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Laboratory and Field Performance of a Continuously Measuring Personal Respirable Dust Monitor

Department of Health and Human Services
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NIOSH

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By Jon C. Volkwein, Robert P. Vinson, Steven J. Page, Linda J. McWilliams,
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ACRONYMS AND ABBREVIATIONS USED IN THIS REPORT

ANOVA	analysis of variance
BMRC	British Medical Research Council
CL	confidence limit
CMDPSU	coal mine dust personal sampler unit
DO	Dorr-Oliver
EOS	end of shift
GSD	geometric standard deviation
HD	Higgins-Dewell
HEPA	high-efficiency particulate air
ISO	International Organization for Standardization
LED	light-emitting diode
LOQ	limit of quantification
MMAD	mass median aerodynamic diameter
MO	mass offset
MRE	Mining Research Establishment (U.K.)
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
PDM	personal dust monitor
PEL	permissible exposure limit
PRL	Pittsburgh Research Laboratory (NIOSH)
PVC	polyvinyl chloride
RH	relative humidity
RMSE	root mean square error
RSD	relative standard deviation
TE	tapered element
TEC	Thermo Electron Corp. (Albany, NY)
TEOM	tapered-element oscillating microbalance
UCL	upper confidence limit

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

hr	hour
in	inch
kg	kilogram
L/min	liter per minute
lb	pound
mg	milligram
mg/m^3	milligram per cubic meter
min	minute
mm	millimeter
mm Hg	millimeter of mercury
sec	second
μg	microgram
μm	micrometer
°C	degree Celsius
°F	degree Fahrenheit

LABORATORY AND FIELD PERFORMANCE OF A CONTINUOUSLY MEASURING PERSONAL RESPIRABLE DUST MONITOR

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Gerald J. Joy,[5] Steven E. Mischler,[6] and Donald P. Tuchman[5]

ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH), through an informal partnership with industry, labor, and the Mine Safety and Health Administration, has developed and tested a new type of instrument known as the personal dust monitor (PDM). The dust monitor is an integral part of the cap lamp that a miner normally carries to work and provides continuous information about the amount of respirable coal mine dust in the breathing zone of that individual. Testing was conducted on 25 prototype instruments in the laboratory to verify the instruments' accuracy as received from the manufacturer and after a period of underground use. The laboratory testing verified previous work; there is a 95% confidence that the individual PDM measurements were within ±25% of reference measurements. In-mine testing determined the precision, durability, and miner acceptance. Data from the mines showed a field precision of 0.078% relative standard deviation for the PDM and 0.052% for the recognized standard— the coal mine dust personal sampler unit. The PDM had about 90% availability for collecting valid information in over 8,000 hr of underground use. Anecdotal comments by miners indicated that they found the PDM more convenient to wear for sampling than currently used instruments because of the integration of the sampler into the normally worn cap lamp. The means of the instruments' pre- and postmine accuracy verification test values were statistically equivalent. Additional data were collected to measure the equivalency of the PDM to the U.K. Mining Research Establishment sampler, as required by U.S. law. However, analysis of the data was more complex than originally anticipated because the variance with increasing concentration required use of a more sophisticated statistical model. Explanation of and results from this work will be the subject of a second publication. Under the broad range of test conditions covered in this work, the PDM functioned as well as the current sampler in terms of availability for use, accuracy, precision, and miner acceptance.

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INTRODUCTION

Measurement of workplace dust is an essential first step in eliminating lung disease caused by overexposure to dust. The Federal Coal Mine Health and Safety Act of 1969, the predecessor to the Federal Mine Safety and Health Act of 1977, mandates that coal mine dust levels be monitored and controlled to at or below 2 mg/m^3 for a shift. To date, this monitoring process has relied upon a coal mine dust personal sampler unit (CMDPSU) to collect a filter sample in the mine environment. The respirable dust-laden filter is then sent to a laboratory for analysis. Results are returned to the mine operators several days or occasionally weeks after the actual samples were taken. Following a long history of developmental efforts associated with light-scattering [Williams and Timko 1984], fixed-site, and personal continuous dust monitors [Kissell and Sacks 2002], the Secretary of Labor and the Federal Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers [U.S. Department of Labor 1996] directed the National Institute for Occupational Safety and Health (NIOSH) to embark on research to improve sampling instrumentation for use in the mining industry. In consultation with labor, industry, and government, NIOSH issued a contract (CDC contract 200–98–8004) to Rupprecht and Patashnick Co., Inc. (now Thermo Electron Corp. (TEC)), Albany, NY, to develop a personal dust monitor (PDM). The PDM is based on an environmental ambient air monitor that has achieved global acceptance for use in air quality monitoring networks. The important aspect of this monitor is that it directly measures the mass of dust on a filter regardless of dust composition, size, or physical characteristics. This contract work successfully miniaturized the air quality monitor's sensor and incorporated the sensor into a prototype person-wearable dust monitor that provided accurate end-of-shift (EOS) data [Volkwein et al. 2004]. Laboratory results from this work demonstrated that with different coal types and size distributions there was a 95% confidence that the individual PDM measurements were within ±25% of reference measurements. Mine test results comparing the PDM prototype with adjacent reference samplers indicated that the measurements were statistically indistinguishable. In mines, the technology proved durable enough to successfully measure 108 shifts of data out of 115 attempts in the mines. Under these specific test conditions, the PDM was shown to be convenient to wear and robust to use, provided accurate and timely data that could be used to monitor and prevent overexposure, and was easy to use.

Encouraged by the promising results from the initial laboratory and in-mine tests of the prototype PDM, the Mine Safety and Health Administration (MSHA) announced in June 2003 that it would suspend all work to finalize the proposed dust rules published in March 2003 and pursue accelerated research on the PDM [MSHA 2003]. In addition, the other PDM development partners, consisting of labor and industry, contributed toward drafting a test protocol to determine if the PDM was in fact suitable for use in coal mines, durable for everyday mine use, and ergonomically acceptable to miners. Another part of the protocol required measuring precommercial PDM performance in the laboratory and in mine environments for accuracy, precision, functionality, and long-term performance.

This report includes the first two of three major areas studied. The first is a confirmation that the laboratory accuracy of the precommercial PDM is similar to that of the prototype instrument and that the accuracy is maintained after in-mine use of the instrument. The second area is a detailed underground evaluation that includes measurement of the precision of the PDM, the CMDPSU, and the impactor to be used to measure the dust size distribution. The detailed underground evaluation also determines the performance of the PDM while in routine use by miners. The third area of this testing—to determine the equivalency of the PDM to standards of the U.K. Mining Research Establishment (MRE) and the International Organization for Standardization (ISO) for underground mines—is more complex than originally anticipated and will require use of a more sophisticated statistical model than originally planned. To proceed with the finished portion of this work, NIOSH has elected to present this work in a second publication.

Quantifying the fraction of dust that is considered respirable is an important part of measuring a worker's risk from dust. The ISO [1995] has recommended that the definition of respirable dust follow the convention described by Soderholm [1989]. Because no device precisely follows this theoretical convention, specific size classification devices that are used exhibit inherent bias when attempting to duplicate the convention. In fact, the 10-mm Dorr-Oliver (DO) dust cyclone currently used in the CMDPSU has bias relative to both the ISO and the British Medical Research Council (BMRC) definition of respirable dust [Bartley et al. 1994]. The BMRC definition was adopted by the MRE as the convention used to relate dust concentrations to worker health effects. The cyclone chosen for use in the PDM required a configuration that could accept a tube originating at the hard hat inlet. The cyclone selected followed the Higgins-Dewell (HD) design previously shown through testing to have low bias relative to the ISO convention [Maynard and Kenny 1995].

This report presents the theory of operation, description, performance of the PDM compared to gravimetric-based reference dust sampling methods, and functionality of the instrument when used by miners. It specifically addresses the accuracy of the instrument before and after mine testing and the in-mine precision.

DESCRIPTION OF THE PDM

The dust monitor described in this report is a precommercial (not for general sale) Model 3600 PDM that functions identically to a prototype monitor originally developed under contract. This PDM differs from the prototype in that it incorporates a stronger case, improved display, more efficient power management, and improved software. The device is intended to be virtually "invisible" to the miner as a replacement for the cap lamp and battery currently used in most mines.

The tapered-element oscillating microbalance (TEOM) mass sensor was the key to the accurate, time-resolved measurements provided by the PDM [Patashnick and Rupprecht 1991]. TEC has applied this mass measurement technique to a variety of arenas requiring time-resolved measurements, including ambient air, diesel, and stack particulate monitoring. This inertial, gravimetric-equivalent, mass measurement technique typically provides a limit of detection equivalent to that of the most sensitive laboratory-based microbalances. The development of the TEOM technique for use in a small personal exposure monitor, subjected to the harsh conditions of an underground mine, brought new challenges. As a result of a multiyear effort, TEC invented a hardware-based momentum compensating approach that effectively isolated the mass monitor from external shocks and was essential to providing microgram mass resolution in challenging applications.

System Configuration

The PDM is a combined respirable dust sampler and cap lamp configured to have dimensions and weight similar to those of a current lead-acid-type miner's cap lamp battery. Components of the device include a sample inlet tube, HD cyclone, air heater, pump, dust sensor, sampler battery, cap lamp battery, electronic control and memory boards, a display screen, and Windows®-based computer interface software called WinPDM. Figure 1 shows some of these components. The PDM case is hardened to withstand the harsh conditions found in the mine environment, with the system designed to meet MSHA drop test requirements for cap lamps (30 CFR[7] 19) as well as intrinsic safety-type approval requirements (30 CFR 18). The PDM system also includes a nonintrinsically safe docking station that is simultaneously used to communicate with personal computer software for programming and retrieving stored data in the instrument and to recharge its batteries for the next work shift (Figure 2).

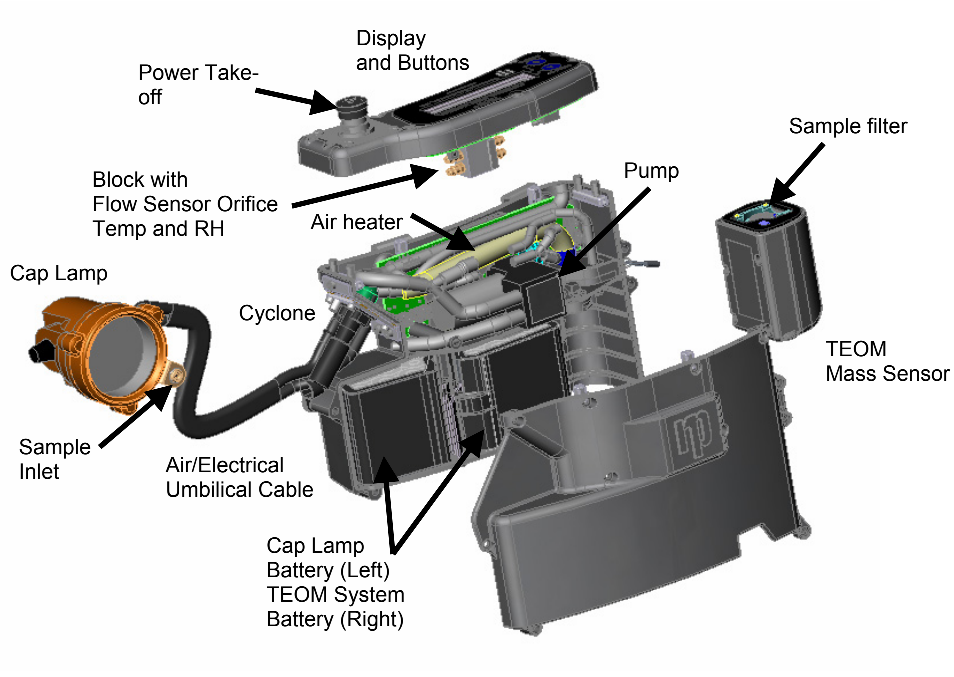

Figure 1.—PDM internal components.

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[7] *Code of Federal Regulations*. See CFR in references.

Figure 2.—Precommercial PDM connected to white docking station *(left)* used for charging and communication with a PC using an RS–232 interface.

Sample Flow Path

A 2.2-L/min flow of particle-laden air from the mine atmosphere enters an inlet adjacent to the cap lamp, mounted on the bill of the miner's hard hat, and passes through flexible conductive tubing before reaching the HD cyclone at the entrance of the PDM. The cyclone separates the dust, allowing particles that could penetrate to the lung (respirable dust) to proceed through a heated section of tubing to remove excess moisture and then enter the unit's mass sensor. As the airflow passes through the mass sensor, an exchangeable filter cartridge collects the respirable particles. The mass sensor can be removed from the PDM by a mine's dust technician (Figure 3) to change the particle collection filter and clean the unit after the end of each work shift.

Figure 3.—Technician changing filter on the PDM mass sensor using a custom-supplied filter tool.

Flow Measurement and Control

Downstream of the mass sensor, the filtered airstream flows through an orifice used in conjunction with a differential pressure measurement to determine the volumetric flow rate. In-line relative humidity (RH) and temperature sensors are located ahead of a computer-controlled sample pump that generates the vacuum needed to sample the mine atmosphere. Other sensors measure the ambient temperature in the vicinity of the cyclone, as well as the atmospheric pressure in the mine. The PDM uses these inputs, together with the sample airstream temperature sensed close to the flow-measurement orifice, to determine the flow rate passing through the HD cyclone. A feedback loop in the PDM uses this information to dynamically control the speed of the pump so that the constant 2.2-L/min volumetric flow rate, required for proper dust size separation, is maintained at the cyclone, under the mine's ambient temperature and pressure conditions.

Battery Configuration

The two identical battery packs inside the PDM provide 12 hr of power to the miner's cap lamp and the particle sampling and analysis system. The batteries can be recharged from a complete discharge in about 6 hr to provide maximum use of the monitor. The batteries make use of the latest lithium-ion technology used in portable computers to provide high-power density and superior charging and life cycle characteristics. The energy storage density enabled by lithium-ion battery technology allows for the packaging of a dust sampling and analysis system together with the batteries required for the cap lamp in a size and weight approximating those of the current battery pack. The PDM as tested weighed 3.0 kg (6.6 lb).

Data Treatment

A microprocessor-based controller collects real-time inputs from sensors and the microbalance to provide a minute-by-minute record of the dust loadings and mine environment. The PDM continuously displays personal dust exposure information to the miner in numeric and graphic formats. Environmental data such as ambient temperature, pressure, and motion of the instrument are measured. Dust and environmental data are stored in the PDM memory for about 20 full-shift sample runs. These data may be selected for downloading and analysis.

An illuminated data display on the top of the PDM continuously shows the previous 30-min dust concentration, cumulative mass concentration to that point in the shift, and an estimated EOS projected concentration exposure. Through the display, miners can gauge their current dust exposure, as well as the effectiveness of actions taken to reduce their dust exposure.

The exposure data described above are always displayed to miners, but are protected from tampering by being accessible only to an authorized person. In addition, the PDM allows miners and management to initiate short-term mass concentration measurements for specific monitoring objectives without affecting the shift-based statistics. This can be helpful to gauge the effectiveness of various dust or ventilation engineering control techniques. These intrashift measurements may be made as often as desired, and data obtained during these trials may be selected for downloading together with the tamper-resistant shift-based information.

TEOM Mass Measurement Technique

At the heart of the TEOM mass sensor is a hollow tube, called the tapered element (TE), which is clamped at its base and free to oscillate at the opposite end. The exchangeable filter cartridge mounted on its free end collects the respirable particles contained in the airstream that passes from the entrance of the mass sensor through the TE. Electronic components positioned around the TE cause the tube to oscillate at its natural (or resonant) frequency and at a constant amplitude. As additional mass collects on the sample filter, the natural oscillation frequency decreases as a direct result. This approach uses first principles of physics to determine the mass change of the collection substrate (filter) and is not subject to uncertainties related to particle size, color, shape, or composition.

The PDM determines the mass concentration of respirable dust in the mine environment by dividing the mass (as determined by the frequency change) collected on its filter over the air volume sampled during the same period. The system updates its mass concentration readings, shown in milligrams per cubic meter, every few seconds. The manufacturer uses mass standards traceable to the National Institute of Standards and Technology to calibrate the mass sensor constant $K0$, which determines the relationship between mass change at the end of the TE and frequency change.

Filter mass is calculated every 5 sec according to

$$MT0 = K0 \times \left(\frac{1}{f_c^2} - \frac{1}{f_i^2} \right) \quad (1)$$

where $MT0$ = mass;
$K0$ = the constant of the tapered element (TE);
f_c = current frequency;
and f_i = initial frequency (i.e., at start of shift).

Mass rate and concentrations are derived from the mass, time, and flow rates of the instrument. Details of these calculations may be found in the operations manual [Rupprecht and Patashnick Co. 2004].

Momentum Compensation: The Key to Miniaturization

In the past, TEOM-based monitors were much too large and delicate to be used for personal exposure monitoring [Williams and Vinson 1986]. The potential for application of the TEOM technology to mining came through the miniaturization of the TEOM mass detector, which was made possible through the development of a patented concept involving momentum compensation. A momentum compensator, built into the PDM mass sensor, oscillates an additional mass at the same frequency, but in opposing phase to the TE. The TE effectively behaves as if it were mounted on a massive base without the use of a large mass. By analogy, a musical tuning fork requires two forks rather than a single fork to freely oscillate. The purpose of the second fork is to provide momentum compensation to the first fork by oscillating in an equal but opposite motion as the primary fork. This momentum compensation allows a user to hold a tuning fork base without extinguishing its motion, and it will ring freely for a long period. A tuning fork would not ring freely with a single fork unless it was held in a base of significant mass and clamped such that there is very little energy loss to the system. By applying this principle, energy loss from the TE oscillator to its surroundings approaches zero with the appropriate proprietary design of the momentum compensator. The size and weight of the TEOM detector are dramatically reduced without compromising performance. In addition, the smaller sensor reduced the thermal heating requirements, enabling greatly reduced power consumption.

METHODS

Laboratory Methods

Performance of the precommercial series 3600 PDM was evaluated in the laboratory to validate instrument accuracy as received from the manufacturer and after use in mines. Using published criteria for comparing analytical techniques [Kennedy et al. 1995], NIOSH showed that for the prototype PDM, “there is a 95% confidence that the individual PDM measurements were within ±25% of the reference measurements” and that the upper 95% confidence limit was met [Volkwein et al. 2004]. The precommercial 3600 PDM uses the same mass measurement methods and algorithms as the prototype, and a detailed repeat of the entire accuracy evaluation was not warranted. However, to confirm this assumption, a limited version of the previous accuracy test was conducted with all of the new instruments.

Dust Exposure Chamber

A laboratory Marple chamber provided a uniform test environment for comparing dust-measuring instruments while maintaining good control of test variables [Marple and Rubow 1983]. The chamber was operated to produce dust concentrations nominally ranging from 0.2 to 4 mg/m^3. While this is the concentration range recommended in NIOSH's *Guidelines for Air Sampling and Analytical Method Development and Evaluation* [Kennedy et al. 1995], it was viewed as a guideline since it pertains to analytes that have very good reference standards. In this case, the reference was a gravimetric sampler. The relative standard deviation (RSD) of these samplers has been demonstrated [Kogut et al. 1997] to significantly increase at mass concentrations of less than 0.5 mg/m^3. When reference mass loadings were less than 0.5 mg/m^3, the number of reference samples was increased to improve the accuracy of the reference mass measurement. Coal dust used in the chamber was from the Pittsburgh Seam and was ground to size by passing the coal through an Alpine AFG Model 100 jet mill (Hosokawa Micron Powder Systems, Summit, NJ). A fluidized bed dust generator with charge neutralizer (TSI, Inc., St. Paul, MN) was used to introduce the dust into the chamber.

Chamber temperature was regulated to between 20 and 25 °C and an RH between 40% and 60%. Instruments were mounted on a turntable in the chamber that was rotated at a rate of one to two revolutions per minute. This eliminated the need for a randomized block design and ensured that each sampling device was exposed equally to all radial portions of the chamber. Chamber dust concentrations were monitored with a commercially available Model 1400a TEOM (TEC, Albany, NY). This was used to help select the correct time intervals to achieve desired mass loadings for the testing.

Samplers

PDM mass measurement accuracy and precision were compared to the average of multiple gravimetric samples. A total of 25 PDMs were used as delivered by TEC. Samplers used for gravimetric analysis were BGI–4CP cyclones with integral filter holders (BGI, Inc., Waltham, MA) connected to MSA Escort ELF sampling pumps (MSA Co., Inc., Pittsburgh, PA). The BGI–4CP cyclone was an HD design, identical to that used in the PDM. The PDMs and the BGI–4CP cyclones were operated at 2.2 L/min. To further minimize test variables, the BGI–4CP samplers were modified to use an inlet and tube configuration identical to that in the PDMs.

PDM

The PDM used Teflon-coated nominal 15-mm-diam filter media TX40H120WW (Pallflex Products Corp., Putnam, CT), manufactured into a special plastic holder that mounted on the end of the hollow TE. This is the same filter medium used in the TEC Model 1400a ambient air monitor. The PDM sampler flow rate was checked and recalibrated if flow variance was greater than ±1% (0.022 L/min). Data on the flow rate and calibration of each instrument were recorded. The analysis of flow rate stability was based upon 10 PDM units for which complete flow calibration histories were known.

PDM samplers were cleaned after each day of use. Cleaning consisted of removing the cyclone grit pot, the TE sensor module, and the filter on the TE. Canned compressed air was then blown from the cap lamp-located inlet tube toward the cyclone, up the cyclone from the grit pot, and from the TE connection back toward the cyclone. The TE module and cyclone grit pot were then cleaned with the compressed air. A new filter was installed on the TE and the module and cyclone grit pot reattached to the PDM.

Gravimetric Reference

The filters used in the BGI–4CP cyclone were 37-mm-diam, 5-µm pore size, polyvinyl chloride (PVC) membranes. Flow-controlled MSA ELF Escort pumps were calibrated on-site at the beginning of each group test using a Gilibrator (Sensidyne, Inc., Clearwater, FL) primary standard flow meter to 2.2 ± 0.022 L/min for the BGI–4CP samplers. A pressure restriction equivalent to the respective samplers was used during pump calibration.

Impactors

Size distributions of the dust in the chamber were measured using a Marple personal cascade impactor (Model 290, TEC, Franklin, MA) operated at a flow rate of 2.0 ± 0.020 L/min using ELF Escort pumps. The device was operated according to the manufacturer's instructions, including correction factors to account for inlet efficiency and wall loss [Rubow et al. 1987].

The impactor has eight collection stages with cut points from 0.52 to 21.3 µm and a final filter (PVC 37-mm-diam, 5-µm pore size). At each collection stage, dust particles impact on a 34-mm-diam Mylar® substrate at six impaction zones. Before using the substrates, the impaction zones were coated with grease to hold the collected particles on the substrates. This was done by covering the 34-mm-diam Mylar substrate with a metal template that has six slots that expose the impaction zones. These slots were then sprayed with a 1- to 10-µm-thick layer of impaction grease (Dow Corning 316 Silicone Release Spray, Dow Corning Corp., Midland, MI). After spraying, the substrates were kept at constant temperature and humidity for 3 days to allow the volatile components of the silicone spray to evaporate and to outgas. The substrates and the PVC final filters were then preweighed and loaded into the eight stage impactors. Impactors were used in triplicate to measure the size distribution of the coal dust. Three substrates and three final filters were used as blank controls.

The size distribution mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD) were determined from a straight line regression of impactor stage data plotted as the inverse cumulative distribution function of the normal distribution or probit of cumulative mass percentages versus the logarithm of stage cut point. The use of straight line regression to find the best-fitting line for this type of plot is recommended only if the regression is truly linear because it overemphasizes the tails of the distribution. Cumulative lognormal plots often show curvature toward the tails, resulting in regression error of the distribution parameters [Hinds 1982]. To account for a potential error caused by overemphasis of the tails of the distribution, data for size distribution analysis were only used if the R^2 values for the regression were greater than 0.95.

Analytical Gravimetric Precision

Gravimetric analysis was performed on a Cahn microbalance (model C–31, TEC, Boston, MA) for the impactor samples and a Mettler-Toledo microbalance (model UMT2, Mettler-Toledo, Inc., Columbus, OH) for the BGI–4CP and CMDPSU samples. Weighing was done in the NIOSH Pittsburgh Research Laboratory's (PRL) weighing laboratory at 73 ± 0.7 °F and 53 ± 2% RH. All samples were pre- and postweighed using control filters. Average blank control filter weights were used to correct the filter mass results for each test employing impactors, BGI–4CP cyclones, and the CMDPSU. However, small cyclic fluctuations in these conditions over the course of a few minutes cannot be totally accounted for by the control filters for two reasons. First, the control filters cannot physically be weighed at the same time as the sample filters. Secondly, the pre- and postweighings are not performed at the same time in relation to the cyclic variation of the room conditions. Therefore, several estimates for the weighing precision will be provided.

Experimental Design

Because of the limited weight and volume capacity of the Marple chamber, the 25 PDMs were usually divided into two groups with 12 and 13 instruments per group. Three replicate test runs were conducted with each group. Each individual test run used 15 BGI–4CP gravimetric samplers. The inlets of all samplers were uniformly arrayed around a central point in the Marple chamber (Figure 4).

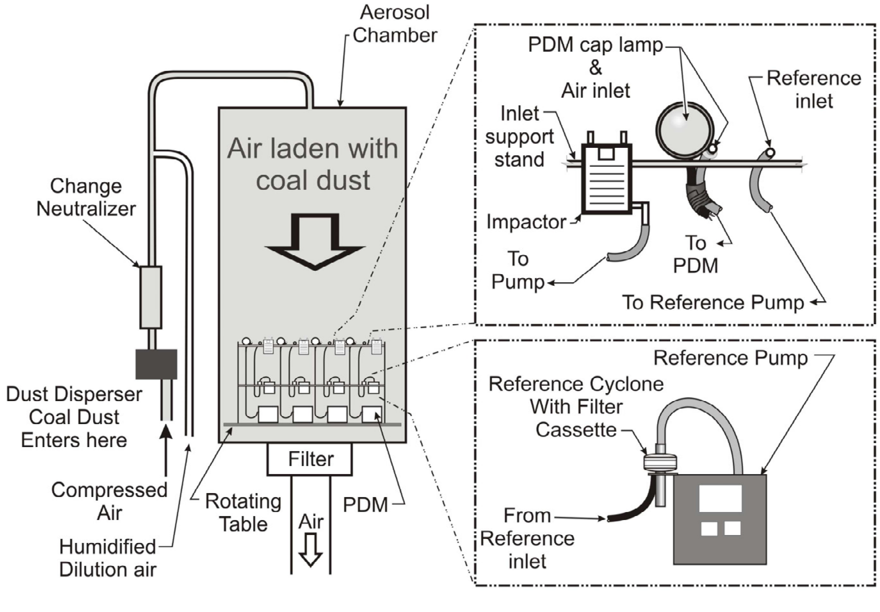

Figure 4.—Laboratory test chamber and arrangement of instruments.

The 15 gravimetric samplers were arbitrarily divided into four test-time interval groups. A test-time interval was defined as the time required to achieve a predetermined mass for a group of instruments. The first time interval used six samplers to account for the increased variability of the reference measurement when mass loadings were less than 0.5 mg/m^3; the second, third, and fourth time intervals used three samplers.

The mass collected by the samplers in each time group was used to determine the average reference gravimetric dust mass during a specific test-time interval. In addition, there were three blank control filters for each test. Control filters were handled in an identical fashion to the test filters, except that the cassette end caps were not removed. Final test filter weights were corrected using the average control filter mass change.

Test-time intervals were selected to achieve filter mass target loadings over the range of about 0.2–4 mg. For a typical test run, the internal computer for each PDM was programmed to automatically start and all gravimetric samplers were manually started at the same time. Because of the large number of gravimetric samplers started manually, they were started sequentially by group and stopped in the same sequence to minimize any time differences between samplers caused by starting and stopping. As mass loaded onto the samplers with time, groups of gravimetric sampling pumps were turned off at predetermined mass loadings, as indicated by the Model 1400a TEOM using an HD cyclone at a flow rate of 2.2 L/min. The mass loading therefore determined the test-time interval. This procedure resulted in four test-time intervals with averaged mass loadings from corresponding groups of BGI–4CP samplers. For each test-time interval, the PDM mass measurements, preserved in data files, were used to determine the mass measured by the individual PDM for that test-time interval.

The three test runs were essentially replicates except that the mass loadings varied as follows:

- *Run 1*.—8-hr duration, test-time interval Nos. 1–4. The chamber was brought to a concentration of about 2 mg/m^3. Gravimetric filters were turned off at equivalent mass target loadings of 0.4, 0.9, 1.4, and 2 mg. Impactor size distribution samples were taken with three impactors to confirm that the size distribution of this study was comparable to previous sizes associated with this coal type.
- *Run 2*.—8-hr duration, test-time interval Nos. 5–8. The chamber was brought to a concentration of about 4 mg/m^3. Gravimetric filters were turned off at equivalent mass target loadings of 1, 2, 3, and 4 mg.
- *Run 3*.—8-hr duration, test-time interval Nos. 9–12. The chamber was brought to a concentration of about 2 mg/m^3. Triplicate sets of filters were turned off at equivalent mass target loadings of 0.2, 0.7, 1.7, and 2.0 mg.

PDM Battery Test

Previous work had demonstrated that the lithium-ion batteries used in the PDM could enable a 12-hr sample to be taken, but did not address what happens to PDM performance as batteries weaken prior to failure. A test was conducted with six PDMs to monitor mass rate of accumulation and flow rate as the instruments' batteries ran out of power. This laboratory testing established a dust concentration of 2 mg/m^3 in the Marple chamber that was continuously monitored using a Model 1400a TEOM and PDMs run to battery failure.

PDM Mass Constant Verification

During this evaluation, the mass constant of the PDM was verified. To determine mass, each individual TE used in a PDM has an empirically derived mass constant.

Definition of Constant

The constant *K*0 (*K* zero) is determined by recording the TE's frequency change due to a known mass applied to the TE's filter and inputting data into the following equation:

$$K0 = \frac{m}{\left(\left(1/f_f^2\right) - \left(1/f_i^2\right)\right)} \qquad (2)$$

where $K0$ = the constant of the TE;
m = the mass in grams added to the TE filter;
f_i = the baseline frequency in hertz of the TE before the mass is added;
and f_f = the frequency in hertz of the TE after the mass is added.

The *K*0 for each TE was determined by averaging five *K*0 measurements. The *K*0 was calculated each time the mass on the TE was changed. The resulting average was then compared with the *K*0 that had been programmed by TEC into each PDM.

Procedure to Determine Mass Constant

All of the PDMs were cleaned and had new filters inserted on their TEs. Their inlets were connected to a high-efficiency particulate air (HEPA) filter to eliminate the possibility of dust contamination. Throughout the tests, each PDM was connected to their battery charger/computer connection, which enabled real-time graphing of the TE frequency. The PDMs were run for a minimum of 1 hr for warmup before any *K*0 measurements were made.

The known masses added to the TE filter were small, preweighed aluminum tabs with adhesive on one side of the tab to couple the tab to the filter surface. The tabs were preweighed just before the tests in the controlled atmosphere of the PRL weighing laboratory.

After warmup, the PDMs were programmed with the WinPDM 5.12A expert software program to activate the mass raw frequency template and to display and log data every second. The software program graphed the raw frequency curve in real time. By observing this curve, we could determine when the raw frequency had stabilized. The stabilized baseline frequency (f_i) was recorded. The TE module was removed from the PDM, and a preweighed aluminum tab was attached near the center of the TE filter. The TE module was then reinserted into the PDM and the raw frequency curve observed. Once the raw frequency had stabilized, the new frequency (f_f) was recorded along with the mass of the aluminum tab. This process was repeated five times. Each additional piece of aluminum mass was uniformly distributed across and adhered to the filter. Mass at each frequency was the summation of the individually added pieces. The *K*0 for each mass was then calculated according to equation 2 and the average *K*0 of the five readings calculated. This averaged *K*0 was then compared with the *K*0 that had been programmed into the PDM.

Analysis

The accuracy and precision were calculated from the data pairs of individual PDM mass measurements to the average gravimetric reference standard. Accuracy, bias, and precision were calculated by the method of Kennedy et al. [1995], who defined *accuracy* to be the ability of a method to determine the true concentration, *bias* to be uncorrectable relative discrepancy between the mean of the distribution and the true concentration, and *precision* to be the relative variability of measurements of replicate samples about the mean of the population of measurements. For these tests, the mass ratio for each datum pair was calculated by dividing the individual PDM mass by the average value for the triplicate gravimetric reference mass measurements of the corresponding time interval. The individual mass ratios were then averaged over each group of data. The RSD was calculated for both PDM and gravimetric reference standards. To reduce the impact of error in the gravimetric reference measurement, the experimental pooled estimate of the RSD of the gravimetric samplers was subtracted from the RSD of the ratios such that the corrected RSD was

$$RSD_x = \sqrt{RSD^2_{\frac{x}{t}} - RSD^2_{\overline{T}_i}} \tag{3}$$

where $RSD_{\frac{x}{t}}$ = relative standard deviation of mass ratio

and the experimental pooled RSD of the gravimetric samplers was

$$RSD_{\overline{T}_i} = \frac{\sqrt{\frac{\sum RSD^2{}_{gravimetric}}{n}}}{2} \tag{4}$$

Bias was then calculated based on the mean concentration minus one. Accuracy was calculated based on the method provided by Kennedy et al. [1995]. Confidence limits were calculated based on the method used by Bartley [2001] using the noncentral Student's *t*-distribution.

The precision of the PDM was analyzed for each test by examining the RSD of the PDM and reference samplers over mass loadings ranging from 0.2 to 4.3 mg. To determine the overall precision of the PDM from the premine laboratory data, an RSD was computed using a one-way analysis of variance (ANOVA). The intratest RSD was estimated by the square root of the mean square error (RMSE). The dependent variable for this analysis was the dust concentration measured in milligrams per cubic meter, and the independent (or grouping) variable was the laboratory test. There were six tests with 12–13 PDMs per test. For each test, dust concentration measurements were collected at four time intervals. For each PDM, the dust measurements were averaged across the time intervals within each individual test. In order to be consistent with the methodology used to calculate the PDM field precision, the concentration measurements were log-transformed (log base *e*) before the analysis was conducted.

Detailed In-mine Test Methods

In this portion of the study, PDMs were used by miners to estimate the long-term mechanical, functional, and ergonomic features of the samplers. The in-mine precision of the PDM and reference samplers was determined.

Criteria for Mine Selection

This testing required a high level of cooperation from the host mine to permit training, allocate working space, and commit labor to maintain the PDMs in the absence of NIOSH personnel. The level of cooperation required prevented selection of mines at random for this portion of the testing. Mines were, however, selected to include a variety of coal types, machine types, geographic locations, seam heights, and workforce sizes. Representative geographic distribution of mines was achieved by selecting one mine from each of the 10 MSHA bituminous coal mining districts. Table 1 shows the characteristics of each mine. Within this sample, selections were made by type of machine and on-section locations to obtain dust samples that were representative of where miners work.

Table 1.—Detailed mine characteristics and location of Lippmann sample

MSHA district	Mine height, in	Mining method	Distinguishing features	Location of sample
2	65	CM	Exhaust vent tube, integral miner bolter	On miner left rear side.
3	70	CM	Exhaust vent tube, integral miner bolter	On miner near left bolter.
4	65	LW	PDM powered remote	Shield 30.
5	48	CM	Scrubber, bridge face haulage	Immediate miner return.
6	56	CM	Small mine	Bolter.
7	50	CM	Pillar section – retreat ventilation to gob	Behind miner toward gob side.
8	46	CM	Super section single split vent, low coal	Immediate miner return.
9	120+	LW	High seam	Shield 20.
10	46	CM	Low coal, super section	Immediate miner return.
11	72	CM	Diesel face haulage	Twin boom bolter.

CM Continuous mining. LW Longwall.

Detailed Mine Procedures

At each detailed mine test site, NIOSH spent 3 days on-site to demonstrate and teach mine personnel how to use and maintain the PDM. Sampling of an entire face crew was conducted over the miners' entire work shift, which included travel to and from the working section. In addition, the precision of triplicate samplers was determined. The PDMs were then left at 6 of the 10 mines for use by the mine without NIOSH present. At the end of the 10th detailed mine study in late spring of 2005, four mining companies conducted extended testing of the PDM at their mines to further evaluate the stand-alone performance of the instrument.

At each mine, NIOSH presented a 45-min training session at the start of the shift. The training contained a short video to ensure that information was presented in a uniform manner. A pocket-sized memory jogger card was given to each miner wearing a PDM to remind him or her about the points discussed in the video. The mine section where miners were to wear the PDM was selected by management and hourly employee representatives. In addition to the section crew, management and labor representatives and safety personnel attended the training. NIOSH provided additional training to the mine employees who would maintain the PDMs at the mine.

Data collected at each mine included the full-shift dust exposure of each miner, the corresponding MSHA-coded occupation, and a notation of any problems in collecting the data. Mine personnel programmed the PDMs to automatically start sampling at the beginning of the shift and to sample for the entire shift length. Between 7 and 14 PDMs were used depending on the size of the section crew. Each day, miners picked up their assigned PDM as they would have normally picked up their cap lamps and returned the PDM to the charger at the end of the shift. A mine employee would then download the data, clean the inlet tube and cyclone, change the filter, and program the samplers for the next shift of sampling. Data from the samplers were considered valid when the PDM ran for the entire shift with no mechanical or electronic faults, or human errors. This mechanically correct sample could later be considered void in the event that the data file showed a flow fault or other sampling abnormality. The number of mechanically correct samples divided by the total number of samples attempted during a shift determined the overall valid or sampling success rate for this testing. Subsequent analysis of the data file may determine that a sample should be voided for cause, but this would not affect the overall valid sampling rate. Flow rates for these PDM samplers were considered acceptable at ±5% of 2.2 L/min. In the event that the PDM flow sensor detected a flow rate change that was greater than ±0.2 L/min of the calibrated flow for a period of 60 sec, the PDM would place an error message on the display and in the datum file for later evaluation of the severity of the fault.

For the first 3 days of sampling, NIOSH personnel collected area samples, were present on-site to help with the PDM sampling, and accompanied the miners underground to answer questions. At the first six mines, NIOSH left all of the PDMs for the section crew at the mine site under the supervision of mine personnel. The same section of miners continued to use the PDMs for the next week. If a miner was absent, the miner's replacement would wear the PDM. Similarly, if the entire crew changed from day to evening shift, the PDMs stayed with that crew to maintain consistency. If extra instruments were available, other miners working outby[8] would occasionally wear a PDM. The following week, NIOSH returned to the mine and accompanied the section crew to work. NIOSH observed and talked to miners about their experience with the PDM. We then collected the instruments and data records. This resulted in 8–11 shifts of data from each PDM from every member of the mining section. The variable number of days resulted from some mines continuing testing through the weekend or scheduled shift changes.

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[8] Away from the area of active mining.

Area Sampling

Area sampling was conducted for 3 days at each mine to determine the precision of the PDM, DO cyclone, and impactor size distribution measurements. A stationary Lippmann-type sampling apparatus [Blachman and Lippmann 1974; Volkwein and Thimons 2001] was used to collect triplicate measurements from the PDM, Marple personal impactors, and CMDPSUs at flow rates of 2.0 L/min and 1.7 L/min. The Lippmann device minimized spatial variability associated with mine sampling. Weighing and calibration procedures for this testing were identical to the laboratory testing. The 3 days of sampling conducted in 10 mines resulted in a total of 30 triplicate measurements from which the precision of instruments was calculated.

Maintenance and Use Log

Over the course of the research, all usage of the project's 25 PDMs was recorded. A chronological record was kept for each PDM unit summarizing the number of hours it actively ran from its delivery date to the end of the project. This included all types of laboratory and field operations, regardless of the nature of the usage, test, or monitoring being performed. Therefore, for the purpose of summarizing overall PDM use, only total hours logged were considered, and the environment or nature of differing instrument deployments was not a distinguishing factor.

Each PDM also had its individual repair history recorded, which included some details of problems experienced and repairs performed to resolve the problems. For these repair records, distinctions were made between types of manufacturer repair. Repairs were categorized as either remedial or critical. Remedial repairs reflected current or pending hardware or software modifications to instrument design that were minor in nature and unlikely to be ongoing issues once fully instituted. Examples of remedial repairs include updating firmware to correct performance problems, correcting manufacturing defects, and replacing failed faceplate keypads or display screens. Critical repairs were defined as repairs necessary for full functional operation of the instrument to collect valid data. Critical repair frequency was regarded as somewhat more reflective of ultimate instrument reliability after design refinements.

Further maintenance log entries were also made to record success or failure of each PDM run. If a PDM completed a run with valid data, the run was evaluated as successful. If a run was not completed or data files were electronically corrupted, the run was considered a failure. While the nature of run failures was recorded, types of failures were not subcategorized. Researchers intervened and corrected unsuccessful PDM performance as soon as problems were recognized. In many instances, minor adjustments were adequate to resolve instrument problems. Less frequently, manufacturer service was required and recorded.

Field Precision Analysis

To determine the precision of the PDM, the DO cyclone at 2.0 L/min, and the DO cyclone at 1.7 L/min, the RSD was computed using a one-way ANOVA. To determine the within-day variability average among the triplicate samplers, a technique using the standard deviation calculated from the ANOVA was used to compute the RSD. Because the distributions of the dust concentrations for each sampler were positively skewed, the data values were log-transformed (log base *e*) before the analysis. The dependent variable for this analysis was the dust concentration measured in milligrams per cubic meter, and the independent (or grouping) variable was the date of the in-mine sampling test. There were 30 unique dates with triplicate measurements collected on each date for each instrument type.

RESULTS

Laboratory Accuracy Verification

The ability of the PDM to determine the true concentration of aerosol in the environment is described as the instrument's accuracy. Evaluation of the data from the prototype PDM to determine whether it met the NIOSH accuracy criterion was reported by Volkwein et al. [2004]. The limited lab premine testing reported here was intended to verify that the precommercial 3600 PDM maintained performance similar to that of the prototype PDM.

Premine Testing

Premine accuracy verification test results in Table 2 present the average mass of dust from the BGI–4CP samplers for each test-time interval, the corresponding individual PDM mass measurements by serial number, and the RSD of both samplers. The overall average RSD for the gravimetric reference sampling for these laboratory samples is 0.041 for the first group of tests and 0.039 for the second group. The RSD for the PDM units for each test-time interval is indicated; the average for these measurements was 0.057 for the first group of tests and 0.043 for the second group. The RSD of the combined data calculated for the PDM was 0.051 (95% CL = 0.048, 0.057). This value will be subsequently used in the discussion of the calculation of field precision.

Table 2.—Premine laboratory data of reference mass measurements and PDM mass measurements

Time interval	Gravimetric avg. mass, mg	RSD	PDM mass by serial number													RSD
			110	112	113	115	119	126	127	128	130	131	132	133	135	
			mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	
1	0.426	0.048	0.377	0.406	0.384	(1)	0.409	0.388	0.359	0.431	0.413	0.393	0.414	0.357	0.381	0.058
2	0.968	0.047	0.901	0.956	0.903	(1)	0.958	0.903	0.939	0.992	0.952	0.897	0.967	0.843	0.881	0.046
3	1.506	0.033	1.384	1.481	1.397	(1)	1.483	1.397	1.462	1.515	1.453	1.363	1.481	1.289	1.354	0.048
4	2.184	0.023	1.931	2.054	1.942	(1)	2.053	1.933	2.036	2.108	2.020	1.887	2.064	1.792	1.884	0.048
5	1.132	0.033	1.050	1.066	0.994	0.955	1.052	1.047	1.013	1.124	1.033	1.009	(1)	0.935	1.061	0.050
6	2.160	0.049	2.104	2.163	1.991	1.929	2.098	2.115	2.032	2.254	2.097	2.000	(1)	1.839	2.115	0.054
7	3.244	0.054	3.075	3.161	2.910	2.833	3.068	3.110	2.976	3.298	3.076	2.923	(1)	2.658	3.087	0.055
8	4.308	0.036	3.980	4.090	3.757	3.675	3.970	4.027	3.843	4.271	3.989	3.795	(1)	3.425	3.975	0.056
9	0.193	0.082	0.196	0.202	0.201	0.202	0.212	0.196	0.204	0.205	0.222	0.197	0.203	0.165	0.214	0.066
10	0.747	0.021	0.732	0.732	0.733	0.727	0.774	0.732	0.741	0.757	0.800	0.701	0.759	0.596	0.797	0.069
11	1.796	0.033	1.688	1.700	1.702	1.689	1.792	1.697	1.720	1.776	1.837	1.637	1.788	1.396	1.833	0.066
12	2.144	0.033	1.967	1.984	1.975	1.959	2.076	1.968	1.993	2.072	2.139	1.909	2.074	1.633	2.124	0.064
Average gravimetric RSD		0.041										Average PDM RSD				0.057

Time interval	Gravimetric avg. mass, mg	RSD	PDM mass by serial number														RSD
			102	105	108	109	111	114	116	120	122	123	124	125	115	132	
			mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	
1	0.424	0.069	0.410	0.377	0.376	0.432	0.451	0.395	0.427	0.391	0.430	0.426	0.372	0.411	0.400		0.061
2	1.003	0.025	0.914	0.854	0.860	0.967	0.989	0.887	0.971	0.889	0.960	0.960	0.840	0.925	0.901		0.054
3	1.572	0.034	1.454	1.354	1.376	1.508	1.571	1.406	1.544	1.415	1.521	1.515	1.331	1.481	1.433		0.052
4	2.115	0.034	1.990	1.865	1.917	2.055	2.149	1.927	2.125	1.949	2.076	2.082	1.836	2.037	1.973		0.049
5	1.111	0.044	1.055	1.008	0.993	1.009	1.089	1.011	1.095	1.059	1.028	1.108	1.048	1.076		1.066	0.035
6	2.169	0.002	2.024	1.928	1.918	1.930	2.097	1.957	2.108	2.035	1.974	2.131	2.016	2.070		2.055	0.036
7	3.224	0.042	2.999	2.890	2.874	2.864	3.130	2.914	3.124	3.028	2.961	3.159	2.978	3.067		3.058	0.034
8	4.213	0.030	3.846	3.709	3.689	3.683	4.002	3.744	4.012	3.891	3.814	4.046	3.809	3.927		3.916	0.032
9	0.185	0.076	0.203	0.202	0.192	0.199	0.204	0.191	0.205	0.194	0.198	0.203	0.181	0.218			0.045
10	0.724	0.025	0.730	0.721	0.692	0.717	0.736	0.703	0.758	0.710	0.724	0.750	0.676	0.768			0.037
11	1.814	0.040	1.742	1.722	1.646	1.702	1.777	1.673	1.798	1.685	1.722	1.772	1.613	1.839			0.038
12	2.035	0.051	2.005	1.985	1.893	1.969	2.041	1.936	2.075	1.952	1.987	2.043	1.867	2.117			0.037
Average gravimetric RSD		0.039												Average PDM RSD			0.043

[1] Test run in group 2.

The average triplicate size distribution measurement of the coal dust in the chamber had an MMAD of 3.91 µm (RSD = 0.007) and a GSD of 2.58. This was comparable to the intermediate-sized Pittsburgh coal dust used in the accuracy determination of the prototype instrument [Volkwein et al. 2004].

Postmine Testing

Postmine testing accuracy verification data in Table 3 show the average mass of dust from the triplicate BGI–4CP samplers for each test-time interval, the corresponding individual PDM mass measurements, and the RSD of both samplers. The overall average gravimetric reference sampling RSD for this work was 0.039 for the first group of tests and 0.049 for the second group. The PDM units' RSD for each test-time interval is indicated. The average RSD for these measurements was 0.056 for the first group of tests and 0.051 for the second group. The average size distribution of the coal dust for postmine testing had an MMAD of 4.01 µm (RSD = 0.079) and a GSD of 2.53.

Table 3.—Postmine laboratory data of reference mass measurements and PDM mass measurements

Time interval	Gravimetric avg. mass, mg	RSD	PDM mass by serial number													RSD
			102	108	112	113	114	115	119	120	123	124	125	127	128	
			mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	
1	0.425	0.026	(1)	0.373	0.445	0.397	0.359	0.386	(1)	0.410	0.404	0.405	0.429	0.418	0.388	0.058
2	0.960	0.030	(1)	0.817	0.953	0.861	0.788	0.832	(1)	0.895	0.880	0.885	0.932	0.892	0.850	0.053
3	1.475	0.065	(1)	1.281	1.463	1.344	1.220	1.278	(1)	1.368	1.369	1.365	1.438	1.373	1.328	0.048
4	1.950	0.029	(1)	1.717	1.955	1.794	1.629	1.720	(1)	1.827	1.833	1.833	1.923	1.822	1.777	0.046
5	1.012	0.049	0.885	0.875	0.995	0.890	0.824	0.865	0.931	0.982	0.946	0.931	1.010	0.947	0.924	0.064
6	1.931	0.038	1.759	1.741	1.972	1.764	1.638	1.740	1.859	1.947	1.870	1.843	1.995	1.891	1.833	0.061
7	2.899	0.033	2.639	2.608	2.958	2.656	2.460	2.627	2.789	2.919	2.809	2.763	2.981	2.827	2.751	0.060
8	3.906	0.038	3.576	3.512	3.997	3.601	3.329	3.566	3.757	3.938	3.801	3.741	4.011	3.821	3.730	0.058
9	0.209	0.048	0.185	0.173	0.202	0.189	0.162	0.179	0.193	0.197	0.191	0.190	0.184	0.193	0.189	0.061
10	0.709	0.047	0.669	0.621	0.692	0.652	0.585	0.647	0.673	0.701	0.707	0.689	0.661	0.675	0.658	0.054
11	1.738	0.042	1.601	1.506	1.672	1.568	1.420	1.560	1.620	1.667	1.714	1.647	1.580	1.628	1.591	0.052
12	2.114	0.028	1.874	1.772	1.963	1.848	1.664	1.836	1.907	1.964	2.000	1.940	1.856	1.913	1.865	0.051
Average gravimetric RSD		0.039											Average PDM RSD			0.056

Time interval	Gravimetric avg. mass, mg	RSD	PDM mass by serial number														RSD
			105	109	110	111	116	122	126	130	131	132	133	135	102	119	
			mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	
1	0.395	0.044	0.361	0.355	0.353	0.323	0.378	0.385	0.371	0.367	0.329	0.342	0.336	0.353	0.363	0.378	0.053
2	0.962	0.062	0.831	0.800	0.786	0.728	0.843	0.869	0.823	0.817	0.758	0.771	0.752	0.786	0.830	0.864	0.053
3	1.425	0.007	1.283	1.228	1.205	1.128	1.313	1.340	1.276	1.272	1.173	1.188	1.169	1.226	1.275	1.328	0.052
4	2.096	0.040	1.854	1.758	1.734	1.617	1.890	1.936	1.838	1.829	1.690	1.719	1.671	1.766	1.837	1.913	0.054
5	1.031	0.029	0.912	0.850	0.844	0.795	0.940	0.931	0.900	0.895	0.889	0.852	0.854	0.888			0.047
6	2.061	0.036	1.856	1.692	1.696	1.590	1.900	1.868	1.804	1.803	1.785	1.716	1.699	1.771			0.051
7	2.909	0.023	2.788	2.519	2.521	2.363	2.825	2.783	2.696	2.696	2.652	2.568	2.523	2.625			0.052
8	3.901	0.093	3.712	3.360	3.371	3.173	3.786	3.721	3.595	3.602	3.573	3.428	3.372	3.502			0.052
9	0.183	0.078	0.175	0.174	0.170	0.163	0.169	0.180	0.189	0.185	0.187	0.180	0.169	0.188			0.049
10	0.722	0.125	0.637	0.583	0.580	0.578	0.613	0.654	0.667	0.637	0.633	0.608	0.595	0.638			0.049
11	1.772	0.020	1.554	1.405	1.385	1.389	1.482	1.582	1.598	1.528	1.524	1.458	1.425	1.539			0.051
12	2.146	0.027	1.853	1.666	1.650	1.652	1.762	1.890	1.907	1.822	1.813	1.740	1.693	1.839			0.052
Average gravimetric RSD		0.049												Average PDM RSD			0.051

(1) Test run in group 2.

Accuracy

The premine test results support the thesis that design changes made between the prototype PDM–1 and the precommercial 3600 PDM did not affect the accuracy of the instrument. Results from the pre- and postmine calculation of accuracy, bias, precision, and 95% upper confidence limits (UCLs) are shown in Table 4. The bias results show that the PDM reads consistently less than the gravimetric reference mass measurement. Pretest bias, as received from TEC, was measured to be 5.2%. Despite the bias, high precision enables the point estimate of accuracy to meet the ±25% criterion. However, there were occasions for both the pre- and posttesting when the results failed to meet the 95% UCL that the PDMs are within ±25%. Failure of an instrument to meet the 95% UCL but to not exceed a 5% CL (failure to meet criterion) results in the decision that the accuracy determination for those samplers is inconclusive. Of particular note for the postmine testing was that bias values greater than –0.13 were associated with all instruments that did not meet the 95% UCL for reasons to be discussed.

Table 4.—PDM pre- and postmine lab accuracy calculations

PDM No.	Premine lab tests				Postmine lab tests			
	Bias	Precision	Accuracy	Upper 95% confidence limit	Bias	Precision	Accuracy	Upper 95% confidence limit
102	–0.04	0.05	12	18	–0.10	0.02	12	14
105	–0.08	0.07	18	26	–0.10	0.03	13	16
108	–0.09	0.05	16	21	–0.13	0.02	15	17
109	–0.05	0.06	14	20	–0.16	0.05	22	27
110	–0.06	0.03	11	15	–0.16	0.05	23	27
111	0.00	0.04	8	11	–0.20	0.04	25	28
112	–0.03	0.03	7	10	–0.01	0.03	5	8
113	–0.07	0.05	14	19	–0.09	0.01	10	11
114	–0.08	0.04	13	18	–0.18	0.02	20	22
115	–0.08	0.06	17	22	–0.11	0.02	14	15
116	0.00	0.04	7	11	–0.10	0.05	16	21
119	–0.02	0.05	10	15	–0.07	0.02	9	11
120	–0.06	0.04	12	16	–0.04	0.03	8	11
122	–0.04	0.05	11	16	–0.07	0.02	11	13
123	–0.01	0.03	7	10	–0.05	0.02	8	10
124	–0.10	0.04	16	20	–0.06	0.01	7	7
125	–0.01	0.07	14	21	–0.03	0.06	12	18
126	–0.06	0.03	10	14	–0.09	0.04	15	20
127	–0.06	0.05	14	20	–0.05	0.02	8	10
128	0.01	0.02	4	6	–0.08	0.02	11	12
130	–0.01	0.07	13	20	–0.11	0.04	17	21
131	–0.09	0.04	14	18	–0.13	0.07	22	28
132	–0.02	0.03	7	10	–0.15	0.05	22	26
133	–0.18	0.04	22	25	–0.17	0.04	22	25
135	–0.04	0.07	16	24	–0.12	0.05	19	24

Even though some of the units' postmine sampling accuracy results were inconclusive, the mean accuracy values of pre- and postmine testing are statistically equal. Results from an independent samples t-test show mean accuracy (premine) was 12.27 (95% CL = 10.52, 14.03) and postmine was 14.67 (95% CL = 12.21, 17.08) (t-value (df = 48) = –1.63, p-value = 0.11). The null hypothesis that the mean premine accuracy is equal to the mean postmine accuracy was not rejected.

One PDM failed to meet the 95% UCL of accuracy during the premine testing and was returned to the factory for examination and recalibration. We were unable to verify that the factory's recheck restored accuracy; consequently, this unit was not used for underground precision determination. However, the postmine verification testing showed that the sampler in question was within the accuracy criterion.

Calibration Constant *K*0

We investigated why some instruments did not meet the posttest 95% UCL. Table 5 presents the results of the laboratory measurement of the constant factor (*K*0) that the instrument uses to calculate mass from the change in frequency of the TE. The RSD of replicate measurements of *K*0 conducted with two of the instruments was 0.0038 and 0.0027.

Table 5.—Comparison of PDM measured *K*0 and programmed *K*0

Unit No.	Premine lab tests		Postmine lab tests		Measured *K*0	Programmed *K*0	*K*0 difference, %
	Accuracy, %	Upper 95% confidence limit	Accuracy, %	Upper 95% confidence limit			
119………..	10	15	9	10	15368	15427	–0.4
127………..	14	20	8	9	15138	15552	–2.7
112………..	7	10	5	8	15827	16028	–1.3
112………..	Rep	Rep	Rep	Rep	15719	16028	–2.0
112………..	Rep	Rep	Rep	Rep	15724	16028	–1.9
110………..	11	15	23	27	15166	15284	1.14
131………..	14	18	22	28	15138	14827	2.1
133………..	22	25	23	26	15107	14361	4.9
132………..	7	10	22	26	14534	13846	4.7
132………..	Rep	Rep	Rep	Rep	14537	13846	4.8
132………..	Rep	Rep	Rep	Rep	14466	13846	4.3

Rep Replicate *K*0 measurement.

We compared the *K*0 factor for units with higher and lower posttest accuracy. For three PDMs with lower or better UCL accuracy during the postmine testing, the programmed *K*0 was within 2.7% of the measured *K*0. However, for four of the PDMs that did not meet the postmine test UCL accuracy (i.e., higher), the difference in the measured *K*0 from programmed *K*0 showed a reduction by as much as 4.9%. Further investigation of the data file logs also indicate that, for some of the PDM units, the programmed *K*0 factor was changed by the factory between the pre- and posttesting when the units were returned for repair. Not all units needed this recalibration. However, any instrument that had a repair in the TE module (i.e., temperature sensing) may have required the *K*0 to be recalibrated. Because the constant is directly proportional to mass, this recalibration may be one reason why the postmine testing did not meet the 95% UCL for accuracy. Bias introduced by the calibration constant may cause some of the inaccuracy observed.

Limit of Detection and Quantification

The traditional limit of quantification (LOQ) [Marple and Rubow 1983] required determining the standard deviation of weighing (S_W) in nine consecutive weighings of a blank filter. Both balances were determined, coincidentally, to have an S_W of 1.4 µg and a resultant LOQ of 14 µg in a single weighing. However, quality control procedures involving control room filters used only in the balance room document that the total standard deviation (S_T) due to S_W and the cyclic fluctuations in weigh room conditions during the course of this study resulted in an S_T of 4.1 µg. Applying traditional formulas for propagation of error in the filter dust weight gains, we obtained

$$S_{\mathrm{filter}} = 2S_T = 8.2\ \mu g \tag{5}$$

The factor 2 results from the fact that there are four weighings required to determine the mass gain of the sample: the pre- and postweighing of both the sample and the control filter average. Similarly, for the calculations derived from the impactor, given that there are nine stages involving 36 weighings, we obtained

$$S_{\mathrm{impactor}} = 6S_T = 24.6\ \mu g \tag{6}$$

Battery Depletion Effects

There was no detectable effect on instrument accuracy, as batteries were intentionally run to failure. The frequency measurement by the TE was unaffected by small drops in battery voltage. Comparing the mass accumulation rate of an individual PDM with a corresponding TEOM 1400a, there was no change in the slope as batteries failed. The most significant effect measured as battery power failed was the decreased flow associated with the pump. Figure 5 shows that the flow diminished from full nominal flow rate of 2.2 L/min ± 5% to 0 L/min in less than 2 min. The resulting change in the cyclone classification as a result of the low flow condition represented about 0.3% of an 8-hr sample time. The data also showed that one instrument failed 518 min into the test. The battery charger cable to this instrument was faulty and was replaced prior to additional testing.

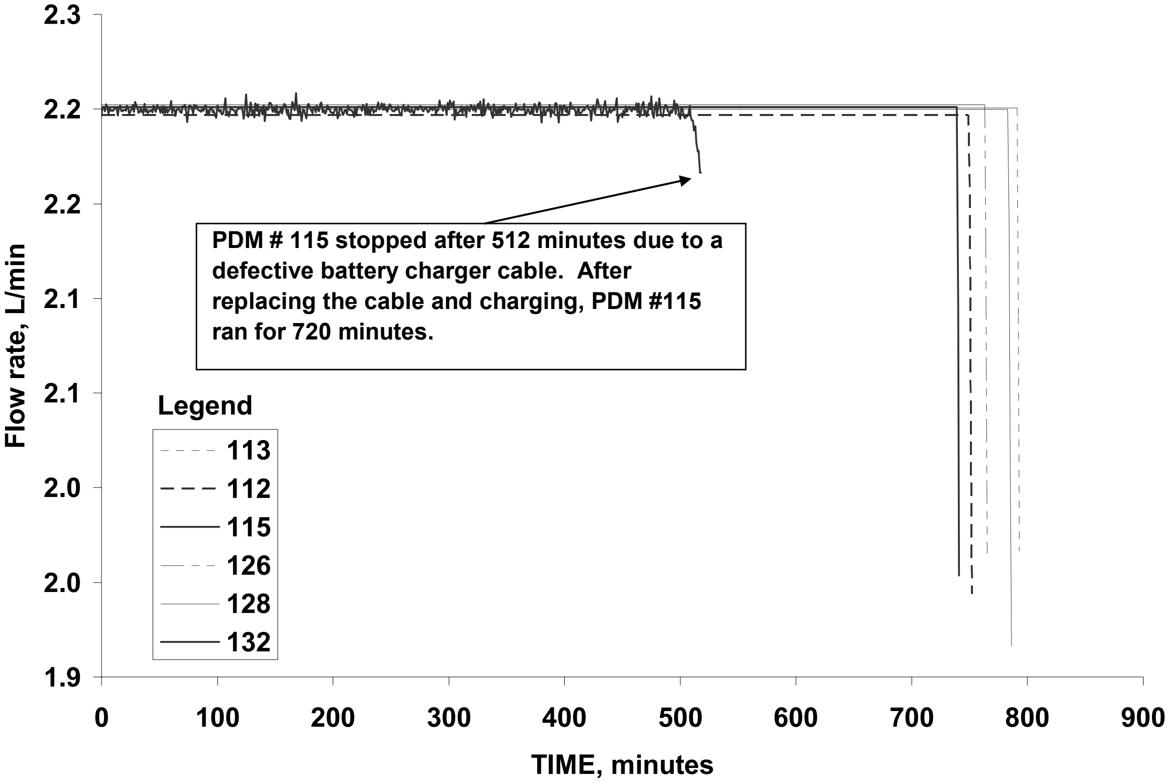


Figure 5.—Battery testing to failure using flow rate as an indicator.

Detailed In-mine Testing

Performance Over Project Duration

Testing was conducted from November 2004 to August 2005. Results in Table 6 show the total number of PDM samples taken in each of the MSHA districts sampled, the number of valid samples recorded, the percentage of valid samples, and a breakdown of whether NIOSH personnel were present or absent on the property. Valid concentration data for each occupation at each of the detailed mine sites are in Appendix A. The data were collected during typical mining operations, and data collection was not associated with any type of negative consequences for the mines. The data represent an overall performance rate of the software, electrical, mechanical, and physical subsystems of the PDM. At the first mine site, a significant error in the internal instrument software resulted in multiple errors and an instrument availability for valid data collection of 51%. All instruments were returned to the manufacturer for reprogramming. Subsequent testing proceeded with average instrument availability of 93%, ranging between 86% and 97%.

Table 6.—Total samples taken during detailed mine sampling and number of valid samples when NIOSH was present or absent from the mine property

MSHA district	NIOSH present			NIOSH absent			Total		
	No. samples	No. valid	% valid	No. samples	No. valid	% valid	No. samples	No. valid	% valid
DETAILED MINE TESTING									
9…………..	31	17	55	64	31	48	95	48	51
3…………..	30	29	97	37	33	89	67	62	92
4…………..	27	22	81	45	40	89	72	62	86
11…………	40	39	98	64	59	92	104	98	94
2…………..	36	34	94	60	53	88	96	87	91
10…………	35	35	100	68	63	93	103	96	93
6…………..	30	28	93				30	28	93
5…………..	33	32	97				33	32	97
8…………..	38	37	97				38	37	97
7…………..	23	22	96				23	22	96
EXTENDED MINE TESTING[1]									
2(1)……….				9	4	44	9	4	44
9(1)……….				22	20	91	22	20	91
2(2)……….				26	23	88	26	23	88
9(2)a……..				7	7	100	7	7	100
9(2)b……..				9	3	33	9	3	33

[1] For the extended mine testing within MSHA districts 2 and 9, each district had two companies ("1" and "2"). Within district 9, company 2 sampled at two mines ("a" and "b").

After testing at the sixth mine site, the percentage of valid samples with NIOSH present or absent showed little difference. NIOSH, in consultation with the PDM Partnership, concluded that the remaining detailed mine testing did not require the second week of testing, and the remaining detailed mine site testing was conducted for only the one week with NIOSH present. Testing concluded in May 2005, followed by a period of extended mine testing.

Extended Testing

A period of extended mine sampling was conducted from June to August 2005. Results of instrument availability in Table 6 are similar, but more variable than the previous detailed mine results. This was caused primarily by one PDM at mine 2(1) and another PDM at mine 9(2)b that failed for the entire trial periods, where mine staff were untrained to recognize such problems. Consequently, mine staff continued to run instruments that normally would not have been used. The problem with each instrument was, however, obvious when downloaded data files were examined.

Feedback from the miners using the PDM during the extended mine testing was consistent with the feedback received during the detailed mine testing, although not all mines provided written feedback to NIOSH. Comments from miners are in the "Discussion" section of this report.
A new issue raised during this testing was that the side entry of the power cord into the cap lamp was not compatible with the flip clip used on the personal air purifying respirators in use at one mine. The flip clip relies on the in-line tension of the cap lamp power cord to maintain the light position when the face shield is raised. The side entry of the PDM cap light creates an off-balance situation.

Maintenance Results

The 25 precommercial PDM instruments logged 10,926 hr of testing, of which 8,023 hr were conducted underground. The average logged use per instrument was 437 hr, with a maximum of 644 hr and a minimum of 246 hr. Hours of use varied based on the type of sampling for which each particular unit was used. The earliest repair episodes before the firmware upgrade were not counted in final PDM repair summaries, as they were regarded only as factory adjustments to the released product.

Table 7 presents the summary of PDM use and repair. Each PDM unit is listed with actual total hours and categorized repairs. Total repair rates and critical repair rates per 1,000 hr of projected instrument use are presented in the table. Data for individual PDMs are ordered first by best critical repair rate and next by best total repair rate. The 25 PDMs are divided into quintiles of 5 PDMs each, with best repair rates at the top of the table. Summary averages are recorded by quintile groups and also for the full set of all 25 PDMs.

Repair frequency varied among the precommercial PDMs. Those in the top two quintiles needed little service, while those in the bottom two quintiles required more repairs by the manufacturer. The bottom quintiles required both remedial and critical repairs, while the top quintiles only required repairs of a remedial nature. The PDM instruments in the top quintile averaged 506 hr of use without needing a critical repair. Their ultimate reliability could not be calculated because no critical repairs were required for them over the full timespan of the project.

Table 8 presents the summary of PDM run success rates for all PDM sampling. Each PDM unit is listed with its count of total runs and successful runs. An invalid run can be caused by human error, such as poor filter placement, in addition to a mechanical failure. Data are ordered by best success rate, with highest percentage rates at the top of the table. Data are again organized by quintile groups, with summary data for all 25 PDMs also recorded. The overall average success rate was 90.18% based on 1,202 total runs. The run success rates for the top two quintiles ranged from 92.42% to 100.00%. Data from Tables 7–8 are independent assessments of instrument reliability. Consequently, repair rates do not correspond to run success rates in part because of researcher intervention to prevent accumulation of unsuccessful samples. In addition, the causes of failed runs were often minor and readily correctable without manufacturer repair.

Table 7.—Summary of PDM use and repair by quintile

PDM No.	Total repairs	Remedial repairs	Critical repairs	Total hours run	Total repairs/ 1,000 hr	Critical repairs/ 1,000 hr
111	1	1	0	612.25	1.63	0.00
114	1	1	0	512.00	1.95	0.00
135	1	1	0	505.00	1.98	0.00
126	1	1	0	482.25	2.07	0.00
130	1	1	0	418.50	2.39	0.00
Means	1.00	1.00	0.00	506.00	2.01	0.00
125	1	1	0	392.50	2.55	0.00
124	1	1	0	390.75	2.56	0.00
115	1	1	0	315.25	3.17	0.00
116	2	2	0	581.25	3.44	0.00
127	1	1	0	246.00	4.07	0.00
Means	1.20	1.20	0.00	385.15	3.16	0.00
112	2	2	0	445.75	4.49	0.00
120	2	2	0	416.25	4.80	0.00
131	2	2	0	384.50	5.20	0.00
128	3	3	0	328.25	9.14	0.00
133	2	1	1	643.75	3.11	1.55
Means	2.20	2.00	0.20	443.70	5.35	0.31
102	2	1	1	581.00	3.44	1.72
122	3	2	1	515.25	5.82	1.94
123	2	1	1	408.25	4.90	2.45
105	2	1	1	406.00	4.93	2.46
113	3	2	1	399.25	7.51	2.50
Means	2.40	1.40	1.00	461.95	5.32	2.22
119	2	1	1	383.50	5.22	2.61
132	3	2	1	373.00	8.04	2.68
110	4	3	1	361.00	11.08	2.77
109	3	1	2	503.50	5.96	3.97
108	3	1	2	321.25	9.34	6.23
Means	3.00	1.60	1.40	388.45	7.93	3.65
Summary means	1.96	1.44	0.52	437.05	4.75	1.24

Table 8.—Overall success rate by quintile

PDM No.	Total count	No. valid	% valid
131	42	42	100.00
135	56	55	98.21
108	36	35	97.22
127	33	32	96.97
105	43	41	95.35
Mean			97.55
126	49	46	93.88
116	61	57	93.44
125	45	42	93.33
114	55	51	92.73
111	66	61	92.42
Mean			93.16
132	39	36	92.31
102	64	59	92.19
112	51	47	92.16
128	33	30	90.91
119	39	35	89.74
Mean			91.46
123	47	42	89.36
122	56	50	89.29
115	42	37	88.10
133	70	61	87.14
109	54	47	87.04
Mean			88.18
130	46	40	86.96
110	37	31	83.78
120	46	38	82.61
124	45	36	80.00
113	47	33	70.21
Mean			80.71
Total	1,202	1,084	
Mean			90.18

Underground Precision

Statistical results from the ANOVA in Table 9 show RSDs of the instruments in the Lippmann chamber used in the detailed mine sampling. All data used in this analysis are in Appendix B. The PDM had an RSD of 0.078 with a 95% CL of 0.066–0.095. Kissell and Sacks [2002] state that for normally distributed data, a 25% accuracy criterion is met with an RSD of 0.125 or less. The CMDPSU at a flow rate of 2.0 L/min had an RSD of 0.052, which can be compared to previous work by Kogut et al. [1997] where an RSD of 0.046 was determined for the same sampler at weight gains of greater than 0.5 mg/m^3. The higher RSD of 0.082 for the CMDPSU at a flow rate of 1.7 L/min is caused by a few influential samples that looked anomalous, but had no physical reason to be excluded from the data set.

Table 9.—Field precision results

Instrument	No. of samples	RSD	95% CL
PDM	88	0.078	.066–.095
CMDPSU: 2.0-L/min flow rate	89	0.052	.044–.063
CMDPSU: 1.7-L/min flow rate	90	0.083	.070–.101

DISCUSSION

Instrument Bias

Mass measurement is determined by the PDM using first principles of physics according to equation 1. Theoretically, therefore, we would expect mass measurement based upon this to be unbiased. However, with many electronic instruments we can measure a systematic discrepancy between the mean of the distribution of measurements and the true mass being measured. This bias was determined for the PDM and, according to Bartley et al. [2003], a bias correction can be made and the expanded uncertainty and accuracy limit can be equivalent to the original determinations. Adding a bias correction to the PDM mass measurement will further improve the accuracy of the instrument.

At the outset of this work, certain technical tradeoffs were made to make the measurement of coal mine dust exposure both functional and accurate. One acknowledged tradeoff is the loss of respirable dust in the tube from the cap light to the cyclone. This source of loss was minimized through the use of conductive tubing, which minimized electrostatic losses, and by the use of an optimized transport velocity. Peters and Volkwein [2003] calculated and measured this loss to be about 2% of the total respirable fraction. Another source of particle loss may occur in the heater between the cyclone and PDM filter. This has not been quantified directly, but is a part of the overall measurement of bias. The measured bias of the PDM is negative and thus consistent with the physical loss of a small amount of particulate mass in the transition zone between the cyclone and filter. This loss will be variable depending on the respirable size distribution of the dust. Results from both the laboratory and the detailed testing in this work indicate that various particulate losses within the PDM are trivial. The technical tradeoffs made to create a more functional instrument have had a minimal impact on instrument comparison to established sampling techniques.

The cause of the increase in the bias of the postmine accuracy verification testing may have arisen from three separate or combined sources. The first is the $K0$ calibration value differences. These are associated with high bias values of some but not all of the instruments. Secondly, the manufacturer discovered that the gasket between the cyclone and PDM could expand (creep) into the airway area, disrupting the flow and likely causing particulate loss. Finally, it was observed in one of the units that did not meet the 95% UCL that a sealant had contaminated the conical cyclone outlet, which would contribute to the creation of turbulence and particulate loss. Regardless of the cause, periodic calibration, inspection, and cleaning of the instrument are advisable.

Precision

It has been suggested that the field precision of the PDM should be adjusted to account for instruments that may be delivered from the manufacturer that did not meet the initial NIOSH accuracy criterion. The logic for this adjustment is that most users would be unable to detect such flaws and that this would actually be a contributing factor in the precision calculation. The adjusted RSD would be calculated from

$$RSD_{new} = \left(RSD_{field} + \frac{n_{fail}}{100 n_{total}} \left(\frac{RSD_{field}}{RSD_{lab}} \right) \right) \tag{7}$$

Only one PDM failed to meet the initial 95% UCL accuracy criterion. The high precision of the lab measurements results in a small change of field precision from 0.0780 to 0.0786. Furthermore, these first instruments were in the precommercial stage of production, and one might expect the manufacturer's quality control to improve with experience, further reducing this impact on the field precision. Therefore, the suggestion that field precision be adjusted is not merited.

Training and Comments

Training sessions on how to use the PDM at each mine were 30–45 min long. This training was important not only to ensure that miners knew how to use the PDM, but also to offer the opportunity for NIOSH to address miners' concerns and objections. Miners were encouraged to provide their opinions and feedback on their experience with the PDM.

A key feature of the PDM is that it be suitable for use by miners. In addition, miners for the first time have a timely way of accurately knowing the dust levels in their work environment. During the course of the study, NIOSH had an opportunity to informally listen to miners' opinions about the PDMs while they were wearing and working with the units. This part of the discussion relates anecdotes recorded by the researchers during the testing. The initial reaction to the PDM during the introduction and training session of the detailed mine visits was one of skepticism and doubt about the size, weight, cap light, and overall benefit of the instrument. By the end of the detailed mine testing, most miners felt that they would prefer their dust monitoring to be done with the PDM mainly because it did not interfere with their work in the way the current sampler does.

The reaction of miners varied from total disinterest, where they treated the PDM just like their cap lamp, to active involvement, where they were correlating what they were doing with what the instrument was telling them. One miner operator said that he glanced at the display after every shuttle car of coal. The data from the PDM offered some surprises to the miners. Some roof bolters expressed surprise that they were "getting dust when they could not see it." A rock duster said he was surprised that his levels were so low when conditions appeared particularly dusty. Most of the miners who paid attention to the PDM thought it was a useful tool. One foreman used the results of the shuttle car operators to vary the haulage routes to minimize exposures.

There were several comments that the curved design of the PDM offsets the slight increase in the weight of the unit over the weight of the lead-acid cap lamp batteries currently used by all of the mines in these trials. One complaint, particularly by the mechanics, was that the PDM was bulkier than the lead-acid batteries and that there was less room for tools on the belt. Miners commented that the quality and brightness of the cap lamp was good, but many did not like the nonfocusable lens system, particularly if the light was not focused correctly. Miners generally preferred the old-style, full-size backup bulb in the cap light over the white light-emitting diode (LED) lamp in the PDM. One mine suggested that the LED bulb should be green to help see in smoke. Unlike feedback during the prototype testing, there were few complaints about the noise of the pump. Workers in outby areas were more likely to comment about the noise than face workers. Noise was more noticeable during dinner break, but not objectionable. The pump outlet that produces most of the noise is highly directional and easily muffled with a coat without affecting the flow. Frequent complaints were made that the cap lamp cord was too long. The longer-length cord was selected for these trials to ensure that the length would accommodate the largest miners. In fact, when shorter cords were installed for the extended mine testing, complaints resulted that the cords were too short. Cord length of production units should be easily exchangeable. Another complaint about the cords was that they were stiff and chafed the necks of miners in warmer mines.

Screen Presentation of Data

The data display screens, shown in Figure 6, show the miner his or her exposure data in different formats. Miners responded differently to this information. Some found value in the graphic format; others preferred one of the numeric formats. The nomenclature used to describe of each of the numeric formats caused confusion. Based on observations in this testing, the cumulative concentration (CUM0), which is mathematically the mass divided by volume sampled to this point in time, becomes a good predictor of the EOS concentration about midway through the shift, provided that conditions do not change. On the other hand, the projected concentration (PROJ), which is mathematically the mass divided by the volume to be sampled for the entire shift, is not a direct estimate of a miner's EOS concentration. Perhaps a better name for this value is "limit concentration." Regardless of the name, the worth of the "PROJ" value is that it will not fluctuate with changes in the concentration; rather, it steadily progresses to the true EOS concentration. If CUM0 exceeds the permissible exposure limit (PEL), steps can be taken to reduce the exposure to stay within the PEL before the EOS. Once the limit (PROJ) is exceeded, it becomes impossible to meet the PEL. Despite the apparent confusion in nomenclature, miners watching the screens quickly learned to identify the meaning of the various formats in relation to their activities.

Figure 6.—Basic PDM screen display formats and information presented. ***Left:*** **graphic format;** ***right:*** **numeric format.**

Performance Issues

During mine testing, small engineering and operational issues occurred that may have affected the availability of the instrument for use or were reported as a nuisance by the miners. Table 10 reports those issues and steps taken to resolve them. As with any new system, especially those used by miners in the challenging underground environment, operational issues such as these will only be discovered through use of the device. The introduction of the currently used CMDPSU into the mining industry underwent several years of issue discovery and problem-solving until the technology matured. The testings of the prototype and the current precommercial PDM have probably not identified all of the possible issues with this new technology, but hopefully have helped shorten the time in which full maturity will be reached.

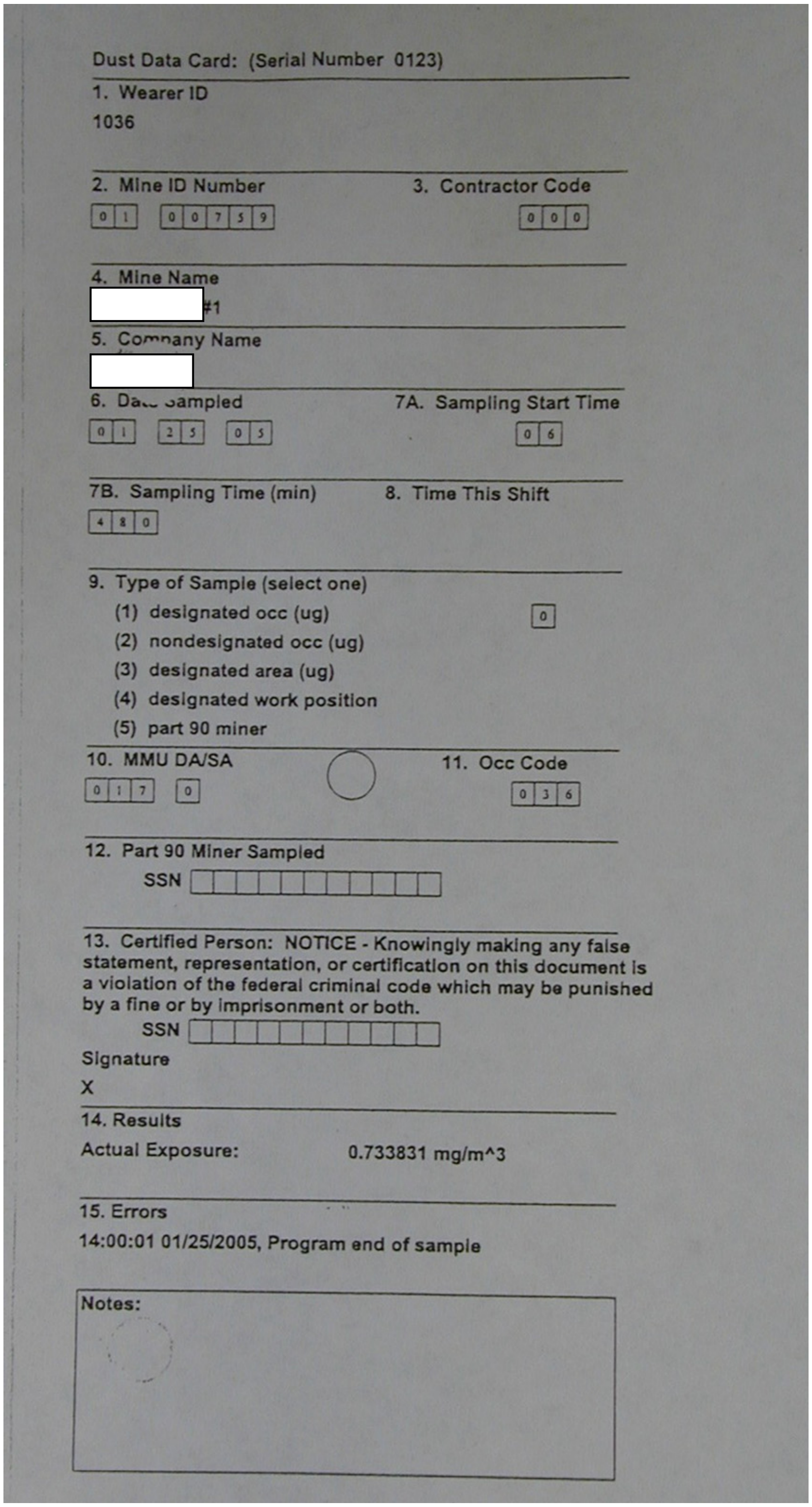
Table 10.—PDM performance issues and comments

Performance issue	Comments
Control of TE temperature	Resolder connection of temperature sensor; heater was OK.
Display malfunction	Poor quality control from supplier; hired new supplier – replaced all keypads or fuses.
Button malfunction	Part of display assembly replaced.
PDM failed to communicate to computer	Software/firmware bug fixed by TEC after first mine trial.
Battery failure	Replaced battery.
Premature cap lamp bulb failure	Reengineer filament thickness. Resubmit for MSHA approval.
Flat line in data file	Intermittent problem; unresolved – possible incorrect filter placement.
Low power	Associated with charging problems; bad battery cell or insufficient charging.
Charger problem, contacts give false indication of charge status.	Clean contacts, design contacts to be self-cleaning. Improve charger-sensing firmware.
High filter load at start of test	Incorrect filter placement.
Broken cyclone inlet	Add better strain relief at inlet.
Cut tube at cyclone inlet	Add better strain relief at inlet.
Bad focus on cap lamp	Reshim bulb; instruct technician on focus procedures.
TE not detected	Design tighter TE connection.
Failed leak checks	Connection between cyclone and PDM leaks; resealed with silicone grease, needs redesign.
Incompatible with new remote controls	TEC to redesign power output cable of PDM to remote to be compatible with new devices.
Cable to cap lamp too long or too short	TEC to offer alternative lengths or be capable to field retrofit.

Data Files

Download

When WinPDM software is used to download data from the PDM to the computer, several options are available to the user. The first option is to print a "dust data card" (Figure 7), which looks similar to the currently used dust data card, but contains the final EOS exposure of the instrument and any error codes recorded by the instrument. In this case, the actual exposure was 0.73 mg/m^3. The instrument currently reports how each sample was terminated in the error code field. In this example, a normal "Program end of sample" message appears in the error code field. Since normal termination of a sample is not an error, this message is inappropriate for that field. The next option during downloading is to visually examine graphs of various parameters such as concentration, mass, flow, pressure, or tilt versus time. This option was not frequently used in this testing, but was useful to provide a quick summary of the day's events. Finally, the data can be saved by the computer in a comma-separated version (.CSV) text file for archiving or more detailed examination using common spreadsheet software.



Dust Data Card: (Serial Number 0123)

1. Wearer ID
1036

2. Mine ID Number
0 1   0 0 7 5 9

3. Contractor Code
0 0 0

4. Mine Name
[redacted] #1

5. Company Name
[redacted]

6. Date Sampled
0 1   2 5   0 5

7A. Sampling Start Time
0 6

7B. Sampling Time (min)
4 8 0

8. Time This Shift

9. Type of Sample (select one)
(1) designated occ (ug)
(2) nondesignated occ (ug)
(3) designated area (ug)
(4) designated work position
(5) part 90 miner
0

10. MMU DA/SA
0 1 7   0

11. Occ Code
0 3 6

12. Part 90 Miner Sampled
SSN ☐☐☐☐☐☐☐☐☐☐☐

13. Certified Person: NOTICE - Knowingly making any false statement, representation, or certification on this document is a violation of the federal criminal code which may be punished by a fine or by imprisonment or both.
SSN ☐☐☐☐☐☐☐☐☐☐☐
Signature
X

14. Results
Actual Exposure: 0.733831 mg/m^3

15. Errors
14:00:01 01/25/2005, Program end of sample

Notes:

Figure 7.—Example of data printout. (MMU = mining machine unit. DA = designated area. SA = surface area.)

Interpretation

Data graphs can be constructed from the text files. Figure 8 shows the results of a plot of the data created from a saved file associated with the dust data card from Figure 7. These data illustrate the effect of a short-term dust spike at 9:00 on the cumulative and projected dust concentrations. The cumulative concentration decreases after the spike, but the projected concentration continues to increase. At the end of the shift, the cumulative and projected concentrations are equal.

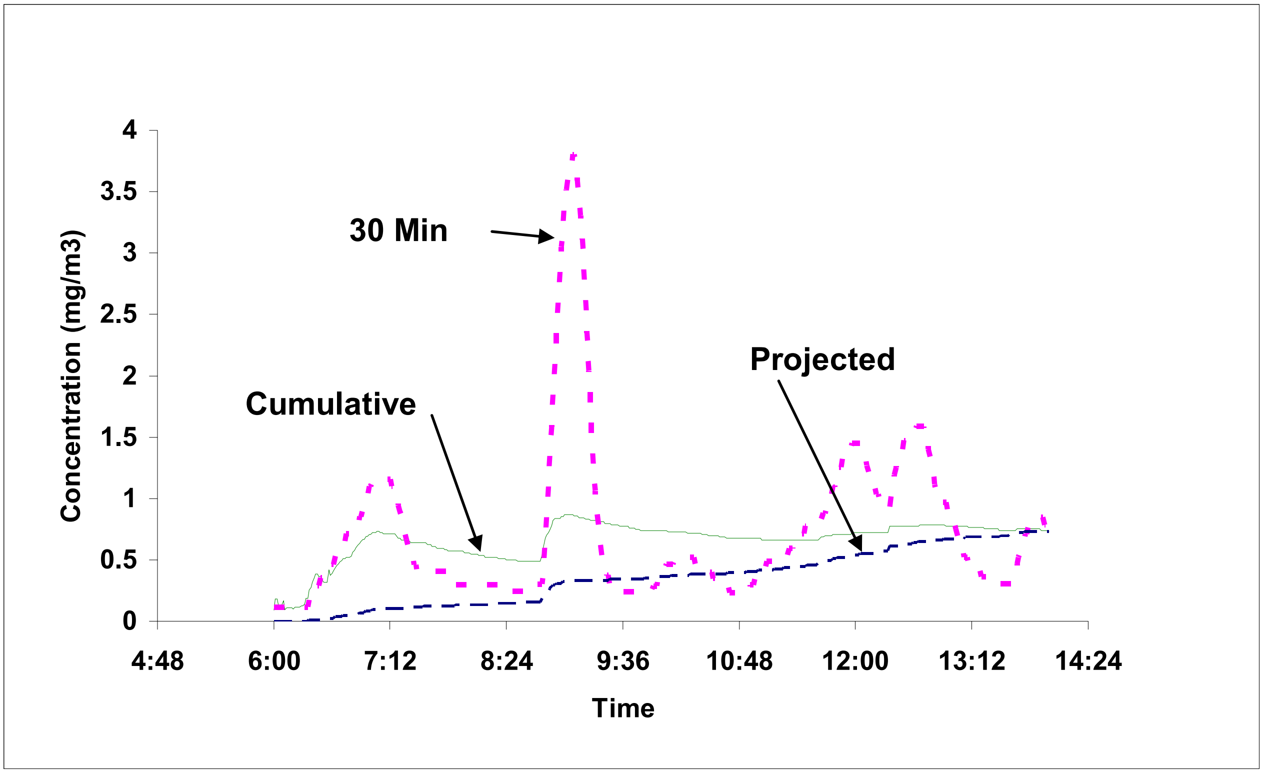


Figure 8.—Detail of results from sample shown in Figure 7.

Error Codes

Meaning and Interpretation

The PDM automatically senses and has the capability to report many useful instrument and environmental parameters. These parameters may be selected by the factory or authorized user and can be stored in memory with the frequency or change interval desired. TEC provides a basic template or digital file of instrument-controlling parameter settings, in addition to a diagnostic template for troubleshooting the device. Templates may be configured to report error flags at various sensitivities and time intervals.

Distinguishing Valid Data

How these error code parameters are set to distinguish valid from invalid samples is an important question. The criteria for selecting the validity of a sample will ultimately lie with the end use of the instrument. A difference between the prototype and precommercial PDM was the way in which errors were determined. The original thinking to distinguish sample validity was to use the tilt sensor to determine if the instrument was inverted and if this action dislodged oversize particles from the cyclone grit pot onto the mass sensor (a rare occurrence based on the data in Appendix C). Prototype results indicated that this was not a reliable method since it gave frequent false indications. In addition to being nonrespirable, oversize particles invalidate a sample under the current system because they result in an excessive, instantaneous mass increase to the filter. As an alternative to using the tilt function, a new algorithm was written for the precommercial PDM in which the rate of filter mass increase would result in a mass offset (MO) error being reported. Thus, the result of the tilt event—oversize particles changing the mass on the filter—rather than the event itself becomes the reason for invalidating a sample.

In this testing, the MO sensitivity settings were initially set to report an error when the mass loading increased by 50 µg over a 2-min time interval. At this setting, MO errors were frequently reported when in fact valid data were being recorded, such as when entering a return airway. This setting was changed after the second mine trial to only report errors when a level of 100 µg over a 1-min time interval was sensed. This change greatly reduced the frequency of MO errors. However, valid data were still being reported as an error, and an even higher mass loading setting is probably warranted.

In addition, when the sample inlet tube is pinched closed, the resulting sudden decrease in pressure in the TE environment is sensed and is reported as a rapid change in mass, resulting in an MO error. This is evident in Figure 9 where the differential pressure and mass are plotted. Note that when the pinch is relieved, the mass returns to the original level so that the EOS concentration measurement is unaffected by the event. Also note that these pinch events may momentarily reduce the flow rate of the instrument. With this information, the manufacturer should be able to refine the MO algorithm to ignore events when a downward pressure spike occurs. If the resulting pinch continues for 2 min, a flow error will occur and the sample may be invalidated for that reason. Similarly, the algorithm could be refined such that if an MO event occurs in conjunction with a tilt event, then a tilt error could be recorded as the reason to invalidate a sample.

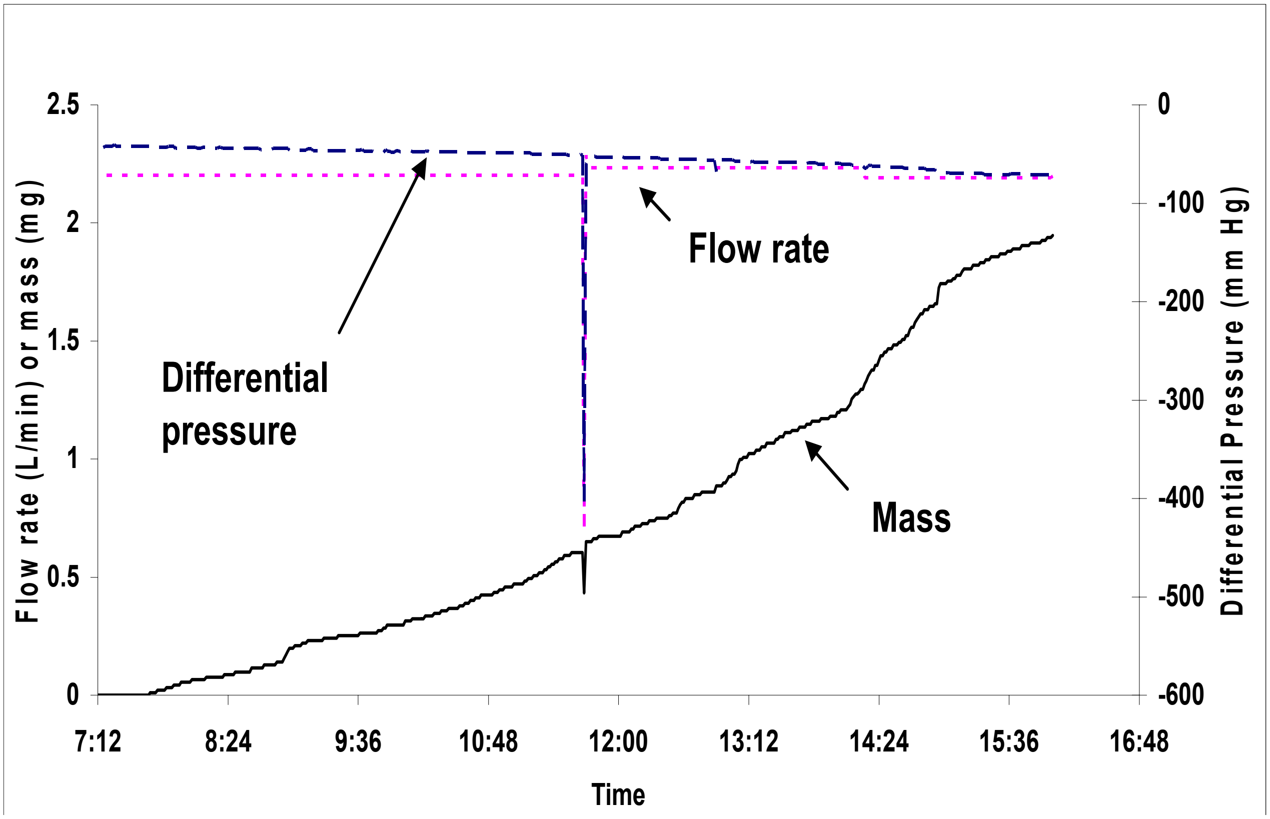


Figure 9.—Mass offset "error" resulting from pinched tube and subsequent recovery of correct mass measurements.

MSHA currently uses a system of void codes to detect events such as those just mentioned. Analysis of MSHA data (Appendix C) for the 10-year period from 1994 to 2004 shows conventional filter sampling success (nonvoid) rates for inspector and operator samples of 92.3% and 83.1% on total samples of 381,335 and 487,713, respectively. Based on the type of void rates and the expanded capabilities of the PDM, we estimate that about half of the MSHA voided samples could have been valid samples using PDM technology.

Maintenance

Ongoing refinements to instrument design make remedial type of service, required in this study, less likely for future manufactured instruments. It is reasonable to expect that further refinements to design and manufacturing quality will ultimately cause all PDM units to perform in a manner consistent with the higher quintiles of these preproduction units once all issues related to minor design remediation and manufacturing practice are addressed.

Calibration

Flow

PDM flow rates did not require frequent calibration. The initial flow calibration of each PDM occurred in late fall of 2004, when all units were returned to the manufacturer for firmware upgrades. Hours logged before this calibration are not included in this analysis. Recalibrations and hours logged are counted from the firmware upgrade service date onward. Two error standards for flow variance from the 2.2-L/min nominal flow rate were maintained for this testing. A ±1% standard was used for laboratory and precision testing, and a ±5% standard was used for the other detailed mine testing because this is the current allowable variance for CMDPSU sampling. Table 11 shows the calibration, flow error, and hours-logged histories for the 10 PDMs with complete flow calibration histories. Each PDM has an initial manufacturer flow calibration. A few units also experienced subsequent researcher recalibration of flow. Only one PDM required recalibration to maintain ±5% flow rate. Three PDMs were recalibrated to meet the more stringent ±1% calibration requirement for the research portion of the testing. A total of 3,354 hr were logged for the 10 units compiled in the table.

Table 11.—Flow calibration history

PDM No.	1%–5% flow recalibration	>5% flow recalibration	Total hr run
111	0	0	459.25
114	0	0	455.50
135	0	0	392.25
126	0	0	321.75
130	0	0	299.75
125	0	0	339.25
124	0	1	264.50
115	1	0	204.25
116	0	0	419.75
127	2	0	197.75
Totals	3	1	3,354.00
Hours per calibration to maintain ±1% flow			239.57
Hours per calibration to maintain ±5% flow			838.50

Currently, MSHA inspectors and mine operators calibrate flows for personal sampling pumps after each 200 hr of use. Although Table 11 cannot indicate a definitive timespan for scheduling periodic instrument flow calibrations, it does provide a reasonable range. For the 10 PDMs examined, approximately 240 hr occurred per calibration to meet a ±1% criterion and approximately 840 hr occurred per calibration to meet a ±5% criterion. Based on this information, flow calibration should occur between 240–840 hr. PDM flow stability is at least as reliable as current pumps and should not require more frequent calibration than current operator sampling procedures.

Mass

Routine laboratory measurement of mass requires that the balances be periodically calibrated to ensure the validity of the measurement. The PDM will likewise need to be periodically audited to ensure its legitimacy. The change in bias with use observed in this testing suggests that the calibration be done on a periodic basis; however, there are insufficient data to determine the calibration period. If a simple audit procedure can be implemented, it makes sense to perform this calibration check at the same time that the flow rates are checked. As more experience with the PDM is gained, this time period for checking mass calibration could be revised.

CONCLUSION

An accurate direct-reading dust monitor for use in coal mines has been demonstrated in laboratory and underground coal mine environments. Through a protocol developed by a partnership of labor, government, and industry, this work verified that the PDM laboratory accuracy met the criterion with 95% confidence that individual PDM measurements were within ±25% of the reference measurements. In addition, accuracy after an extended period of mine use did not differ from the initial accuracy measurements. However, some individual units did exceed the 95% UCL after testing, and a shift in the bias of the instrument was a suspected cause. This leads to the recommendation that a periodic calibration check of the instrument mass measurement be considered in the operating procedures.

Mine testing of the PDM, when worn by miners during normal work, demonstrated durable performance with about a 90% availability rate, which is similar to existing dust sampling devices. Many miners commented that they would prefer to use the PDM over the current sampler for dust measurements because of the integration of the sampler into the cap lamp that they normally wear. They further appreciated the immediate feedback of the screen-displayed exposure information. Some miners quickly learned to use the information to take action to minimize their exposures.

Mine data demonstrated that the precision of the PDM operating in coal mines had an RSD of 0.078. The final demonstration of equivalency to the MRE standard will be the subject of a subsequent publication.

Future work includes how miners might make use of the data from the PDM to actually lower exposures. A study will be conducted to document how miners make use of the new dust exposure information they receive from their PDMs. Structured interviews will be conducted with approximately 50 miners representing each major category of underground mining job. Effective strategies for using PDM information will be documented, published, and shared throughout the coal industry. Although data were collected to measure the equivalency of the PDM to the MRE, as required by U.S. law, the analysis of these data was more complex than originally anticipated because the variance with increasing concentration required use of a more sophisticated statistical model than originally planned. Another publication containing a detailed analysis comparing the PDM samplers used in this work to MRE and ISO standards is in progress.

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APPENDIX A.—DETAILED MINE PDM CONCENTRATION DATA

MSHA DISTRICT 9

	Occupation and MSHA code												
Date	Shearer 64	Mechanic 4	Shearer 64	Shift foreman 49	Faceman 41	Faceman 41	Faceman 41	Faceman 41	Mechanic 4	Headgate 40	Dust sampler 414	Fixed return 61	Fixed return 61
Nov. 2		2.51	1.87	1.37	0.73	0.62	1.72	1.68					
Nov. 3	2.03	1.81	2.17	0.61	2.24	2.8		2.73		1.62			
Nov. 4	0.87	1.75	0.47	0.57	1.32	1.24	0.976	1.74	1.48				
Nov. 5[1]	0.44	0.28			0.59		0.37	0.57		0.32	0.23	0.23	0.64
Nov. 6[1]	0.25		0.12			0.17		0.15		0.17			
Nov. 7[1]	0.82				0.99	0.66				0.86			
Nov. 8	0.92	0.48	0.8		0.91	1.35	0.77						
Nov. 9		1.6	2.35		3.35	3.41	3.19	3.13					
Nov. 10	2.42				2.68								
Nov. 11			0.91		1.52	1.37	1.47						

[1] No production.

MSHA DISTRICT 3

	Occupation and MSHA code									
Date	Miner operator 36	Tube side bolter 48	Intake side bolter 19	Loader operator 43	Standard shuttle car 50	Off-standard shuttle car 73	Mechanic 4	Foreman 430	Center bolter 46	Center bolt helper 47
Dec. 14	0.38	0.69	0.31	1.09	0.26	0.37	0.35	0.5	0.35	0.33
Dec. 15	0.55	0.49	0.54	0.41	0.28	0.33	0.32	0.93	0.6	0.46
Dec. 16	0.48	0.72	0.45	0.37	0.26	0.31	0.4		0.45	0.54
Dec. 17		0.37	0.31	0.35	0.35	0.33	0.36	0.4	0.92	
Dec. 20	0.69		0.57	0.44	0.33	0.36	0.4	0.48	0.07	
Dec. 21		0.32	0.39	0.27	0.24	0.3	0.19	0.72	0.87	
Dec. 22	0.31	0.41	0.4	0.24	0.24	0.19	0.23	0.66	([2])	

[2] Cyclone broken, but ran in office.

MSHA DISTRICT 4

	Occupation and MSHA code							
Date	Shearer head operator 064	Shearer tail operator 040	Mechanic 1 004	Mechanic 2 004	Jack setter 1 041	Jack setter 2 041	Utility 053	Foreman 049
Jan. 4	0.84	0.66	0.66	0.55	0.97	0.72	0.7	0.79
Jan. 5	1.41	1.07		0.69	1.4	1.29	1.3	
Jan. 6	1.52	1.53	0.57	0.8	1.58	1.69	1.07	1.2
Jan. 7	1.4	0.64	0.56	0.66	1.43	1.33	1.13	1.71
Jan. 10	1.47	1.53	1.36	0.85	1.54	1.51	1.27	1.63
Jan. 11	1.86	1.84	0.25	1.02	2.07	1.56	1.42	1.88
Jan. 12	0.85	0.75	0.59	0.13	1.01	0.97	0.96	0.77
Jan. 13	1.45	1.44	1.05	0.85	1.21	1.24	1.07	1.56

MSHA DISTRICT 11

	Occupation and MSHA code												
Date	Miner operator 36	Miner helper 35	Intake side bolter 12	Return side bolter 14	Ram car 2 50	Ram car 3 50	Ram car 4 50	Foreman 49	Scoop 54	Curtain 8	Bratticeman 32	Outby intake bolter 12	Outby return bolter 14
Jan. 25	0.73	0.85	0.9	1.26	0.57	0.46	0.58	0.86	0.92	1.09		1.3	
Jan. 26		1.23	0.65	0.9	1.17	0.98	1.16	1.23	0.67	0.58	0.66	0.54	0.52
Jan. 27	0.61	0.67	1.5	1.31	0.64	0.67	0.61	1.01	0.88	1.67	0.6	0.64	1.43
Jan. 28	0.58	0.95	0.51	0.43	0.7	0.6	0.58	0.39	0.7	0.41	0.64	0.22	0.21
Jan. 31	0.53	0.64	0.78	0.79	0.89	0.92	0.96	0.59	0.65	1.01		0.68	0.52
Feb. 1	0.5	0.78	1.06	1.05	0.32	0.27	0.36	0.66	0.45		0.36	0.56	0.69
Feb. 2	0.63	1.16	1.22	1.4	1.13	1.01		0.96		1.53		0.49	
Feb. 3	0.77	1.35	2.63	1.65	1.05	0.69	0.86	0.51	1	1.28			

MSHA DISTRICT 11—Continued

	Occupation			
Date	Guest	Beltman	Utility	Motorman
Jan. 25	0.88		0.84	
Jan. 26				
Jan. 27	0.48			
Jan. 28			0.46	
Jan. 31		0.33		
Feb. 1				
Feb. 2				0.57
Feb. 3				

MSHA DISTRICT 2

Date	Occupation and MSHA code											
	Standard shuttle car	Center bolter	Left return side bolter	Off-standard shuttle car	Outby utilityman	Center bolter helper	Mechanic	Miner operator	Foreman	Load machine operator	Right intake side bolter	Tubeman brattice
	50	46	14	73	53	47	4	36	49	43	12	32
Feb. 8	0.23	0.21	0.67	0.38	0.42	0.19		0.50	0.25	0.27	0.65	
Feb. 9	0.14	0.19	0.55	0.21	0.19	0.17	0.19	0.41	0.31	0.18	1.74	0.86
Feb. 10	0.42	0.4	0.78	0.25	0.48	0.24	0.31	0.42	0.31		0.89	0.73
Feb. 11	0.18	0.25		0.23	0.29	0.41	0.30	0.40	0.45	0.27	0.51	0.64
Feb. 14	0.22	0.20	0.79	0.16		0.24	0.21	0.43	0.29	0.22	0.66	0.55
Feb. 15	0.15	0.24	1.63	0.29		0.21	0.19	0.38	0.52		0.87	0.58
Feb. 16	0.24	0.26	0.82	0.42	0.04	0.26	0.34	0.39	0.42	0.63	0.93	0.96
Feb. 17	0.17	0.18	1.06	0.28		0.32		0.54	0.51	0.41	0.79	1.17

MSHA DISTRICT 10

Date	Occupation and MSHA code											
	Right miner operator	Left miner operator	Right bolt opposite operator	Right bolter operator	Left bolter opposite operator	Left bolter operator	Shuttle car 1	Shuttle car 2	Shuttle car 3	Shuttle car 4	Foreman	Mechanic
	36	36	12	14	12	14	50	50	50	50	49	4
Mar. 1	0.86	1.63	0.76	0.55	1.33	1.76	0.82	0.74	0.66	0.63	0.6	0.59
Mar. 2	1.12	1.23	1.1	0.98	1.34	0.99	0.75	0.75	0.72	0.67	0.69	0.57
Mar. 3	1.07	1.73	1.71	0.6	2.48	2.46	0.77	0.83	0.7	0.78	0.56	
Mar. 4	0.68	1.58	0.62	0.6	1.57	[3]2.45	0.85	0.97	0.79	0.86	0.52	1.35
Mar. 5	0.31	1.62	0.59	1.29	1.5	1.32	0.68	0.8		0.76	1.04	
Mar. 7		1.31	0.32	1.08		2.09	0.77	0.78	0.77	0.66	0.62	0.88
Mar. 8		1.64	0.73	0.92		1.32	0.74	0.89		0.8	0.78	0.89
Mar. 9	1.96	1.96	0.84	1		1.55	1.03	1.08	0.95	0.87	0.7	1.08
Mar. 10	0.67	1.64	0.7	[3]12.12		[3]6.32	0.75		0.76		0.53	1.11

[3] Data valid, voided for cause.

MSHA DISTRICT 6

Date	Occupation and MSHA code										
	Roof bolter operator	Left miner operator	Shuttle car	Electrician	Left bolter operator	Right miner operator	Shuttle car	Foreman	Left bolter	Shuttle car	Right miner operator
	12	36	50	2	14	36	50	49	12	50	36
Mar. 15	1.57	1.53	0.66	0.29	1.9	1.08	0.26	0.82	2	0.23	
Mar. 16	1.22	1.7	0.9	1.47	1.65		0.56	1.75	1.7	0.52	0.98
Mar. 17	1.14	1.6		0.52	1.68		0.34	0.71		0.33	1.16

MSHA DISTRICT 5

Date	Occupation[4]											
	#1 Bridge	Left bolter/ right side	Mechanic	#2 Bridge	Right bolter/ left side	MSHA	Scoop	Right bolter/ right side	#3 Bridge	Foreman	Left bolter/ left side	Miner operator
Mar. 29	1.42	1.25	0.63	0.58	1.19	1.31	NS	1.02	1.38	0.85	1.04	5.84
Mar. 30	0.34	1.62	1.48	0.87	3.43	NS	3.52	3.01	1.61	2.18	1.26	1.63
Mar. 31	0.32	0.72		0.5	1.17	NS	1.34	0.98	0.7	1.01	0.54	0.84

NS Not sampled. [4] MSHA code not available.

MSHA DISTRICT 8

Date	Occupation and MSHA code											
	Right miner operator	Left miner operator	Right intake side bolter	Right return side bolter	Left intake side bolter	Left return side bolter	Coal hauler 67	Coal hauler 69	Foreman	Utility	Mechanic	Mechanic
	36	36	12	14	12	14	50	50	49	53	4	4
Apr. 19	NS		1.61		0.95	2.92	1.64	1.6	1	1.19	1.37	1.05
Apr. 20	NS	1.46	1.75	2.72	1.58	2.52	1.08	1.09	1.68	0.96	0.5	0.54
Apr. 21	0.42	4.24	2.19	3.34	1.15	2.84	1.74	1.74	1.46	1.08	0.74	0.83

MSHA District 8—Continued

Date	Occupation and MSHA code	
	Safety	Coal hauler 66
		50
Apr. 19	0.72	1.6
Apr. 20	0.69	1.27
Apr. 21	NS	NS

NS Not sampled.

MSHA DISTRICT 7

Date	Occupation and MSHA code									
	Miner operator	Pinner operator	Standard shuttle car	Off-standard shuttle car	Electrician	Scoop	Foreman	NIOSH 1	NIOSH 2	MSHA
	36	12	50	73	2	54	49			
May 17	0.35	0.24	0.29	0.24	0.34	0.23	0.17	0.47		
May 18	1.27	0.32	0.3		0.58		0.25	0.29	0.963	0.7
May 19	1.01	0.6	0.26		0.28	2.67	0.27			

APPENDIX B.—DETAILED MINE LIPPMANN SAMPLER DATA

	PDM					Dorr-Oliver 2 L/min						MRE	Dorr-Oliver 1.7 L/min					Size distributions		
Date	PDM No.	Conc. mg/m^3	Avg. mg/m^3	Std. mg/m^3	RSD	Mass, mg	Time, min	Conc. mg/m^3	Avg. mg/m^3	Std. mg/m^3	RSD	equiv. conc. mg/m^3	Mass, mg	Conc. mg/m^3	Avg. mg/m^3	Std. mg/m^3	RSD	Inst. No.	MMAD	GSD
TWENTYMILE MINE, MSHA DISTRICT 9																				
Nov. 2	102	1.367				0.731		1.030					0.753	1.248				1	9.38	2.65
	122	1.475	1.397	0.068	0.049	0.750	355	1.056	1.046	0.014	0.013	1.443	0.711	1.178	1.228	0.044	0.036	2	9.35	2.51
	108	1.349				0.746		1.051					0.760	1.259				3	8.85	3.00
Nov. 3	102	1.630				0.787		1.234					0.788	1.453				4	10.00	2.99
	122	1.771	1.662	0.097	0.058	0.788	319	1.235	1.204	0.052	0.043	1.662	0.777	1.433	1.432	0.021	0.015	5	7.13	2.58
	108	1.586				0.730		1.144					0.765	1.411				6	8.27	2.59
Nov. 4	102	1.239				0.645		0.849					0.658	1.019				7	8.67	2.84
	122	1.307	1.215	0.106	0.087	0.664	380	0.874	0.842	0.036	0.043	1.161	0.667	1.033	1.010	0.027	0.027	8	7.48	2.57
	108	1.099				0.610		0.803					0.633	0.980				9	7.43	2.74
BLACKSVILLE MINE, MSHA DISTRICT 3																				
Dec. 14	115	0.365				0.059		0.271					0.062	0.335				7	8.68	2.34
	130	0.363	0.358	0.012	0.033	0.053	109	0.243	0.245	0.025	0.103	0.338	0.058	0.313	0.309	0.027	0.088	8	8.17	2.89
	135	0.344				0.048		0.220					0.052	0.281				9	8.19	3.06
Dec. 15	115	1.506				0.614		1.023					0.679	1.331				10	6.56	2.59
	130	1.602	1.479	0.137	0.093	PF	300		1.045	0.031	0.029	1.442	0.636	1.247	1.252	0.077	0.061	11	7.32	2.90
	135	1.331				0.640		1.067					0.601	1.178				14	7.26	2.39
Dec. 16	115	0.755				0.331		0.522					0.319	0.592				16	7.08	2.58
	130	0.826	0.764	0.058	0.076	0.342	317	0.539	0.515	0.029	0.057	0.710	0.314	0.583	0.622	0.060	0.096	17	7.53	2.57
	135	0.711				0.306		0.483					0.372	0.690				19	7.54	2.44
HARRIS MINE, MSHA DISTRICT 4																				
Jan. 4	115	2.655				0.954		2.129					0.866	2.273				1	5.49	2.83
	120	2.472	2.549	0.095	0.037	0.906	224	2.022	2.087	0.057	0.028	2.880	0.851	2.234	2.302	0.086	0.038	2	6.11	3.13
	135	2.519				0.946		2.111					0.914	2.399				3	5.34	3.02
Jan. 5	115	1.988				0.447		1.519					0.413	1.651				4	6.06	2.92
	120	2.151	2.051	0.088	0.043	0.444	147	1.509	1.481	0.058	0.039	2.043	0.413	1.651	1.687	0.062	0.037	5	6.13	2.87
	135	2.013				0.416		1.414					0.440	1.759				6	5.92	2.90
Jan. 6	115	1.812				0.517		1.520					0.451	1.559				7	5.96	2.90
	120	1.887	1.868	0.049	0.026	0.498	170	1.464	1.457	0.066	0.046	2.010	0.481	1.663	1.629	0.060	0.037	8	7.17	2.66
	135	1.905				0.472		1.387					0.481	1.663				25	6.24	3.27
PITTSBURG & MIDWAY MINE, MSHA DISTRICT 11																				
Jan. 25	115	2.129				0.745		1.816					0.699	2.005				1	7.10	3.21
	120	2.147	2.228	0.156	0.070	0.735	205	1.792	1.774	0.054	0.030	2.448	0.692	1.985	2.023	0.050	0.025	2	6.93	3.23
	127	2.407				0.703		1.714					0.725	2.079				3	6.03	3.18
Jan. 26	115	0.609				0.267		0.474					0.256	0.535				4	10.09	3.87
	120	0.599	0.626	0.038	0.061	0.264	281	0.469	0.461	0.019	0.042	0.636	0.262	0.548	0.546	0.011	0.019	5	9.21	3.23
	127	0.670				0.247		0.439					0.266	0.556				6	9.15	3.47
Jan. 27	115	1.732				0.761		1.435					0.700	1.553				7	6.67	3.29
	120	1.794	1.760	0.031	0.018	0.771	265	1.454	1.418	0.047	0.033	1.957	0.700	1.553	1.558	0.009	0.006	8	6.21	3.48
	127	1.754				0.724		1.365					0.707	1.569				25	6.08	3.32
EMERALD MINE, MSHA DISTRICT 2																				
Feb. 8	115	0.750				0.156		0.630					0.138	0.656				16	8.19	2.61
	120	FL	0.827	0.109	0.132	0.142	124	0.574	0.594	0.031	0.053	0.820	0.141	0.670	0.685	0.038	0.055	17	10.89	2.82
	127	0.904				0.143		0.578					0.153	0.727				18	10.68	2.44
Feb. 9	115	2.310				0.735		1.802					0.681	1.965				19	7.23	2.68
	120	2.300	2.373	0.118	0.050	0.749	204	1.837	1.779	0.073	0.041	2.454	0.708	2.042	2.017	0.045	0.022	20	7.25	2.89
	127	2.510				0.692		1.697					0.708	2.042				21	6.91	2.78
Feb. 10	115	0.660				0.213		0.539					0.204	0.607				22	11.44	3.20
	120	NF	0.710	0.071	0.100	0.217	198	0.549	0.529	0.027	0.051	0.729	0.213	0.634	0.631	0.022	0.036	23	13.15	3.16
	127	0.760				0.197		0.498					0.219	0.652				24	11.60	3.34
FREEDOM MINE, MSHA DISTRICT 10																				
Mar. 1	115	1.839				0.518		1.727					0.461	1.808				7	7.33	3.08
	124	1.879	1.861	0.020	0.011	0.486	150	1.620	1.659	0.059	0.036	2.289	0.476	1.867	1.841	0.030	0.016	8	9.02	3.62
	127	1.865				0.489		1.630					0.471	1.847				9	6.82	3.08
Mar. 2	115	1.255				0.554		1.045					0.269	0.597				10	5.44	2.84
	124	1.322	1.308	0.048	0.036	0.559	265	1.055	1.045	0.010	0.010	1.442	0.545	1.210	0.995	0.345	0.347	11	5.75	2.87
	127	1.347				0.548		1.034					0.531	1.179				12	5.40	2.97
Mar. 3	115	1.749				0.768		1.542					0.708	1.673				13	5.56	3.29
	124	1.770	1.800	0.072	0.040	0.768	249	1.542	1.524	0.031	0.021	2.103	0.735	1.736	1.693	0.038	0.022	14	6.02	3.26
	127	1.882				0.741		1.488					0.707	1.670				15	5.35	3.20

PF Pump failure.
FL PDM file data was a constant value.
NF Filter not installed.

Date	PDM					Dorr-Oliver 2 L/min						MRE equiv. conc. mg/m^3	Dorr-Oliver 1.7 L/min					Size distributions		
	PDM No.	Conc. mg/m^3	Avg. mg/m^3	Std. mg/m^3	RSD	Mass, mg	Time, min	Conc. mg/m^3	Avg. mg/m^3	Std. mg/m^3	RSD		Mass, mg	Conc. mg/m^3	Avg. mg/m^3	Std. mg/m^3	RSD	Inst. No.	MMAD	GSD
JOHN'S CREEK MINE, MSHA DISTRICT 6																				
Mar. 15	115	2.550				1.094		2.223					1.037	2.479				1	6.52	2.90
	124	2.704	2.683	0.124	0.046	1.040	246	2.113	2.162	0.056	0.026	2.983	0.988	2.362	2.445	0.072	0.030	2	6.27	3.01
	127	2.796				1.058		2.150					1.043	2.493				3	6.93	2.95
Mar. 16	115	3.955				0.874		3.610					0.815	3.960				4	5.14	3.74
	124	4.181	3.494	1.000	0.286	0.812	121	3.354	3.504	0.134	0.038	4.836	0.784	3.810	3.857	0.090	0.023	5	5.94	3.56
	127	2.347				0.859		3.548					0.782	3.800				6	6.37	3.46
Mar. 17	115	4.400				1.072		4.219					0.953	4.413				7	7.44	3.02
	124	4.534	4.631	0.292	0.063	0.982	127	3.865	4.009	0.186	0.046	5.533	0.967	4.477	4.476	0.063	0.014	8	9.85	3.46
	127	4.960				1.002		3.944					0.980	4.538				9	8.86	3.17
FORK RIDGE MINE, MSHA DISTRICT 5																				
Mar. 29	124	12.149				1.128		9.400					1.171	11.480				1	5.80	2.86
	127	13.241	12.370	0.785	0.063	1.141	60	9.508	9.578	0.221	0.023	13.217	1.125	11.029	11.261	0.226	0.020	18	5.66	2.67
	130	11.719				1.179		9.825					1.150	11.275				19	5.89	2.97
Mar. 30	124	3.633				0.810		3.045					0.759	3.357				20	4.12	2.66
	127	3.741	3.668	0.064	0.017	0.595	133	2.237	2.774	0.466	0.168	3.829	0.761	3.366	3.351	0.018	0.005	21	4.24	2.80
	130	3.629				0.809		3.041					0.753	3.330				22	4.19	2.95
Mar. 31	124	2.165				0.753		1.651					0.703	1.814				23	4.03	3.03
	127	2.287	2.184	0.094	0.043	0.804	228	1.763	1.722	0.062	0.036	2.377	0.632	1.631	1.786	0.144	0.081	24	4.40	3.15
	130	2.101				0.799		1.752					0.742	1.914				25	3.97	2.68
AIR QUALITY MINE, MSHA DISTRICT 8																				
Apr. 19	111	3.332				1.312		3.066					1.164	3.200				1	4.04	4.86
	114	3.188	3.241	0.079	0.024	1.246	214	2.912	3.012	0.087	0.029	4.157	1.149	3.159	3.179	0.021	0.006	2	3.71	4.63
	126	3.203				1.309		3.059					1.156	3.178				3	3.52	4.75
Apr. 20	111	4.549				1.114		4.253					0.949	4.263				4	3.89	3.90
	114	4.492	4.495	0.053	0.012	1.100	131	4.200	4.210	0.039	0.009	5.810	0.991	4.451	4.276	0.169	0.039	5	4.14	3.70
	126	4.443				1.094		4.177					0.916	4.115				6	3.56	3.49
Apr. 21	111	6.881				1.274		6.372					1.075	6.325				7	4.55	3.52
	114	6.779	6.748	0.151	0.022	1.218	100	6.092	6.095	0.275	0.045	8.411	1.124	6.614	6.525	0.174	0.027	8	3.95	3.46
	126	6.584				1.164		5.822					1.128	6.637				9	3.90	3.63
PANTHER MINE, MSHA DISTRICT 7																				
May 17	111	4.269				1.122		3.320					1.138	3.961				7	4.32	2.47
	114	4.218	4.274	0.058	0.014	1.151	169	3.405	3.409	0.092	0.027	4.705	1.129	3.930	3.909	0.065	0.017	8	4.36	2.86
	126	4.334				1.184		3.503					1.102	3.836				9		
May 18	111	6.529				1.399		5.032					1.437	6.081				10	4.35	2.89
	114	6.342	6.425	0.095	0.015	1.437	139	5.169	5.199	0.184	0.035	7.175	1.344	5.688	5.863	0.200	0.034	11	4.27	2.91
	126	6.405				1.500		5.396					1.375	5.819				12	4.52	2.29
May 19	111	2.594				0.741		2.047					0.709	2.304				13	5.91	3.02
	114	2.566	2.565	0.029	0.011	0.719	181	1.986	2.044	0.057	0.028	2.821	0.699	2.272	2.277	0.025	0.011	14		
	126	2.536				0.760		2.099					0.694	2.255				15	6.25	2.38

APPENDIX C.—ANALYSIS OF VOIDED RESPIRABLE COAL MINE DUST SAMPLES COLLECTED, 1995–2004

The causes for void samples in the table below include factors in addition to mechanical faults of the samplers. Samples collected by both inspectors and coal mine operators are listed. Use of the PDM may significantly reduce the number of samples voided for a number of different causes. The types of causes amenable to prevention by the PDM are those that relate to documentation, timing, and, in some cases, sample weight issues. The PDM generates a unique data file for each sample that includes the date, time, and various instrument operating parameters, eliminating many documentation issues. The PDM is also programmable to start and stop at specific times, avoiding excess sample times. In addition, the PDM provides EOS mass and concentration values, eliminating shipping, holding, and some laboratory issues. Causes that are considered amenable to reduction by the PDM are indicated by a footnote in the table below. Note that certain codes apply only to either inspector or operator samples.

	Inspector samples	Operator samples
Total samples collected	381,335	487,713
Nonvoided samples	357,936 (93.9%)	430,710 (88.3%)
Voided samples	23,399 (6.1%)	57,003 (11.7%)
BREAKDOWN OF VOIDED SAMPLES		
Abnormal tamper-resistant	NA	14
Abnormal white center	NA	6
Broken[1]	204	1,452
Cassette did not match card[1]	63	897
Cassette not received[1]	2	45
Contaminated[1]	1,166	3,023
Dated before notice[1]	NA	1,459
Designated area not in producing status	3	2,123
Designated work position not in producing status	2	919
Discarded sample (too old)[1]	NA	2,487
Dust data card not received[1]	3	5
Excess sample[1]	1	17,431
Inspector void; rain	264	NA
Insufficient dust observed	189	867
Insufficient weight gain	27	3,966
Invalid certification number	76	610
Invalid initial weight[1]	108	320
Invalid occupation code	4	NA
Invalid or missing date[1]	2	2
Invalid or missing time[1]	5,407	4,477
Invalid Part 90 miner ident	NA	1
Invalid production	11,359	9,923
Invalid sample type	547	1,410
Invalid work position	21	1
Invalid work shift	2,473	20
Malfunctioning pump[1]	1,115	15
Mine not in producing status	2	NA
Mining machine unit not in producing status	NA	1,101
Nonapproved equipment	NA	5
Occupation code–meth mining mismatch	4	NA
Operator void; equipment	10	2,083

NA Not applicable.

[1] Amenable to prevention by the PDM.

BREAKDOWN OF VOIDED SAMPLES—Continued

Operator void; location	2	492
Operator void; miscellaneous	36	116
Operator void; production	30	470
Operator void; rain	6	15
Operator void; time	13	385
Oversize particles[1]	263	390
Part 90 miner not available	NA	8
Predated[1]	4	88
Quartz laboratory void	7	45
Sample not voided	357,936	430,710
Sample received while in hold[1]	NA	191
Unacceptable timeframe[1]	NA	4
Unauthorized work position	6	137
Total	381,355	487,713
Voided samples potentially prevented by PDM	8,338	32,286
Percent of voided samples potentially prevented by PDM	35.6	56.6

NA Not applicable.

[1] Amenable to prevention by the PDM.

Source: MSHA [2005].

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