APPLICATIONS OF THERMAL AND LASER-BASED METHODS FOR MONITORING AIRBORNE PARTICULATES IN COAL MINES

Kent Thomas Phillips

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Emily Sarver, Committee Chair

Cigdem Keles, Member
Nino Ripepi, Member

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ACADEMIC ABSTRACT

The purpose of this thesis is to examine applications of thermal and laser-based methods to monitor airborne particulates in underground coal mines. Specifically, coal and mixed mineral mine dust, as well as, diesel particulate matter (DPM). These particulates have historically, and continue to have, significant health impacts on underground miners. Chapters 1 and 2 of this thesis concentrate on using a novel method of thermogravimetric analysis (TGA) to characterize respirable coal and mixed mineral mine dust and presents the results of this method being applied to samples collected in Appalachia coal mines. Appalachia has been a geographic "hotspot" for the rise in occupational lung disease amongst underground coal miners, which began in 1990's after decades of steady decline. This has led researchers to propose there could be something unique about the respirable dust composition in Appalachia coal mines, which resulted in the surge of lung disease cases; however, the knowledge base regarding the actual composition of respirable coal mine dust is limited. The results of this thesis show that most of the mass fraction of respirable Appalachia coal mine dust is not coal, but rather carbonates and non-carbonate minerals (i.e. silica and silicates). These findings are significant as many researchers now suspect silica and silicates to be the true culprit in the occupational lung disease of coal miners.

DPM presents an additional occupational health hazard to underground coal miners where diesel equipment is used and is difficult to monitor due to its complex nature. In underground metal/non-metal mines, airborne DPM is regulated and monitored using carbon surrogates. However, due to the potential interference from coal-sourced carbon, DPM in coal mines is monitored only by taking samples at the tailpipe of each piece of equipment. This thesis aims to investigate the potential for a laser-based instrument, the FLIR Airtec, to be used in underground coal mines. In particular, what effect the coal dust will have on the instrument, as it measures DPM by way of elemental carbon (EC). The results of this study show that while the Airtec will not over-estimate coal-sourced EC, there could be some sampling artifacts associated with its operation in coal mines, which may inhibit its effectiveness.

APPLICATIONS OF THERMAL AND LASER-BASED METHODS FOR MONITORING AIRBORNE PARTICULATES IN COAL MINES

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PUBLIC ABSTRACT

The purpose of this thesis is to examine applications of thermal and laser-based methods to monitor airborne particulates in underground coal mines. Airborne particulates such as, coal dust, silica and other mixed mineral dust, and diesel particulate matter (DPM) have historically, and continue to this day, to have health impacts on underground coal miners. Characterizing and monitoring the composition and concentration of these particulates is crucial from a health and safety engineering approach. Chapters 1 and 2 of this thesis concentrate on using a novel method of thermogravimetric analysis (TGA) to get the mass fraction composition of respirable coal mine dust, while Chapter 3 examines potential interferences with using a DPM monitor in underground coal mines (e.g. it is currently only used in underground metal/non-metal mines).

The results of Chapters 1 and 2 indicate that the majority of the mass fraction of respirable coal mine dust is actually not coal, but rather carbonate and non-carbonate minerals (i.e. silica and silicates). This is significant from a health and safety viewpoint as many researchers now suspect silica and silicates may be the true culprits in the occupational lung disease which still plagues underground coal miners to this day. The results of Chapter 3 show that while the DPM monitor in the study could potentially be used to monitor DPM in an underground coal mine, there could be some operational issues presented by airborne coal dust, which would not be present in an underground metal/non-metal mine.

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Many thanks to the Appalachian coal miners and operators who so graciously gave their time and support to this project. The impetus of the work presented here is to better protect your health and safety.

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PREFACE

. Respirable dust and diesel particulate matter (DPM) are both recognized as serious occupational health hazards. Exposures can lead to a range of outcomes from respiratory irritation to debilitating lung disease, which can be fatal with prolonged exposure. Mitigating exposures to these airborne particulates in underground coal mines presents a unique set of challenges for engineers from a health and safety viewpoint, not the least of which is the difficultly in characterization and monitoring.

This thesis presents applications of both thermal and laser based methods for monitoring airborne particulates in underground coal mines. Chapters 1 and 2 apply a novel thermogravimetric analysis (TGA) method to characterize the composition of mixed respirable coal mine dust into three mass fractions – coal, carbonates, and non-carbonate minerals (e.g., silica and silicates). In Chapter 1, the TGA method is used to characterize a set of area dust samples collected in coal mines located in three distinct regions of Appalachia. In Chapter 2, the method is applied to personal dust samples collected by volunteers in two of these regions.

In Chapter 3, the potential for laser-based DPM monitoring in coal mines is addressed. This chapter reports a preliminary study to investigate how a commercially available DPM monitor, which measures elemental carbon as a surrogate for DPM, may respond to coal dust. This is an important issue since DPM monitoring in coal mines is currently limited due to potential analytical interferences from coal-sourced carbon.

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Kent Phillips[1], Cigdem Keles[1], Meredith Scaggs[1], Victoria Johann[1], Mohammad Rezaee[1], Emily Sarver[1]

[1]Virginia Tech, Blacksburg, Virginia

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Abstract

Respirable dust in coal mines is an occupational health hazard, and chronic exposures can lead to irreversible lung diseases such as Coal Worker's Pneumoconiosis and silicosis. Much of what is known about dust exposures has been learned from conventional monitoring efforts, which focus on two main metrics: the total mass concentration of particles (mg/m^3) in the respirable size range and the mass fraction of quartz in this range. However, recent and unexpected increases in lung disease incidence amongst coal miners in the US and elsewhere, have prompted many questions regarding what is not yet known about respirable dust – including its whole composition. Thermogravimetric analysis (TGA) is relatively quick and inexpensive, and can provide additional information about dust samples. Namely, the mass fractions of coal and non-coal (i.e., total mineral matter) can be estimated; and in some cases the carbonate (and non-carbonate) mineral fractions can also be estimated. Such information could advance the understanding of how conditions and activities in the mine relate to dust composition, as well as provide insights into miner health outcomes with respect to dust exposure characteristics. This paper presents TGA results from respirable samples collected in various locations of seven underground mines in Appalachia. The results demonstrate that the ratio of coal to total mineral mass can be quite low, and that carbonate and non-carbonate mass fraction can be very high.

1. Introduction

Coal Workers' Pneumoconiosis (CWP, or "black lung") and silicosis are irreversible and often debilitating occupational lung diseases that have long been known to affect miners.[1] They are attributed to chronic exposures to respirable dust – specifically quartz, or crystalline silica, in the case of silicosis – which is generally defined as particles less than about 10 microns in aerodynamic diameter.[2] Despite significant efforts to mitigate such diseases amongst coal miners in the US and elsewhere, they still represent major health concerns. In some particular regions of central Appalachia, for example, an apparent increase in incidence rate of CWP was observed between about 2000 and 2014 – following nearly four decades of steady declines.[3-7] Further, an alarming number of miners in these regions, including relatively young miners, have been diagnosed with progressive massive fibrosis (PMF), meaning that their disease is advanced and severe. Between 2000 and 2009, 138 coal miners in West Virginia were diagnosed with PMF,[8] for perspective, there were just over 14,000 underground coal miners working in that state in 2009.[9] An uptick in occupational lung disease amongst Australian coal miners has also recently been noted, again following decades of declining incidence rates.[10-11] To date, such unexpected trends have not been fully explained.

In central Appalachia, several factors have been raised as potential contributors, including the relatively small mine sizes in this region.[7] Small mines may generally be expected to have fewer workers covering a range of job roles, who could therefore be exposed to quite variable dust conditions. Several researchers have speculated that the increasingly thin coal seams being exploited in this region may also translate to fundamentally different dust exposure characteristics (i.e., as opposed to mines in other regions where seams are thicker).[4,12] Thin seams typically require mining relatively high proportions of roof and/or floor rock with the coal, which may generate more non-coal (i.e., mineral) dust particles.[6,12-13] In instances where such rock strata have high quartz content, as is the case in many parts of central Appalachia,[12] this could pose a particular health hazard. Roof-bolting activities (including drilling and maintenance of dust collectors) could additionally contribute to significant concentrations of high-quartz respirable dust.[14] Beyond quartz, generation of other respirable mineral particles (e.g., alumino-silicates, carbonates) associated with rock strata could be important too. At present, neither exposure characteristics (e.g., concentrations, size distributions) nor health

effects of such particles have been widely explored. Importantly, a recent study by Cohen et al.[15] did find inclusion of significant silicate mineral particles (in addition to silica) in lung tissue of 13 Appalachian (i.e., PA, KY and WV) coal miners with severe disease (i.e., silicosis and/or PMF). Douglas et al.[16] also previously reported that "ash" (i.e., non-coal) content of respirable coal mine dust could be positively correlated to the retained dust in lung tissue of coal miners with severe disease.

Much of what is known about respirable dust exposures in coal mines has been learned through routine monitoring. In the US, monitoring efforts have often been related to demonstrating regulatory compliance via collection and analysis of dust samples (i.e. 30 CFR Part 70). This has resulted in tracking two primary metrics: the total mass concentration of particles (mg/m^3) in the respirable range, and the mass fraction of quartz in this range. A new dust rule was passed in 2014 and fully implemented in 2016, [17] which lowered the personal exposure limit (i.e., from 2.0 to 1.5 mg/m^3 for a full shift) and mandated use of new monitoring technology (i.e., the continuous personal dust monitor or CPDM) in some areas of a coal mine. The CPDM provides a near real-time measurement of cumulative dust exposure (i.e., mg/m^3), but a better understanding of respirable dust characteristics is still needed.

As part of an ongoing investigation, the authors' research group has investigated two avenues for gaining more comprehensive information about respirable dust. Using computer-controlled scanning electron microscopy with energy dispersive x-ray (CCSEM-EDX), a method has been developed to estimate particle size, shape and chemistry distributions in coal mine samples.[18] This method provides very detailed characteristics, but is cost and time intensive. As an alternative, a thermogravimetric analysis (TGA) method has also been devised.[19-20] It is relatively quick and inexpensive, but it does require careful sample preparation. TGA effectively tracks weight change of a sample under carefully controlled temperature conditions. Similar to proximate analysis of bulk coal materials, this allows for estimation of coal and non-coal (i.e., total mineral) mass fractions in a dust sample; and with sufficient sample size, the carbonate (and thus non-carbonate) mineral mass fraction may also be estimated. While these mass-based results are much less detailed than particle-level data, even a basic understanding of

the whole composition of respirable dust would be very valuable to miners, operators, regulators and researchers alike.

Comparison of the coal and non-coal – particularly the non-carbonate mineral – mass fractions of dust within and between mines may provide key insights into discrepancies amongst health outcomes of miners working in different primary job roles or at different operations. Further, tracking coal and non-coal mass fractions in dust samples may provide better awareness regarding the primary sources of dust particles, or how changes in coal and rock strata or mining practices impacts dust characteristics.

With respect to the importance of understanding the carbonate-mineral mass fraction of respirable dust, specifically, the issue of rock dusting has increasingly become an issue of interest. (Rock dusting refers to the practice of applying an inert material, such as finely crushed calcium carbonates, to mine surfaces in order mitigate explosibility hazards.) Since rock dust products are very fine,[21] one concern is that they may significantly contribute to the total respirable dust concentration in some mine environments; although little information is currently available to support or refute this. Another concern is the possible health impacts of respirable dust associated with rock dust products, but again available information on this topic is limited. While non-silica, pure calcium carbonate minerals have not conventionally been suspected to contribute to lung disease,[22] recent questions have arisen regarding this presumption. Newer research suggests that chronic exposures may in fact increase respiratory symptoms such as coughing, wheezing, and phlegm production.[23] Considering these concerns, some way of monitoring the contribution of rock dust products to respirable dust concentrations would be beneficial. In environments where other sources of carbonate-mineral dust are relatively minor, the mass fraction of carbonates in respirable samples may serve as an acceptable surrogate – and TGA may allow for estimating this value.

Between 2014 and 2015, a large collection of respirable dust samples was gathered in various locations of underground coal mines in three distinct regions of Appalachia. In this paper, TGA results including coal, non-coal, and carbonate and non-carbonate mineral mass fractions are reported and discussed with respect sampling location and mine region.

2. Materials and Methods

2.1. Dust sample collection

Concurrent with the TGA method development, field sampling was conducted in eight underground coal mines. Two mines were located in northern Appalachia (MSHA Districts 2 and 3), four mines were in mid-central Appalachia (MSHA District 4), and two mines were in south-central Appalachia (MSHA District 12). Table 1.1 shows the primary characteristics of interest for each mine. Within each mine, samples were collected in various locations that represent a range of dust conditions

Table 1.1: Characteristics of mines where TGA samples were collected.

	MCA				NA		SCA	
	Mine 1	Mine 2	Mine 3	Mine 4	Mine 5	Mine 6	Mine 7	Mine 8
Seam thickness (ft)	3-5	3-4	4.5	2-4	6-8	6.5	5-6	4-4.5
Total mining height (ft)	5	5.5	6	4	8	8	6-7	6
Primary rock strata	sandstone	sandstone	shale/ sandstone	sandstone	sandy shale/ slate	shale	sandy shale/ slate	shale
Production sections	2 CM	2 CM	2 CM	2 CM	1 LW; 3 CM	1 LW; 5 CM	3 CM	2 CM

CM = continuous miner, LW = longwall

A total of 147 respirable dust samples were collected for TGA, some of which were replicates (i.e., collected side-by-side and at the same time). Of these, a total of 106 samples were viable, meaning enough dust could be recovered from them to complete the analysis as described below. While collecting the samples for TGA, samples were also collected for SEM-EDX analysis; for every TGA sample, at least one SEM sample was taken (i.e., side-by-side and at the same time).

All samples were collected using standard equipment for respirable dust sampling in coal mines. Escort ELF pumps were calibrated to a flow rate of 1.7 L/min, and used with 10mm Dorr-Oliver cyclones (i.e., to discard particles greater than10µm, and achieve roughly 50% capture of particles approximately 4µm). Samples were collected using two-piece plastic cassettes on 37mm filters. TGA samples were collected on either mixed cellulose ester (MCE, 5µm pore) or polyvinyl chloride (PVC, 5µm pore) media; SEM samples were collected on polycarbonate (PC, 0.4µm pore) media. Each sample was collected over approximately 2-4 hours.

2.2 Dust sample analysis

The TGA method used here is described in detail by Scaggs,[19] including sample preparation. It was developed to estimate the coal, non-coal and carbonate mineral mass fractions in a respirable dust sample; in this work, the convention is to report mass fractions as percentages (e.g., 0-100% coal). The method requires that dust be removed from the filter media for analysis.[20] It is assumed that the dust recovered from the filter is representative of the entire sample. Briefly, preparation of each TGA sample was conducted as follows: the filter was sonicated in a test tube with deionized water to remove dust; water was then evaporated by oven and the dust particles removed from the test tube by rinsing with isopropyl alcohol; and dust was finally deposited in a clean, pre-tared platinum TGA pan. Detailed sample preparation can be found in Scaggs.[19]

The TGA method itself was carried out using a Q500 Thermogravimetric Analyzer (TA Instruments, New Castle, DE), equipped with an autosampler, which allows multiple samples to be analyzed successively. In all cases, the number of samples in a given set was limited to eight or less. At least one empty pan was run at the beginning of each set, and another empty pan was run at the end of each set, which allows correction for the instrument's internal drift. Per Scaggs,[19] the TGA method was run in high purity air (i.e., oxidizing conditions), and has a carefully controlled thermal ramping program designed to discriminate between weight changes in three specific temperature regions: 1) loss of volatiles and filter residue at temperature less than 360°C; 2) oxidation of coal between 360-480°C; and 3) evolution of carbon dioxide (CO_2) between 480-750°C as carbonate minerals (i.e., assumed to be predominantly calcium carbonate, $CaCO_3$) are decomposed.[19] At the end of a sample run, the residual weight is attributed to non-oxidizable minerals (i.e., calcium oxide, CaO, resulting from $CaCO_3$ decomposition, and other non-carbonate minerals contained in the sample such as silicates or silica).

In addition to correcting TGA data for instrument drift (i.e., using empty pan calibration results), corrections are also made to account for loss of filter residue in the coal oxidation and CO_2 evolution regions, as well as premature CO_2 loss. Subsequently, the mass fraction of coal in a sample can be estimated based on the ratio of weight loss in the coal oxidation region to the total recovered dust weight. The mass fraction of non-coal material (i.e., total mineral matter) is

simply the balance of the total recovered dust weight. Assuming that CO_2 is evolved primarily from $CaCO_3$, the mass fraction of calcium carbonate can be estimated stoichiometrically; and this value can be used as a proxy for carbonate minerals. Finally, the mass fraction of non-carbonate minerals is the balance of material after accounting for coal and carbonate. As reported by Scaggs,[19] the accuracy of TGA results using this method is correlated to the recovered dust sample weight. Recovered dust weights greater than about 50µg generally yield more accurate results (i.e., coal mass fraction within 25% of expected value). For estimation of the carbonate minerals mass fraction, accuracy is correlated to both recovered sample weight and observed CO_2 evolution (on the thermogram). When the product of these two values is greater than about 3,500μg^2, the carbonate mass fraction is generally within 25% of the expected value.

Given that the dust weights recovered from the field samples collected for TGA were quite variable (i.e., between 1-5,253 µg), results from the field samples collected for SEM-EDX analysis were used to validate the TGA results reported here. Johann[24] provided a preliminary report of the number-based size and chemistry distributions for the SEM samples collected for this study. The CCSEM-EDX routine used to analyze the samples has also been described [18]. It was developed based on a manual routine previously detailed by Sellaro et al.[25] for respirable coal mine dust samples. Briefly, the CCSEM routine scans a dust sample at 1,000x magnification and collects size and chemistry composition data on a total of 500 particles. Johann et al.[18] showed this method to be accurate (i.e., particles appropriately classified with respect to chemistry) and reproducible (i.e., multiple scans of the same sample produced statistically similar results). Based on the particle dimensions and chemistry classifications, mass fractions of coal, non-coal, and carbonates were determined as described by Sellaro et al.[25]

To validate TGA results reported here, the TGA-derived coal mass fraction for each sample was compared with the corresponding SEM-derived coal mass fraction for a duplicate sample. If the two values were within 25% (i.e., using an absolute difference), the TGA result was accepted. Using this screening criterion, 86 of 106 (81%) of the TGA sample results were accepted. From this group, the TGA- and SEM-derived carbonate mass fractions were also compared – again using agreement within 25% as a validation criterion. For carbonate, only 47 of the 86 (55%) sample results were accepted.

3. Results and Discussion

Table 1.2 shows coal, carbonate and non-carbonate (where applicable) mass fractions (i.e., as percentage values), as well as total recovered dust weight, for all 86 TGA samples validated by the SEM results (not shown). Consistent with expectations based on Scaggs,[19] samples with higher recovered dust weights tended to agree more often with SEM results. The average recovered dust weight was 306μg for the 86 validated samples found to be in agreement with SEM results on the basis of coal mass fraction, whereas it was only 34μg for the 20 TGA samples (not shown) that did not agree with SEM results. The trend was similar in the case of carbonate mass fraction agreement between TGA and SEM. The average recovered dust weight and observed CO_2 for the 47 TGA samples found to be in agreement with SEM results was 459μg and 82μg, respectively. For the 39 samples not in agreement (not shown), the average dust weight and observed CO_2 were only 123ug and 22μg, respectively. These observations reiterate the importance of sample size for the TGA method, particularly where carbonate results are desired. As mentioned by Scaggs,[19] the simplest way to increase sample size is to increase sample collection time.

From Table 1.2, some insights regarding reproducibility of results (i.e., from sample collection through TGA) can also be gleaned. In the table, sets of replicate TGA samples are boxed in dashed lines. Within the reported sample results, there were 19 sets of replicates (i.e., two or more TGA samples collected at the same time and in the same location). Of these 19 sets, all samples in 15 sets had coal mass fraction values that were within 25% agreement. A total of nine replicate sets had multiple samples with reportable carbonate mass fraction values. For all nine of these sets, all carbonate values were within 25% agreement. Thus, where replicate results could be reported here, they were in fairly good agreement overall.

Table 1.2: SEM validated coal, carbonate and non-carbonate mineral mass fractions (reported as %) derived from TGA results. Recovered dust weights (µg) are also shown for all samples. Replicate samples are enclosed with dashed boxes. Average mass fraction values for each sampling location in a given mine represent the average value of all sampling events (i.e., replicate samples were averaged to determine a value for the respective sampling event, which was then included in the average for a given location and mine.) Due to the small number of samples for mines in the MCA region, averaged values are presented for the region (rather than for each mine).

Mine/ Region	Sample	Intake				Return				Feeder				Bolter				Continuous Miner			
		coal	carb	non-carb	(dust)	coal	carb	non-carb	(dust)	coal	carb	non-carb	(dust)	coal	carb	non-carb	(dust)	coal	carb	non-carb	(dust)
MCA Mine 1	1					26	-	-	(47)	41	-	-	(8)	16	17	67	(103)	17	-	-	(86)
	2													12	-	-	(16)				
	3													13	-	-	(43)				
	4													0	0	0	(6)				
MCA Mine 2	1	10	0	90	(73)	2	11	87	(154)	37	-	-	(19)	7	6	87	(1115)	26	0	74	(11)
	2													8	9	83	(798)				
MCA Mine 3	1	0	-	-	(4)	12	-	-	(22)					17	39	44	(42)	17	22	61	(107)
	2																	20	14	66	(129)
MCA Mine 4	1					30	35	35	(30)												
	avg	5	0	90		18	23	61		39	-	-		10	14	56		21	9	69	
NA Mine 5	1					51	24	25	(92)	43	52	5	(19)	4	-	-	(39)				
	2					9	63	28	(843)												
	3					39[2]	26	35	(51)												
	avg	39	26	35		30	38	29		43	52	5		4	-	-					
NA Mine 6	1	12[1]	29	59	(38)	0	82	18	(5253)	26	-	-	(11)	12	66	22	(32)				
	2	29	65	6	(17)	0	77	23	(4964)												
	3	2	-	-	(68)	7[2]	81	12	(280)												
	4	13	-	-	(70)	22[2]	-	-	(52)												
	5	3[3]	-	-	(11)																
	avg	13	47	33		7	81	16		26	-	-		12	66	22					
SCA Mine 7	1	0	-	-	(7)	26	-	-	(18)	35	-	-	(13)	34	34	32	(29)	43	42	15	(34)
	2	32	45	23	(20)	22	-	-	(54)	19	33	48	(30)	25	42	33	(39)	17	-	-	(20)
	3					23	14	63	(76)	4	13	83	(71)	0	-	-	(15)	21	30	49	(38)
	4					15	-	-	(58)	5	-	-	(81)	23	-	-	(40)	33	42	25	(25)
	5					1	-	-	(181)	31	-	-	(45)					11	-	-	(24)
	6					13	20	67	(81)												
	avg	16	45	23		19	17	65		16	23	66		21	38	33		25	39	26	
SCA Mine 8	1	12	-	-	(23)	18	23	59	(50)	0	0	100	(2)	7	-	-	(71)	9	-	-	(17)
	2	0	0	100	(1)	0	5	95	(224)	35	-	65	(12)	7	13	80	(103)	0	9	91	(130)
	3	27	-	-	(21)	2	8	90	(110)	37	-	-	(59)	14	22	64	(91)	9	7	84	(150)
	4	34	0	66	(20)	0	-	-	(27)	37	0	63	(8)	11	-	-	(127)	29	17	54	(181)
	5					5[4]	62	33	(1414)	7	-	-	(22)	0	-	-	(96)	4	3	93	(2703)
	6					2[4]	59	39	(523)									3	4	93	(1492)
	7					0[4]	55	45	(244)									4	0	96	(1699)
	8					4[4]	59	37	(1075)												
	avg	16	0	83		7	29	63		21	0	76		7	18	72		8	7	85	

[1]Sample was collected from headgate of longwall shearer. [2]Sample was collected from tailgate of longwall shearer.
[3]Sample was collected from track. [4]Sample was collected from return adjacent to active trickle duster.

Regarding the actual coal and mineral mass fractions estimated for these field samples, the results seem somewhat surprising considering the context. As illustrated in Figure 1.1, the coal mass fraction is generally quite low – across the entire dataset. Of the 86 reported results, the samples contained an average of only 15% coal. A total of 37 samples had 10% or less coal and only one sample had more than 50% coal. Also, it should be noted that a consistent negative bias of the TGA method for coal mass fraction is unlikely, based on both method verification results reported by Scaggs[19] and the comparison between TGA and SEM results used to validate samples here. (i.e., of 86 samples within an absolute difference of 25%, the TGA value was greater than the SEM value for 51 samples, and vice versa for the other 35 samples).

From Figure 1.1, substantial variability in coal (and thus non-coal) mass fractions of the TGA field samples is evident with respect to sampling location, mine/mine region, and sampling event (i.e., in cases where samples were collected in the same location of the same mine, but on different days). Variability in coal mass fractions between sampling events in a given location are likely a function of multiple complex factors including ventilation conditions (e.g., relative position of dust generation activities with respect to air flow), production conditions (e.g., seam thickness, advance rate, cutting bit age), or the level of other activities in the mine (e.g., rock dusting). For instance, samples were collected on four different occasions near the continuous miner in mine 7 and the coal fraction of these samples varied between 11 and 41%. This suggest that sampling efforts targeted at assessing the whole composition of dust should consider sample collection on a relatively large number of occasions representing a range of conditions.

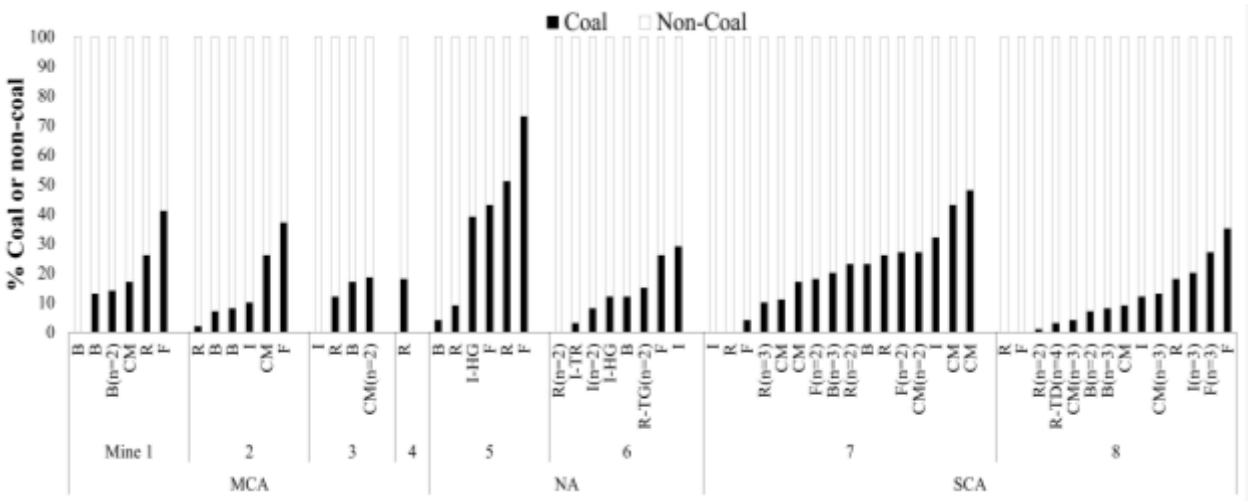

Figure 1.1: Coal and non-coal mass fractions by mine number and sampling location. Locations are denoted as: B = Roof Bolter, CM = Continuous Miner, R = Return (where TG = tailgate, HG = headgate, and TD = trickle duster, specifically), F = Feeder, I = Intake (where TR = track, specifically). In cases where replicate sample results are reportable, the results have been averaged and the number (i.e., n value) of replicate samples is shown.

Although the number of TGA samples reported for this study is too small to make many statistical comparisons, some qualitative assessment of variability in coal mass fractions between different sampling locations and mines/mine regions can be made. In general, samples collected near a feeder system had some of the highest coal fractions in a given mine. This is consistent with expectations, and preliminary findings by Johann[24] based on particle number distributions in the SEM samples collected alongside the TGA samples described here. Near a feeder, raw coal is being broken and dropped onto a moving conveyor, which may generate or aerosolize additional coal particles in higher proportions than non-coal particles. In some cases (e.g., in the MCA mines), samples collected in the ventilation returns also had relatively high coal fractions with respect to other samples in a given mine. Again, this can be considered consistent with expectations since the returns are receiving airflow directly from production activities; but, as noted below, rock dusting in the return of some mines appears to be contributing very high levels of carbonate to the total respirable dust such that the coal mass fraction is proportionally small. In most mines (i.e., all but mine 7 in MCA), samples collected near a roof bolter generally had relatively low coal fractions, which is consistent with drilling into roof rock (i.e. non-coal strata). With respect to variation between mines/mine regions, Figure 1.1 also illustrates that mine 7 (in the SCA region) and mine 5 (in the NA region) had the highest coal fractions overall. This observation may be partially due to relatively thick coal seams in these mines.

Based on the 47 samples where carbonate (and hence non-carbonate mineral) mass fractions could be reported, a better understanding of the non-coal components of dust can also be gained. From Figure 1.2, two primary observations can be made regarding the carbonate values. First, the carbonate mass fraction was relatively high in the NA mines (i.e., average carbonate was 41% for mine 5 and 67% for mine 6); but lower in the SCA mines (i.e., 29% in mine 7 and 18% in mine 8) and CA mines (i.e., 14% on average across all mines in this region). Second, the results suggest there may be multiple sources of carbonate minerals in the samples collected for this study. In some cases (e.g., samples collected near a trickle rock duster machine in mine 8, or samples collected in some other returns or intakes), rock dusting activities were observed during sample collection. Based on this, and particularly in cases where the recovered dust sample weight is very high (e.g., return samples in mine 6), it is reasonable to assume that carbonate in these samples is largely related to the rock dust product that was being applied in the mine. On the other hand, samples collected near roof bolters or continuous miners are not expected to be heavily influenced by rock dusting activities but still contain significant carbonate (i.e., 6-66%). This finding suggests that cutting rock strata in these mines may also be contributing carbonate minerals to respirable dust in some cases and should be considered when determining rock dusting activities on total respirable dust concentrations

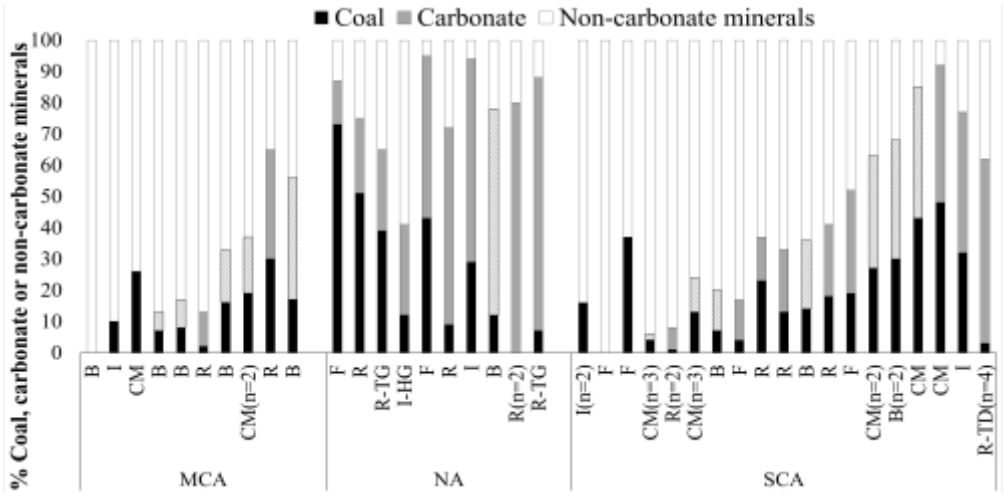

Figure 1.2: Percent carbonate by mine region and location. Locations and replicate samples are denoted as in Figure 1.1. Hatched portions of columns are carbonate values at locations not expected to be heavily influenced by rock dusting activities.

Other key observations can also be made upon examining the non-carbonate mineral values in Figure 1.2. Like the carbonate mass fractions, the non-carbonate fractions tend to vary by mine

region. Non-carbonate values in the NA mines were relatively low (i.e., 23% for both mines); but higher in the SCA mines (50% in mine 7 and 73% in mine 8) and CA mines (72% across all mines). This is consistent with expectations since the NA mines were cutting less roof and/or floor rock – and many of the samples reported from this region were also heavily influenced by rock dusting activities. In contrast, the MCA mines had particularly thin coal seams with respect to their total mining height, and therefore were cutting significant rock strata. Less rock dusting was also observed in the MCA mines. The difference between the non-carbonate mineral values in mines 7 and 8 may also be related to the relative coal versus rock heights in these mines; mine 7 was cutting significantly less rock than mine 8 during sampling. Despite differences in non-carbonate mineral fractions between the three mine regions, clear trends with sampling location could not be observed. This may be partially due to the small number of samples with reportable results here. However, the fact that relatively high non-carbonate values were observed across sampling locations in most mines indicates that these particles are not localized. Rather, they are being generated or moved throughout the mine.

4. Conclusions

A better understanding of respirable dust characteristics in underground coal mines is needed to shed light on potential health outcomes and implement appropriate mitigation strategies. Advanced dust characterization requires additional monitoring and/or analysis methods, and the current study demonstrates the usefulness of a relatively simple TGA method for estimating mass fractions of coal, carbonates and non-carbonate minerals. Here, small dust sample sizes were a clear limitation, but future work could overcome this issue by increasing sample collection times or perhaps using an alternative filter media.

In samples from three distinct sub-regions of Appalachia, TGA results showed the coal mass fraction of respirable dust is generally quite low. This finding is generally consistent with available historical data. For instance, data compiled by the International Agency for Research on Cancer,[26] mostly from outside of the US and prior to 1970, showed that the non-coal component of coal mine dusts could be relatively high (i.e., 30% or more by mass). However, aside from quartz-specific data (e.g., available from the MSHA database) and other studies by the authors in Appalachia (e.g., see Sellaro and Sarver[27] Johann[24]), recent research is scarce

that is directly related to the whole composition of respirable coal mine dust in this specific region or elsewhere. Results from the current study indicate that, within the non-coal fraction of respirable dust, both carbonate and non-carbonate minerals can be high. In some cases, the carbonate appears to be clearly related to rock dusting activities; but in others, the results suggest that drilling or cutting rock strata can also contribute significant carbonate minerals. This possibility should be considered as methods are devised to quantify the contribution of rock dust products to total respirable dust concentrations in underground coal mines. Moreover, from a health perspective, the relatively high non-carbonate mineral fractions reported here may be important – especially in light of recent results from Cohen et al.,[15] which indicate silicates, in addition to silica, may play a role in occupational lung disease.

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2 Coal and Mineral Mass Fractions in Personal Respirable Dust Samples Collected by Central Appalachian Miners

Kent Phillips[1], Cigdem Keles[1], Meredith Scaggs[1], Emily Sarver[1]

[1]*Virginia Tech, Blacksburg, Virginia*

Abstract

Coal Worker's Pneumoconiosis (CWP) is an occupational lung disease caused by chronic exposure to respirable mine dust. After decades of steady decline, CWP incidence appears to be on the rise since the mid-1990s, particularly in some regions of Appalachia. Alarmingly, many of these cases have rapidly progressed to the most advanced form of CWP, referred to as Progressive Massive Fibrosis (PMF). Most of what is currently understood about respirable mine dust has been gleaned from routine regulatory monitoring, which tracks total mass concentration of respirable dust (mg/m^3) and, less frequently, silica mass content. This paper focuses on the use of thermogravimetric analysis (TGA) as an option to provide basic characterization of the whole composition of the dust, allowing it to be classified into three mass fractions – coal, carbonate, and non-carbonate minerals. TGA was conducted on 59 dust samples collected by miners from eight coal mines in central Appalachia, and the are discussed in terms of differences between mines, regions, and primary occupations. Consistent with prior results on area dust samples from some of the same mines, results of the personal samples generally show that the coal mass fraction of the dust is relatively low. Carbonate and non-carbonate minerals thus tend to make up the bulk of the dust mass, and vary across occupations and specific mines.

1. Introduction

After nearly four decades of decline, the prevalence of Coal Workers' Pneumoconiosis (CWP, or "black lung") in the US has been on the rise since the mid-1990s (Laney et al., 2014; Laney et al., 2010; Suarthana et al., 2011; Pollock et al., 2010; Antao et al., 2005; Blackley et al., 2016). Particularly alarming is the number of cases of progressive massive fibrosis (PMF), which is the most advanced form of the disease (Pollock et al., 2010; Antao et al., 2017; Blackley et al., 2017; Laney et al., 2017). A recent study by Laney et al. (2017) looked at 192 US coal miners

participating in the Coal Workers' Health Surveillance Program (CWHSP) who had been diagnosed with PMF since 2000. Of the 163 (85%) that had a normal radiograph on file to use as a baseline, 27 (17%) of these individuals had progressed from a normal radiograph to PMF diagnosis in less than 10 years. Moreover, 162 (84%) of the individuals in that study worked in KY, WV or VA, and 169 (88%) had only ever mined underground. Blackely et al. (2016) also reported on a group of 60 PMF cases that were discovered by a single black lung clinic in eastern KY. Since seeking care at such clinics and participation in the CWHSP are voluntary, and could be influenced by a number of factors, some bias may exist in these recent reports that overestimates the degree of resurgence in severe disease (i.e., versus disease that was previously under-reported). Even so, they highlight a critical need to better understand the cause(s) of disease development and progression – such that effective interventions can be devised.

The notable uptick in CWP and PMF rates amongst miners in central Appalachia has led to this region being called a "hot spot" for disease (Pollock et al., 2010; Antao et al., 2005; Blackley et al., 2014; Laney et al., 2017). While the geographic clustering of CWP has been well documented (Pollock et al., 2010; Antao et al., 2005; Wade et al., 2011; Wang et al., 2014), the root cause is still unknown. Leading hypotheses have focused on the relative amount rock being cut along with coal in many central Appalachian mines, as they have tended toward increasingly thinner coal seams over the past couple of decades (Laney et al., 2010; Schatzel, 2009). This shift has likely been accompanied by changes in specific dust exposure factors, such as increased abundance of particularly harmful dust constituents (e.g., silica or silicates) or increased frequency of harmful exposures (e.g., due to work in more risky environments) (Pollock et al., 2010; Blackley et al., 2016; Cohen et al., 2016; Douglas et al., 1986).

With respect to dust characteristics, most of what is currently understood about exposures in underground coal mines has been learned from regulatory compliance sampling (i.e., under 30 CFR Part 70). For this, two primary metrics of personal exposures are routinely monitored: total mass concentration of respirable dust (mg/m3), and the mass fraction of quartz (i.e., crystalline silica) in the respirable fraction. However, little is known about the whole composition of respirable dust with regard to constituents other than silica.

While characterization of dust mineralogy is still too tedious for routine monitoring (Johann et al., 2017), previous work by Scaggs et al. (2015) suggested that thermogravimetric analysis (TGA) could be used to provide a coarse characterization of respirable dust by estimating mass fractions of coal and total minerals (i.e., non-coal). A TGA method for this purpose was outlined by Scaggs (2016) and verified on laboratory-generated respirable dust samples. With sufficient dust mass, the non-coal mass fraction can be further delineated between carbonates and non-carbonate minerals. For a cursory breakdown, the non-carbonate fraction might serve as a crude surrogate for dust sourced from cutting rock in the mine; and the dust constituents that are commonly accepted as most harmful (e.g., silica and silicates) should be represented in this fraction. The carbonate fraction, on the other hand, might be related to rock dusting activities[1] in mines that do not cut significant carbonate-bearing rock.

The first field application of the TGA method described by Scaggs (2016) was on a large set of area dust samples collected from eight mines across northern and central Appalachia. Results of that effort were recently reported by Phillips et al. (2017). In all mines, the samples were taken in locations deemed to be representative of the intake or return (i.e., just outby of the production face), production areas (i.e., nearby active coal cutting or roof bolting), or near the feeder (i.e., adjacent to the feeder breaker or coal transfer belt). From a total of 86 samples where TGA results were verified based on corresponding analysis by electron microscopy, the mass percentage of coal was generally found to be low across all regions and sampling locations (i.e., average of 14%, with a standard deviation of 13%). Within the non-coal fraction, the percentages of carbonate and non-carbonate minerals varied regionally (based on verified results from 47 samples). In central Appalachia, where more rock was being mined with the coal, the percentage of non-carbonate minerals was significantly higher than in northern Appalachia (i.e., 64% versus 23%, respectively, on average). Conversely, the carbonate percentage was generally much higher in northern than in central Appalachia (i.e., 41 versus 19%, respectively, on average), and this finding was consistent with field observations of typically heavier rock dusting in the northern Appalachian mines. Importantly, several results from central Appalachian mines did suggest that

[1] Rock dusting is the process of applying a pulverized inert material, usually limestone or dolomite (i.e.carbonate), to coal dust in underground mines to reduce the propagation of coal dust explosions (MSHA, 2015).

significant carbonate percentages could also be related to roof-rock cutting in some mines, such that the carbonate percentage of respirable dust may not always be an appropriate proxy for particles sourced from rock dust products.

While the results reported by Phillips et al. (2017) provide insights into the composition of respirable dust collected at different stationary locations in underground coal mines, they do not necessarily reflect a miner's personal exposure. Here, results are presented on TGA of 59 personal dust samples collected by volunteers in central Appalachia – including four of the same mines from which the aforementioned area samples were analyzed.

2. Materials and Methods

Between July, 2014 and September, 2015, a total of 59 volunteers were recruited from eight active coal mines in two distinct sub-regions, referred to herein as mid-central Appalachia (MCA, MSHA District 4) and south-central Appalachia (SCA, MSHA District 12) (Table 2.1). In addition to the two MCA and two SCA mines from which area samples were also collected and previously analyzed by TGA (Table 2.1), an additional four MCA mines were represented in the current study. However, because there were only one or two volunteers from each, their sample results are only included in analysis done on a regional or job classification basis.

Table 2.1. Key characteristics of four mines where most personal dust samples were collected by volunteers (adapted from Phillips et al., 2017).

	MCA		SCA	
	Mine 2	Mine 3	Mine 7	Mine 8
Number of miners included in study	7	13	13	19
Coal seam thickness (ft)	3-4	4.5	5-6	4-4.5
Total mining height (ft)	5.5	6	6-7	6
Ratio of coal thickness: total mining height	0.64	0.75	0.85	0.71
Primary rock strata	sandstone	shale and sandstone	sandy shale and slate	shale
Production sections	2 CM	2 CM	3 CM	2 CM

CM: Continuous miner

Each miner collected a single respirable dust sample over a full shift of regular work (i.e., about 8-10 hours). Samples were collected using standard equipment for coal mines, and volunteers were instructed to use the equipment just as they would for standard dust sampling (i.e., tube inlet located on or near lapel, care to avoid tube compression, normal work activities). For each volunteer, the research team delivered an Escort ELF dust pump with flow rate set at 1.7 L/min. The pump was fitted with 10mm Dorr-Oliver cyclone (i.e., to discard particles greater than 10µm and achieve a D_{50} cut point of 4µm), and a pre-loaded filter cassette (i.e., 2-piece with 37-mm filter and cellulose support pad). The filters were either mixed cellulose ester (MCE, 5µm pore) or polyvinyl chloride (PVC, 5µm pore) media. Immediately after sampling, the research team retrieved the equipment and samples.

All dust samples were prepared and analyzed by the TGA method described in detail by Scaggs (2016) to determine coal, carbonates, and non-carbonate mineral mass fractions. Briefly, the dust was removed from the filter by placing it in a clean borosilicate glass test tube and sonicating in deionized water (DI). The DI water was then evaporated off in an oven (180 °C).

Isopropyl alcohol was used to rinse the dust into the bottom of the tube, and then it was pipetted into clean and pre-tared TGA sample pans and allowed to evaporate prior to analysis.

The samples were analyzed using a Q500 Thermogravimetric Analyzer (TA Instruments, New Castle, CE), per the thermal profile described by Scaggs (2016). The entire method is run in high purity air (i.e., oxidizing atmosphere), and includes three primary temperature regions: In the first region, the sample is heated to 360°C to remove volatiles, including filter residue. In the second region, the temperature is ramped to 480°C, and weight loss in this region is attributed to the oxidation of coal. In the third region, the temperature is ramped to 750°C, and weight loss is attributed to CO_2 evolution from degradation of carbonates. The remaining weight at the end of the method is attributed to the non-oxidizable sample constituents (i.e., the non-carbonate minerals and the oxides formed during degradation of carbonates). Figure 2.1 illustrates how the mass fractions of coal, carbonates, and non-carbonate minerals are derived from the observed weight losses during the TGA method. As demonstrated by Scaggs (2016), the TGA method accuracy is improved with increased dust weight (i.e., recovered from the sample filter to the TGA pan).

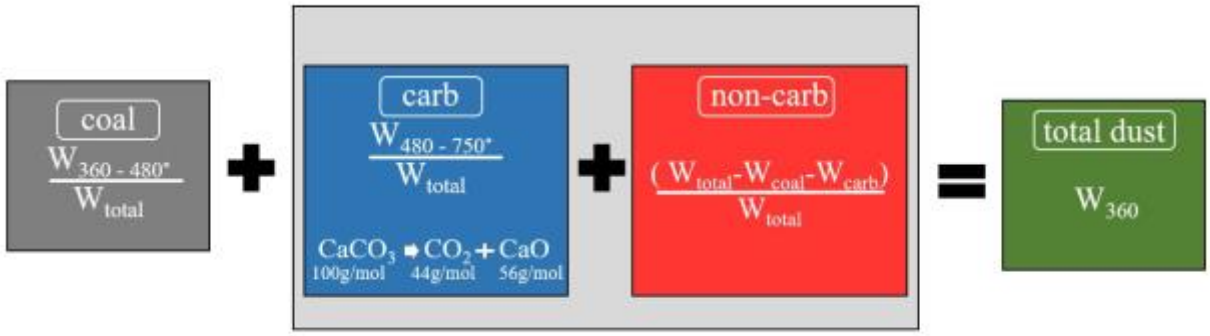

Figure 2.1. Derivation of coal, carbonate, and non-carbonate mineral mass fractions based on observed weights (W) at specific temperatures during TGA. Total dust refers to the dust recovered from the filter sample to the TGA pan.

3. Results and Discussion

Table 2.2 displays the mass percentages of coal, carbonate, and non-carbonate minerals derived from the TGA results for all 59 personal miner samples included in this study. Overall, the percentage of coal was found to be generally low, and hence non-coal (i.e., carbonate plus

non-carbonate minerals) was generally high, which is consistent with observations on area samples previously reported by Phillips et al. (2017).

Table 2.2 Mass percentages of coal, carbonate, and non-carbonate minerals determined from TGA of personal respirable dust samples. Total dust is the dust mass recovered from the filter sample to TGA pan. MCA mines listed as NA are those where two or less samples were collected.

		Job	Total Dust (µg)	Coal	Carb	Non-Carb
MCA	Mine # NA	Fireboss	13	1%	99%	0%
		Fireboss	18	35%	62%	2%
		Foreman	39	19%	34%	47%
		Move Crew	801	24%	68%	9%
		Outby Worker	19	34%	20%	45%
		Outside Mine Worker	19	34%	55%	12%
		Outside Mine Worker	23	0%	27%	73%
		Mine NA Avg (STDV) (n=7)	133 (295)	21 (15)	52 (27)	27 (28)
	Mine # 2	Continuous Miner Operator	35	18%	31%	52%
		Move Crew	48	20%	34%	45%
		Roof Bolter	307	10%	12%	78%
		Roof Bolter	226	10%	12%	78%
		Scoop Operator	12	0%	93%	7%
		Shuttle Car Operator	30	16%	42%	42%
		undisclosed	33	15%	40%	45%
		Mine 2 Avg (STDV) (n=7)	99 (117)	13 (7)	38 (27)	49 (24)
	Mine # 3	Continuous Miner Operator	508	8%	10%	81%
		Electrician	50	5%	95%	0%
		Outby Worker	108	16%	26%	58%
		Rock Dust Crew	653	2%	67%	31%
		Rock Dust Crew	558	1%	72%	27%
		Rock Dust Crew	127	6%	18%	76%
		Roof Bolter	12	6%	67%	27%
		Roof Bolter	625	7%	11%	82%
		Safety Represenative	29	25%	49%	25%
		Scoop Operator	34	16%	38%	46%
		Shuttle Car Operator	13	17%	53%	30%
		undisclosed	451	1%	63%	36%
		undisclosed	145	10%	16%	74%
		Avg (STDV) (n=13)	255 (258)	9 (7)	45 (27)	46 (26)
		MCA Avg (STDV) (n=27)	183 (243)	13 (11)	45 (27)	42 (24)
	Mine # 7	Continuous Miner Operator	50	16%	34%	49%
		Electrician	22	24%	57%	19%
		Fireboss	9	24%	72%	4%
		Foreman	20	39%	61%	0%
		Outby Worker	27	5%	95%	0%
		Outside Mine Worker	33	17%	56%	27%
		Roof Bolter	11	24%	73%	3%
		Scoop Operator	20	23%	59%	18%
		Section Boss	17	27%	71%	3%
		Section Boss	14	48%	49%	3%
		Shuttle Car Operator	19	32%	50%	18%
		undisclosed	12	35%	63%	2%
		undisclosed	17	33%	67%	0%
		Avg (STDV) (n=13)	21 (11)	27 (11)	62 (15)	11 (15)
SCA	Mine # 8	Electrician	209	0%	58%	42%
		Electrician	11	21%	77%	2%
		Electrician	11	29%	65%	6%
		Electrician	15	19%	64%	17%
		Maintenance Foreman	22	10%	87%	3%
		Move Crew	15	9%	39%	52%
		Outby Worker	5	0%	100%	0%
		Outside Mine Worker	41	5%	26%	69%
		Roof Bolter	26	1%	49%	50%
		Roof Bolter	39	12%	25%	63%
		Roof Bolter	173	6%	12%	82%
		Roof Bolter	290	8%	10%	82%
		Roof Bolter	32	15%	42%	42%
		Scoop Operator	32	4%	41%	55%
		undisclosed	48	17%	38%	45%
		undisclosed	8	10%	90%	0%
		undisclosed	8	0%	100%	0%
		undisclosed	15	27%	62%	10%
		undisclosed	18	0%	65%	35%
		Avg (STDV) (n=19)	54 (79)	10 (9)	55 (28)	35 (29)
		SCA Avg (STDV) (n=32)	40 (63)	17 (13)	58 (23)	25 (27)
		All Samples Avg (STDV) (n=59)	106 (184)	15 (12)	52 (25)	33 (28)

For the four mines where area sample results were previously reported, Figure 2.2 shows a direct comparison of the results. In all cases, the personal samples appear to have much higher percentages of carbonate, on average, than area samples collected in the same mine. This may simply mean that average personal exposures are not well represented by average dust compositions obtained from prior area sampling (i.e., miners were spending time in areas with higher carbonate concentrations than those selected for stationary sampling in the prior study by Phillips et al., 2017). Even face workers like continuous miner operators, for example, may spend significant time in intake areas where carbonate from rock dusting activities may contribute substantially to respirable dust concentrations. Moreover, to the extent that carbonate is indeed a reliable surrogate for rock-dust product related respirable dust, the respirable dust composition may vary widely since rock dusting activities do (i.e., rock dusting upstream of typical work areas is not done continuously, and product characteristics and application techniques may greatly influence the effects on respirable dust compositions).

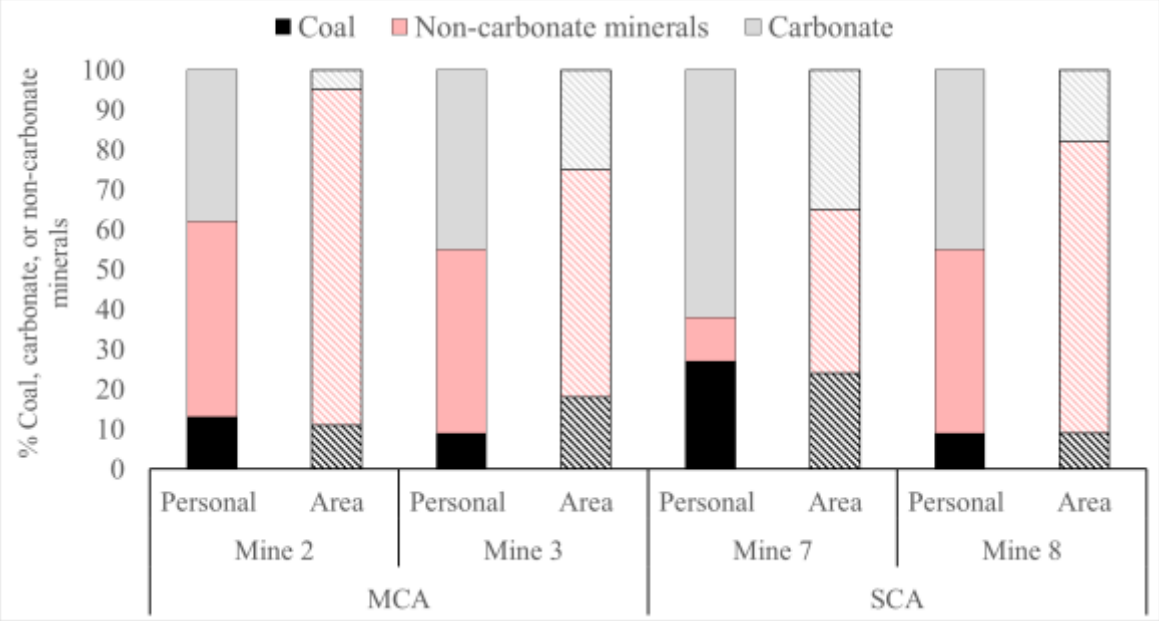

Figure 2.2. Comparison of average mass percentages of coal, carbonate, and non-carbonate minerals for personal dust samples versus area samples (hatched bars) collected in the same mines. Area sample results were previously published in Phillips et al. (2017).

To gain more direct insight about how mining of coal and rock strata may affect respirable dust composition, the personal dust results were normalized to exclude carbonate – which effectively assumes that carbonate minerals in respirable dust are contributed only by rock dusting activities. Figure 2.3 shows the same personal dust data presented in Figure 2.2 after normalizing to exclude carbonate; and the coal and rock height are also shown as percentages of the total mining height (i.e., based on Table 2.1). In three of the four mines, the average ratio of coal to non-carbonate minerals in the dust samples significantly overestimates the ratio of coal to rock height being cut in the mine during the dust sampling. Assuming that non-carbonate mineral mass in respirable dust is generally sourced rom rock cutting in the mine, this basic analysis suggests that mining practices contribute an inordinate amount of dust from rock strata versus coal strata to work environments. Possible explanations for such an outcome may include better dust control on shearers as opposed to rock drills, or disproportionate generation of respirable-sized dust from rock versus coal materials. Whatever the case, these results are concerning from a health perspective since the constituents that are widely considered to be most harmful should be contained in the non-carbonate minerals fraction of the dust.

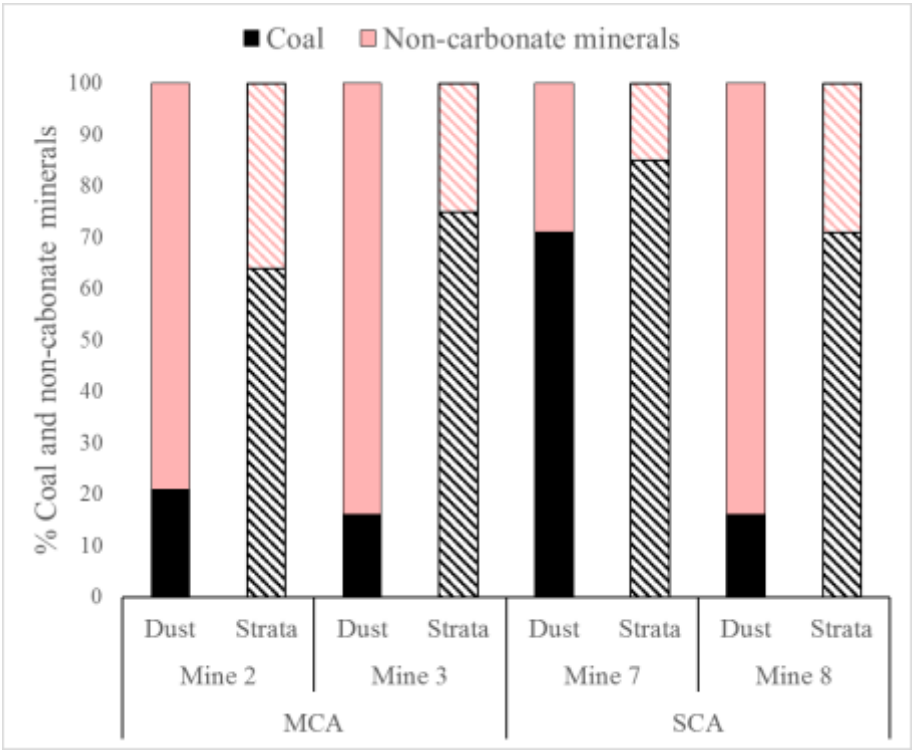

Figure 2.3. Comparison of average mass percentages of normalized coal and non-carbonate minerals for personal dust samples versus percentages of coal and rock heights with respect to the total mining height.

Figure 2.4 shows the normalized personal dust samples for roof bolters and continuous miner operators. For comparison, the figure again shows the relative ratio of coal and rock heights in each mine; and it also shows results of area samples collected near roof bolters and continuous miners, which were previously published by Phillips et al (2017). The roof bolter samples had relatively low ratios of coal to non-carbonate minerals mass fractions as compared to the mine strata. This is consistent with expectations since bolters generally drill into roof rock (not coal) and operate upwind of coal face cutting. However, the continuous miner samples also had relatively low coal to non-carbonate minerals ratios. Since the continuous miner is cutting into the entire height of mined strata (i.e., coal plus rock), this observation may indicate that the miner shearer generates relatively more respirable particles from the rock than from the coal. Considering the importance of such a finding, and the limited basis of the current work, additional research is needed to elucidate differences between coal and roof-rock dust particle generation by shearing equipment.

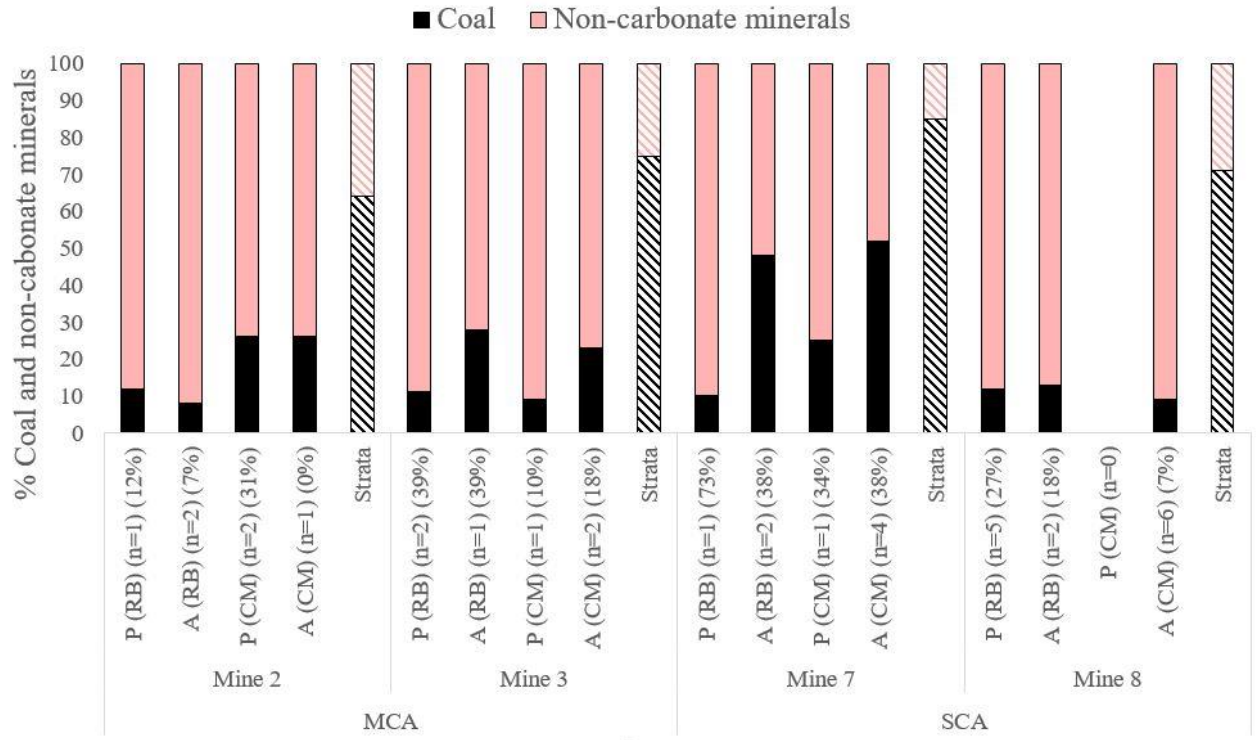

Figure 2.4. Average mass percentages of normalized coal and non-carbonate minerals for roof bolter (RB) and continuous miner (CM) personal (P) and area (A) dust samples versus percentages of coal and rock heights with respect to the total mining height. The area sample results were previously published by Phillips et al., (2017). n values are shown for each dust sample category, as are the average percentages (%) of carbonates in each category prior to normalization.

Figure 2.5 shows the personal dust sample results averaged for each occupational category. Even without removing carbonates, the continuous miner operators and roof bolters had the highest non-carbonate minerals (i.e., 59% and 61%, respectively). This finding is important because the non-carbonate mass fraction of respirable dust is expected to contain the most harmful constituents (e.g., silica and silicates). Notably, Pollock et al. (2010) previously reported that roof bolters and miner operators are generally exposed higher percentages of quartz than other occupations, and several studies have also concluded that roof bolters and miner operators have relatively higher risk of developing PMF than other occupations (e.g., see Antao et al., 2005; Cohen et al, 2015; Blackley et al., 2016). It should of course be reiterated that the results presented here indicate relative mass fractions of the whole respirable dust composition, but they cannot be used to interpret total mass concentration of dust. For instance, while individuals in the "outside mine worker" category also had relatively high percentages of non-carbonate minerals, these individuals likely had relatively low total respirable dust exposures.

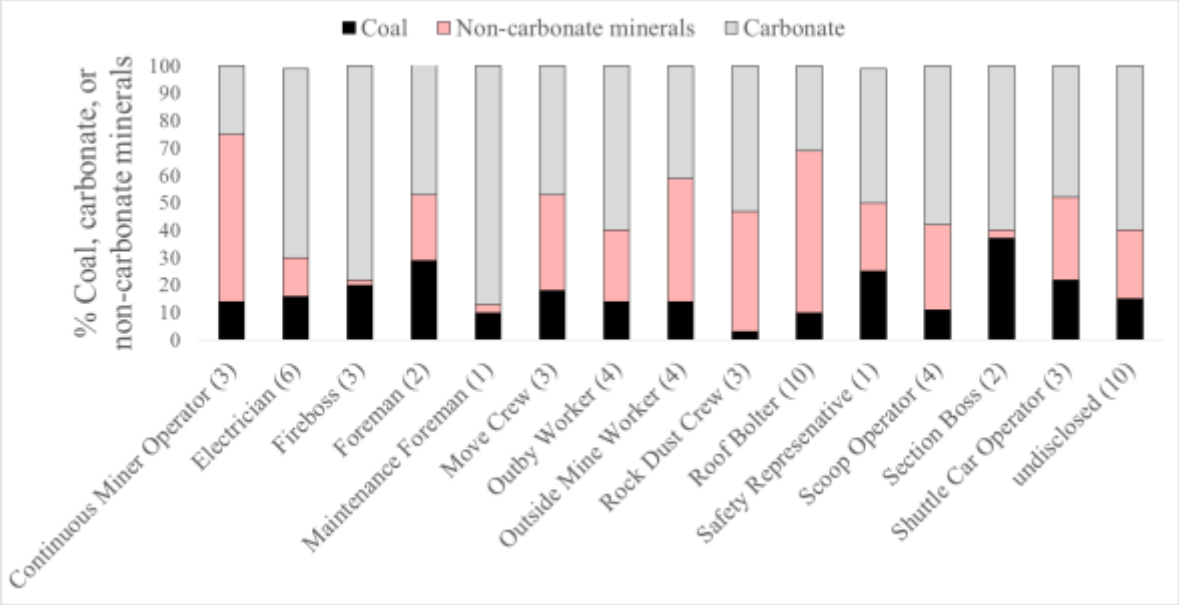

Figure 2.5. Average coal, carbonate, and non-carbonate mineral mass fractions for TGA samples by occupation. Number of samples averaged is in parenthesis.

The TGA method used here, or a similar method, may provide useful information for understanding the major sources of respirable dust. Coupled with other data, like that from the Continuous Personal Dust Monitors (CPDM), even further insights could be gained to pinpoint specific dust sources in the mine. For example, pairing TGA mass fractions with time series data,

such as that derived from Continuous Personal Dust Monitors (CPDM), to better determine which areas of the mine the highest rock dust exposure occurs. i.e. If a miner's personal TGA sample has a high fraction of carbonate, however, area TGA samples taken where they most often work show little carbonate, it would indicate carbonate exposure likely occurs during travel. This could then be corroborated with CPDM time series data (i.e. A spike in dust concentration during travel times).

4. Conclusions

The results presented here suggest that respirable dust exposures in Appalachian coal mines can include significant non-coal material, including carbonates and non-carbonate minerals. These results support similar findings by Phillips et al. (2017), which presented the area sample TGA results for this study. In terms of dust exposure composition by occupation, continuous miner operators and roof bolters were found to have the highest composition of non-carbonate minerals. This finding is not surprising, as these occupations are most directly associated with the cutting and drilling of mine strata, of which a significant portion may be non-coal.

It should be noted that the personal sample dust data presented here was not SEM verified for accuracy as was done in Phillips et al. (2017). The next step in this research will be to improve a model for sample verification and confidence, using dust weight removed from the filter (i.e. larger dust weights increase method accuracy and confidence as described in Scaggs (2016)). Further research should also include work to increase the efficiency of dust removal from the filter, as again, the accuracy of this method is dependent on dust weight removed from the filter. Current experiments by the authors are investigating the potential of using a different filter media to enhance dust recovery. Alternatively, dust weights could also be increased by sampling for longer periods of time.

Acknowledgements

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participated in the dust sampling campaign, and industry partners that coordinated access to their operations to allow volunteer recruitment. Miner recruitment and participation was done in accordance with a protocol approved by Virginia Tech's Institutional Review Board.

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3 Response of the FLIR Airtec Monitor to Airborne Coal Dust

Kent Phillips[1], Emily Sarver[1], Emanuele Cauda[2]

[1]Virginia Tech, Department of Mining and Minerals Engineering, Blacksburg, Virginia

[2]NIOSH, Pittsburgh, Pennsylvania

Abstract

Diesel particulate matter (DPM) exposures are a serious occupational health hazard in underground mines. While the complex nature of DPM makes direct analysis difficult, its primary component, elemental carbon (EC), can be used as surrogate. The near real-time FLIR Airtec monitor measures EC mass based on laser extinction. It was developed for use in underground metal/non-metal mines, and calibrated to the NIOSH 5040 Standard Method. Its effectiveness has not been demonstrated in coal mines, however, where coal-sourced EC could produce analytical interference. To gain preliminary insights regarding the Airtec's performance in the presence of coal dust, experiments were conducted in a controlled laboratory chamber. The Airtec EC results consistently underestimated NIOSH 5040 EC for both respirable-sized and submicron coal dusts. While underestimation of coal-sourced EC bodes well for limiting coal interference for DPM measurement, one key reason for the observed trend was non-uniform coal particle deposition on the Airtec filter. This may be problematic in coal mines where DPM and coal dust occur together in the instance that DPM deposition is also non-uniform.

1. Introduction

Diesel particulate matter (DPM) is an occupational health hazard (NIOSH, 2012), and underground miners have the potential for very high exposures due to their work in confined environments with diesel powered equipment (NIOSH, 2011). While the complex nature of DPM does not allow direct measurements (Birch and Cary, 1996; Noll et al., 2006), elemental (EC) and total carbon (TC) often serve as good surrogates (Birch and Noll, 2004; Noll et al., 2015). EC is the "soot" component of DPM, whereas TC also includes particulate organic carbon (OC) (Noll et al., 2007). EC and OC can be measured in filter samples using the NIOSH 5040 Standard Method (NIOSH, 2003), and summed to obtain TC.

In US underground metal/non-metal mines, DPM is regulated under 30 CFR Part 57, which states that an underground miner's permissible exposure limit (PEL) must not exceed an 8-hour time weighted average concentration (TWA_8) of 160 $\mu g/m^3$ total carbon (TC). In US coal mines, regulation is done "at the tailpipe" under 30 CFR Part 72 due to potential interferences of coal dust with TC measurements. This approach effectively limits the total DPM that can be emitted in the mine, but does not directly monitor personal exposures. Although TC is used as the regulatory surrogate for US mines, EC has also been suggested as an appropriate surrogate in mines because it generally exhibits a linear correlation with TC (Birch and Cary, 1996; Noll et al., 2006; Noll et al., 2007). In fact, Australia not only recommends an EC basis for DPM monitoring in underground coal mines, but it does so for personal exposures by contending that the potential interference from coal dust is relatively minor. The Australian TWA_8 personal exposure limit is 0.1 mg/m^3 EC, as measured by the 5040 method (AIOSH, 2013).

Regardless of whether EC is used for regulatory purposes, it can be tracked in near real time using instruments that continually measure laser extinction as the sample is collected on a filter (Noll et al., 2013). This is an important capability for empowering mine personnel to monitor DPM and make timely decisions, and the FLIR Airtec monitor was developed specifically for this purpose (Noll et al., 2013). The Airtec has been described in detail elsewhere (see Noll et al., 2013).But, briefly, as DPM is continuously deposited on filter by an air pump, the EC fraction – which is black – increasingly inhibits laser light transmittance through the filter. An optical sensor periodically records voltage values related to the light transmittance, and these can be used to determine accumulated EC mass via a standard calibration curve (i.e., with 5040 EC). To minimize interferences in the measurements that could be caused by dust particles (i.e., from geologic strata being mined), the Airtec is usually operated with a cyclone and impactor assembly that discards particles larger than about 0.8μm; in general, DPM is considered to occur in the sub-micron range while most (hardrock) mine dusts occur in the supra-micron range (Noll et al., 2005).

While the Airtec's effectiveness has been demonstrated in metal/non-metal mines, it has not been widely tested in coal mines. Aside from permissibility issues (e.g., in US mines), potential problems with the Airtec's operation in coal mining environments may stem from analytical

interferences caused by coal or mineral dust. In most coal mines, the mined material is cut by machines using continuous shearers (i.e., continuous miners or longwalls). This reduces selectivity such that some rock is cut with the coal, and it can also result in relatively fine dust particles. To reduce Airtec interferences from larger particles, the same cyclone and impactor assembly described above could be used (Noll and Birch, 2004). However, interferences of sub-micron dust may still present challenges. Some historical data (e.g., see that compiled by Birch and Noll, 2004; Rubow et al., 1988) suggests that the mass concentration of all sub-micron dust in coal mines is generally quite small – though increasingly powerful cutting techniques may well be increasing the amounts of sub-micron dust. Indeed, more recent field data collected in seven mines by Birch and Noll (2004) showed that sub-micron dust could represent up to 50% of the respirable dust in some areas of a coal mine. If that dust poses an analytical interference for measurement of DPM-sourced EC, this would affect the Airtec's performance in a coal mining environment.

Interference from coal particles, specifically, is expected to result in positive bias of the Airtec's measurements since the coal is dark in color like DPM-sourced EC. To support research related to use of the NIOSH 5040 method to monitor DPM-sourced EC in coal mines, Birch and Noll (2004) investigated the relative amounts of sub-micron EC in three mines using diesel equipment and five mines that were not. They concluded that sub-micron EC from coal dust should generally be much lower than that from DPM. Thus, the 5040 method, which determines EC based on its thermal and chemical properties, may be appropriate for use in monitoring DPM-sourced EC in coal mines. However, since the Airtec works based on laser extinction, any colored particles may affect measurements – and the relative color of the particles should be important (i.e., darker particles should result in less light transmittance than lighter particles, all else being equal). Coal is comprised primarily of EC and organic carbon (OC), with relative OC to EC ratio and the color of the coal changing based on the coal rank (i.e., the coals with the highest rank have the lowest OC to EC ratio and are blackest in color) (Birch and Noll, 2004).

As a first step in evaluating whether the Airtec or a similar technology may be appropriate for DPM monitoring in coal mines, the goal of this study was to determine the instrument's response to coal dust particles. Tests were performed in a controlled laboratory environment

using coal dust from three different sources, and the Airtec EC results were compared to EC values measured using the NIOSH 5040 Standard Method.

2. Experimental Details

Four tests were conducted during separate sampling events for this study (Table 3.1), each using coal dust from a particular source. Coal samples were received from three different active operations in Appalachia (Table 2.2). One sample was anthracite (Pennsylvania), and the other two were sub-bituminous coals (West Virginia and Virginia); all were taken from clean coal products following processing in order to limit mineral (i.e., ash) content. All three samples were ground and sized to minus 325 mesh (44 μm), and then was sealed in airtight bags prior to use. Calorific values and ash content were determined in the prepared dust samples by Standard Laboratories, Inc. Bulk EC and OC content were also determined for each sample per the 5040 Method, using a OC/EC Carbon Aerosol Analyzer (Sunset Laboratory, Tigard, OR). Carbon in the anthracite was nearly all present as EC, but there were roughly equal EC and OC fractions in the sub-bituminous coals.

Table 3.1. Coal type and sampling instruments for each test.

Test	Coal Sample	Airtec Monitors		ELF Pumps (5040 samples)	
		respirable	sub-micron	respirable	sub-micron
1	A	3	3	3	3
2	A	1	2	3	3
3	B	2	3	3	3
4	C	2	3	3	3

Table 3.2. Coal characteristics.

Sample	Coal Rank	Coal Seam	Coal Origin	EC/TC (NIOSH 5040)	Ash % (Dry Basis)	BTU/lb
A	Anthracite	Mammoth	Pennsylvania	0.98	9.09	13350
B	Bituminous	Pocahontas 3	West Virginia	0.49	6.58	14687
C	Bituminous	Jawbone	West Virginia	0.51	7.12	14390

All tests were conducted inside a Marple Chamber (Figure 3.1) at the Office of Mine Safety and Health Research's diesel laboratory in Pittsburgh, PA. The chamber is approximately 1.2 m in diameter and 2.5 m tall, and was specially designed for evaluation and calibration of air

monitoring instruments (Marple and Rubow, 1983). It promotes uniform distribution of particulates, such that multiple sampling instruments can be used simultaneously with minimal spatial variation in resultant measurements. Dust was introduced to the chamber using a fluidized bed aerosol generator (FBAG), and passed through a Kr-85 source 3012 aerosol neutralizer (TSI, Shoreview, MN) to eliminate static charge. Between tests, the chamber and FBAG were cleaned with compressed air to minimize any cross-contamination between coal samples.

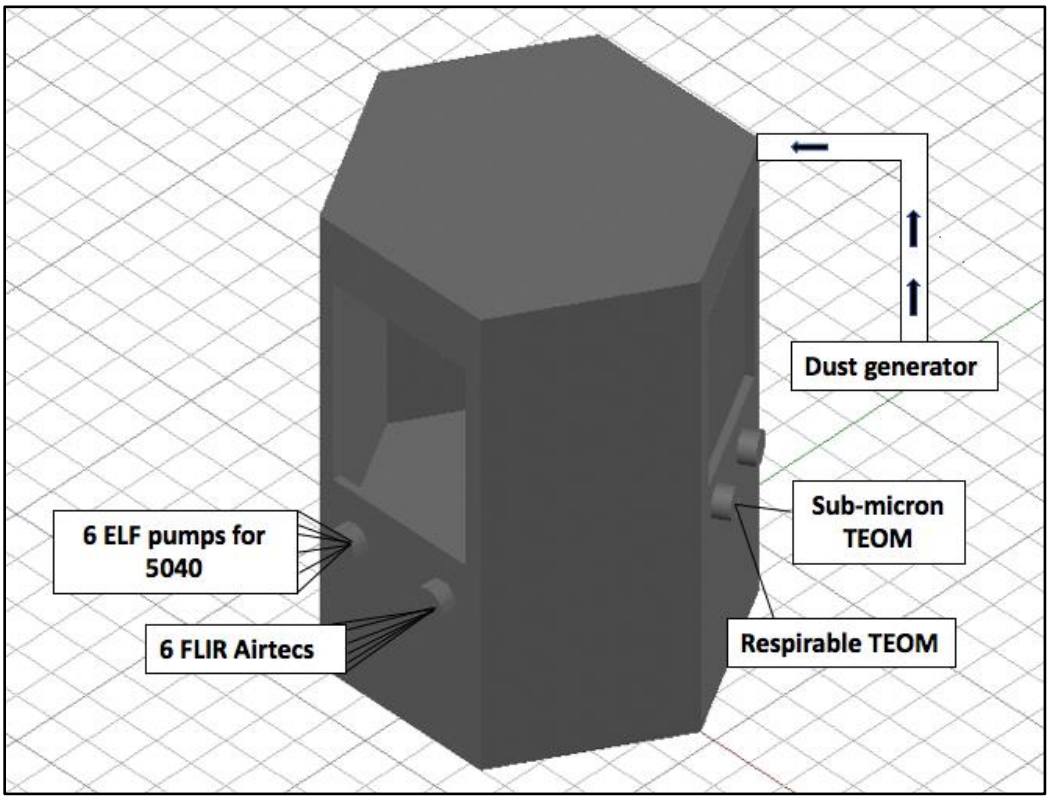

Figure 1.1. Schematic of the Marple Chamber and experimental set-up.

For this study, the general test setup included the Airtec monitors, Escort ELF personal air sampling pumps (Zefon, Ocala, FL) to collect samples for EC analysis by the 5040 Method, and two 1400a ambient particulate monitors (Thermo Fisher Scientific, Franklin, MA) that use a tapered element oscillating microbalance (TEOM) for real-time measurements. All instruments were equipped with size selectors to collect only either respirable (i.e., less than 10 um, and with a d_{50} of about 4 um) or submicron particulates (i.e., less than about 0.8 um). For respirable samples, the size selector was a nylon Dorr-Oliver cyclone (Zefon, Ocala, FL); and for the submicron samples, a Dorr-Oliver cyclone and DPM impactor (DPMI; SKC, Eighty Four, PA) were used in combination. The standard DPMI cassette contains a sample filter just downstream

of the impactor for collection of 5040 samples; but for the Airtec, the DPMI cassette only contains the impactor (see below). A total of six ELF pumps were used in all tests (i.e., to collect three respirable and three submicron samples collected), but fewer Airtecs were used in some tests based on availability of these monitors (Table 3.1).

In all tests, one TEOM was used to monitor the concentration of submicron dust inside the chamber while the other was used to monitor respirable dust. This allowed real-time observations to guide introduction of dust into the chamber such that a desirable concentration could be reached (i.e., to allow sufficient mass collection over a reasonable sampling time). For reliable 5040 Method analysis, about 100-150 µg of submicron dust (per sample filter) was targeted; the mass of respirable dust samples was always higher than this since a larger fraction of dust is in the respirable size range. Use of the TEOMs also ensured that the dust concentration was fairly stable before sampling began. When it was, all Airtecs and ELF pumps were turned on simultaneously. After the desired sampling time, they were all turned off simultaneously.

The target flow rate for all instruments was 1.7 L/min to maintain the desired cut sizes of the size selectors (noted above). Flow rates were measured on each Airtec and ELF pump at the beginning and end of each test using a Defender 520 flow calibrator (Mesa Labs, Butler, NJ), and the average of the pre- and post-test values was used to determine the total volume of air sampled by a particular instrument during that test.

The inlet tube and size selector(s) for all sampling instruments were placed inside the Marple chamber, and were connected by flexible tubing to the Airtecs or ELF pumps located outside of the chamber. For the Airtecs, the particulate sample is collected on a filter housed within a closed three-piece plastic cassette that sits inside the instrument (i.e., such that the laser transmittance through the filter can be monitored in real-time) (Noll et al., 2014). To minimize dust particles sticking via static charge on the tubing between the size selector(s) and the sample filter, conductive tubing was used for these. Filter cassettes were assembled using 37 mm PTFE filters (Pall Corporation, Port Washington, New York).

The Airtec records (in its datafile) cumulative EC mass collected (μg) on a 1-minute basis. For each test, the final EC mass value was converted to an average EC mass concentration (μg/m^3) in the chamber over the test period using the total volume of air sampled by the Airtec (m^3).

For the ELF pumps (i.e., 5040 samples), samples were collected on 37 mm quartz fiber filters (Pall Corporation, Port Washington, New York). For the respirable samples, primary and secondary filters (and cellulose support pad) were housed in a closed three-piece cassette just downstream of the size selector(s). Prior to cassette assembly, the quartz filters were pre-burned (i.e., at 800 °C for 90 minutes) to drive off impurities. For the submicron samples, the primary and secondary filters and support pad were located inside the standard DPMI cassette, which comes pre-assembled. .

The 5040 samples were analyzed by the standard 5040 Method (NIOSH, 2003) using the same OC/EC analyzer noted above. The EC results are obtained from the primary filter, which collects the particulates. To obtain OC results, the values from primary filter must be corrected by those from the secondary filter (i.e., to subtract out any gas-phase OC that was present in the particulate) (Noll and Birch, 2008). TC is simply the sum of the EC and corrected OC results. The OC/EC analyzer outputs results as mass per unit of filter area (M, μg/cm^2). This was converted to average mass concentration (i.e., μg/m^3 of either EC or TC) inside the chamber over the test period, such that 5040 results could be compared to the Airtec results. The conversion was done using Equation 1, here A is the total exposed 5040 filter area (8.5 cm^2) and V is the volume of air sampled (m^3) through that filter.

$$5040\ EC\ concentration = M \times A \div V \qquad \text{(Equation 1)}$$

3. Results and Discussion

Results from all four tests are displayed in Table 3.3. With the exception of the results on submicron particles from coal C, the Airtec consistently underestimated the 5040 EC concentration. A bias factor was calculated for each set of paired Airtec and 5040 results (i.e., the average of either all respirable or submicron samples in a particular test) using Equation 2: where *X* is the average Airtec EC concentration for a given sampling event and size selection and *Y* is the average 5040 EC concentration for the same sampling event and size selection.

$$Bias\ factor = 1 - \left(\frac{X}{Y}\right) \qquad \text{(Equation 2)}$$

Figure 3.2 shows the bias factor as a function of 5040 EC concentration, which suggests a mass dependence. With increased concentration in the chamber (and increased mass collected on the sample filter), the Airtec EC results deviate further from the 5040 results. No real trend with coal type or particle size range is apparent in the data presented here, though only a limited number of tests were conducted for this study.

Table 3.3 Summary of test results.

Test and Coal Type	Average (STDV) EC/TC (5040)	Sampling Time (minutes)	TEOM Concentration (µg/m^3)	Size Range	Airtec EC Concentration (µg/m^3)	5040 EC Concentration (µg/m^3)	Bias Factor
1-A	0.90 (0.04)	98	-	Resp	458 487 613	2828 2927 2714	0.82
	0.65 (0.05)	98	539	Sub	138 151 144	278 294 411	0.56
2-A	0.92 (0.04)	262	1232	Resp	180 - -	856 894 845	0.79
	0.65 (0.05)	262	355	Sub	55 54 -	91 108 111	0.47
3-B	0.46 (0.15)	225	-	Resp	85 90 -	526 410 830	0.85
	0.13 (0.04)	225	253	Sub	9 9 7	8 16 15	0.34
4-C	0.24 (0.04)	141	1791	Resp	184 270 -	382 399 483	0.46
	0.17 (0.04)	141	605	Sub	58 57 53	50 38 74	-0.04

It should be noted that, as expected, the average EC/TC ratio for respirable samples of coals A and B were found to be in fairly good agreement with the ratio measured on the bulk dust samples (Table 3.2). However, for the respirable samples of coal C and submicron samples of all coals, the ratio was substantially lower than that of the bulk samples. This observation might be an artifact of the 5040 Method accuracy being dependent on sample mass, since lower mass here seems to correlate with lower EC (and thus higher OC) than expected based on the bulk analysis. In that case, the actual bias factor for the Airtec may be higher than reported here for some test conditions.

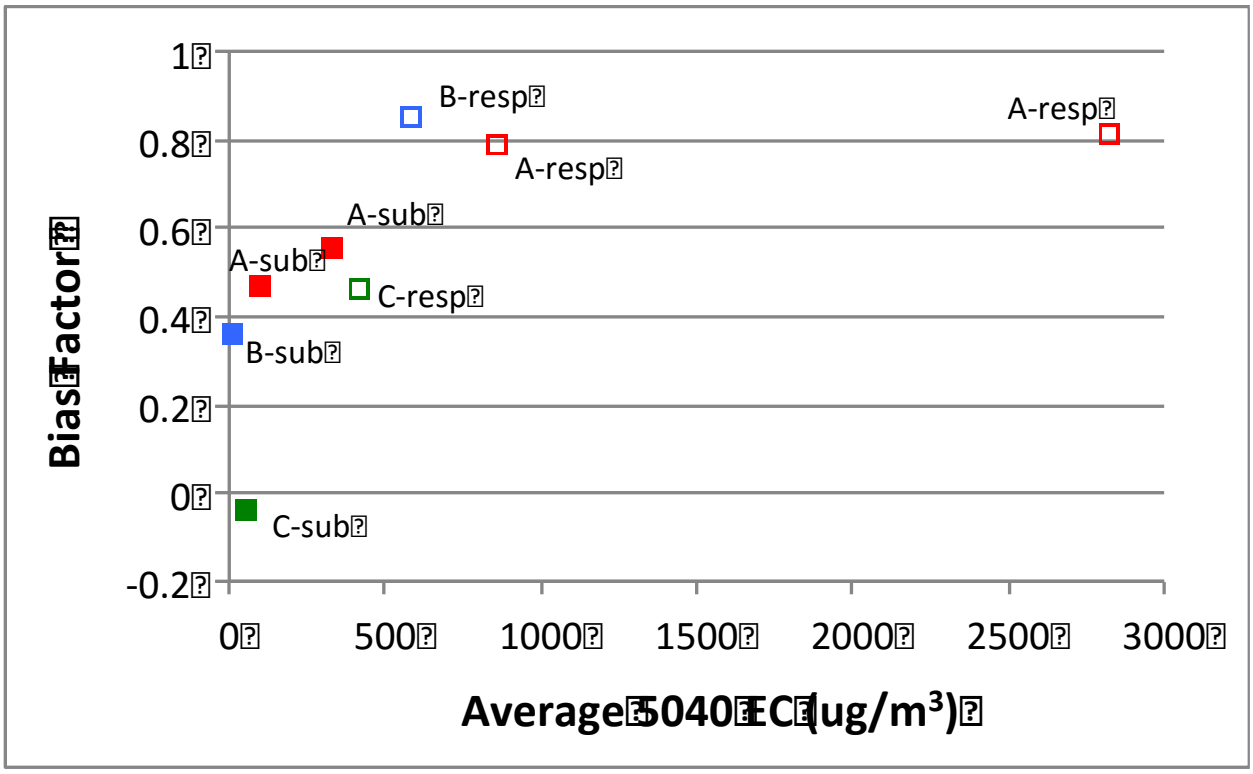

Figure 3.2. Bias factor as a function of average 5040 EC concentration. Each data point is labeled with the corresponding coal type and particle size range sampled.

With respect to possible cause(s) for underestimation of coal-sourced EC by the Airtec, the sample deposition pattern on the Airtec filters is revealing. Figure 3.3 shows examples of the Airtec and 5040 filters with submicron and respirable dust collected from coal A. On both 5040 filters, the dust deposition visually appears to be uniform. However, on the Airtec filters, the deposition is clearly non-uniform with a preference for deposition in the center of the filters. This pattern was consistently observed on nearly all of Airtec filters, and was always more prominent for the respirable samples (i.e., which had more mass and larger particles than the submicron samples) (see Appendix A for images). Importantly, such a pattern has not been previously reported when using the Airtec in its intended application for DPM monitoring in metal/nonmetal mine environments.

Because the Airtec reads laser transmittance at a particular filter spot (i.e., illustrated by the red dots in Figure 3.3), it relies on an assumption of uniform particulate deposition on the filter to accurately calculate EC mass accumulation – and thus EC concentration in the sampling

environment. Therefore, the preferential deposition of coal dust in the center of the filter at least partially explains underestimation of EC by the Airtec versus the 5040 Method.

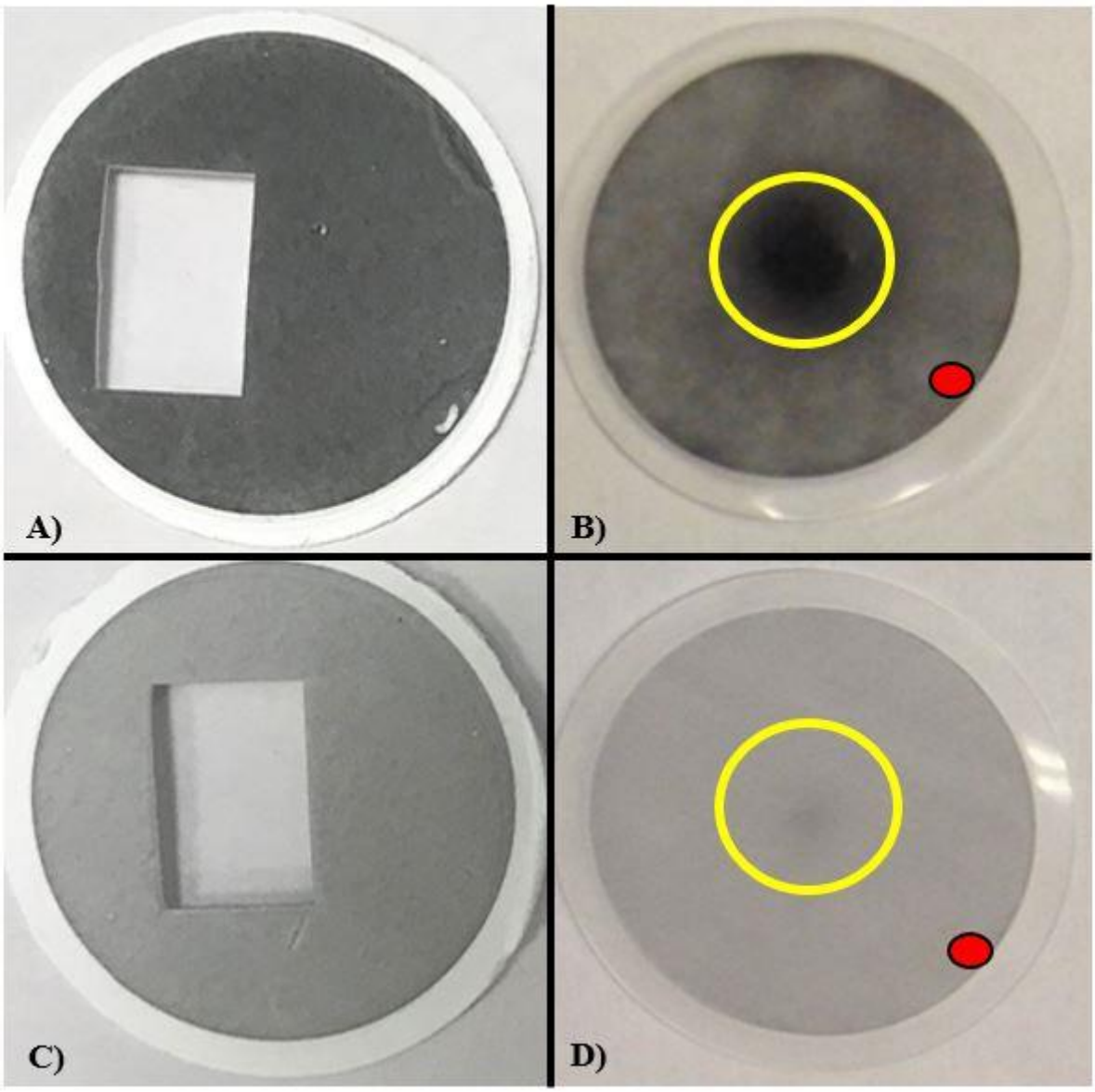

Figure 3.3. Example filter samples collected in test 2 (coal A) by the Airtecs and ELF pumps (for 5040 Method analysis). Images show a) respirable 5040, b) respirable Airtec, c) submicron 5040, and d) submicron Airtec. The red dots on the Airtec filters show the approximate location of laser and optical sensor, and the yellow circles show the preferential center-deposition of dust. The rectangular voids in the 5040 filters are where a punch was removed for analysis.

Problems surrounding deposition uniformity are well-established in the context of sampling airborne particulates onto filter media in closed-face cassettes (e.g., see Miller et al., 2013; Chen et al., 2010). Here, however, use of closed-face cassettes cannot explain the problem since the same three-piece cassettes were used for collecting respirable coal dust with both the Airtec and the ELF pump – and the ELF pump filters had uniform deposition (e.g., see Figure 3.3).

To determine the cause of the coal dust deposition pattern on the Airtec filters, some follow-up experiments were conducted. For these, two Airtecs and one ELF pump were used to collect submicron dust particles (coal A) from a small dust box. To ensure that in-house assembly of the Airtec cassettes (i.e., as was done for the tests conducted in the Marple chamber), one Airtec had an in-house cassette, and the other had a standard Airtec cassette, which came preassembled from FLIR. Both Airtecs were used with new DPMIs. The ELF pump was used with a new DPMI, which was pre-assembled with the quartz filters and support pad (i.e., like was used for sampling in the Marple chamber). Dust was loaded into the box, and was aerosolized using a small fan. All sampling tube inlets were placed in close proximity one another and oriented in the same direction, and the pumps were started simultaneously. After about 20 minutes of sampling, all pumps were turned off simultaneously, and the filters were photographed (Figure 3.4). Then dust was collected on the filters again for two more 10-minute increments (i.e., such that photographs were taken at 30 and 40 minutes of total sampling time).

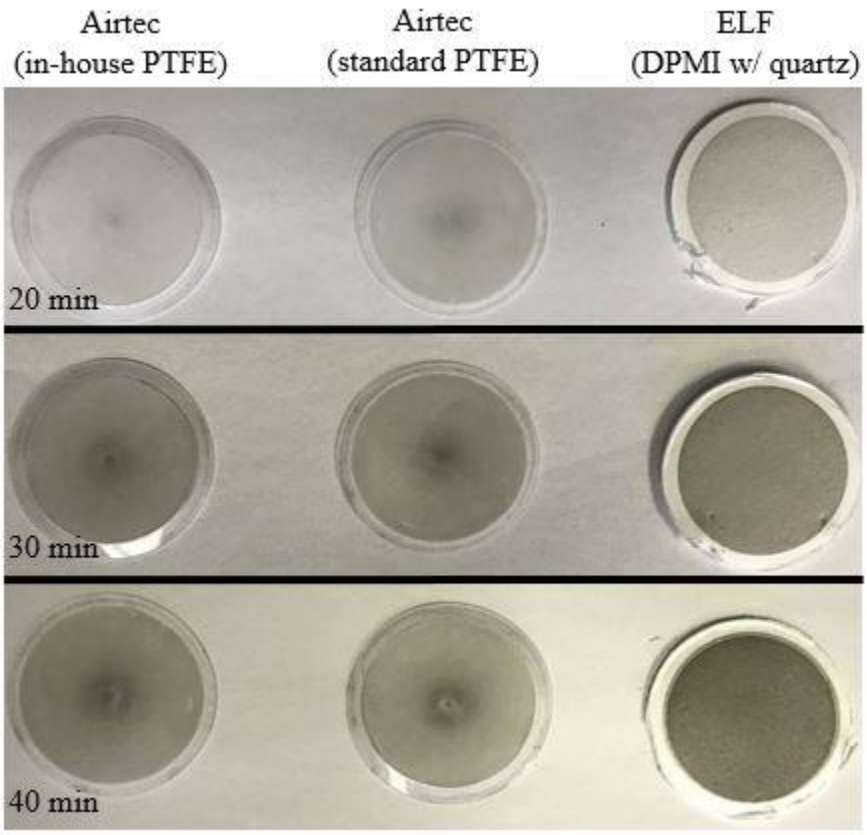

Figure 3.4. Samples collected in Virginia Tech dust chamber loaded with coal dust A. From left to right, the filters were collected as follows: Airtec submicron sampler with in-house filter cassette, Airtec sub-micron sampler with standard FLIR filter cassette, and NIOSH 5040 submicron sampler with quartz filter. The top set shows samples after 20 minutes of sampling, the middle set are the same filters after 30 minutes of sampling, and the bottom set shows filters after 40 minutes of sampling.

As evidenced in Figure 3.4, the center-deposition pattern again occurred on both the in-house and standard Airtec cassettes, and became more apparent with sample mass. The 30- and 40-minute Airtec filters, in particular, show very pronounced "bulls eye" patterns, with the darkest spot in the very center and then another dark ring around that spot. Deposition on the filter by the ELF pump was again visually uniform.

To rule out any effect of the filter media (i.e., quartz versus PTFE), the dust box experiment was run again using an Airtec to collect submicron dust (coal A) on a quartz filter and an ELF pump to simultaneously collect dust on a PTFE filter. Figure 3.5 shows the resulting filter samples, which indicate that the collection pattern is indeed unique to the Airtec – not the PTFE filter media. One feature of the Airtec's design may provide some explanation. When filter cassettes are installed in the Airtec, the pump tube is inserted into the cassette outlet (Figure 3.6).

This design effectively reduces the cross-sectional area of the airway, which must result in a local increase in air velocity. This does not occur when using the same cassette (or the DPMI cassette with internal filter) with the ELF pump. In that case, the pump tubing fits around the outside of the cassette outlet (Figure 3.6). The cross-sectional airway area difference between sampling with the ELF pump DPMI cassette and the Airtec was found to be approximately 3.1mm^2 (i.e. 4.9mm^2 with the Airtec, 8.0mm^2 with the ELF pump set-up). This difference should yield a 38% higher sampling velocity for the Airtec.

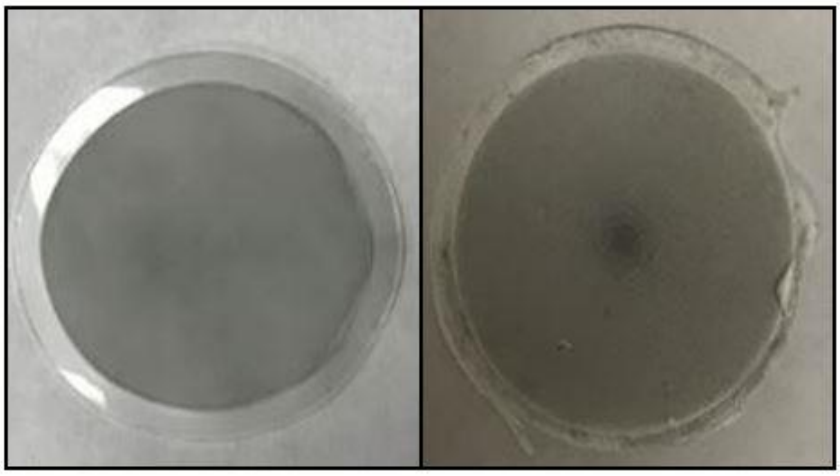

Figure 3.5. The image on the left shows an Airtec filter collected in a NIOSH 5040 set-up and the right image shows a quartz filter collected with an Airtec set-up.

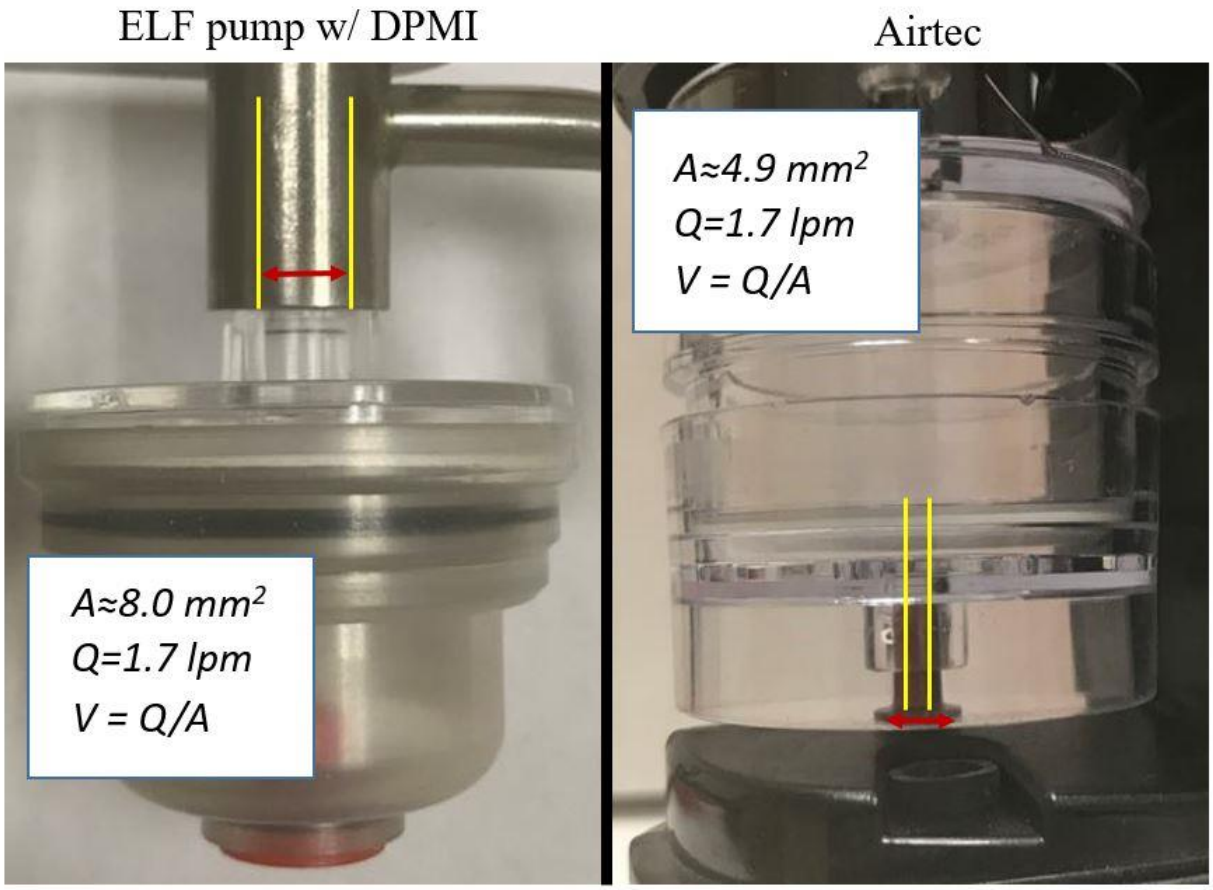

Figure 3.6. Differences in cross-sectional areas of ELF pump (5040) assembly and Airtec assembly.

Interestingly, the localized airflow restriction that occurs in the Airtec design has not been reported to cause non-uniform deposition of DPM. One possible difference when using the instrument to sample coal dust is particle size distribution. While use of the DPMI ensured that all dust particles being collected for the "submicron" samples were less than about 0.8 μm, these particles were likely larger than DPM – which is typically reported to have peak number concentrations between about 0.06 μm – 0.12 μm (Harris and Maricq, 2001). Using a TSI 3330 Optical Particle Sizer (OPS; TSI, Shoreview, MN) to estimate relative particle concentrations in the range of about 0.3-0.9 μm, it was determined that most of the submicron particles in the three coal dust samples tested here were very close to the DPMI cut size (Figure 3.7). The preferential center-deposition of relatively large particles on filter samples has been previously documented (e.g., see Harper, 2004).

Aside from the issue of particle deposition uniformity, the Airtec's consistent underestimation of coal-sourced EC in this study could also be related to other factors. While the Airtec was developed and calibrated for monitoring DPM-sourced EC, coal-sourced EC may be optically different. For example, the size and shape characteristics of coal versus DPM may lead to different laser transmittance for the same mass accumulation. As a hypothetical explanation, this could happen because coal dust particles are larger than DPM particles, and they also generally deposit on a sample filter as individual particles (Johann-Essex et al., 2017), whereas DPM often occurs and is deposited as aggregate chains of spherical soot particles (Burtscher, 2005). These differences may mean that coal dust deposition leads to relatively larger void spaces between particles, which may increase laser transmittance – and thus result in a lower apparent EC mass. It is also possible that differences in particulate constituents (e.g., the type and amount of OC present) may be playing a role in the way that the Airtec measures coal-sourced as opposed to DPM-sourced EC.

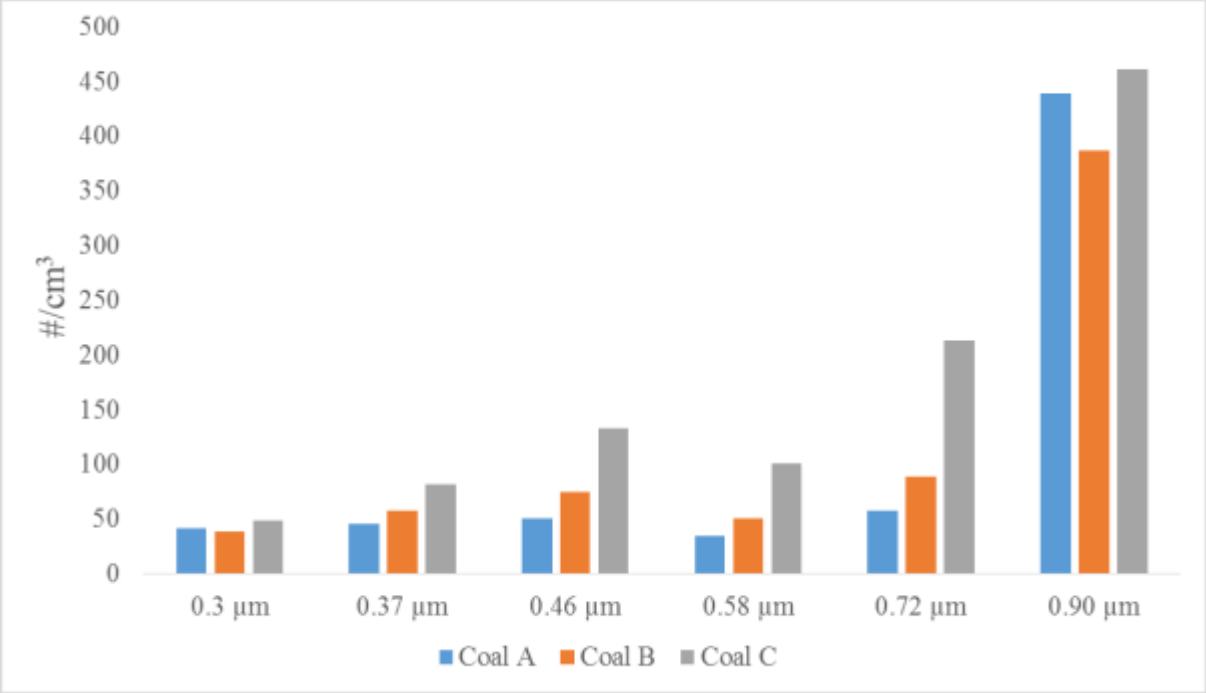

Figure 3.7. Size distribution (i.e., between 0.3-0.9 um) of the three coal dust samples.

4. Conclusions

In this study, the handheld Airtec monitor consistently underestimated coal-sourced EC mass versus EC measured by the NIOSH 5040 Standard Method. One reason for this was non-uniform coal deposition on the Airtec filter, such that dust preferentially collected in the center of the filter. While underestimation of coal-sourced EC itself may not be a problem for use of the Airtec in a coal mine (i.e., since this would limit analytical interference for DPM-sourced EC), the preferential deposition pattern may be problematic if DPM is also affected. Further research is required to determine what deposition patterns might be expected in an environment where submicron coal dust and DPM co-occur.

It should also be noted that this study only investigated dust particles suspended from relatively pure coal samples. The composition of submicron dust in coal mines is expected to be highly variable, and significant dust concentrations of any type could result in interferences for the laser measurement employed by the Airtec (e.g., mineral particles may reflect laser light). Finally, although the current work sheds some light on the potential use of the Airtec in coal

mine applications, the instrument has not been MSHA certified as intrinsically safe – which would be necessary for use in permissible areas of US mines.

In regards to the continuation of this research, the next likely step would be to perform a co-occurrence of coal dust and DPM study. This study would be similar to the one presented here, however instead of only coal dust present in the Marple Chamber, DPM would also be present. This would help to identify potential sampling issues with coal and DPM particle interaction (i.e. would DPM attach to the larger coal dust particles and be excluded by size selection?) And again, this study would be crucial to identify whether or the non-uniform deposition of the coal dust on the filter would result in DPM non-uniformity as well. Finally, the advancement of the knowledge base regarding how much of coal mine dust is in fact sub-micron would be extremely beneficial to this research.

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Appendix A

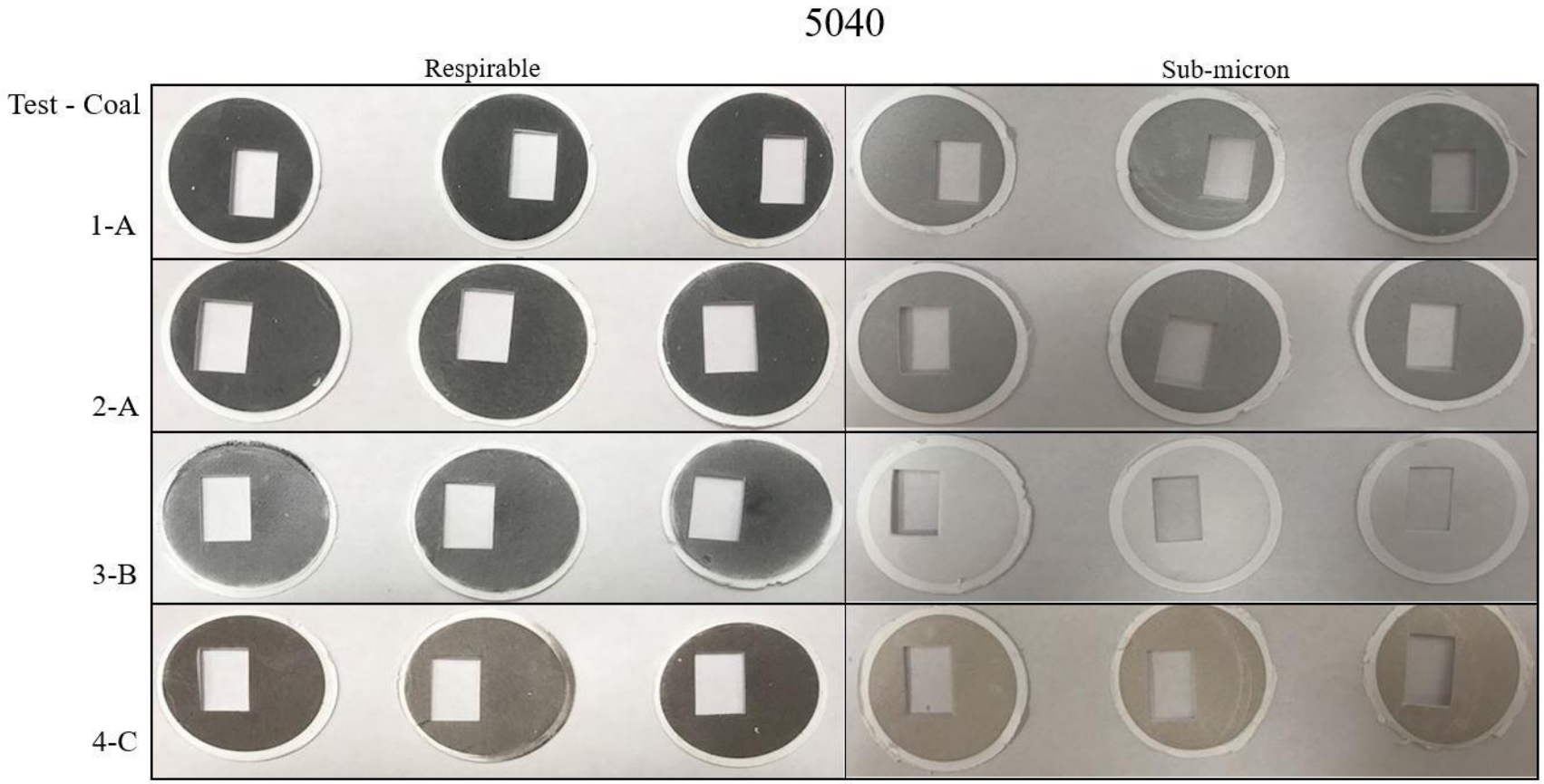

Figure A.1. NIOSH 5040 quartz filters.

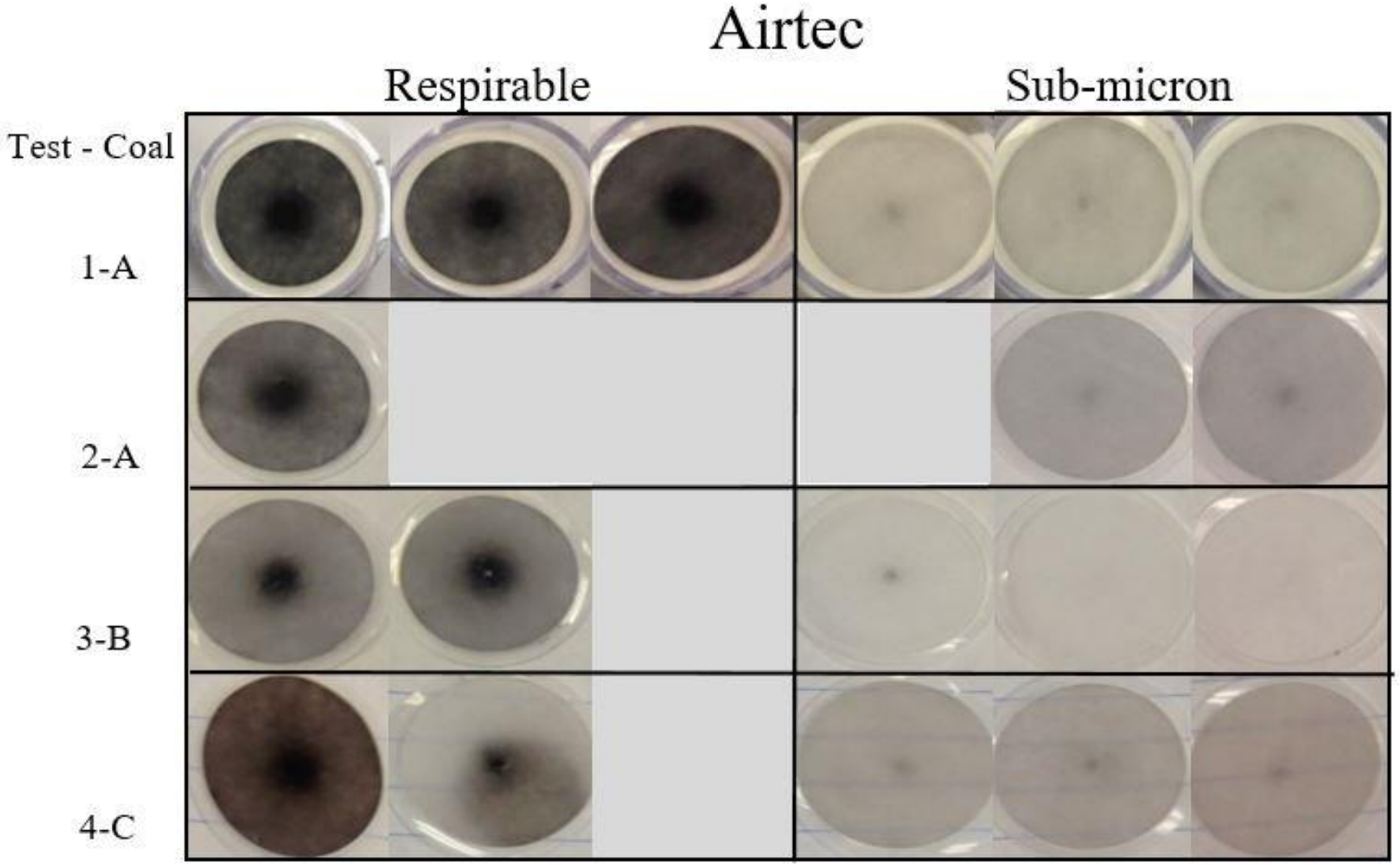

Figure A.2. Airtec PTFE filters.