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## An Evaluation of Sharp Cut Cyclones for Sampling Diesel Particulate Matter Aerosol in the Presence of Respirable Dust

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### Abstract

Two prototype cyclones were the subjects of a comparative research campaign with a diesel particulate matter sampler (DPMS) that consists of a respirable cyclone combined with a downstream impactor. The DPMS is currently used in mining environments to separate dust from the diesel particulate matter and to avoid interferences in the analysis of integrated samples and direct-reading monitoring in occupational environments. The sampling characteristics of all three devices were compared using ammonium fluorescein, diesel, and coal dust aerosols. With solid spherical test aerosols at low particle loadings, the aerodynamic size-selection characteristics of all three devices were found to be similar, with 50% penetration efficiencies ( $d_{50}$ ) close to the design value of 0.8  $\mu\text{m}$ , as required by the US Mine Safety and Health Administration for monitoring occupational exposure to diesel particulate matter in US mining operations. The prototype cyclones were shown to have ‘sharp cut’ size-selection characteristics that equaled or exceeded the sharpness of the DPMS. The penetration of diesel aerosols was optimal for all three samplers, while the results of the tests with coal dust induced the exclusion of one of the prototypes from subsequent testing. The sampling characteristics of the remaining prototype sharp cut cyclone (SCC) and the DPMS were tested with different loading of coal dust. While the characteristics of the SCC remained constant, the deposited respirable coal dust particles altered the size-selection performance of the currently used sampler. This study demonstrates that the SCC performed better overall than the DPMS.

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## Keywords

cyclone; diesel particulate matter; DPMS; mining; sampler

## INTRODUCTION

Health issues associated with workplace exposure to diesel particulate matter (DPM) have received substantial attention and regulatory scrutiny. Currently, the Mine Safety and Health Administration (MSHA) regulates DPM exposures in US metal and non-metal mines to  $160 \mu\text{g m}^{-3}$  total carbon (71 Fed. Reg. 28924, 2006). The International Agency for Research on Cancer has labeled diesel exhaust as a human carcinogen (Benbrahim-Tallaa *et al.*, 2012), while the National Institute for Occupational Safety and Health (NIOSH, 1988) has identified DPM as a *potential* occupational carcinogen (NIOSH, 2012). A recently published NIOSH study reported that heavy exposure of non-metal miners to diesel exhaust increased their risk of death from lung cancer (Attfield *et al.*, 2012) and the National Cancer Institute (NCI) has shown additional evidence of lung cancer mortality risk (Silverman *et al.*, 2012).

Aerosols in mine environments, where diesel-powered equipment is used, exhibit an aerodynamic bimodal distribution with a distinct accumulation mode peak near 120 nm and a coarse mode peak at  $\sim 6 \mu\text{m}$  with a minimum between both modes at  $\sim 0.8 \mu\text{m}$ . The diesel exhaust aerosol is the major source for the accumulation mode, while the aerosol from the mining operation is primarily in the micrometer mode (Marple, 1986; Cantrell and Rubow, 1991). The US Bureau of Mines demonstrated that mine dust and diesel exhaust aerosol can be separated and measured on the basis of size, with the preferred cut-off size being  $0.8 \pm 0.1 \mu\text{m}$  (Cantrell and Rubow, 1991). Due to these considerations, a personal diesel aerosol sampler was designed employing an impactor as a size selector and the performance of this sampler has been continually improved (Noll *et al.*, 2005). Currently, this DPM cassette sampler is used by MSHA in US underground metal/non-metal mines during enforcement-related inspections (Mine Safety and Health Administration, 2001), and it is also used by mine operators to measure engineering control efforts in mines. The filter from the DPM sampler is analyzed using NIOSH method 5040 (Birch, 2002) to measure the concentration of elemental carbon (EC) and total carbon. During the above-mentioned NCI study, the relationship of respirable EC (REC) and submicron EC (SEC) collected with the Bureau of Mines samplers was also investigated. The analysis of the data obtained from air monitoring surveys, conducted between the 1998 and 2001, showed that REC is highly correlated with SEC and that a linear relationship between REC and SEC 'extends over a very broad concentration range and across different environments' (Vermeulen *et al.*, 2010). The same air monitoring surveys showed how the submicron non-combustible dust was a small fraction of the respirable dust (Vermeulen *et al.*, 2010). MSHA adopted the DPM cassette sampler to minimize the collection and potential confounding effect of respirable dust.

Respirable coal mine dust and DPM measurements are areas where direct-reading devices can provide a more timely evaluation of control technologies or worker exposure. NIOSH has developed and tested a number of direct-reading monitor technologies in mines (Volkwein *et al.*, 2004, 2006; Noll *et al.*, 2013). Based on the success of these endeavors,

MSHA has incorporated direct-reading monitors into its proposed coal dust rule (75 Fed. Reg. 64412, 2010). Direct-reading DPM monitoring needs to separate the diesel aerosol from the super-micrometer mining dust (e.g. coal) to avoid analytical interferences. Direct-reading DPM monitors generally use optical properties of the DPM and EC as the analytical approach and the interferences from respirable mine dust are extremely problematic (Noll *et al.*, 2013). In principle, the separation can be accomplished by using a size selector such as an impactor, as in the DPM cassette sampler. Limitations of impactors, however, include the need and expense of replacing a disposable unit or an oiled impaction substrate after each use. Potential overloading of the impactor during sampling in very dusty conditions is an additional unexplored concern. Other size selectors, such as cyclones, offer an alternative to impactors if a similar  $d_{50}$  cut point, sharpness, and mass penetration can be obtained. Cyclones have been widely used for particle size-selective sampling of ambient, workplace, and indoor air. They can be designed to obtain the desired  $d_{50}$  at the desired flowrate (Kenny and Gussman, 2000; Stein and Wells, 2010). Evidence from ambient aerosol sampling suggests that, in relation to size-selection characteristics, cyclones are in general less susceptible to particle loading effects than impactors. The results of a study on an ambient PM<sub>2.5</sub> cyclone (BGI Inc., VSCC 4.764) showed that the cut point was not affected when the cyclone was challenged with a dust load of 3 mg. During the same study, the US Environmental Protection Agency Well Impactor Ninety-Six PM<sub>2.5</sub> impactor showed impaired performance with similar dust loading (Kenny *et al.*, 2004).

This study evaluates the use of a cyclone as a preselector for DPM aerosol in mine environments. Two candidate prototype cyclones were designed on the basis of pre-existing family models (Kenny and Gussman, 1997) to give a cut point of 0.8  $\mu\text{m}$  at 2.2 l.p.m. while maintaining a sharp cut. These cyclones were evaluated to determine penetration, gravimetric collection efficiency, and the effect of loading when sampling DPM and mining dust.

## EXPERIMENTAL DESIGN AND METHOD

The size-selecting device employed in the DPM cassette is a two-part unit consisting of a Dorr-Oliver (DO) cyclone followed by an SKC diesel particulate impactor (225–317, SKC Inc., Eighty Four, PA, USA). Throughout this article, this two-part unit is referred to as the diesel particulate matter sampler (DPMS). Two different cyclones (Fig. 1), a Sharp Cut Cyclone 0.695 (SCC) and an Extra Sharp Cut Cyclone 0.746 (ESCC) (BGI Inc., Waltham, MA, USA) were compared to one another and to the DPMS. The flowrate through the SCC and ESCC was set at 2.2 l.p.m. throughout the study. The flowrate through the DPMS (DO cyclone and impactor) was maintained at the 1.7 l.p.m. used in the DPM cassette sampler (Giliblator, Gilian Instrument Corp., Wayne, NJ, USA).

### Size selector penetration measurement

The penetration efficiency of the three devices was evaluated via a commonly used method (Maynard and Kenny, 1995; Maynard *et al.*, 1999; Görner *et al.*, 2001). In a calm air chamber (Fig. 2), ammonium fluorescein (C<sub>20</sub>H<sub>15</sub>NO<sub>5</sub>; AF) polydisperse aerosols were generated by a Sonotek ultrasonic atomizing nozzle (Sonotek Inc., Highland, NY, USA) connected to a compact infusion syringe pump (Harvard apparatus, Holliston, MA, USA).

The feed rate for the infusion pump was maintained at  $5 \times 10^{-3} \text{ ml s}^{-1}$ . The nozzle of the generator was located at the top of the chamber and was surrounded by three  $^{210}\text{Po}$  radioactive sources to neutralize the aerosol. Three AF solutions of different concentrations were prepared to generate aerosols with the targeted count median aerodynamic diameters of 0.6, 0.8, and 1.7  $\mu\text{m}$ . Scanning electron microscopy (Jeol USA, Peabody, MA, USA—operated at NIOSH, Morgantown, WV, USA) observations showed only spherical dry particles. The cylindrical fiberglass chamber (0.45 m diameter, 2.4 m high) was fed with compressed filtered air and a rotameter (F-4100, Gilmont Instruments, Barrington, IL, USA) controlled the flowrate of 20 l.p.m. to eight radial inlets at the top of the chamber. The generated aerosol was fed at a constant rate at the same cross-section of the filtered air to ensure adequate mixing. The relative pressure of the chamber was maintained negative at 2.49 Pa (0.01"  $\text{H}_2\text{O}$ ) measured by a magnehelic gauge (Dwyer Instruments Inc., Michigan, IN). The calm air conditions were ensured by a downward air velocity of 2  $\text{mm s}^{-1}$ . Preliminary investigations showed that the aerosol in the sampling area of the calm air chamber was spatially and temporally stable and uniform.

The AF aerosol present in the chamber and that penetrating through the size selector were measured by sampling alternately from either source to a 3321 Aerodynamic Particle Size (APS) analyzer (TSI, Shoreview, MN, USA) placed directly below and outside the chamber. The inlet for the chamber aerosol was the end of a 1/4 in. diameter conductive silicon rubber tube that had a clamp used to adjust the inlet pressure at the APS to match that determined when the size selector's output was being sampled. The inlet velocity was varied from 2.2 to 2.9  $\text{m s}^{-1}$  based on the selected flowrate for the DPMS and cyclones. A switch valve (ASCO, Florham Park, NJ, USA) was used to alternate sampling between the chamber aerosol and the output from the size selector. By disconnecting the sheath flow from the APS inlet, a sampling rate as low as 1 l.p.m. under standard operating conditions was provided from the chamber to the APS. To match the overall sampling rate to the required values for each device, clean 'makeup flow' was introduced via an additional line via a rotameter connected to a vacuum exhaust. The APS calibration was checked before the experiment with monodisperse polystyrene latex particles (Duke Scientific, Palo Alto, CA, USA).

For each of the three size-selecting devices and three aerosols generated, the APS was set to measure stable size-segregated particle number concentration with (W) and without (WO) the tested device present in the following series of seven settings for one experiment [24 scans (20 seconds per scan)]:  $\text{WO}_1\text{-W}_1\text{-WO}_2\text{-W}_2\text{-WO}_3\text{-W}_3\text{-WO}_4$ . For each device (DPMS, SCC, and ESCC), the number of concentrations for each size bin of the APS for the three AF particle size distributions were summed to determine the overall number distribution with and without the device. This summation was done to enhance statistical rigor by providing an adequate number of particles across the relevant size range. Penetration by particle size was calculated as the particle number concentration measured with the tested device (W) divided by the background concentration determined using the mean number concentration immediately preceding and following the device measurement (WO). The penetration characteristics for the three tested devices (DPMS, SCC, and ESCC) were compared graphically by plotting the mean penetration  $\pm$  95% confidence interval versus particle size (Statistica, Version 6, Statsoft, Tulsa, OK, USA). The penetration versus

particle size graph for each device was inspected to obtain the particle size associated with the 50% ratio ( $d_{50}$ ), the 84% ratio ( $d_{84}$ ), and the 16% ratio ( $d_{16}$ ). The sharpness of the size selectors was calculated as  $(d_{16}/d_{84})^{0.5}$ .

### Mass collection tests

The second phase of the study was conducted in two identical Marple aerosol chambers (Marple and Rubow, 1983), one specifically for coal mine dust studies and the second specifically for DPM studies. These aerosol test chambers with hexagonal cross-sections are 2.44 m high with an inside diameter of 1.19 m. The aerosol is introduced at the top of the chamber and thoroughly mixed in this region by the energy of air jet entering at the side of the chamber. From this mixing area, the aerosol flows downward through a 10-cm-thick honeycomb structure where turbulence in the air is reduced providing a low velocity downward flow through the test section portion of the chamber. A table supporting the samplers can be rotated, reducing the effects of any variation in the dust concentration within the chamber. Past work (Marple and Rubow, 1983) has shown the sampling zone of the chambers, even without rotation, to be very uniform (relative standard deviation between samples <0.05).

In the first Marple chamber, three Pittsburgh Seam coal dusts (Pitt A, Pitt B, and Pitt C) were individually aerosolized using a TSI 3400A fluidized bed dust generator (TSI) and dispensed into the chamber. The size characteristics of the three coal dusts are provided in Table 2. Before entering the chamber, the aerosol was neutralized by a TSI 3012A NRC Aerosol Neutralizer (TSI). In the second separate chamber, a portion of the exhaust emissions from a Kubota diesel engine attached to a 10-kW generator provided DPM aerosol. Three resistive load conditions were employed for the DPM generator (20, 50, and 80%).

In each chamber, each size selector device (DPMS, SCC, and ESCC) was connected to a preweighed 37-mm polyvinyl chloride (PVC) membrane filter (GLA-5000, Pall, Port Washington, NY, USA) in order to collect aerosol for gravimetric analysis. Filter cassettes used with cyclones were modified to permit the cyclone outlets to extend ~1.5 mm into the filter cassette to minimize cyclone outlet loss in this region. In addition, three BGI-4CP cyclones (BGI Inc.) using a Higgins–Dewell (HD) design, operated at a flowrate of 2.2 l.p.m., were used to collect respirable dust samples. The concentration in the chambers was monitored using a tapered element oscillating microbalance (TEOM) 1400a (Thermo Scientific, Franklin, MA, USA) with a BGI-4CP cyclone inlet operated at 2.2 l.p.m.

For coal dust tests, a respirable mass loading of ~4 mg was targeted to provide a quantifiable amount on the filter samples. Three repetitions were conducted for each type of coal dust. For the diesel tests, the target respirable mass loading was 2 mg to obtain adequate masses on the filters. Three repetitions were conducted for each type of coal dust and for each DPM generator load condition.

Gravimetric samples were equilibrated, neutralized, and pre- and post-weighed in a controlled environment set at  $22 \pm 0.7^{\circ}\text{C}$  and  $50 \pm 2\%$  relative humidity. Balance precision was better than 5  $\mu\text{g}$  and the gravimetric analysis had an overall limit of quantification = 14

µg in a single weighing (Page and Volkwein, 2009). Blank filters were used to correct the final mass determination. Post-weights of the filters were used to determine the aerosol mass penetrating the size selector device in each testing condition.

The mass obtained from the DPMS samples was adjusted to take into account the different flowrate for this device compared to the cyclones. The Kruskal–Wallis analysis of variance (ANOVA) was used to compare the masses of diesel or coal penetrating through the three devices (Statistica, Version 6, Statsoft). The Kruskal–Wallis ANOVA is the appropriate test for comparing multiple independent samples when limited by a small sample size and a data set that is not normally distributed (Siegel, 1956; Cena and Peters, 2011). When the Kruskal–Wallis ANOVA indicated significance, a *post hoc* multiple comparison test was used in a pairwise comparison to determine which device's mass was significantly different from each of the other devices (Conover, 1999; Black *et al.*, 2007).

### Coal dust-loading tests

To investigate the impact of dust loading on the penetration through the size selectors, additional tests were conducted with different loading of coal dust. In the Marple chamber, Pitt C was aerosolized; this dust was selected because it had the largest diameter particles. Nine DPMS and nine SCC were connected to pre-weighed 37-mm PVC membrane filters in order to collect aerosol for gravimetric analysis. The nine SCC used for the dust-loading tests were identical to the prototype used in the previous phases but in this case were made of stainless steel. The respirable coal dust concentration in the chamber was maintained constant and different respirable target loadings were achieved by selecting different sampling intervals. After the first respirable target loading of 1 mg was achieved, the sampling of one set of three DPMSs and three SCCs was stopped. Similarly, sampling continued for the two other sets of three DPMSs and three SCCs to achieve the respirable target loadings of 2 and 4 mg. The concentration in the chambers was monitored using a TEOM 1400a (Thermo Scientific) with a BGI-4CP cyclone inlet operated at 2.2 l.p.m.

After loading the two types of devices, the penetration curves of the nine loaded DPMS and SCC preselectors were determined in the AF aerosol and the protocol described above.

## RESULTS AND DISCUSSION

The mean penetrations by size through the three tested size selectors are provided in Fig. 3. The mean penetrations were obtained by combining the data from the three aerosols, and the 95% upper confidence limit [ $\text{MMAD}_{\text{part}} + 2 \text{ geometric standard deviation (GSD}_{\text{part}})$ ] for the largest aerosol was used as upper cutoff limit (6.7 µm). The penetration values for the DPMS were found between the values for the two cyclones for the range 0.7–1 µm. We note that, for the particles with an aerodynamic diameter larger than 1 µm, the penetration through the DPMS device is consistently higher compared to that for the two cyclones. The small consistent error over the size range of 2–6.7 µm suggests a systematic error and not particle bounce. This could be an artifact of the inlet difference between the small (~1 mm) DPMS system Dorr-Oliver cyclone inlet and the relatively larger 6.4-mm background tubing inlet. This difference is less with the cyclone inlets, whose inlets taper up to 4.7 mm. The



enlarged graph for particle sizes below 1.2  $\mu\text{m}$  more clearly shows the cut comparisons of the three devices.

Table 1 summarizes the cut characteristics of the three size selectors tested. The values of the cut point and sharpness for the DPMS device obtained in this phase can be compared with previous published results that showed a count  $d_{50}$  of 0.762 and a sharpness of 1.403 (Olson, 2001). The cut points ( $d_{50}$ ) obtained for the cyclone selectors were all well within 10% of the DPMS. Compared to the DPMS device, the calculated sharpness was slightly better (a lower value) for the two cyclones. These results suggest that either of the two prototype cyclones could replace the combined DPMS system in sampling DPM aerosols.

In the second phase of the study, the measurement of the mass penetration of DPM and coal dust particles demonstrated a more complicated scenario. Table 2 summarized the results of the mass collection testing. As expected, the mass penetration of DPM particles is close to the HD reference value for all three size selectors. The statistical analysis of the collected mass indicated no significant difference among the three devices, even when the results for different engine loads were pooled to obtain more statistical power. In contrast, the results for the coal mass penetration testing showed different performances between the DPMS and the cyclones. The performances of the ESCC and DPMS were significantly different when the coal dust data were considered as a whole. The SCC cyclone showed higher penetration of coal particles compared to the DPMS sampler; however, the two-way *post hoc* comparison indicated that the difference was not significant.

The mass fraction of coal dust particles penetrating through the DPMS is in line with an earlier characterization of the DPM sampler (Olson, 2001). The average mass penetration fraction through the DPMS did not vary substantially when the device was exposed to the different coal dust aerosols, whereas the penetration through each cyclone gradually increased as the mass median aerodynamic diameter (MMAD) of the coal aerosol increased. The  $d_{50}$  of the ESCC is somewhat higher than the DPMS (Table 1), but this is not enough to explain the marked difference in coal mass penetration.

An important factor underlying performance in this experiment is that the DPMS is a two-part size-selective system, while the SCC and ESCC are one-stage devices. Although the DPMS received the same aerosol as the SCC and ESCC, the Dorr-Oliver cyclone passed only a sub-fraction of the aerosol to the DPMS impactor stage, whereas the prototype cyclones were challenged with the aerosol without preseparation. This means that the SCC and ESCC size separated an aerosol that had not only a larger size distribution but also a considerably higher mass concentration than the aerosol separated by the impactor stage of the DPMS. The respirable Dorr-Oliver cyclone is intended to protect the impactor in the DPMS from exposure to the non-respirable fraction of particles that might cause its overloading. The coal aerosols used in these tests were characterized using Marple Personal cascade impactor samples (Table 2) (Model 290, Thermo Electron Corp., Franklin, MA) (Volkwein *et al.*, 2004) and reconstructing the size distributions by applying an inversion method (Raabe, 1978). The aerosol mass loadings applied to the different samplers could then be calculated from the size distributions of the three coal dust aerosols. This showed that the effective loading mass corresponding to 4 mg of respirable particles was different

for each of the three different test aerosols. While the mass loading on the DPMS impactor was consistently around 4 mg, the aerosol mass loading on the two cyclones varied from ~5 mg (Pitt A) to 13 mg (Pitt C). As a result of the significant difference in coal penetration between the DPMS and ESCC, the ESCC prototype was excluded from the subsequent testing.

To quantify the effect of dust loading on the performance of the size selectors, the SCC and DPMS were used to sample 1, 2, and 4 mg of respirable Pitt C coal dust. After each loading in the Marple chamber, the penetration curves of each device were determined with AF aerosol in the calm air chamber. The average penetration characteristics for each device at each loading are summarized in Fig. 4 and Table 3. For the SCC, the  $d_{50}$  values were not significantly different for the different loadings (Kruskal–Wallis ANOVA  $P = 0.366$ ) and loading did not affect the sharpness values (Kruskal–Wallis ANOVA  $P = 0.2033$ ). Loading affected the DPMS and moved the penetration curve downward allowing fewer small particles (within the range of the APS) through the device with each increase in loading. By using the APS, it was not possible to measure the entire penetration curve for the loaded DPMS; however, the effect of loading can be clearly seen. The only DPMS values that could be statistically compared for the different loadings were the  $d_{50}$  metrics for 0 versus 1 mg and these were significantly different (Mann–Whitney  $U$ -test,  $P = 0.0495$ ). Since the  $d_{84}$  values could not be obtained on the loaded DPMS, sharpness values could not be determined for any DPMS loading except the clean (0 mg) condition.

These results have important implications. The penetration through the SCC is constant when the size selector is challenged with dust loadings common during sampling in a mining environment. The aerosol mass depositing inside the SCCs did not affect the penetration characteristics ( $d_{50}$  and sharpness) of the cyclone. It is important to remember that the coal dust aerosols entering the SCC cyclones were not only in the respirable size range but also contained non-respirable particles. This outcome is crucial because the separation of DPM aerosols from mine dust during field campaigns relies on the characteristics of the size selector.

The loading experiments showed that the penetration characteristics of the DPMS are not consistent, but they are affected by the presence of dust particles deposited inside the impactor. This is an intrinsic problem with impactors because the separation carried out by any impactor is governed by the jet-to-collector separation distance and a host of other factors governing the adhesion of deposited particles to the impaction surface (Hinds, 1999). A previous study conducted on the DPMS sampler (Cantrell and Rubow, 1991; Noll *et al.*, 2005) did not assess the consistency of the penetration characteristics of DPMS when loaded with mine dust. This study demonstrates that respirable coal dust particles deposited in the DPMS have obviously altered its size-selection performance.

## CONCLUSIONS

This study compared two prototype cyclones to a combined respirable cyclone and impactor DPM sampler. Currently, the combined system is employed as a size selector to separate mine dust and its related potential analytical interferences from DPM. The objective of this



study was to evaluate the possible replacement of the DPMS sampler with a reusable SCC, with a view to developing direct-reading monitors for both DPM and mine dust. The performance of the devices was assessed by studying the penetration characteristics of the three size selector systems, the mass penetration of coal dust and DPM, and the effect of loading.

The cut points ( $d_{50}$ ) obtained for the two prototypes were all well within 10% of the DPMS and the calculated sharpness was slightly better (a lower value). The two prototypes allowed the same penetration of DPM-alone aerosol in terms of mass. The mass penetration of coal aerosols was found to be significantly higher for one prototype (ESCC) compared to the DPMS. Explanations for this finding were provided. For this reason, this candidate cyclone was excluded from the third phase testing.

The results of the loading study on the DPMS and remaining prototype cyclone (SCC) showed that the DPMS and SCC have similar penetration characteristics when both size selectors are clean. The SCC maintains these characteristics when loaded with coal dust particles that have been separated from DPM. On the other hand, the penetration characteristics of the DPMS are affected by mass loading with coal dust. The performance of the current DPMS under loading is a new concern and this deficiency needs to be further evaluated and more precisely quantified. In addition, the effect of this deficiency of the current DPMS on bias in sampling DPM samples in mining environment should be investigated. Due to this loading problem, shifting the cut characteristics of the DPMS even with a preselecting respirable cyclone, the SCC performed better overall than the currently used DPMS. The results of this study indicate that the SCC could be used as a size selector for DPM measurement and sampling as it has appropriate penetration characteristics and low susceptibility to loading.

## ACKNOWLEDGEMENTS

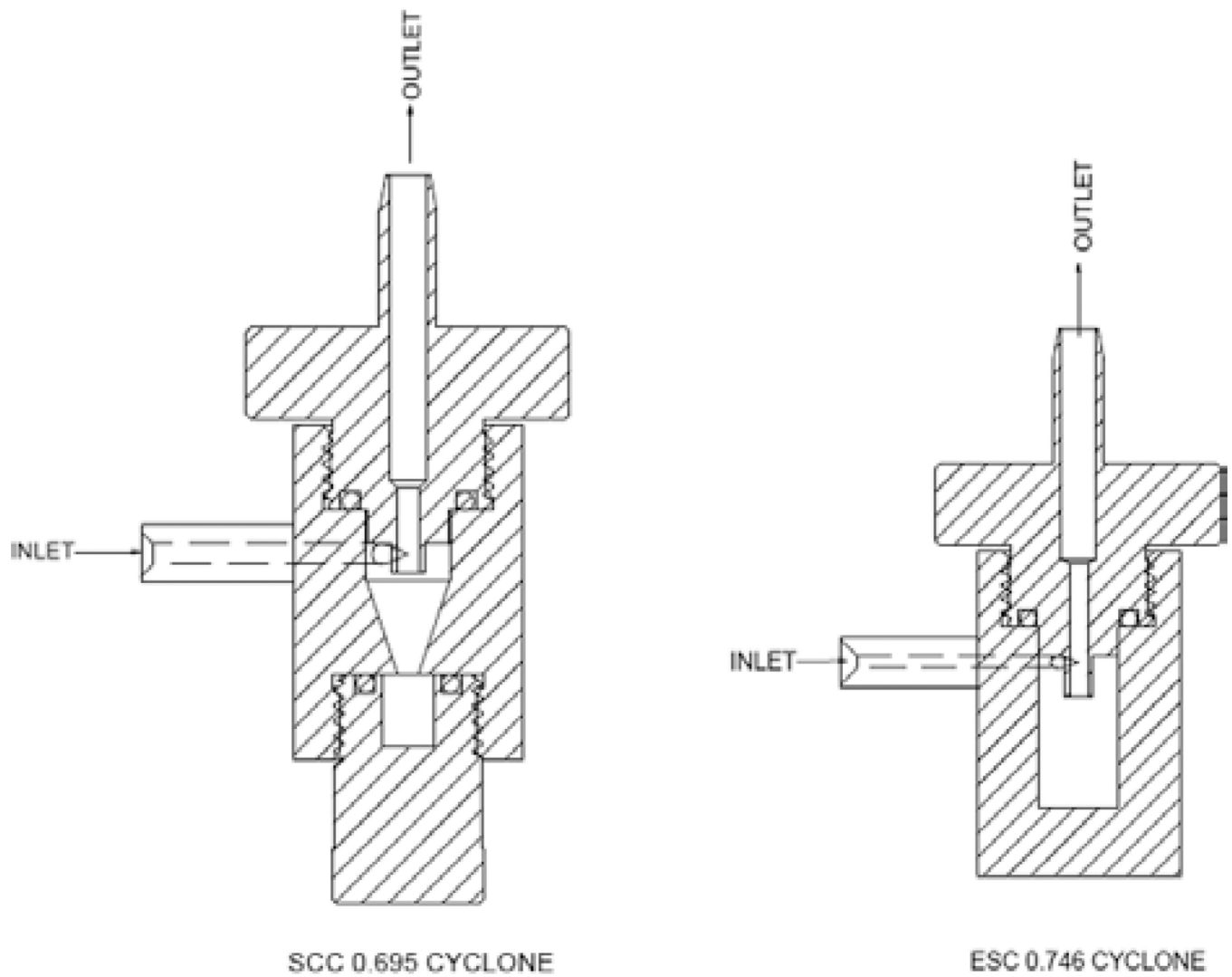
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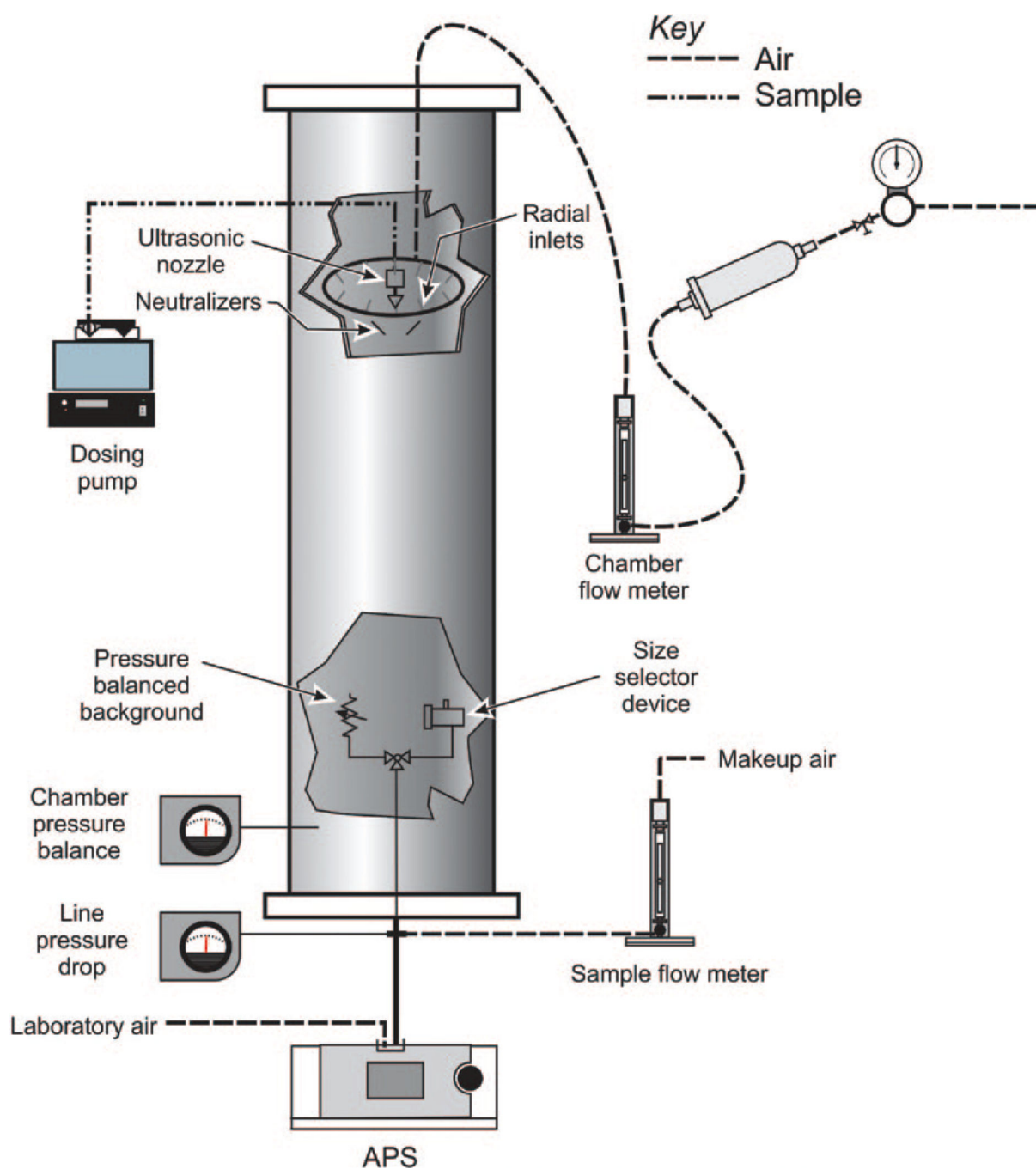
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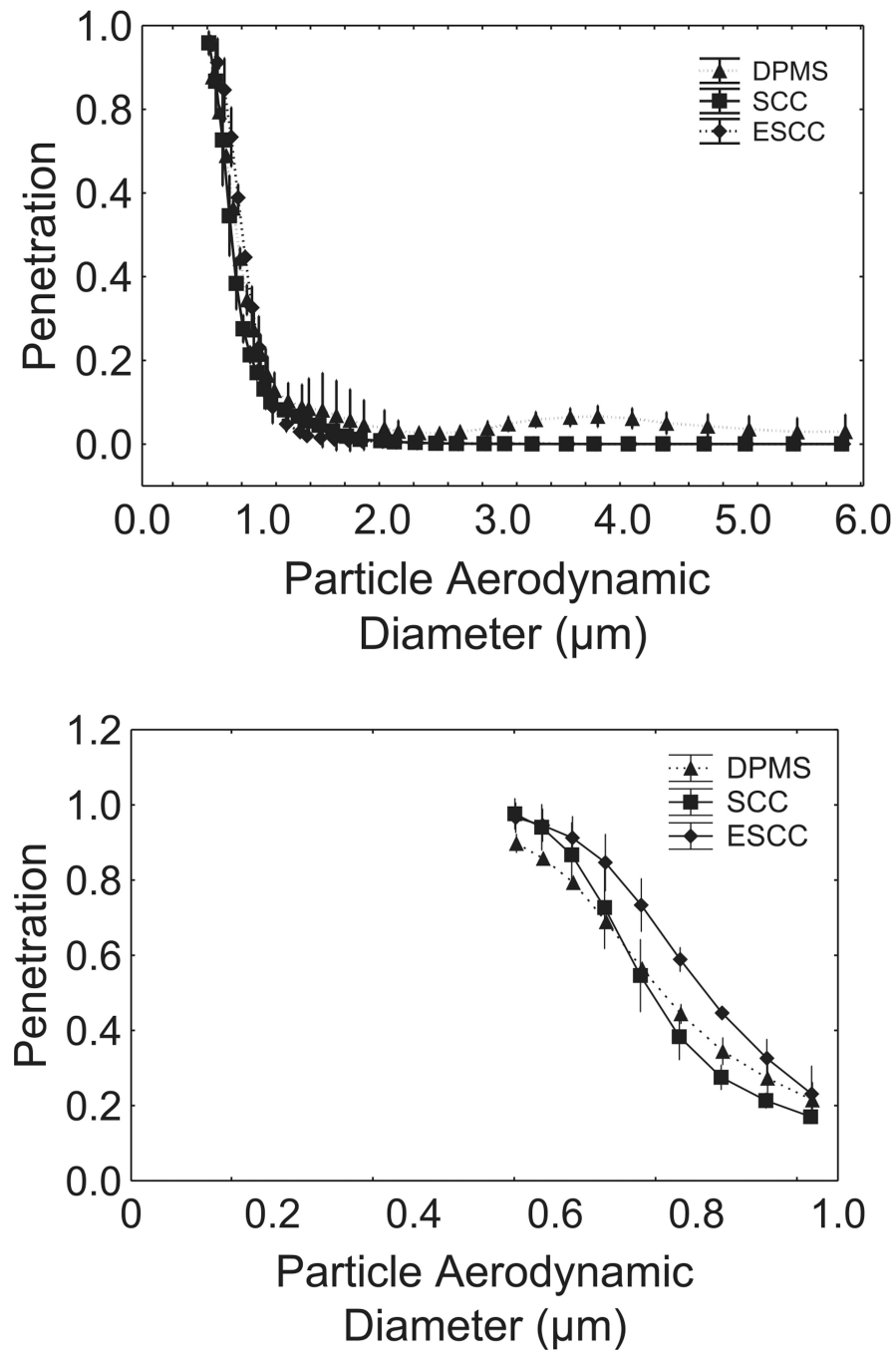


**Figure 1.**

Cyclones used in the study. Drawings are to scale and the outside diameter of the cyclone body is ~2.5 cm. The inside diameters of the inlets are 1.676 and 1.067 mm for the SCC (left) and ESCC (right), respectively.



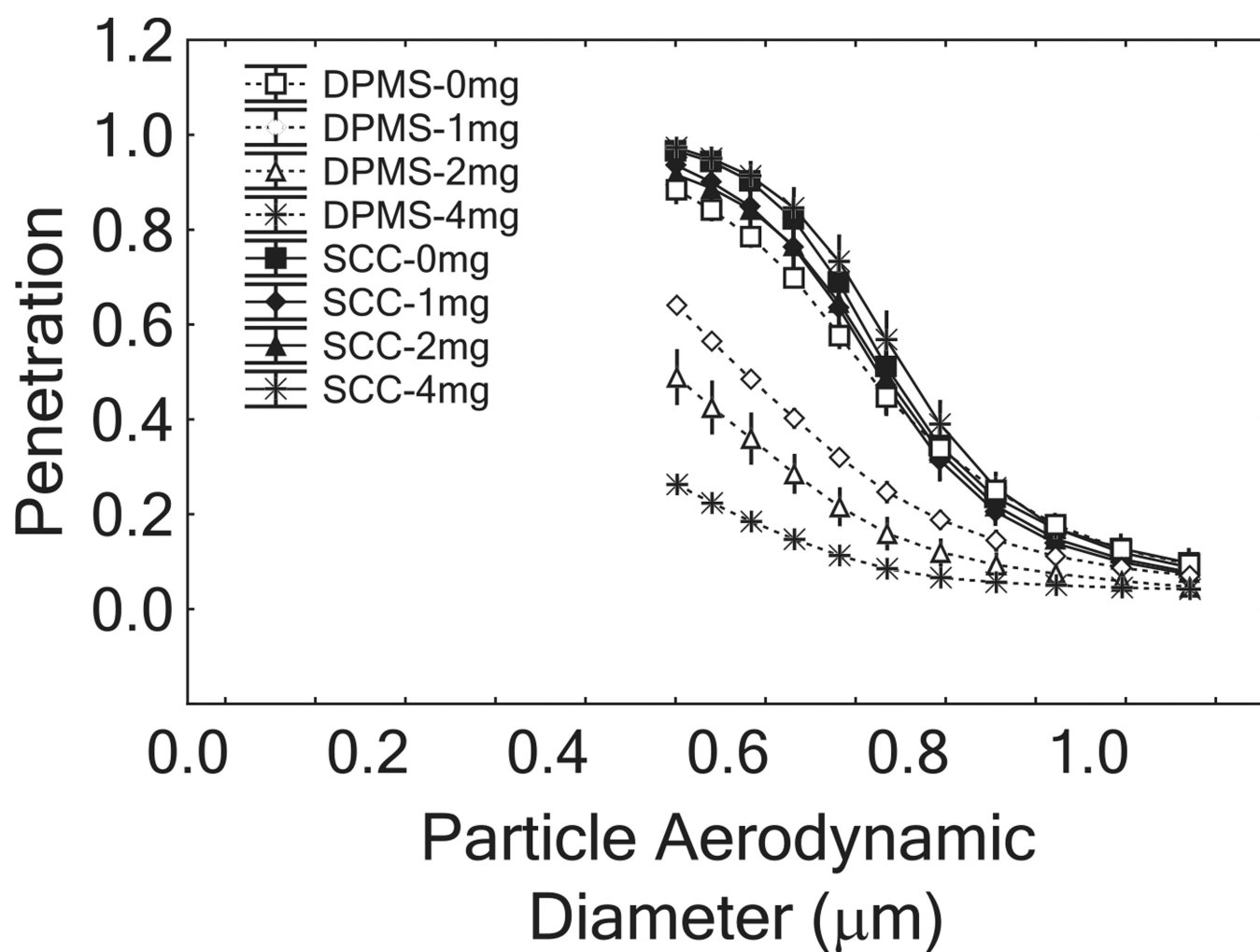
**Figure 2.**  
Layout of the experimental setup used to characterize the size selector devices using AF.



**Figure 3.**

(Top) Comparison of the mean penetration by size  $\pm$  95% confidence interval for the three devices using the combined AF aerosol  $<6.7 \mu\text{m}$ . (Bottom) An enlarged version of the penetration region below  $1.2 \mu\text{m}$ .





**Figure 4.**  
Comparison of the mean penetration by size  $\pm 95\%$  confidence interval for the clean DPMS and SCC and when loaded with coal dust particles.

**Table 1**

Cut characteristics of the three clean devices determined using AF during Phase I of the study

Device	$d_{50}$	$d_{84}$	$d_{16}$	Sharpness
DPMS				
Mean ( $\mu\text{m}$ )	0.757	0.600	1.056	1.33
SD ( $\mu\text{m}$ )	0.005	0.003	0.032	0.02
SCC				
Mean ( $\mu\text{m}$ )	0.740	0.631	0.978	1.25
SD ( $\mu\text{m}$ )	0.014	0.009	0.018	0.00
ESCC				
Mean ( $\mu\text{m}$ )	0.808	0.661	1.040	1.25
SD ( $\mu\text{m}$ )	0.001	0.016	0.033	0.03

Table 2

Mass collected by the three size selectors during the mass collection tests

Mass collected	Kruskal–Wallis ANOVA $\alpha = 0.05$			
	HD (mg)	DPMS (mg)	SCC (mg)	ESCC (mg)
Diesel particulate results				
Diesel 20% load: CMD = 0.09 $\mu\text{m}$				
Test 1	2.302	1.958	2.193	2.432
Test 2	2.276	2.113	2.137	2.292
Test 3	2.229	1.981	2.094	2.218
Diesel 50% load: CMD = 0.11 $\mu\text{m}$				
Test 1	1.859	1.724	1.724	1.993
Test 2	1.688	1.576	1.589	1.818
Test 3	1.648	1.567	1.552	1.82
Diesel 80% load: CMD = 0.13 $\mu\text{m}$				
Test 1	1.384	1.249	1.265	1.535
Test 2	1.544	1.475	1.414	1.677
Test 3	1.488	1.402	1.308	1.683
Coal dust results				
Pitt A: MMAD = 1.62 $\mu\text{m}$ , GSD = 2.10				
Test 1	4.195	0.06	0.077	0.147
Test 2	3.961	0.085	0.074	0.136
Test 3	3.817	0.123	0.122	0.184
Pitt B: MMAD = 4.27 $\mu\text{m}$ , GSD = 2.01				
Test 1	4.028	0.108	0.107	0.189
Test 2	4.266	0.06	0.155	0.16
Test 3	4.335	0.06	0.214	0.254
Pitt C: MMAD = 5.45 $\mu\text{m}$ , GSD = 2.33				
Test 1	3.953	0.092	0.204	0.284
Test 2	4.037	0.096	0.226	0.339
Test 3	4.034	0.092	0.204	0.306

$P = 0.0009$ , significant  
(*post hoc*  $P = 0.0006$ ,  
significant DPMS versus  
ESCC)

The size of the aerosols is represented by count median diameter (CMD) for diesel and MMAD and GSD for coal dust. Kruskal–Wallis ANOVA and multiple comparisons test *post hoc* results are shown.

**Table 3**

Cut characteristics of the size selectors under different coal loading conditions using AF to determine the cut

Device and load	Mean (SD) $d_{50}$ ( $\mu\text{m}$ )	Mean (SD) sharpness
SCC 0 mg	0.782 (0.037)	1.21 (0.02)
SCC 1 mg	0.774 (0.050)	1.20 (0.02)
SCC 2 mg	0.787 (0.057)	1.21 (0.02)
SCC 4 mg	0.796 (0.041)	1.20 (0.02)
DPMS 0 mg	0.762 (0.003)	1.30 (0.01)
DPMS 1 mg	0.617 (0.002)	Cannot determine
DPMS 2 mg	Cannot determine	Cannot determine
DPMS 4 mg	Cannot determine	Cannot determine