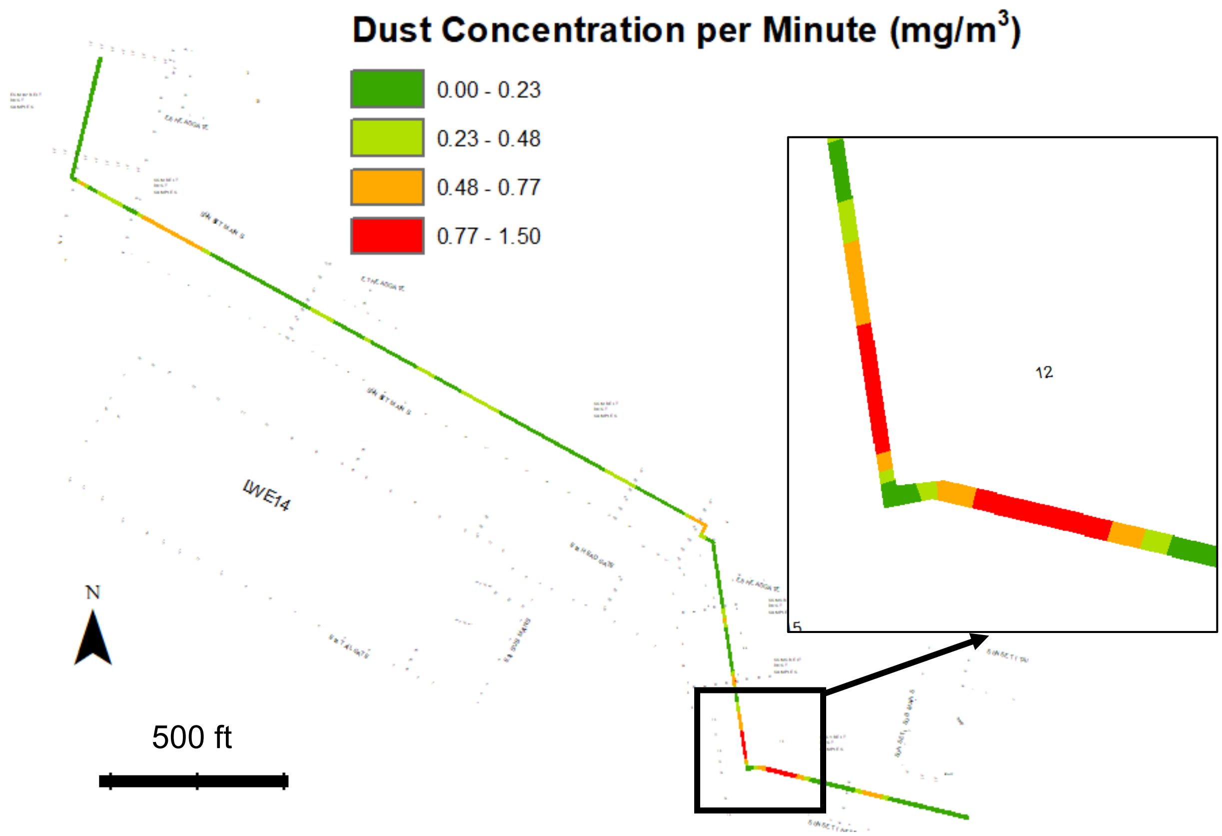


Figure 13. Heat map for dust concentration per minute values at West Elk Mine

4.6. Respirable dust particle analysis

Researchers used three different approaches to measure and collect airborne dust and particles at the West Elk Coal Mine for this study. Three approaches include using (1) personal dust monitor (PDM) for measuring respirable sized particles mass concentration and direct reading real-time instruments (RTIs) for measuring particle number concentrations, (2) the diffusion sampler (TDS), a newly designed sampling device for collecting nanoparticles and electron microscopy analysis, and (3) National Institute for Occupational Safety and Health (NIOSH) Manual of Analytical Methods (NMAM) 0501/0500 for dust collection.

4.6.1. Airborne particle measurements

Two PDMs were used to monitor dust mass concentrations at two researchers for breathing zone concentrations. Direct RTIs including a NanoScan scanning mobility particle sizer (NanoScan SMPS) and an optical particle sizer (OPS) were used for concentration measurements at the area location. These two instruments measure particle size ranges of 10–420 nm and 0.3–10 μm, respectively, and provide the size-fractionated particle number concentration with a 1 min response time. The NanoScan SMPS was operated at a flow rate of 0.9 L/min, and the OPS was operated at a flow rate of 1.0 L/min. The size distribution data of airborne particles measured from RTIs were analyzed.

4.6.2. Sampling using TDS

The TDS is a sampling method designed for respirable and nanoparticle collection (Tsai and Theisen 2018; Tsai et al. 2018). It has features to efficiently collect particles in low concertation environments or for short term sampling when the particle mass often is below the limits of detection of other methods. The sampling substrates were a silicon oxide filmed TEM grid and a 25-mm diameter 0.22-µm pore size polycarbonate membrane filter (Millipore, Billerica, MA, USA) with the grid attached at the center and away from center of the filter, and TDS was operated at a flow rate of 2 L/min. One polycarbonate filter and two TEM grids were used to collect particles for each sample. Three samples were collected, one at the area location, away from the belt and close to the man entrance, two samples were collected at two researchers' breathing zone by attaching the samplers at the top chest area of the vest. All filters were weighed before and after the experiments to obtain the total mass concentrations and were kept sealed until the microscopic analysis. Particles collected on the filter and on the grid using TDS were analyzed separately. Particles collected on the polycarbonate filters were analyzed through scanning electron microscopy (SEM) (JSM-6500F, JOEL, Peabody, MA, USA) and attached EDS (model 51-XMX1015, Concord, MA, USA) at 15 kV to determine particle characteristics and elemental compositions. The grids were analyzed with TEM and EDS at 200 kV.

4.6.3. Particle Counting Method NMAM 0500/0501

NMAM 0500/0501 is a method used for particulates not otherwise regulated for total aerosol mass. We refer to this method to collect dust and evaluate the mass concentrations in comparison with the TDS method. Three samples were collected side by side with TDS sampling, one at the area location, away from the belt and close to the man entrance, two samples were collected at two researchers' breathing zone by attaching the samplers at the top chest area of the vest.

The sampler includes a two-piece 37-mm close face cassette and a 5 µm PVC membrane filter operated at a 2 L/min flow rate for particle collection. The PVC filters were pre-weighted and post-weighted to obtain the mass concentrations.

4.6.4. Sampling Procedure and Locations

The area sampling was taken adjacent to the worker entrance into the belt area. Two RTIs for particle counting, one TDS and one 37 mm cassette were placed on an object which was approximately 4 ft height above the ground for sampling and measurement. The air inlets to the sampling tube were facing the belt side. PDM, TDS and 37 mm cassette were placed on researchers for measuring and collecting particles while researchers were walking along the belt from the entrance to the face area. Measurements and collections were taken approximately 90-100 minutes.

4.6.5. Particle Analysis Results

Dust collected on the filters of TDS and 37 mm cassettes were visibly seen as shown in Figure 14. Images in Figure 14a - 14c are filters on TDS samplers, and Figure 14d include 3 PVC filter samples of 37 mm cassettes. Sample 1 taken at the area location was found to have less dust collected compared with the personal breathing zone samples taken at two researchers while walking along the belt area.

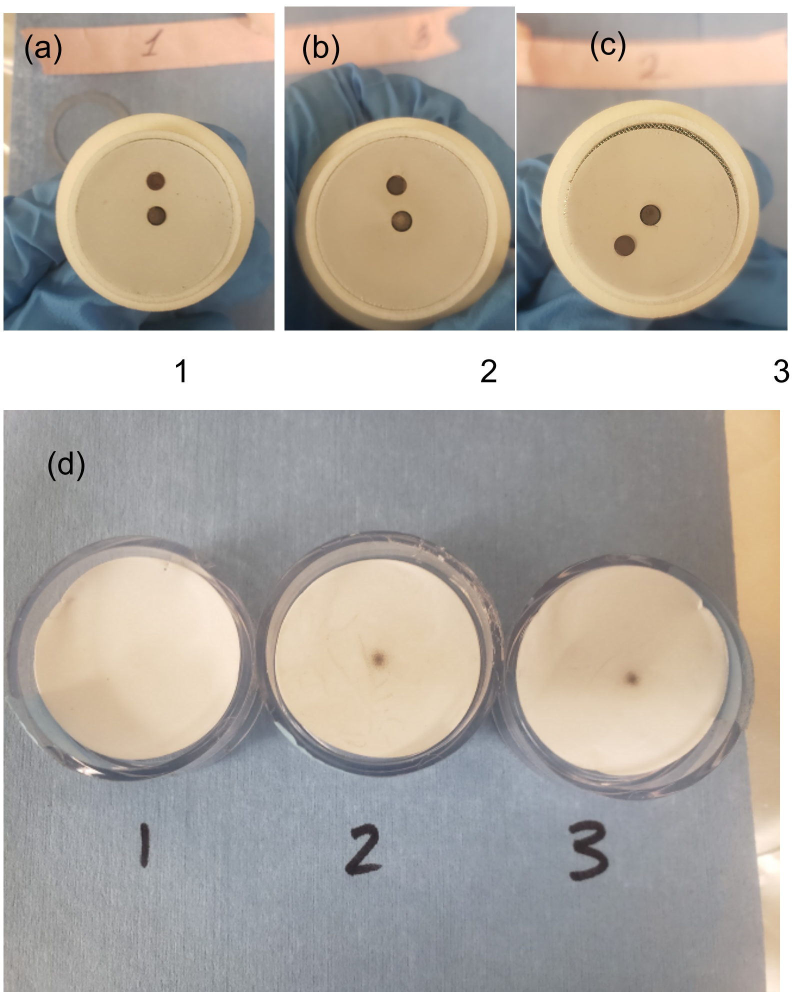


Figure 14. Photos of filters after collecting dust at West Elk Mine. a) Area sample by TDS, b) breathing zone sample by TDS on researcher one, c) breathing zone sample by TDS on researcher two.

The mass concentration and collected dust information are listed in Table 1. The mass concentrations at breathing zones (BZ) were much higher than the mass concentration measured at the stationary area location. The average BZ mass concentrations were found to be around 1.21 mg/m^3 for TDS and 1.16 mg/m^3 for PVC filter sampling.

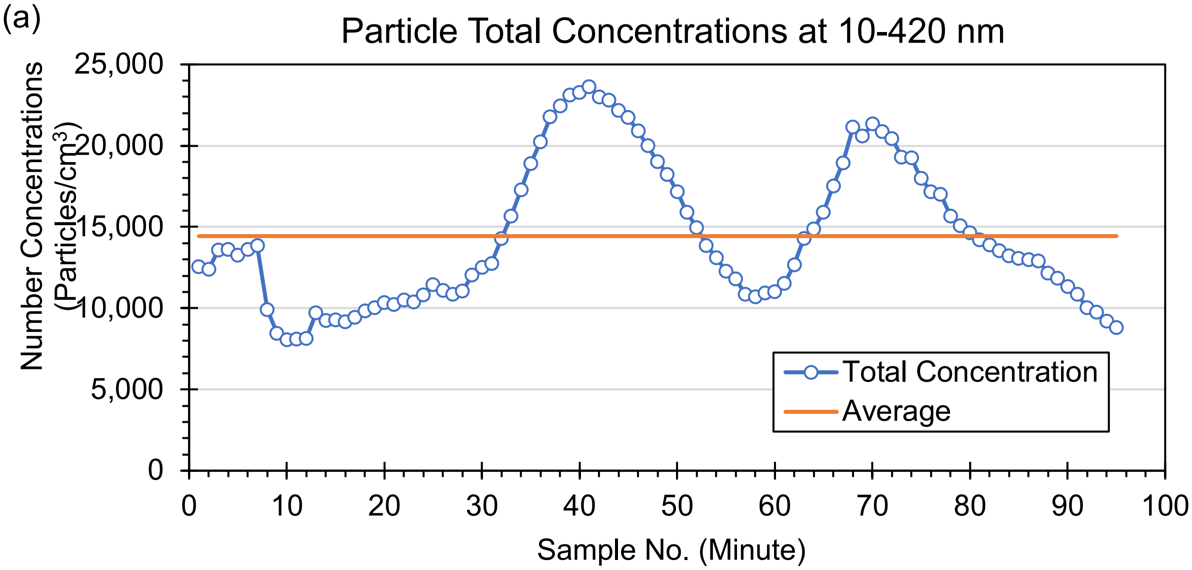
Table 1. Mass and mass concentrations of dust collected on filter samples, for two filter types

TDS PC Filter.					
Sample		**Mass (mg)**	**Sampling time (min)**	**Flow (L/min)**	**Mass C (mg/m³)**
1-Area	Avg	0.0900	97	2	0.464
	STD	0.0000	97	2	±0.0000
2-BZ	Avg	0.1600	97	2	0.825
	STD	0.0141	97	2	±0.0729
3-BZ	Avg	0.295	92	2	1.60
	STD	0.0071	92	2	±0.0384
37 mm PVC filter					
Sample		**Mass (mg)**	**Sampling time (min)**	**Flow (L/min)**	**Mass C (mg/m³)**
1-Area	Avg	0.0450	97	2	0.232
	STD	0.0212	97	2	±0.109
2-BZ	Avg	0.203	97	2	1.05
	STD	0.0252	97	2	±0.13
3-BZ	Avg	0.233	92	2	1.27
	STD	0.0306	92	2	±0.166

Particle number concentrations measured by RTIs NanoScan SMPS and OPS, are presented in Figure 15 for the total concentrations during the entire measurement period, and in Figure 16 for showing the size-fractioned particle number concentrations. The total particle number concentrations of sub-micrometer sized particles (10-420 nm) were found to range from about 8,000 particles/cm^3 to above 24,000 particles/cm^3 during the entire measurement period. The average concentration was about 14,500 particles/cm^3 as seen in Figure 15a. Particles above 0.3 μm in sizes were found a lot more during this measurement, the total particle concentrations ranged from 20,000 to 200,000 particles/cm^3. Although micrometer sized particles are much more than the submicrometer sized particles from this measurement, the concentrations of submicron are multiple times higher than typical indoor environment, which are about 5,000 particles/cm^3.

Majority of particles < 420 were found in sizes of 100-200 nm as seen in Figure 16a. Particles in the range of 03-10 μm were mostly smaller than 0.5 μm according to data shown in Figure 14b. All data have shown that a large amount of submicron meter sized particles were found in this underground coal mine at the location nearby the entrance and away from the belt.

(a)



(b)

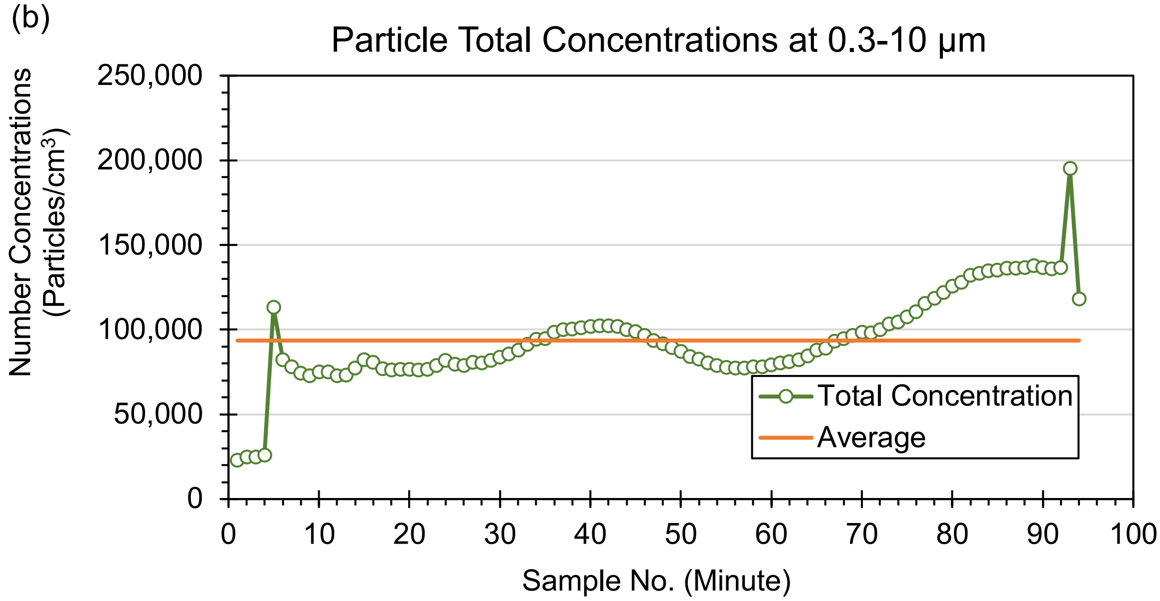
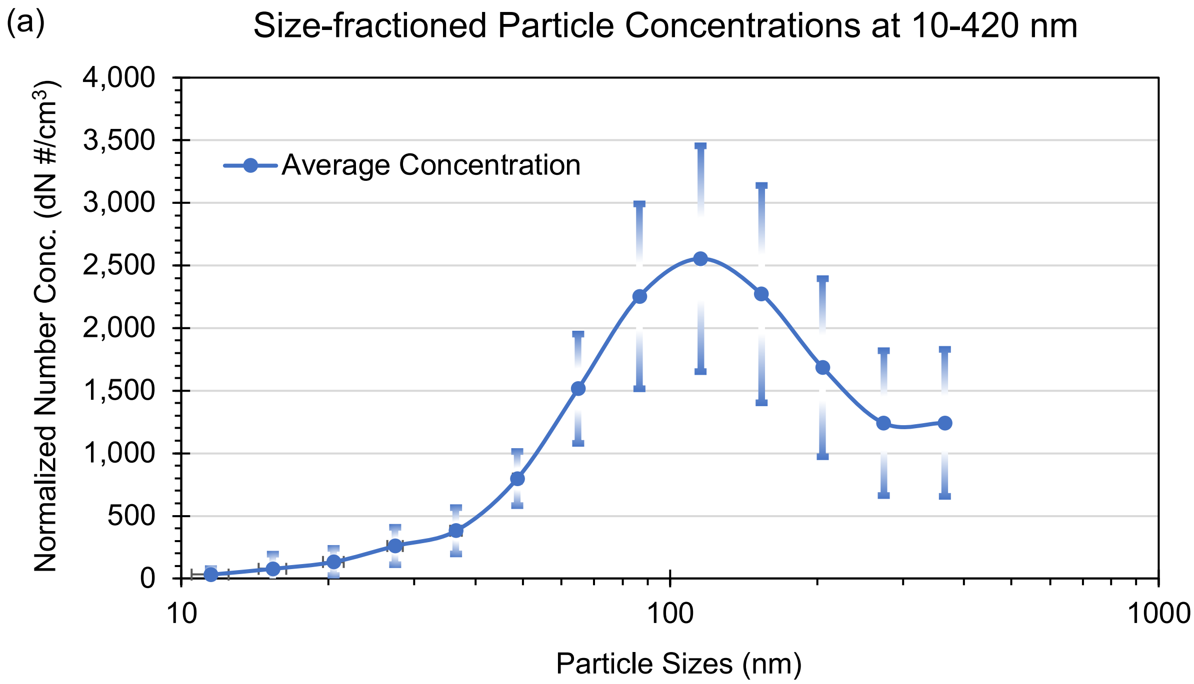


Figure 15. Particle total number concentrations during the entire measurement period. a) Concentration of particles sizes in 10-420 nm measured by NanoScan SMPS, b) Concentration of particle sizes in 0.3-10 μm measured by OPS.



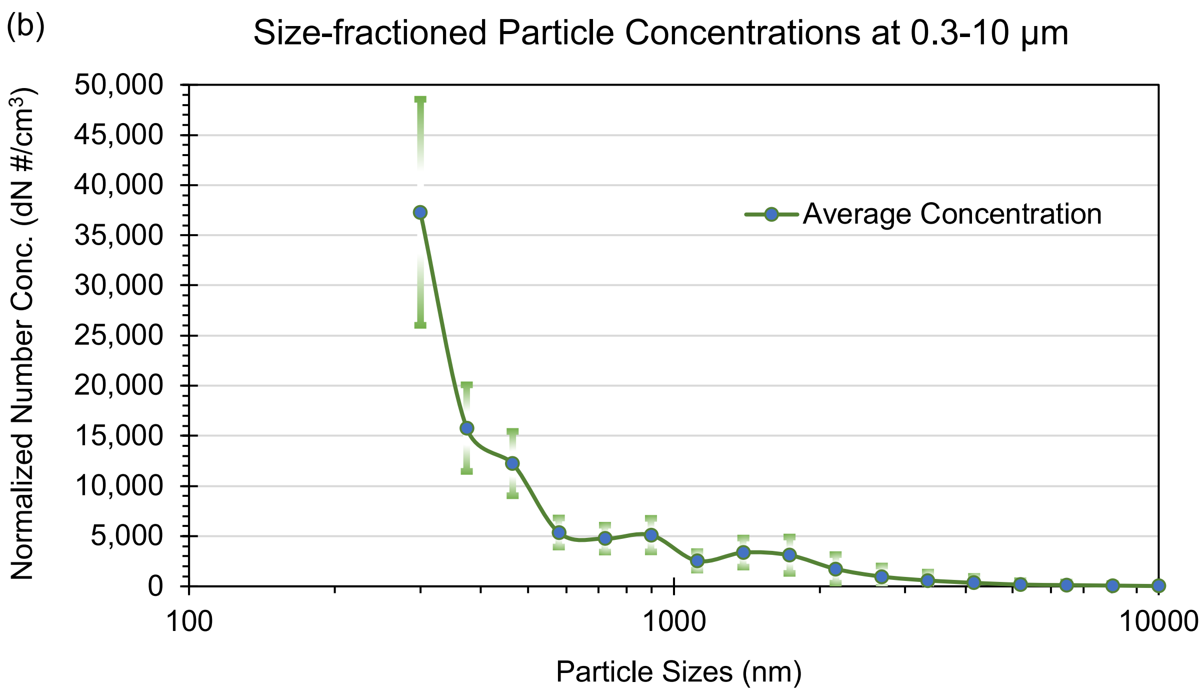


Figure 16. Particle size-fractioned number concentrations showing average concentration of the entire measurement period and the deviations. a) Particles sizes in 10-420 nm measured by NanoScan SMPS, b) Particle sizes in 0.3-10 µm measured by OPS.

To further prove the existence of sub micrometer sized particles in the air at this site. The collected particles on the polycarbonate filters and TEM grids of TDS samplers were analyzed and shown in Figures 17 and 18. Particles in all the sizes shown in the RTI measurements were clearly seen on Figure 17b. The sub micrometer and nanometer sized particles were seen with arrow marks as examples on Figure 17d with an image under a magnification of ×20,000. Particles at the area location were much less than those found in the BZ samples as seen with comparison on images between Figure 17a to 17b and 17c to 17d.

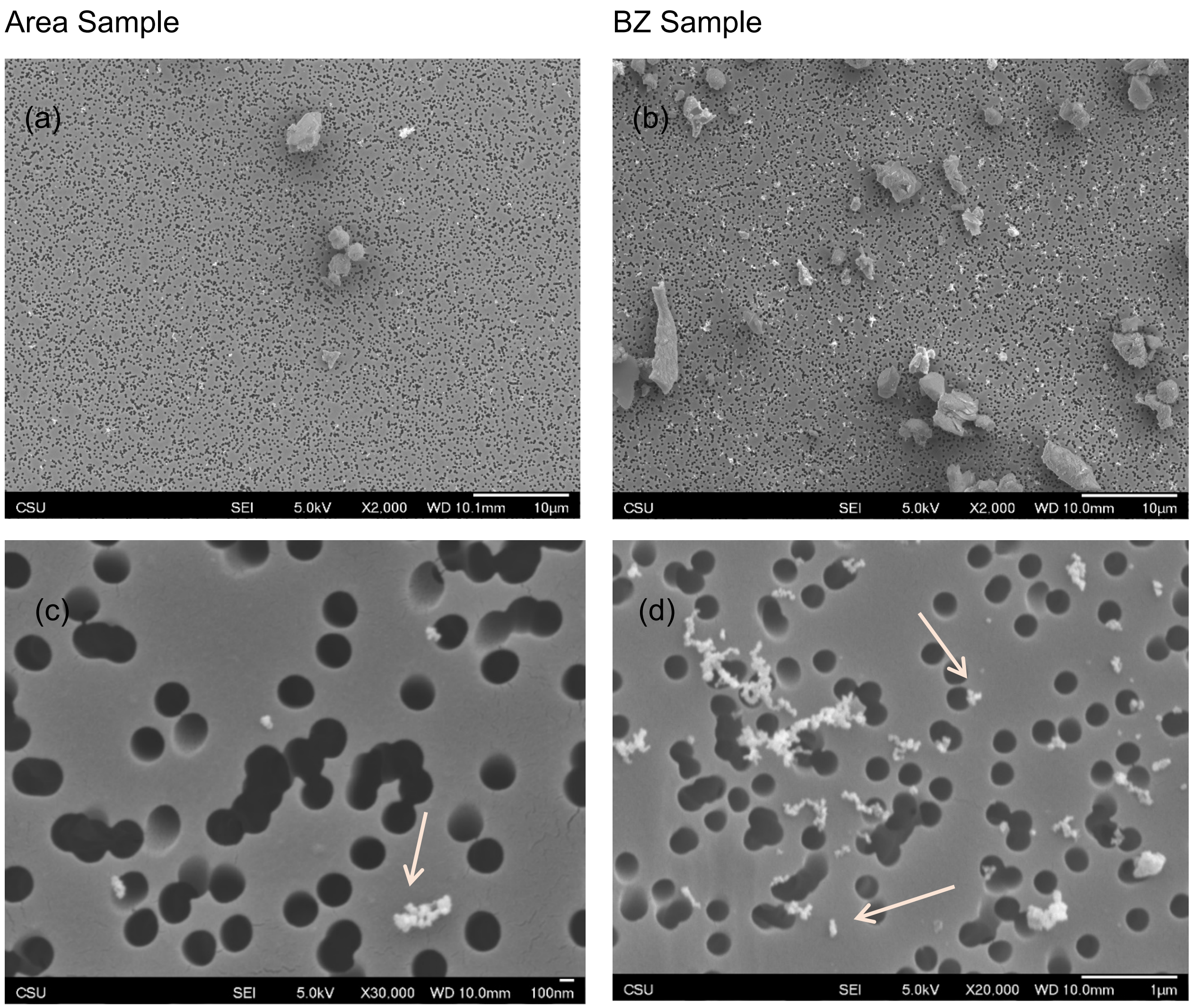


Figure 17. SEM images of particles collected on the polycarbonate filters of TDS. a) and c) Particles collected at the area location, b) and d) Particles collected at researchers' BZ.

Similar results were seen on particles collected on the filmed TEM grids as shown in Figure 18. Particle sizes and morphology are similar at both area location and researchers' BZ as seen in Figure 18a and 18b. The BZ samples have more particles as expected caused by the higher level of dust while walking. The dust settled on the ground were disturbed and resuspended into the air contributed additionally to the existing dust in the air. Clearly, the resuspended dust contained a large amount of sub-micrometer sized particles as well. Examples of the individual or small agglomerate of particles were shown in Figure 18c and 18d, which some of them are smaller than 100 nm such as the one shown in Figure 18c.

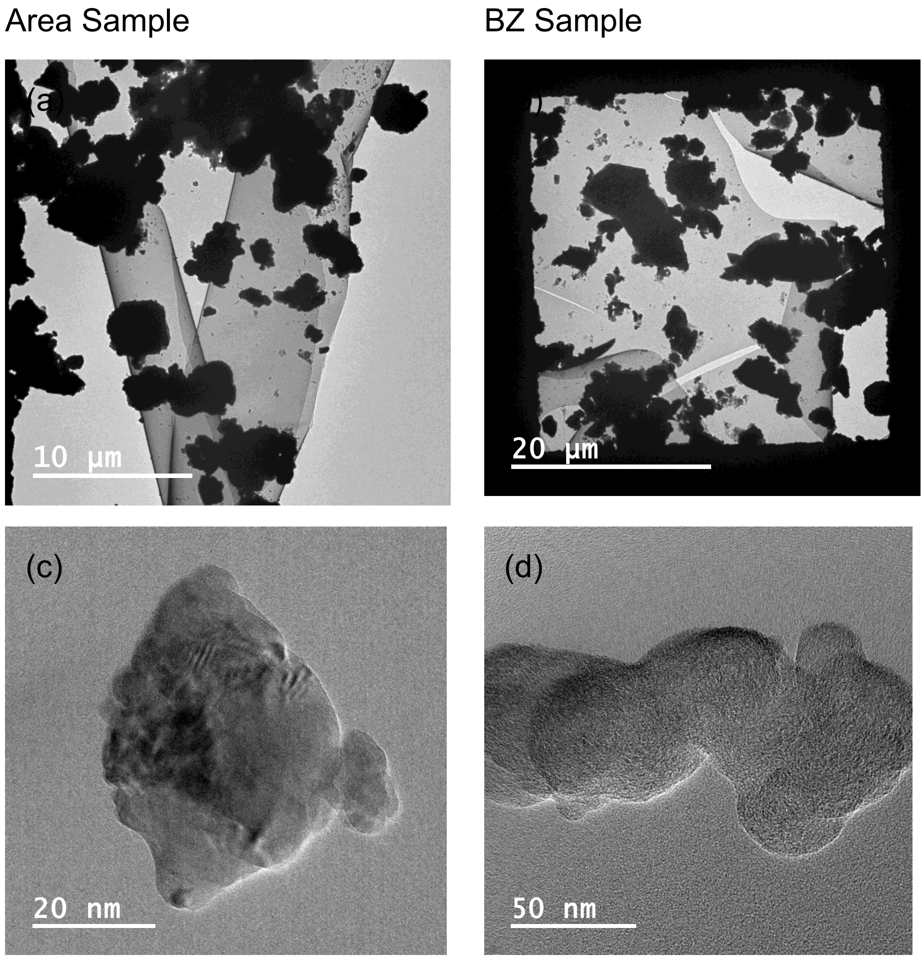
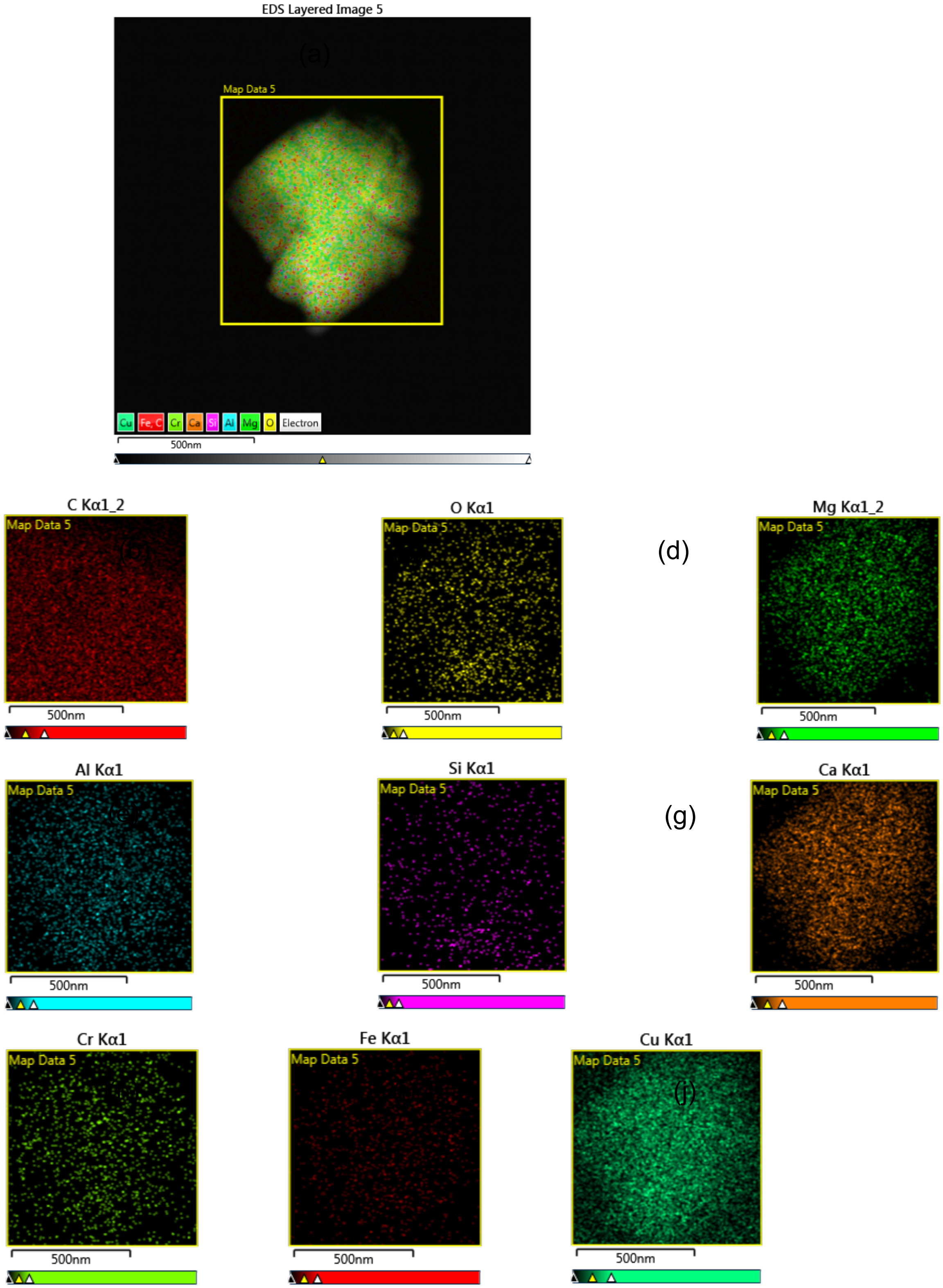


Figure 18. TEM images of particles collected on the filmed grids of TDS. a) and c) Particles collected at the area location, b) and d) Particles collected at researchers' BZ.

The elemental compositions of the particles in the air are important for us to know the harmfulness of such particles and can further identify the sources of those particles. An example of our elemental composition analysis was presented in Figure 19. A submicron sized particle collected on the TEM grid of the TDS sampling was analyzed and shown with various metal and non-metal elements. The image of particle is presented in Figure 19a, with elements found shown in Figure 19b-19j, which include Mg, Al, Si, Ca, Cr, Fe, and Cu in addition to C and O. The intensity of each element can be seen in Figure 17k, it shows a high level of Mg, Al, Ca and Cu on the spectrum.


EDS Layered Image 5
(a)
Map Data 5
Cu
Fe, C
Cr
Ca
Si
Al
Mg
O
Electron
500nm
C Kα1_2
O Kα1
(d)
Mg Kα1_2
Al Kα1
Si Kα1
(g)
Ca Kα1
Cr Kα1
Fe Kα1
Cu Kα1
(j)

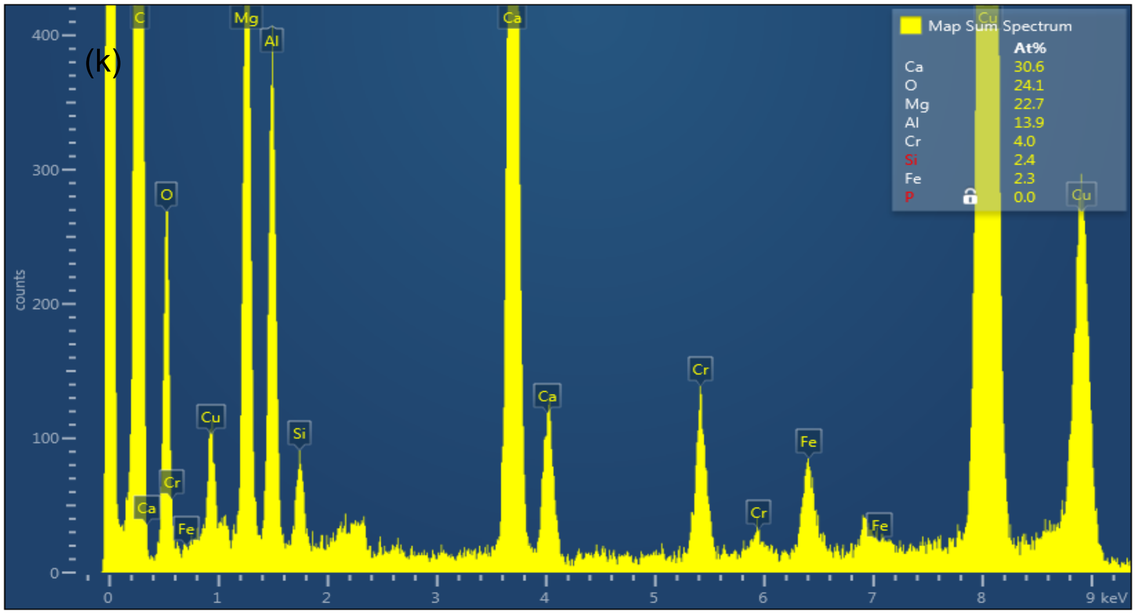


Figure 19. Elemental composition analysis of a submicron particle collected at research BZ. a) Image of the particle, b)-j) Elements tested and found on the particles, k) A profile of element spectrum.

4.6.6. Conclusions from particle size analysis

Mine dust particle size analysis identified a significant fraction of particles in the nanometer range, i.e., below 1 µm. These particles remain airborne for very long times, especially in the turbulent mine air environment, where they may remain airborne for several hours or never settle (Cecala, 2019). This must be considered when identifying and tracking locations of dust exposure: Fine dust may originate from a source far away from the location where it was recorded by the PDM.

4.7. Developing an RFID-based Location Tracking System

Because testing in the West Elk Mine did not permit evaluating miner tracking data as a location-time series, researchers developed a simple, electronic miner tracking system for the Edgar Experimental Mine. This system provided a second, useful set of location information in addition to the earlier test that used the GPS. Details of the RFID tracking system development are presented in Jones (2021).

4.7.1. System Design

Underground mine localization and tracking systems are commonly based on WiFi or RFID technologies. This section describes a passive, reverse RFID trilateration with map matching to localize a user in both an indoor and underground mine environment. The only infrastructure required for the system to operate are clusters of passive RFID tags sparsely placed throughout the area. Inertial motion unit (IMU) dead reckoning localizes the user in between tag clusters while the RFID tag clusters reset the drift errors accrued by the IMU. Map matching projects the dead reckoned values onto a path, sacrificing a user's lateral distance from the path for a significant increase in accuracy. The system presented successfully localized the wearer at the Colorado School of Mines Edgar experimental mine.

A hybrid localization algorithm is developed based on incorporating RFID passive tags, IMU sensor readings, as well as map matching techniques. The IMU sensors produce reasonable estimates of a user's linear travelled distance but produces poor heading information at longer time scales due to small cumulative errors compounding into larger ones. In contrast, RFID tags can be used to produce localization of a user to a given area without the cumulative errors, although fine resolution is difficult to achieve. These different techniques produce superior accuracy when combined than any individually.

By placing a series of RFID passive tags inside a mine, zones are created that have known positions that are used to reset the cumulative errors in IMU estimation. Multiple RFID tags are located in each zone to allow for the received signal strength (RSSi) based methods to produce a more accurate initial estimate of the user's location in a zone. The positional data can then be synced using the timestamps with other sensors the miner is wearing, such as a dust monitor, to create a map of a mining safety metric across the mine. The presented system uses a post-processing localization algorithm rather than a real-time positioning algorithm. Since the focus of this research was to map hazards in a mine, there is not an immediate need to turn this into a real-time algorithm. The developed system is optimized to be low-cost, robust, and accurate. By wearing the expensive reader, hundreds of cheap passive RFID tags can be placed throughout the mine with indifference to other communication infrastructure. This is inverse from other algorithms which use readers setup in various places of the environment and read tags on the users. This system does not require other infrastructure improvements beyond the tag installation making it easy to install. The system is robust because the reader needs to read at least one tag in a zone to be categorized and only three tags to determine the initial position. Constant tag reads are not required. Zones can be spaced far apart giving the user the ability to tradeoff positional accuracy with the number of tags required to divide up an environment. The use of more than the necessary number of tags in a zone, will allow the system to be operational even when mining hazards lead to the destruction of a couple of tags. Finally, the system exhibits greater accuracy over only IMU dead reckoning algorithms by the identification of zones using RFID tags and the application of the map matching process.

The prototype localization system uses two RFID readers, two custom-made antennas, a power supply circuit with a battery, an inertial measurement unit (IMU), and a Raspberry Pi. Figure 20 shows a block diagram of the prototype, Figure 21 shows the main components of the prototype, and Figure 22 shows the final prototype, without the hardhat. The user controls the system through the Raspberry Pi which is connected to a touchscreen. Collected data are recorded to the Raspberry Pi, that is accessed at the end of a shift using USB or Wi-Fi to offload the data to a post-processing computer running MATLAB. Figure 23 shows a block diagram of the various scripts the Raspberry Pi executes to collect data and the resulting data files that are transferred to the computer. The pre-characterization files will be discussed in the next section.

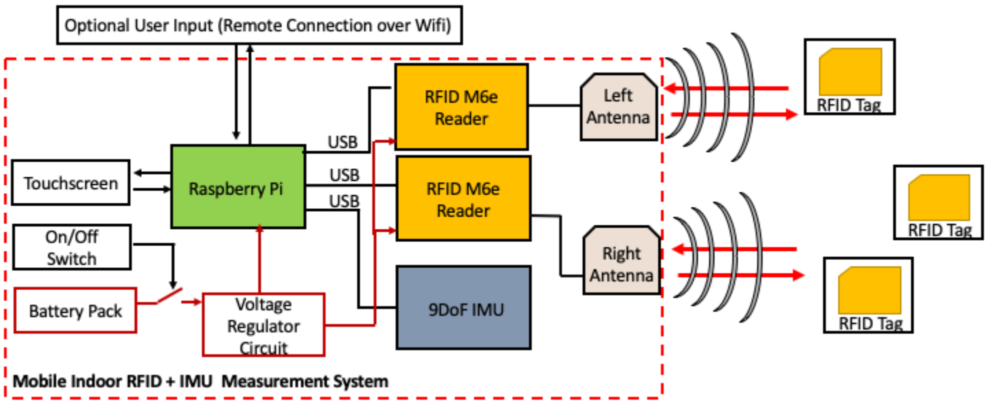


Figure 20: Hardware block diagram of the localization prototype

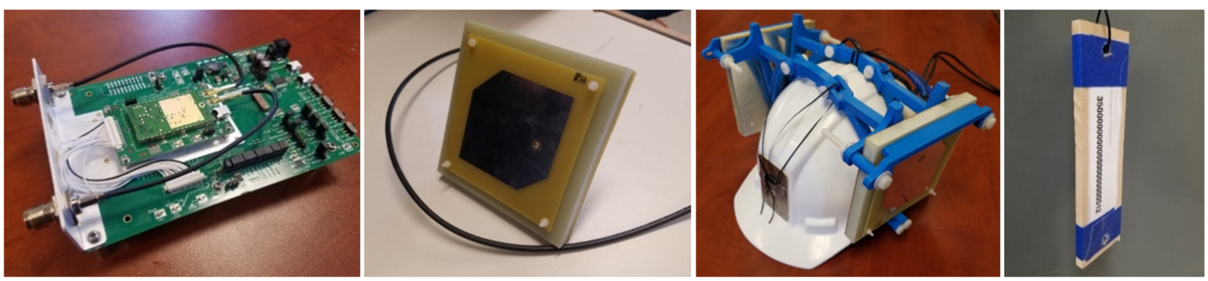


Figure 21: Individual hardware components. From left to right: M6e RFID reader, circularly polarized patch antenna, 3D printed mount on hardhat holding the two antennas, and one of the RFID tags with wood backing.

Figure 22: Complete wearable prototype. The vest contains two RFID readers, IMU, battery, and power circuit.

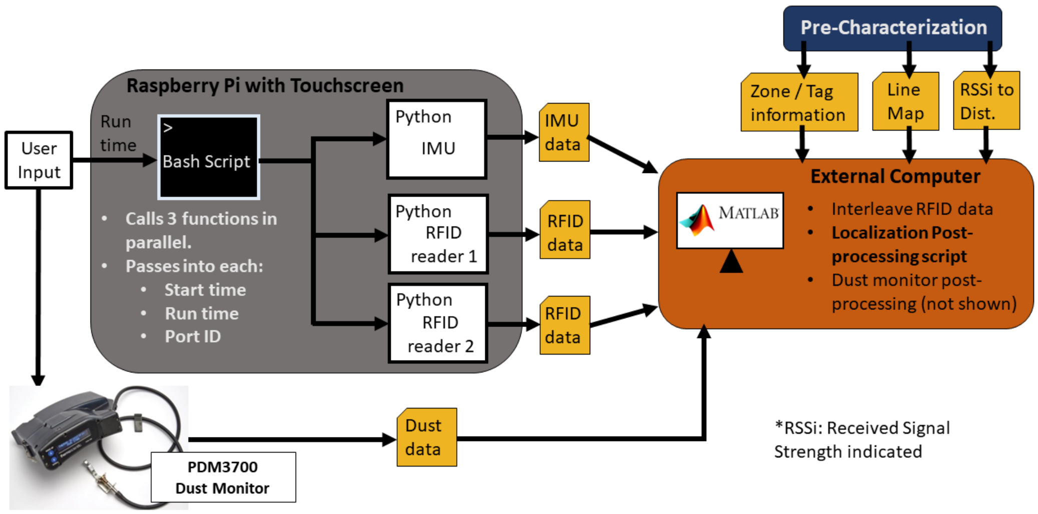


Figure 23: Diagram of the acquisition software and data flow.

4.7.2. Localization Algorithm

Before conducting a localization measurement, the user must setup the environment. For the Edgar mine experiment, these steps took a total of 25 hours, which mainly consisted of hanging 78 tags and recording their positions. The steps to setup the environment are as follows:

- Install all RFID tags in the environment, recording by hand their IDs, coordinates, and which zone they belong to.
- Create the map of the environment by recording the center coordinates of all intersections or changes to the path heading. These coordinates will mark the starts and stop of the lines that will approximate a zone. These coordinates are based on a user-defined X and Y axes and measured values are in feet, that all points are based off of. For example, in the Edgar mine the long tunnel running through the center of the mine was used as the Y axis and one of the side branches was used as the X axis.
- Estimate the user's gait length by counting the user's steps along a known distance.
- Measure the RSSi with a single antenna from known distances. Conduct many of these tests in different parts of the environment to build up enough data for the RFID reading look-up-table. It is very important to do this step with the reader set to the same power and frequency that will be used in the localization measurements.

Once the pre-processing steps are finished the user can now take a measurement. Using the data from the measurement, the post-processing code will determine the user's path through the mine with time stamps that can be synced with other sensors, such as a dust monitor, to create a map of a particular hazard. The post-processing code is called the zone categorization algorithm (ZCA) as it uses the zone structure to split apart the data into bins. These bins correspond to each zone the user transitions into. A zone transition is a change in zone, not just that zone. Figure 24 shows a diagram of the zone categorization as the user transitions between zones.

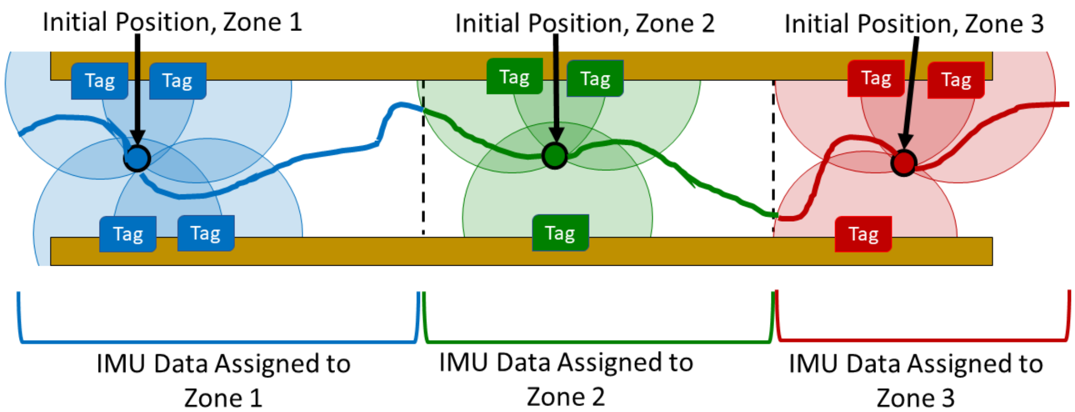


Figure 24: Illustration of the IMU zone categorizations. Starting from the left, the user progresses from Zone 1 to Zone 2 and finally to Zone 3. The large tinted circles are the approximate areas where the tags can be read. Zone transitions are indicated by the dotted black lines. The colored lines indicate which zone the dead reckoned position belong to. The blue line changes to green as soon as a single tag in Zone 2 (green) is read and the green line turns into red as soon as a single tag in Zone 3 (red) is read.

The flow diagram of the zone calculation algorithm (ZCA) is shown in Figure 25. In each index in the loop, the ZCA will calculate the 2D position using just the RFID values using the first coordinate at the user's initial position, determine at what indices in the IMU data the user stepped, determine the user's heading using the gyroscope component of the IMU data, calculate the user's 2D position through the entire zone, and then finally map matching these positions to the mine map.

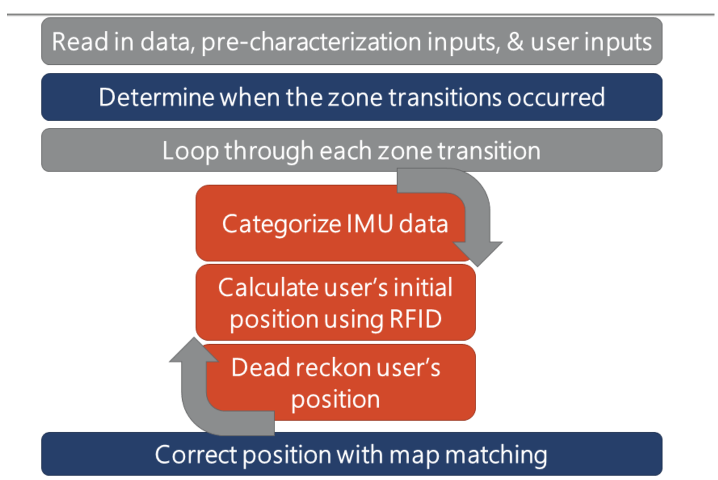


Figure 25: Flow diagram of the post-processing code

4.7.3. Testing the RFID localization system

In this part, the RFID-based localization system is combined with the PDM, and a final test was conducted at Edgar Experimental Mine. Figure 26 shows the data collection location for this final test.

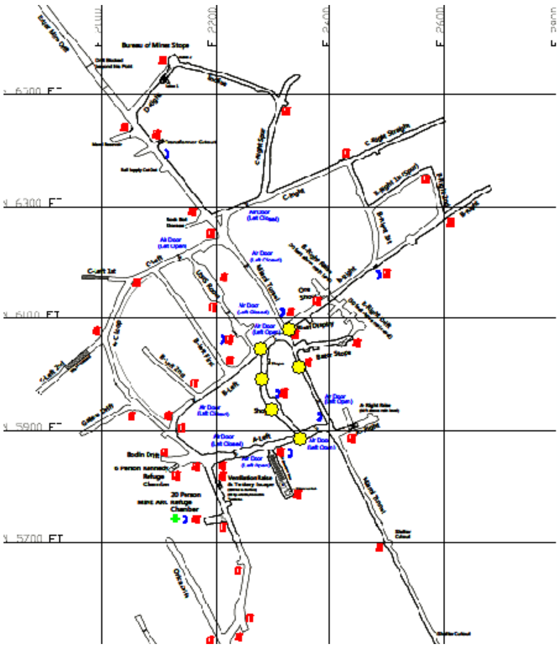


Figure 26. Data collection locations for the combined RFID – PDM test

Using the same methodology described in Section 4.2, plumes of dust were released while a mock-up dummy wearing the PDM and the RFID/IMU tracker was placed in the test locations. Instantaneous concentrations ranged between 0.4 and 6.0 mg/m^3.

No persons were exposed to the excessive dust concentrations as the compressed air releases were controlled remotely. The data was processed and a heat map generated. In this test, higher than normal dust concentration values were obtained because of the artificial dust created by releasing compressed air to mine entries. Figure 21 shows the final heat map.

Figure 27 shows that the combined PDM + RFID prototype was successful at collecting data that can be used to generate heat maps. The output shows high dust concentrations at the locations where dust was released using the compressed air distribution system.

Figure 27. Heat map for the final test at Edgar Mine

4.8. Discussion of findings

In this project, researchers improved the functionality of PDM by adding geolocation capabilities to dust monitoring data as a proof-of-concept. Integrating location with dust exposure information provides miners and mine operators an additional tool that will allow them to track where the dust overexposures occurred. The heat maps generated in this study presents this information in a user-friendly, graphic environment.

The key research findings of this project are listed as follows.

- The experiments confirmed that it is possible to “marry” the time series of location data from several different devices with the time series of dust concentration data in the form of heat maps.
- Researchers found that, while commercial miner tracking systems track and record a time series of miner locations, these locations are not available as a system output due to privacy concerns. This shortcoming made it impossible for researchers to complete Task 5.
- Dust concentration per minute values can be calculated using the PDM outputs, by directly processing the PDM’s TEOM frequencies that are recorded at 1-minute intervals.

- PDM dust concentration values can be interpolated over the data collection route using spline interpolation to produce a raster surface. This technique produces a heat map that mine operators can use to identify major sources of mine dist.
- Dust particle size analysis revealed that mine dust contains a significant portion of particles in the nanometer range that remain airborne for long times. The PDM location methodology may not be suitable to identify sources of nanosized dust as it may have originated from a faraway location unrelated to that recorded with a miner tracking system coupled to the PDM. Also, the PDM is only designed to record particle mass in the respirable range from about 2 to 10 µm. Submicron sized particles will not contribute much to the mass recorded by the PDM and will not be registered by the current, gravimetric exposure limit.

The accomplishments for each research task are given below:

1. Combine a PDM with a location tracking unit to collect dust exposure data and testing the assembly in a surface laboratory environment.

The methodology to generate heat maps using PDM data was tested using manual, GPS and RFID location tracking. Tests were conducted at the Colorado School of Mines Campus and at the Edgar Experimental Mine where manual and RFID tracking was employed in the underground mine workings.

2. Develop a mapping tool to visualize dust exposure locations to improve miners' and management awareness of overexposures to respirable dust.

Researchers developed a mapping tool to generate heat maps that visualize dust exposure locations in a user-friendly way. The tool uses PDM output converted to dust concentrations minute-by-minute, and utilizes spline interpolation method to generate the heat map.

3. Combine a PDM with an underground miner location tracking system, most likely RFID, and testing the assembly in a laboratory environment.

Researchers used manual and RFID tracking in the Edgar underground mine where they created dust releases in various locations and identified these locations by combining PDM and tracking data.

4. Field-test the PDM + Tracking prototype in Offeror's underground Edgar Experimental Mine using multiple measurement tools.

Researchers used both manual location tracking mine and a specially designed, RFID and IMU-based miner tracking system at the Edgar Experimental Mine. The methodology to generate heat maps was first tested in Edgar Underground Mine using manual location tracking. During these tests, high dust concentrations were artificially created by releasing blasts of compressed air. These tests proved the success of the methodology. Later, the

PDM was combined with an RFID tracking system and tested in the Edgar underground mine. The resulting heat map showed that the prototype successfully collected data and it can easily be used to develop user-friendly visualizations that can help mine ventilation professionals to identify areas of high dust-exposure.

5. Create an AI model and software using the localization algorithms to extract and combine the time series of dust exposure data, operational environments, and miner activities from the PDM with location information from the tracking system, and to manage the data effectively.

In this project, researchers established the infrastructure of real-time dust data collection, using PDM combined with an RFID tracking prototype. During testing at the West Elk Mine, it was revealed that the existing miner tracking system does not provide direct, bulk output of miner location data. This restriction is related to confidentiality. Mine operators can only look up miner locations by direct query. Therefore, researchers were unable to generate an AI model from several series of PDM + Tracking data sets. Researchers have a suitable AI modeling infrastructure but the AI model needs data from long time execution of the developed prototype, over multiple days and using multiple PDM units, on the same route with different activities taking place in the Mine. This type of "big data" would be able to represent the nature of dust exposures occurring at a mine and also allows one to study and understand the effects of operational environments and miner activities on dust exposure. Researchers have developed and tested a generic set of AI models, for making spatio-temporal predictions. However, they are not adapted and tested for dust exposure data as it was not possible to collect a large data sets to train AI models. Due to the limited access to underground mines during the Covid-19 pandemic, researchers have not been able to establish a large data set yet at an active underground mine. Therefore, this specific aim is intended to be completed as future work.

6. Field-test the heat map generation solution for PDM data in an operating underground coal mine using multiple measurement tools.

The methodology for heat map generation was tested at the West Elk Underground Coal Mine in Somerset, CO. The heat map successfully showed the locations of dust exposure in a simple way, with the limitation that PDM location and time data had to be collected manually. Still, results demonstrate the success of the methodology at an active mine as a proof-of-concept.

7. Semi-annual progress reports to the Alpha Foundation. Reporting and publishing the findings of the research in peer-reviewed scientific and technical journals.

Quarterly and annual progress reports were submitted to the Alpha Foundation in a timely manner. Researchers also submitted a peer-reviewed conference paper to the Mine Dust Control Symposium at Freiberg University in Germany. This conference was originally scheduled for October 2020 but postponed to October 6, 2021 due to the Covid-19 pandemic. It has been presented by PI Jürgen Brune and published in the conference proceedings.

Results from the particle size analyses and studies have been published at the 9th International Symposium on Nanotechnology, Occupational and Environmental Health, Denver, 2020 and at the SME 2021 Annual Conference and Exhibit.

The heat mapping and AI methodology was published as an application to locating adverse ground conditions in the Journal of Rock Mechanics and Geotechnical Engineering and at the 54th US Rock Mechanics/Geomechanics Symposium, Golden, 2020.

Researchers have initiated procedures to secure a patent on the combination of PDM dust exposure with location data and subsequent heat mapping.

All related publications are listed in Section 5.

5 PUBLICATION RECORD AND DISSEMINATION EFFORTS

This research produced the following publications:

Isleyen, E., Brune, J.F., Duzgun, H.S. (2021). Continuous respirable dust monitoring with localization. 5th Symposium FreiBERGbau Dust and Dust Control. Freiberg, Germany. Oct 5th-6th, 2021.

Cruz-Hernandez, A; Maksot, A; Shin, N; Lee, C; Brown, J; Brune, J and Tsai, C (2020): The effect of coal and mine respirable dust size on lung cells and exposure assessment, 9th International Symposium on Nanotechnology, Occupational and Environmental Health, Denver, 2020

Tsai, C; Brune, JF and Janes, D: Development of a direct sensing sampler for submicron mining particles including coal, silica and nano-sized diesel particulates, SME 2021 Annual Conference and Exhibit,

Jones, RD (2021): A zone-based, underground localization system using passive reverse RFID and IMU technologies. Master's thesis, Colorado School of Mines, Electrical Engineering, Golden, CO, 2021

Isleyen, E., Duzgun, H. S., Carter, R. (2021) Deep learning to identify geological structures for prediction of roof fall hazards: a workflow with synthetic images and data sampling. Journal of Rock Mechanics and Geotechnical Engineering.

Isleyen, E., Duzgun, H. S., Carter, R. M., Miller, T. Using artificial intelligence for roof fall hazard identification in limestone mines, 54th US Rock Mechanics/Geomechanics Symposium, Golden, Colorado, USA, June 28-July 1 2020.

6 CONCLUSIONS AND IMPACT ASSESSMENT

Mine workers continue to suffer from overexposures to respirable dust, with debilitating health consequences that eventually lead to death. Despite having a near real-time dust exposure with personal dust monitoring devices, miners' working locations are not tracked along with their associated dust exposure levels. Location monitoring and tracking is necessary to identify sources and areas of excessive dust exposure.

In this project, the researchers improved the functionality of the PDM by adding RFID-based geolocation capabilities to the respirable dust exposure monitoring data. The final output of the proposed system is a spatial-temporal graphic environment which presents respirable dust exposure data in a user friendly way. This provides both miners and mine operators additional information that will allows them to track dust overexposures.

The system is developed as a proof-of-concept, and it has been tested in several locations including Colorado School of Mines campus, Colorado School of Mines Edgar Experimental Mine, and West Elk Underground Coal Mine. These tests revealed that the developed system is able to accurately capture the dust overexposure locations and visualize them in an easily interpretable way. Miners' access to the information provided by the system can increase their awareness of dust overexposures and its effects on health and safety. It can also increase their ability to effectively communicate the dust overexposure sources to the supervisors. Also, the data provided by the developed system can help mine management to take more effective mitigation measures.

A shortcoming of this research project was that researchers were unable to extract miner tracking data from the RFID-based system installed at the West Elk Mine. While the system generates this data and makes it available on an individual query basis, confidentiality concerns prevent the system from releasing bulk data about the locations of miners. This issue will need to be addressed when incorporating tracking into the dust monitoring process. Researchers believe that the confidentiality concerns could be overcome when the system output is limited to producing heat maps generated from multiple PDM samples.

Researchers will engage with Thermo Fisher, the manufacturer of the PDM, to explore the possibility of incorporating a tracking unit into the PDM so that dust exposure locations can be recorded along with the respective dust concentrations.

Researchers have also initiated the process for patenting this concept.

7 RECOMMENDATIONS FOR FUTURE WORK

The methodology presented in this report was tested as a proof-of-concept. For future work, researchers recommend developing a prototype for RFID-based PDM and tracking solution and testing it at an active underground coal mine. Testing with mine personnel would require human subjects research approval.

The development of an AI model that utilizes localization algorithms to extract time series of dust exposure data, operational environments and miner activities with the location information has the potential to improve the response time of the mine management for high dust exposure cases. The development of such AI tools requires the collection of large amounts of data that represent the characteristics of high and low dust exposure cases that result from different mining activities and areas.

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