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Performance of a New Personal Respirable Dust Monitor for Mine Use

Department of Health and Human Services
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U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	mg/m^3	milligrams per cubic meter
hr	hour	mm	millimeter
in	inch	µm	micrometer
L/min	liter per minute	°C	degrees Celsius
mg	milligram	%	percent

PERFORMANCE OF A NEW PERSONAL RESPIRABLE DUST MONITOR FOR MINE USE

By Jon C. Volkwein,[1] Robert P. Vinson,[2] Linda J. McWilliams,[3] Donald P. Tuchman,[4] and Steven E. Mischler[5]

ABSTRACT

A personal dust monitor (PDM) was developed to measure respirable coal mine dust mass to provide accurate exposure data at the end of a work shift. Additionally, the new monitor continuously displays near-real-time dust exposure data during the shift. The PDM uses a tapered-element oscillating microbalance to measure the mass of dust deposited on a filter and continually displays the cumulative exposure concentration data. The accuracy and precision of the instrument was determined by comparison to gravimetric filter samplers in the laboratory and in four mines. Laboratory results with different coal types and size distributions showed that there is a 95% confidence that the individual PDM measurements were within ±25% of the reference measurements. Mine test results indicate that data taken with adjacent PDM and reference samplers are indistinguishable. 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 demonstrated that it was convenient to wear, robust, provided accurate data, provided timely data that could be used to prevent overexposure, and was easy to use.

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INTRODUCTION

Measurement of personal exposure to coal mine dust has remained essentially unchanged for the last 35 years under the Federal Coal Mine Health and Safety Act of 1969 (Public Law 91-173), the predecessor to the Federal Mine Safety and Health Act of 1977 (Public Law 95-164). Following a long history of developmental efforts associated with the fixed-site and personal continuous dust monitors, the National Institute for Occupational Safety and Health (NIOSH) embarked on research to improve sampling instrumentation for use in the mining industry at the recommendation of the Secretary of Labor and the Federal Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers [U.S. Department of Labor 1996]. In consultation with labor, industry, and government, NIOSH issued a contract to Rupprecht & Patashnick Co., Inc. (R&P), Albany, NY (contract 200-98-8004) to develop a one-piece personal dust monitor (PDM). The objective of this work was to miniaturize a tapered-element oscillating microbalance (TEOM) technology into a form suitable for a person-wearable monitor that would enable accurate end-of-shift dust exposure information to be available to miners. It was a further objective of this work to develop a person-wearable dust monitor that minimizes the burden to the wearer by incorporating the monitor into the mine worker's cap lamp battery where exposure data are continually displayed during the shift, which enables workers and management to react to changes in dust exposure.

The current personal dust sampler used to measure exposure to coal mine dust uses a person-wearable pump, a cyclone that separates dust that can enter the inner lung, and a filter to collect dust that is then weighed [MSHA 1989]. Knowing the volume of air sampled and the mass of dust collected, a concentration is calculated. This procedure normally takes several days, but occasionally weeks before miners know the results of a given day's dust exposure. In that time, the mining workplace has moved and conditions may have substantially changed. Consequently, this current sampling method cannot be used to intervene, in a timely manner, to prevent overexposure to coal mine dust.

Coal worker's pneumoconiosis (CWP) results from long-term overexposure to respirable coal mine dust. Federal law is quite specific in stating that coal mine dust levels in the work environment must not exceed 2 mg/m^3 for any 8-hr work shift [30 CFR[6] 70.100]. The Mine Safety and Health Administration (MSHA) uses a periodic method to audit compliance with this standard and to assess the effectiveness of a mine's dust control plan. Under the current dust control strategy, MSHA relies mainly on the implementation of a well-designed dust control plan and not on sampling to prevent overexposures on individual shifts. This periodic method of audit and plan verification works well in other industries when dealing with fixed worksites because it assumes that conditions from one sample to the next are essentially unchanged. This may be a poor assumption in the mining industry in view of the continuing occurrence of more than 1,000 annual deaths attributed to complications from CWP in U.S. coal mines [NIOSH 1999].

Accurate real-time monitoring of coal mine dust has been a longstanding goal of miners. In 1983, the U.S. Bureau of Mines (USBM) and NIOSH funded the development of a prototype TEOM personal dust monitor [Patashnick and Rupprecht 1983]. The prototype monitor was a system configured for end-of-shift measurements. It was not a real-time monitor, but used oscillating microbalance technology to "weigh" the collection filter before and after dust sampling. The USBM evaluated this prototype system in the laboratory for both end-of-shift and near-real-time applications [Williams and Vinson 1986]. These early attempts to construct a person-wearable form of the TEOM required a substantial mass in the base of the element to dampen the vibrations, thus reducing the concept's "wearability."

More recently, to address the continuing incidence of CWP, the Secretary of Labor in 1995 commissioned an advisory committee to study ways to prevent this illness. The committee recommended that improved personal dust monitoring instruments for continuous monitoring of dust controls be developed and that timely results be given directly to the miners. NIOSH and MSHA began development of improved dust monitors in 1996 in support of the advisory committee's recommendations.

The NIOSH Pittsburgh Research Laboratory (PRL) issued a contract to develop an accurate, end-of-shift, one-piece dust monitor. The monitor directly measures mass of dust deposited on a filter using a TEOM that was successfully being used in large stationary environmental monitors commercially produced by R&P. However, substantial redesign to miniaturize and electronically stabilize the microbalance was needed to enable the sensor to be incorporated into a person-wearable monitor.

Another essential feature of this person-wearable dust monitor was that it had to be acceptable to the miners. This was accomplished by incorporating the device into the existing miner's cap lamp and battery system, moving the dust sample inlet from the lapel to the bill of the hard hat, and transporting the sample through a tube to the belt-worn unit for analysis. The new dust inlet location is closer to the worker's nose and mouth and easily within an industrial hygiene definition of a breathing zone [Guffey et al. 2001; Cohen et al. 1983; 30 CFR 70.207(e)].

The fraction of dust that is considered respirable is an important part of measuring a worker's risk from dust. The International Standards Organization [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 will have inherent bias when attempting to duplicate the convention. In fact, the currently used 10-mm Dorr-Oliver (DO) dust cyclone has bias relative to the conventions of both the ISO and the U.K.'s former Mining Research Establishment (MRE) [Bartley et al. 1994]. The cyclone chosen for use in the PDM required an inlet that could accept the tube coming from the hard hat inlet. The cyclone followed the Higgins-Dewell (HD) design, which had been

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

previously tested to have low bias relative to the ISO convention [Maynard and Kenny 1995].

The use of a different cyclone, however, complicates the direct comparison between the PDM and the current personal coal mine dust sampling unit because the difference in cyclones may cause somewhat different results according to the size distribution of the dust [Hearl and Hewett 1993; Bartley and Breuer 1982]. Therefore, the PDM's ability to accurately measure a mass of respirable coal mine dust must be judged against the identical HD sample inlet and cyclone and not the DO cyclone used in the traditional personal sampler. To assess the comparison to the existing personal sampler, we must also measure the size distribution of the dust. Knowing the size distribution enables the respirable mass to be calculated according to either the ISO or MRE definitions of respirable dust. We can calculate from these measurements the bias introduced by the HD cyclone and the bias introduced by the 10-mm DO cyclone when determining the respirable mass for different coal mine aerosols.

This report evaluates the performance of the PDM compared to gravimetric-based reference dust sampling methods. The work was conducted in two parts. The first part compares the new instrument to reference mass samplers and samplers currently used by coal mines in a controlled laboratory dust chamber. The second part examines instrument performance when worn by a miner in underground mines.

DESCRIPTION OF THE PDM

The PDM is a respirable dust sampler and gravimetric analysis instrument that is part of a belt-worn mine cap lamp battery. Components of the device include a sampling inlet tube, HD cyclone, air heater, pump, dust sensor, battery for the sampler, battery for the cap light, electronic control and memory boards, a display screen, and Windows®-based computer interface software. Figure 1 illustrates some of the components.

The inlet of the sampler is located adjacent to the lens of the miner's cap light that is worn on the front of the hard hat. The air to be sampled is pumped through a rounded inlet and carried through a 0.48-cm (0.19-in) internal-diameter conductive silicone rubber tube running beside the cap light cord to the beltworn sampler. At the sampler, dust is separated using an HD cyclone into coarse and respirable fractions. When operated

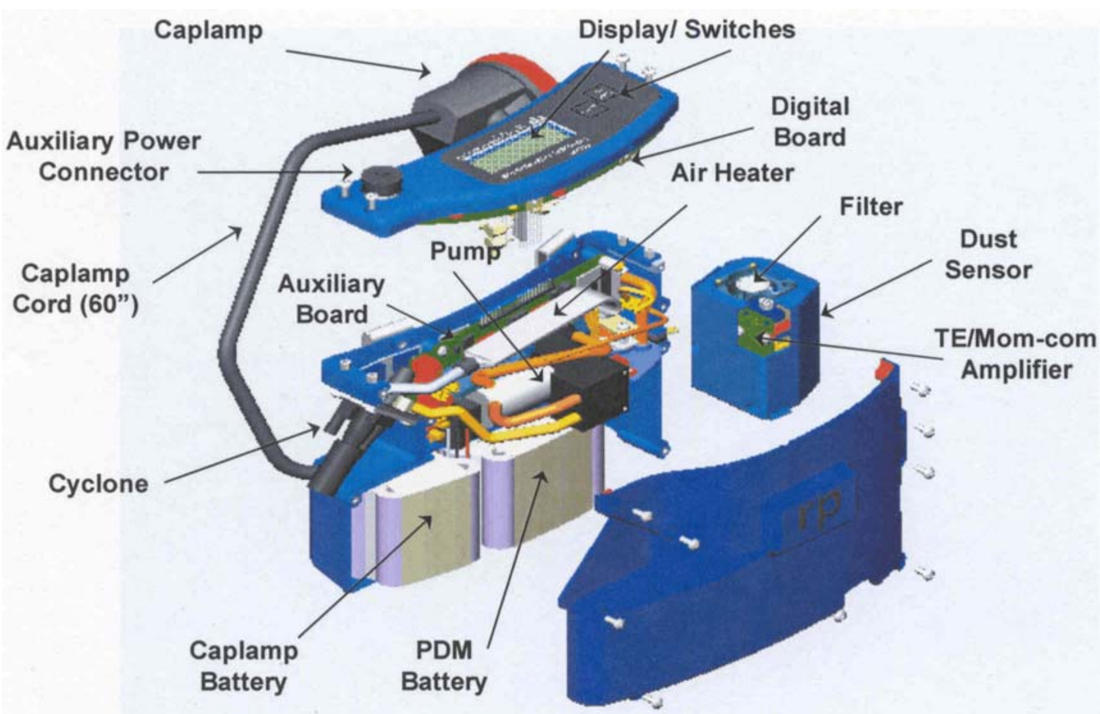

Figure 1.––Internal PDM components.

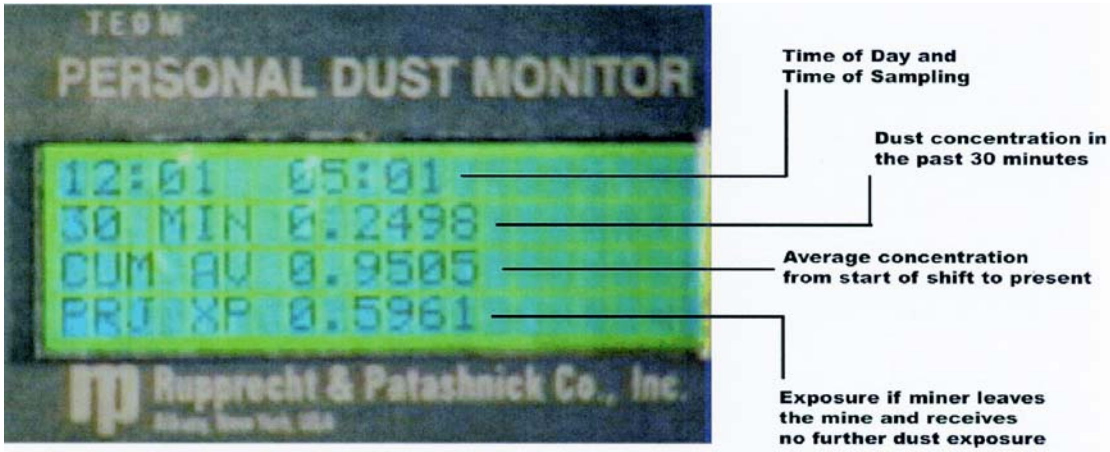

Figure 2.—Screen display of PDM.

at a flow rate of 2.2 L/min, this cyclone [Bartley et al. 1994] best approximates the classification of dust according to the ISO definition of respirable dust [ISO 1995]. The coarse dust remains in the cyclone grit pot while the respirable fraction continues into the analytical portion of the unit.

The sample is heated to a constant temperature, typically 45 °C, in an elliptical cross-section metal tube designed for low particulate loss. The sampled dust is then deposited on a 14-mm-diam Teflon-coated glass fiber filter. The filter is mounted on an inertial mass detector (TEOM) [Patashnick and Rupprecht 1991]. The TEOM has been miniaturized and stabilized using proprietary technology to enable its use as a person-wearable device [Patashnick et al. 2002].

Custom software is used to program the PDM through any personal computer. The mass on the TEOM filter is analyzed by the internal electronics, and several concentrations based on flow rate and times are calculated. These data are displayed on the top of the battery, as seen in figure 2. Concentration data and other operational parameters (flow rate, filter pressure, tilt status, shock status, temperature, and TEOM frequency data) are simultaneously recorded to internal memory.

Lithium-ion battery packs independently power both the sampler and cap light. A combination charging and down loading cradle is used to charge both cap lamp and dust monitor batteries simultaneously. In addition, the cradle provides contacts that connect the sampler to a computer's RS-232 data port.

The instrument may be operated in shift or engineering modes. The shift mode is programmed through the personal computer software interface. In this mode, a technician programs the instrument to start at a specific time and run for the expected duration of the shift. Also during programming, various sample identification codes may be entered into the instrument in a form typical of the currently used dust sampling data card. Once programmed, the only way to alter the instrument is to use the original computer interface. At the end of the programmed shift time, the unit retains the final exposure data in the screen display until the memory from the sampler is downloaded by a personal computer. Depending on the number and frequency of recording data, several shifts of data can be retained in the instrument's internal 2-megabyte memory. A typical shift file size varies from 40 to 250 kilobytes. Shift data are retained in the instrument until memory capacity is reached, then the oldest data are overwritten. If a new program is not loaded into the PDM after a download, the instrument may be operated in the engineering mode. This mode allows manual startup and control of the instrument through a series of button presses on the top of the battery pack without need of a personal computer.

METHODS

Performance of the PDM was evaluated in the laboratory and through in-mine testing. The laboratory portion of the testing determined the PDM mass measurement accuracy and precision compared to existing personal samplers. The bias of the HD cyclone used in the PDM and the DO cyclone used in the personal sampler was compared to the ISO and MRE definitions of respirable dust. In-mine testing measured the durability of the instrument, compared the PDM concentration measurements to those of side-by-side reference samplers, and determined cyclone bias.

LABORATORY

Laboratory testing was conducted in a dust chamber at PRL. We first determined if the PDM mass measurement was accurate when compared to the filter mass measurement method using a defined accuracy criterion. We also compared the PDM to the existing personal sampler method of dust measurement using a more complex study design that accounted for the PDM's use of a different cyclone to define the respirable dust fraction. This bias analysis procedure [Bartley et al. 1994] was used to determine if the HD cyclone had less than or equivalent bias compared to the DO cyclone when using either the MRE or ISO definition of respirable dust.

Samplers

Six identical PDM dust monitors were produced by R&P. Four units were available for laboratory evaluation, and two units were provided for the in-mine testing. Instruments were used as delivered to PRL from R&P. Other samplers used for gravimetric analysis included the personal coal mine dust sampling unit (MSA Co., Inc., Pittsburgh, PA) and the BGI-4CP dust sampler (BGI, Inc., Waltham, MA). The personal coal mine dust sampling unit, hereafter referred to as the personal sampler, uses a 10-mm DO nylon cyclone to select the respirable portion of the total dust aerosol. The HD cyclone used in the PDM unit was designed to perform identically to the cyclone used in the BGI-4CP sampler.

Size distributions of the dust in the chamber were measured using a Marple personal cascade impactor (Model 290, Thermo Electron Corp., Franklin, MA) operated at a flow rate of 2 L/min. The device was operated according to the manufacturer's instructions, including correction factors to account for wall loss [Rubow et al. 1987].

Dust Exposure Chamber

A Marple chamber provided a uniform atmosphere 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 our case, the reference was the personal gravimetric sampler. These personal samplers have been demonstrated [Kogut et al. 1997] to have significantly higher relative standard deviations (RSDs) in multiple sampler comparisons at mass concentrations of less than 0.5 mg/m^3. To minimize error in the accuracy measurement of the PDM caused by inaccuracy of the reference sampler, mass loadings were maintained above 0.5 mg/m^3.

A turntable in the Marple chamber that holds the instruments 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 environment was regulated to between 20 and 25 °C and a relative humidity between 40% and 60%.

Chamber dust concentrations were monitored with a commercially available Model 1400 TEOM (R&P, Albany, NY). This was used to help select the correct time intervals to achieve desired mass loadings for the testing.

Coal Types

Three types of coal dust were used: Keystone, Illinois, and Pittsburgh. The Keystone coal was a commercially available ground coal manufactured by Keystone Filler and Manufacturing Co., Muncy, PA. The Pittsburgh and Illinois No. 6 coal dusts were obtained from The Pennsylvania State University's coal collection. The target median mass aerodynamic diameters of the Keystone and Illinois coals were 3 and 8 µm, respectively. The Pittsburgh coal was ground at Penn State into three separate sizes to provide nominal median mass aerodynamic diameters of 4, 10, and 20 µm. Five laboratory experiments were conducted, three with Pittsburgh coal of three sizes and two with the other coals. These coal types were chosen to represent a range of coal types and a range of size distributions within one coal type.

Filters and Pumps

Filters for the gravimetric samples were preweighed at PRL's controlled atmosphere weighing facility using established procedures. The filter cassettes used in the personal sampler differ from commercially available units in that the aluminum wheel assembly and check valve were not used. The filters used in the BGI-4CP sampler were 37-mm-diam, 5-µm pore size, polyvinyl chloride (PVC) filters similar to those used in the coal mine personal cassette filter. Flow-controlled MSA Escort ELF pumps were calibrated on-site at the beginning of each test week using a Gilibrator (Sensidyne, Inc., Clearwater, FL) primary standard flow meter to 2.0 ± 0.020 L/min for personal coal mine gravimetric pumps and impactor pumps and 2.2 ± 0.022 L/min for the BGI-4CP sampler pumps. An equivalent pressure restriction for the respective samplers was used during pump calibration. The PDM sampler flow rate was checked before each coal type and mine test and recalibrated if flow variance was greater than 5% of the set rate of 2.2 L/min.

Three filter blanks for each type of filter were also used for each day of testing and were kept with experimental filters, but not exposed to the dust atmosphere. Average blank filter weights were used to correct the filter mass results for each test. Blank filters were also used to calculate the limit of detection (LOD) and limit of quantification (LOQ) of the experiments. All filters were returned to PRL's weighing facility for posttest mass determination using procedures identical to those of the pretest weighing.

Impactor Preparation

Model 290 Marple impactors, connected to MSA Escort ELF pumps operating at 2.0 ± 0.020 L/min, were used to measure the particle size distributions of the various test dusts. The Model 290 impactor has eight collection stages with cut points from 0.7 to 21.3 µm and a final filter (PVC 34-mm-diam, 5-µm pore size). At each collection stage, dust particles impact on the 34-mm-diam Mylar substrates 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 having 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 ingredients of the silicone spray to evaporate and to allow outgassing of the Mylar. Substrates and the PVC final filters were then preweighed and loaded into the eight-stage impactors. Each lab test run used 51 Mylar substrates and 6 final filters. Three substrates and three filters were used as controls.

Experimental Design

For each of the five coal types or size distributions, three replicate test runs were conducted. An individual test run used 12 personal samplers and 12 BGI-4CP samplers. To accurately compare the mass measurement capability of the PDM to gravimetric filter methods, the BGI-4CP samplers were modified to use identical inlet and tube configurations to eliminate these as variables. These samplers were uniformly arrayed around a central point in the Marple chamber. Three to six PDM units, depending on availability, were uniformly interspersed into that array. Each gravimetric sampler type was divided into four test-time interval groups of three samplers. Figure 3 illustrates a typical chamber test run setup.

The average mass of the three individual samplers in each time group was used to determine the gravimetric dust mass during a specific test-time interval. In addition, there were three blank control filters for each test run for each type of filter used. Control filters were handled in a manner identical to that of the experimental filters except that the end caps were not removed or for the PDM, the closed filter holders were not opened.

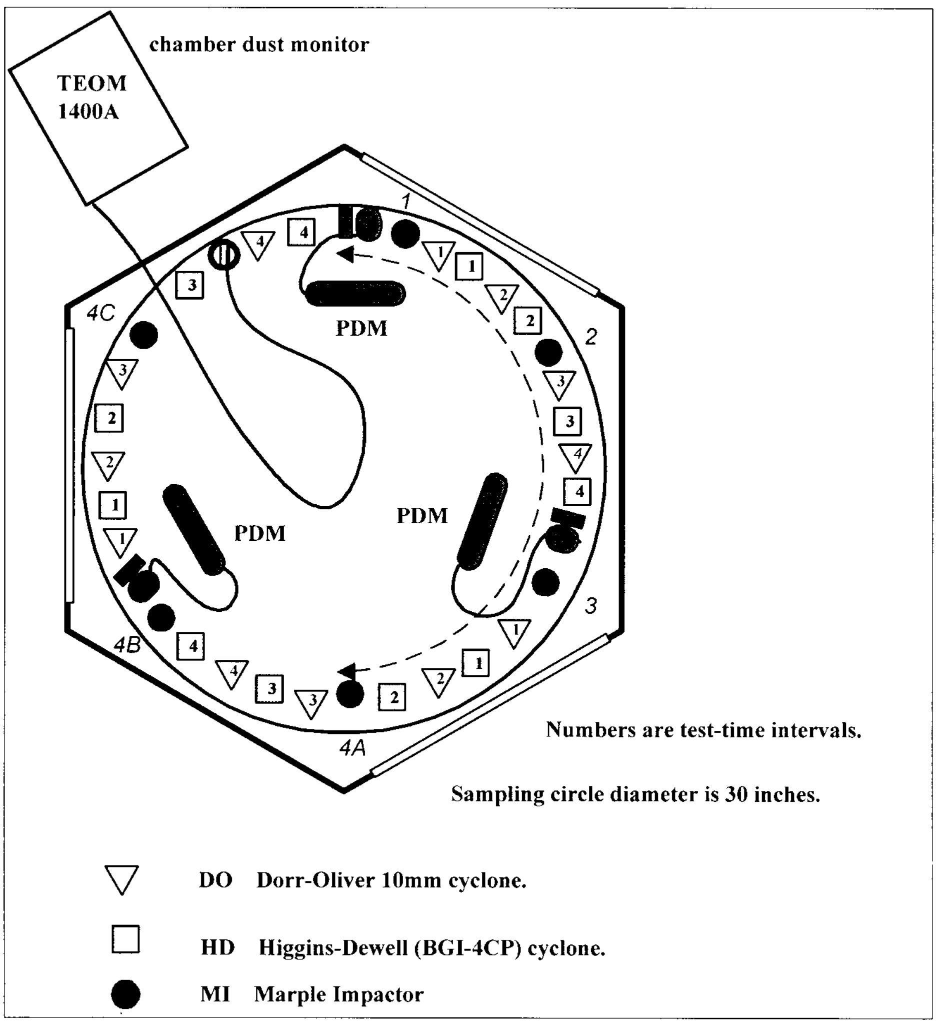

Figure 3.–Plan view of a typical test setup in the Marple chamber.

We selected test-time intervals to achieve filter mass target loadings over the range of about 0.5 to 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 determined by the Model 1400 TEOM. The mass loading then determined the test-time interval. This procedure resulted in four test-time intervals with averaged mass loadings from corresponding groups of personal samplers, BGI-4CP samplers, and impactor samples. For each test-time interval, the PDM measured mass, recorded in each data file, was read to determine the mass measured by the individual PDM for that test-time interval.

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

Run 1: 8-hr duration, test-time interval Nos. 1-4. The chamber was brought to an MRE equivalent concentration of about 2 mg/m^3. Gravimetric filters were turned off at equivalent mass target loadings of 0.5, 0.8, 1.6, and 2 mg.

Run 2: 8-hr duration, test-time interval Nos. 5-8. The chamber was brought to an MRE equivalent 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: 12-hr duration, test-time interval Nos. 9-12. The chamber was brought to an MRE equivalent concentration of about 2 mg/m^3. Triplicate sets of filters were turned off at equivalent mass target loadings of 0.7, 1.2, 1.8, and 2.5 mg.

Size Distribution Measurements

Impactor size distribution samples were taken for a representative portion of each test-time interval. The Marple personal impactors used were susceptible to mass overloading that could invalidate the sample. To prevent overloading and to obtain a representative size distribution over the entire sampling time, an intermittent sampling strategy was used. One impactor was assigned to each test-time interval of a test run. All impactors were started with the gravimetric samplers. The run time of each impactor, T_R, contained a portion of each time interval. These portions were determined as follows:

Interval 1 (T_1): $T_R = T_1$
Interval 2 (T_2): $T_R = T_1/2 + T_2/2$
Interval 3 (T_3): $T_R = T_1/3 + T_2/3 + T_3/3$
Interval 4 (T_4): $T_R = T_1/4 + T_2/4 + T_3/4 + T_4/4$

The size distribution for interval 4 was determined using the average of three impactors, identically operated to obtain the experimental precision of the size distribution measurement. In one case, all of the single impactors failed, but previous data indicated that chamber size was constant, so the averaged results from interval 4 were used as representative of time intervals 1-3.

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 probit of cumulative mass percentages versus the logarithm of stage cut point. The use of least squares regression to find the best-fitting straight 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. To account for this, data were used only if the R-squared values for the regression were greater than 0.95.

Low Mass Measurements

After the completion of the initial test series, a separate test was conducted to determine the performance of the PDM in measuring low mass loadings between 0.20 and 0.50 mg. This test series was also used to confirm the performance of the PDM units after some minor electronic modifications for intrinsic safety approval were made to the units. These tests were conducted in a manner similar to that of the laboratory tests using only the Pittsburgh 20-µm coal. No size distribution or DO cyclone reference measurements were taken. To minimize error with the reference samplers at low mass loadings, the number of reference samplers was increased from three to six when mass loadings were less than 0.5 mg.

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 from the method of Kennedy et al. [1995]. For these tests, the mass ratio for each data pair was calculated by dividing the individual PDM mass by the average value for the triplicate gravimetric reference mass of the corresponding time interval. The individual concentration ratios were then averaged over all laboratory data, and by coal type or size. The RSDs were calculated for both PDM and gravimetric reference standards.

To reduce the impact of error in the personal sampler 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:

$$RSD_x = \sqrt{RSD^2_{\frac{x}{t}} - RSD^2_{T_i}}$$

where $RSD_{\frac{x}{t}}$ = *Relative standard deviation of mass ratio* and the experimental pooled RSD of the gravimetric samplers was:

$$RSD_{\overline{T_i}} = \frac{\sqrt{\frac{\sum RSD^2_{gravimetric}}{n}}}{2}$$

Bias was then calculated based on the mean concentration minus one. Accuracy was calculated from the method of Kennedy et al. [1995]. Confidence limits were calculated based on the method used by Bartley [2001] using a noncentral Student's t-distribution. These laboratory data were used mainly to judge the PDM's mass measurement capability.

The precision of the PDM was analyzed by examining the RSD of the PDM and reference samplers over different mass loadings. These loadings were 0.2 to 0.49 mg, 0.5 to 0.99 mg, 1.0 to 1.49 mg, 1.5 to 1.99 mg, and 2.0 to 6.5 mg. The average and confidence limits of the RSDs were reported.

Data from all laboratory testing were combined on a scatter plot to help visualize the agreement and range of differences between the PDM and reference samplers. This included a linear regression equation and a computation of the R-squared value of the entire data set.

A second analysis determined how well the PDM compared to the currently used personal sampler. An indirect analysis was used for the comparison. Here the bias between the HD and DO chamber gravimetric mass determinations was calculated against both the ISO and MRE respirable mass definitions as determined from the size distribution measurements. This fraction varied with dust size distribution and coal types used. The size distribution data were used to calculate the ISO respirable fraction as defined by Soderholm [1989]. This calculation used the mass from each impactor stage multiplied by the percentage defined as respirable for that stage to arrive at the ISO respirable mass for that stage. The summation of all respirable stage masses determined the ISO defined mass. The procedure of the American Industrial Hygiene Association [Lodge and Chan 1986] was used. A similar procedure was used for the MRE fraction. From the calculated ISO or MRE respirable mass data, differences from the HD and DO gravimetric reference standards were calculated. All DO concentration data were converted to MRE equivalent concentration basis by multiplying by a factor of 1.38. This second analysis was also done on a coal type or size basis, and results were averaged. The mean bias was computed for each cyclone by coal type and overall. A 95% confidence interval (CI) was then calculated for each mean.

IN-MINE TESTING

In-mine testing used pair-wise testing to partially take into account the increased variability associated with personal sampling in mining conditions and examined the mine worthiness issues of the instrument when worn by miners performing their normal duties. Limited testing was conducted for five shifts in each of four coal mines. This testing compared the end-of-shift gravimetric concentration measured by the PDM with the end-of-shift gravimetric concentration measured with a reference filter sampler using an HD cyclone and an analytical balance. The HD cyclone used an inlet and tubing configuration identical to the PDM inlet and tube configuration to minimize the number of variables.

Six PDM units were available for mine testing. Three units were allocated for mine workers to wear, two units were worn by NIOSH personnel, and one was designated as a spare and worn by various people during the testing. The spare unit was unavailable for testing at the first mine.

Mine Sites

Mine sites were chosen to represent various areas of the country, types of mines, ventilation systems, and types of equipment. Both union and industry participated in the selection of the test mines. The mines were located in Pennsylvania's Pittsburgh Seam, central Appalachia's Eagle Coal Seam, central Utah's Hiawatha Seam, and Alabama's Blue Creek and Mary Lee Seams. Mine sections were selected to provide different types of equipment and mining situations, such as a longwall mining machine, continuous mining machines, scrubber-equipped mine machines, diesel-powered equipment, and all-electric-powered equipment.

Sampling Mine Workers

Mine workers wore a PDM that replaced their normal cap lamp battery and one personal BGI-4CP sampler with a tubing inlet. The tube was identical in length and inlet configuration to that of the PDM, but was connected to a BGI-4CP sampler located at the belt of the miner. The inlets of both tubes were co-located on the cap lamp assembly. The inlet was attached to the cap lamp at about the 7:00 o'clock position, opposite the PDM's 5:00 o'clock inlet position when viewed from the front of the lens. Escort ELF flow-controlled pumps, set at a flow rate of 2.2 L/min, were used to power the BGI-4CP dust samplers. NIOSH personnel carried two blank control filters into the mine each test day, but did not expose them to dust. Work occupations to be sampled were selected to be representative of the mine section, with emphasis given to the MSHA-assigned designated occupation.

Sampling was conducted for the entire shift length. The PDM was operated in program mode, and the shift length, start time, and other identification data were entered before the start of the shift. The PDM started automatically and warmed up in the mine office. Miners picked up the PDM as they would normally get the cap lamp at the start of a shift. As the shift started, the reference samplers were manually turned on to correspond with the PDM start time. At the end of the shift, the PDM automatically turned off and the reference samplers were manually turned off and the pump times recorded. Miners then removed the PDM and returned it to the charging cradle or table. At times, the shift finished before the PDMs shut down. In those instances, the samplers were removed from the miners, but both reference and PDM samplers were run in the mine office until the PDMs finished sampling.

At the end of each shift, the PDM units were downloaded in the mine office to a laptop computer. Tubes and cyclones were cleaned with compressed air, the used filters were removed, new filters were installed, and the units were programmed for the next day's test. Batteries were charged overnight in the mine office.

Research Samples

Two NIOSH research technicians wore PDM and reference sampling equipment identical to those of the miners. In addition, the NIOSH personnel wore three additional samplers that were used to measure cyclone bias. These samplers included a personal sampler with a DO cyclone, a BGI-4CP sampler with an HD cyclone modified with a tube inlet, and a Marple personal impactor. These instruments were operated identically to those used in the laboratory. The Marple impactors, however, were run for the entire shift. The inlets for all samplers were located in a small quart-size paint can with a central 1-in-diam inlet. The purpose of this arrangement was to minimize spatial variability commonly found in field sampling. The use of an inlet into the paint can would clearly change the size distribution of a sampler in the can relative to a sampler outside of the can. However, this difference is not relevant in this experiment where only samplers inside of the apparatus are compared.

Ten size-distribution, DO-cyclone, and HD-cyclone measurements were made at each mine. The technicians generally shadowed, for a period of 6 to 8 hr, an occupation that was being tested at each mine site to obtain size distribution data for the cyclone bias calculations. Because of the can inlet and the need for NIOSH technicians to be in safe sampling locations, the size distribution measurement may not be exactly representative of the size of dust to which the PDM was exposed; however, it was representative of the dust to which the other reference cyclones in the can were exposed. Thus, the bias calculations were consistent.

Analysis

Mine worker sampling measurements were expected to be less precise than the laboratory measurements because of the increased variability associated with personal sampling. Data from the miners and NIOSH technicians that compared PDM to reference samplers were evaluated using a paired t-test. This test postulates that the mean difference score of the paired samples is equal to 0. The level of statistical significance was set at $\alpha = 0.05$. For the mine worker sampler comparisons, a minimum of 13 pair-wise data sets were available from each mine.

To assess the degree of agreement between the PDM and the reference sampler, an intraclass correlation coefficient (ICC) was computed [Shrout and Fleiss 1979; McGraw and Wong 1996]. Because systematic differences between samplers were considered relevant, an ICC for absolute agreement was used. This type of ICC addressed the question: "Are the two samplers (PDM and reference) interchangeable?"

A scatter plot of all mine data was constructed to help visualize the comparability of the two instruments. This included a linear regression equation and a computation of the R-squared value of the data set.

RESULTS

LABORATORY

Laboratory testing was conducted during the spring of 2003. A total of 316 laboratory comparisons of PDM to reference samplers were conducted. In addition, 60 laboratory determinations of cyclone bias to ISO and MRE definitions were conducted.

Mass Results

The laboratory results in table 1 show the average mass of dust from the triplicate BGI-4CP samplers for each test-time interval and the corresponding RSD of the reference samplers. The overall average RSD for the gravimetric reference sampling for this work was 0.047. Table 1 also contains the mass measurements for individual PDM units for each test-time interval. The RSD for the PDM units for each test-time interval is indicated; the average RSD for these measurements was 0.060. Note that the mass measurements from PDM serial No. 105 were consistently low and consequently increased the RSD of the PDM measurements. Subsequent inspection of the cyclone to heater transition in unit 105 indicated that an obstruction in the air sample path may have been the reason for the lower measurements from that unit.

For the laboratory experiments, the LOD, as defined by the mean filter blank mass value plus three standard deviations, for the HD and DO filters was 0.055 and 0.026 mg, respectively. The LOQ, as defined by the mean filter blank mass plus 10 standard deviations, for the HD and DO filters was 0.125 and 0.056 mg, respectively. The difference in these limits is partly a reflection of the different filter tare weights and the different balances used for the gravimetric mass determinations.

Accuracy Criterion

Bias, precision, accuracy, and confidence limit calculation results presented in table 2 are for individual instruments by coal type and for the overall laboratory experiments. For the overall

Table 1.—Overall laboratory data comparing laboratory reference mass measurement to PDM mass measurement

Coal type	Gravimetric			PDM				
	Test-time interval	Average BGI-4CP HD Classified mass, mg	BGI-4CP Relative Standard Deviation std/mass	Serial No. 101 mg	Serial No. 102 mg	Serial No. 104 mg	Serial No. 105 mg	PDM Relative Standard Deviation std/mass
Keystone	1	0.563	0.04	0.532	0.548	0.566	0.509	0.045
	2	1.151	0.03	1.113	1.089	1.115	1.039	0.032
	3	1.742	0.01	1.655	1.611	1.651	1.542	0.032
	4	2.351	0.03	2.188	2.137	2.178	2.046	0.030
	5	1.128	0.01	1.168	1.140	1.141	0.989	0.073
	6	2.188	0.09	2.256	2.179	2.218	1.939	0.067
	7	3.406	0.03	3.383	3.202	3.266	2.959	0.056
	8	4.517	0.04	4.477	4.246	4.321	3.948	0.052
	9	0.852	0.04	0.804	0.852	0.884	0.750	0.071
	10	1.724	0.03	1.618	1.637	1.731	1.453	0.072
	11	2.510	0.04	2.455	2.444	2.593	2.182	0.071
	12	filters unsealed		3.311	3.258	3.459	2.931	0.069
Illinois No. 6	1	0.727	0.034	0.728	0.668	0.655	0.598	0.080
	2	1.293	0.017	1.442	1.321	1.309	1.182	0.081
	3	2.153	0.069	2.105	2.029	1.972	1.820	0.061
	4	3.065	0.024	2.708	2.663	2.621	2.396	0.053
	5	1.210	0.079	1.222	1.007	1.195	(1)	0.102
	6	2.492	0.058	2.591	2.172	2.472	(1)	0.090
	7	3.932	0.104	4.015	3.354	3.787	(1)	0.090
	8	6.045	0.038	5.406	4.508	5.118	(1)	0.092
	9	1.060	0.059	1.080	1.038	1.072	0.838	0.113
	10	2.195	0.035	2.200	2.046	2.166	1.707	0.111
	11	3.354	0.063	3.283	3.057	3.252	2.564	0.109
	12	4.262	0.096	4.335	4.021	4.278	3.417	0.105
Pittsburgh 20 µm	1	0.587	0.084	0.383	0.568	0.563	0.524	0.170
	2	1.281	0.034	0.989	1.149	1.193	1.129	0.079
	3	1.878	0.045	1.585	1.689	1.801	1.674	0.053
	4	2.549	0.027	2.118	2.193	2.375	2.203	0.049
	5	1.070	0.012	0.960	1.068	1.069	0.951	0.065
	6	2.211	0.087	2.006	2.169	2.162	1.948	0.054
	7	3.462	0.021	3.046	3.297	3.250	2.956	0.052
	8	4.787	0.049	4.119	4.412	4.365	3.957	0.051
	9	0.741	0.049	(2)	0.706	0.755	0.668	0.061
	10	1.489	0.054	(2)	1.467	1.455	1.315	0.060
	11	2.253	0.052	(2)	2.235	2.205	1.980	0.065
	12	3.135	0.029	(2)	3.011	2.920	2.661	0.063
Pittsburgh 4 µm	1	0.683	0.021	0.663	0.660	0.658	0.634	0.020
	2	1.198	0.037	1.128	1.109	1.119	1.050	0.032
	3	1.741	0.017	1.625	1.579	1.620	1.514	0.032
	4	2.331	0.016	2.117	2.038	2.117	1.964	0.036
	5	1.034	0.014	1.012	1.017	(3)	0.997	0.010
	6	2.042	0.030	1.898	1.936	(3)	1.902	0.011
	7	3.127	0.020	2.779	2.858	(3)	2.797	0.015
	8	4.325	0.008	3.666	3.800	(3)	3.717	0.018
	9	0.762	0.029	0.726	0.729	0.722	0.756	0.021
	10	1.551	0.046	1.442	1.466	1.425	1.490	0.019
	11	2.389	0.014	2.166	2.205	2.142	2.247	0.021
	12	3.124	0.056	2.912	2.919	2.848	2.993	0.020
Pittsburgh 10 µm	1	0.570	0.037	(2)	0.530	0.553	0.465	0.088
	2	1.100	0.108	(2)	1.006	1.050	0.883	0.088
	3	1.542	0.116	(2)	1.491	1.530	1.285	0.092
	4	2.164	0.157	(2)	1.971	1.965	1.694	0.084
	5	0.965	0.088	(2)	0.891	0.976	0.883	0.056
	6	2.041	0.032	(2)	1.698	1.926	1.792	0.063
	7	2.999	0.057	(2)	2.622	2.829	2.635	0.043
	8	4.248	0.069	(2)	3.592	3.764	3.503	0.037
	9	0.715	0.066	(2)	0.644	0.704	0.708	0.052
	10	1.417	0.083	(2)	1.263	1.348	1.392	0.049
	11	2.366	0.004	(2)	1.894	2.009	2.116	0.055
	12	3.212	0.025	(2)	2.533	2.670	2.812	0.052
		Average HD Exp. RSD	0.047				Average PDM Exp. RSD	0.060

[1]Incorrect program start time.
[2]Bad heater.
[3]No display.

Table 2.—Laboratory accuracy results and confidence limits

Coal type	Unit serial No.	Bias	$RSD_{x/r}$	Accuracy	Confidence Limits Upper 95%
Keystone	101	-0.03	0.04	7.80	11.8
	102	-0.04	0.03	8.40	11.6
	104	-0.01	0.04	6.70	10.4
	105	-0.12	0.02	15.00	17.00
Illinois No. 6	101	0.00	0.06	10.40	15.70
	102	-0.10	0.08	20.80	28.4
	104	-0.05	0.06	13.10	19.1
	105	-0.19	0.06	25.40	31.7
Pittsburgh 20 µm	101	-0.11	0.02	14.90	22.6
	102	-0.05	0.05	11.10	15.20
	104	-0.04	0.03	7.20	9.5
	105	-0.13	0.02	16.10	18.4
Pittsburgh 4 µm	101	-0.07	0.04	12.60	16.3
	102	-0.07	0.04	11.80	15.00
	104	-0.07	0.03	11.00	13.4
	105	-0.08	0.05	15.8	21
Pittsburgh 10 µm	101				
	102	-0.12	0.06	18.4	22.90
	104	-0.06	0.06	13.2	17.80
	105	-0.13	0.08	21.7	27.80
Overall	101	-0.04	0.06	12.5	15.10
	102	-0.08	0.06	15.80	17.7
	104	-0.05	0.05	11.30	12.9
	105	-0.12	0.06	20.00	21.9

data, there is a 95% confidence that the individual PDM measurements were within ±25% of the reference measurement according to the method of Kennedy et al. [1995]. From the CI data, we can predict that 95% of future random samples will be within ±25% of a reference sampler measurement. The bias data in table 2 are consistently negative, which indicates that the PDM undersamples relative to the gravimetric standard. The instruments have high precision, indicated by the low $RSD_{x/r}$. Subsets of data for PDM serial No. 105 again illustrate high negative bias. This negative bias was traced to a poorly constructed heater transition by the instrument manufacturer. After repair of this defect by the manufacturer, subsequent data indicate that the bias of unit 105 is now equivalent to that of the other PDM units (see table 3). PDM serial No. 102 also exceeded the upper confidence limit for the subset of Illinois No. 6 coal.

Low Mass Measurements

Results from the additional testing to investigate the low mass measurement capabilities of the PDM are in table 3. Data from unit 105 were not used in one of the test runs because there was an abnormal pressure spike that corresponded with a decrease in the mass of unit 105. This is believed to have been caused by a pinched or blocked inlet tube for that sampler. Also, there was a communications port failure with unit 104 of unknown origin that resulted in lost data for that run. An accuracy analysis of this low mass data set had values of 15%, 10%, 14%, 10%, and 16% for PDM unit Nos. 101, 102, 104, 105, and 106, respectively.

All Laboratory Data

Both initial and low mass data are combined in the plot in figure 4. The linear regression of individual pairs of data lends support to the accuracy analysis in that the trend of the data shows a largely negative bias of the PDM toward the reference samplers.

Distribution of Precision

Table 4 shows the precision of all laboratory data as determined by the RSD of both the BGI-4CP gravimetric sampler and PDM for various concentration ranges. The RSD for the BGI-4CP sampler increased as expected for mass loadings less than 0.5 mg. The PDM RSD did not increase as much as the BGI-4CP RSD for the low mass measurements.

Cyclone Bias Results

For the combined laboratory data, the bias of the HD cyclone was less than that of the DO cyclone using either the ISO or MRE definitions of respirable dust. Table 5 presents the impactor-defined MRE and ISO respirable concentrations compared to the measured DO and HD cyclone sampler measurements. The DO measurements were corrected to the MRE equivalency with a factor of 1.38.

Table 5 also contains the MMAD and GSD for each test-time interval. Good agreement of the size data is evident within each set of coal type data. Further evidence of the precision of the size data is evident in the triplicate size distribution measurements of the T-4 time interval, where the calculated MMAD had an average RSD of 0.06. To compare the bias between the

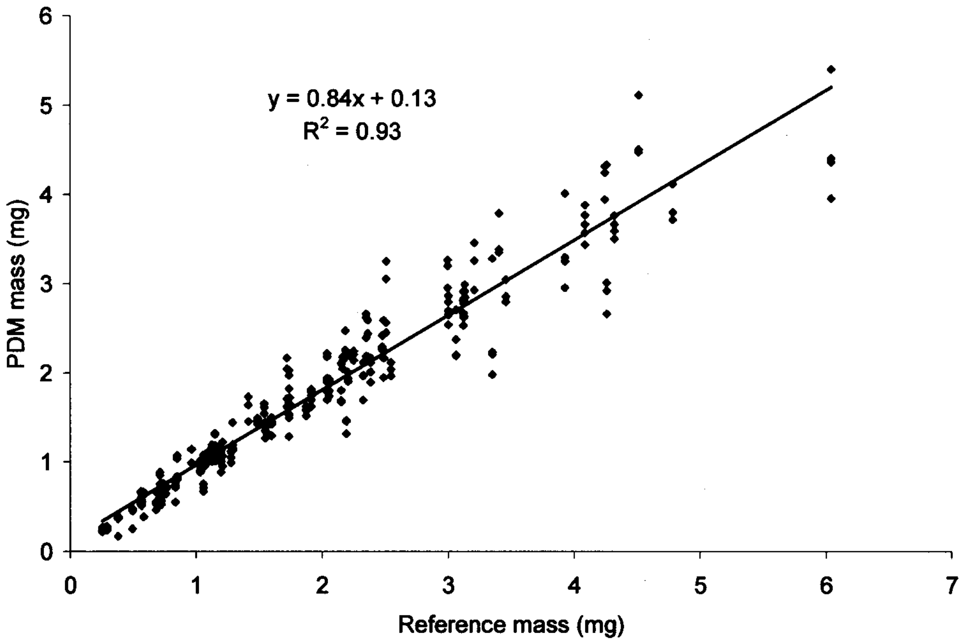

Figure 4.–Regression analysis of total laboratory data set.

Table 3.—Low mass data results comparing reference mass to PDM mass measurement

Test-time interval target	Average BGI-4CP HD Classified mass, mg	BGI-4CP Relative Standard Deviation std/mass	PDM Serial No. 101 mg	PDM Serial No. 102 mg	PDM Serial No. 104 mg	PDM Serial No. 105 mg	PDM Serial No. 106 mg	PDM Relative Standard Deviation std/mass
T-1	0.26	0.02	0.24	0.22	0.22	0.22	0.24	0.036
T-2	0.71	0.08	0.68	0.63	0.63	0.64	0.62	0.035
T-3	1.13	0.05	1.14	1.09	1.09	1.09	1.13	0.023
T-4	1.75	0.04	1.72	1.61	1.62	1.62	1.65	0.027
T-5	2.48	0.02	2.42	2.27	2.26	2.26	2.29	0.029
T-1	0.29	0.04	0.24	0.28	0.25	0.27	0.25	0.067
T-2	1.04	0.01	0.91	0.97	0.92	0.99	0.90	0.042
T-3	2.06	0.01	1.80	1.93	1.79	1.91	1.74	0.045
T-4	3.00	0.01	2.70	2.87	2.65	2.79	2.54	0.047
T-5	4.09	0.01	3.67	3.88	3.57	3.77	3.44	0.047
T-1	0.38	0.06	0.37	0.39	0.36	NU	0.38	0.029
T-2	0.50	0.01	0.46	0.48	0.45	NU	0.46	0.021
T-3	0.84	0.04	0.74	0.78	0.74	NU	0.72	0.035
T-4	1.60	0.07	1.27	1.28	1.24	NU	1.21	0.027
T-5	1.92	0.04	1.82	1.79	1.75	NU	1.70	0.029
T-1	0.23	0.12	0.25	0.26	0.24	0.27	0.26	0.052
T-2	0.29	0.07	0.29	0.30	0.32	0.31	0.30	0.041
T-3	0.38	0.11	0.37	0.40	0.37	0.40	0.38	0.042
T-1	0.26	0.06	0.28	0.24	DL	0.26	0.23	0.085
T-2	0.28	0.09	0.33	0.28	DL	0.31	0.25	0.109
T-3	0.41	0.09	0.42	0.37	DL	0.40	0.36	0.079

DL Data lost; could not download data.
NU Not used - pressure spike in file; pinched tube.

Table 4.—RSD of reference samplers and PDM samplers by mass loading ranges

Mass range	BGI-4CP Average	BGI-4CP 95% CI	PDM Average	PDM 95% CI
0.2 to 0.49	0.074	(0.058, 0.102)	0.060	(0.047, 0.082)
0.5 to 0.99	0.047	(0.038, 0.061)	0.058	(0.047, 0.075)
1.0 to 1.49	0.043	(0.035, 0.055)	0.061	(0.050, 0.078)
1.5 to 1.99	0.046	(0.036, 0.063)	0.042	(0.033, 0.058)
2.0 to 6.5 .	0.043	(0.038, 0.050)	0.056	(0.049, 0.065)

HD and DO cyclones, the CIs were inspected to determine if they overlapped. Because of the small number of measurements for each cyclone within coal type (n=12), the CIs tended to be wide, so the chance for overlap was increased. A statistically significant difference in bias was found when the two CIs did not contain an overlapping value. These results varied by coal type; however, for the overall bias data, there was a significant difference between the cyclones, with the HD cyclone exhibiting smaller bias than the DO. The results for the 95% CIs are presented in table 6.

Table 5.—Laboratory cyclone bias compared to impactor-defined ISO and MRE respirable mass concentrations and size distribution data

		DO MRE equiv. conc. mg/m^3	HD conc. mg/m^3	Impactor ISO conc mg/m^3	Impactor MRE conc mg/m^3	DO/ISO	HD/ISO	DO/MRE	HD/MRE	MMAD	GSD
Keystone Run 1	T-1	3.122	2.413	1.921	2.062	1.63	1.26	1.51	1.17	2.89	2.47
	T-2	2.924	2.315	2.216	2.403	1.32	1.04	1.22	0.96	3.29	2.30
	T-3	2.914	2.281	1.828	1.913	1.59	1.25	1.52	1.19	2.78	2.50
	T-4	2.866	2.288	1.808	1.918	1.59	1.27	1.49	1.19	3.51	2.72
Keystone Run 3	T-1	5.413	4.204	3.797	4.104	1.43	1.11	1.32	1.02	([1])	([1])
	T-2	5.286	4.110	4.033	4.388	1.31	1.02	1.20	0.94	([1])	([1])
	T-3	5.344	4.253	3.723	3.989	1.44	1.14	1.34	1.07	([1])	([1])
	T-4	5.277	4.233	3.851	4.160	1.37	1.10	1.27	1.02	4.54	3.00
Keystone Run 4	T-1	2.729	2.151	1.783	1.906	1.53	1.21	1.43	1.13	4.32	2.47
	T-2	2.684	2.165	1.700	1.810	1.58	1.27	1.48	1.20	5.12	3.10
	T-3	2.769	2.097	1.979	2.128	1.40	1.06	1.30	0.99	5.37	3.35
	T-4	2.784	([2])	1.812	1.952	1.54	([2])	1.43		6.08	3.03
Ill. No. 6 Run 5	T-1	3.122	2.413	2.498	2.889	1.25	0.97	1.08	0.84	4.85	2.25
	T-2	2.924	2.315	2.505	2.939	1.17	0.92	1.00	0.79	([3])	
	T-3	2.914	2.281	2.459	2.831	1.18	0.93	1.03	0.81	5.50	2.35
	T-4	2.866	2.288	2.382	2.766	1.20	0.96	1.04	0.83	5.54	2.38
Ill. No. 6 Run 6	T-1	4.808	4.702	4.237	4.851	1.13	1.11	0.99	0.97	5.82	2.21
	T-2	5.134	4.739	4.019	4.551	1.28	1.18	1.13	1.04	5.48	2.24
	T-3	5.220	4.965	4.258	5.000	1.23	1.17	1.04	0.99	5.09	2.03
	T-4	5.377	5.713	4.131	4.838	1.30	1.38	1.11	1.18	5.47	2.27
Ill. No. 6 Run 7	T-1	2.626	2.647	2.202	2.581	1.19	1.20	1.02	1.03	5.89	2.23
	T-2	2.617	2.741	2.220	2.606	1.18	1.24	1.00	1.05	5.86	2.20
	T-3	2.634	2.798	1.990	2.339	1.32	1.41	1.13	1.20	6.04	2.17
	T-4	2.713	2.668	2.143	2.495	1.27	1.25	1.09	1.07	7.29	2.22
Pgh. 20 µm Run 8	T-1	2.521	2.187	2.019	2.243	1.25	1.08	1.12	0.97	11.30	2.26
	T-2	2.625	2.405	2.136	2.343	1.23	1.13	1.12	1.03	10.82	2.77
	T-3	2.712	2.352	2.598	2.898	1.04	0.91	0.94	0.81	11.75	3.01
	T-4	2.755	2.394	2.311	2.585	1.19	1.04	1.07	0.93	12.49	2.86
Pgh. 20 µm Run 9	T-1	4.675	3.988	4.136	4.563	1.13	0.96	1.02	0.87	11.14	3.00
	T-2	4.920	4.135	3.909	4.352	1.26	1.06	1.13	0.95	10.76	2.82
	T-3	5.912	4.335	3.741	4.122	1.58	1.16	1.43	1.05	9.89	2.87
	T-4	5.361	4.495	3.858	4.234	1.39	1.17	1.27	1.06	9.62	2.80
Pgh. 20 µm Run 10	T-1	1.973	1.850	1.832	2.029	1.08	1.01	0.97	0.91	10.09	2.70
	T-2	2.093	1.860	1.708	1.880	1.23	1.09	1.11	0.99	10.62	2.66
	T-3	2.193	1.872	1.782	2.000	1.23	1.05	1.10	0.94	11.55	2.74
	T-4	2.262	1.958	1.748	1.964	1.29	1.12	1.15	1.00	12.57	2.75
Pgh. 4 µm Run 11	T-1	3.137	2.545	2.095	2.291	1.50	1.21	1.37	1.11	2.31	2.14
	T-2	2.628	2.242	1.949	2.124	1.35	1.15	1.24	1.06	2.13	2.03
	T-3	2.491	2.174	1.822	1.971	1.37	1.19	1.26	1.10	2.33	2.45
	T-4	2.419	2.185	1.929	2.110	1.25	1.13	1.15	1.04	2.23	2.07
Pgh. 4 µm Run 12	T-1	4.269	3.884	3.310	3.668	1.29	1.17	1.16	1.06	2.98	2.18
	T-2	4.144	3.836	3.108	3.415	1.33	1.23	1.21	1.12	3.06	2.11
	T-3	4.193	3.916	2.396	2.769	1.75	1.63	1.51	1.41	2.97	2.07
	T-4	4.228	4.071	3.050	3.420	1.39	1.33	1.24	1.19	2.79	1.99
Pgh. 4 µm Run 13	T-1	2.127	1.902	1.691	1.873	1.26	1.13	1.14	1.02	2.62	2.00
	T-2	2.164	1.942	1.564	1.751	1.38	1.24	1.24	1.11	2.94	2.02
	T-3	2.200	1.992	1.618	1.784	1.36	1.23	1.23	1.12	2.41	1.99
	T-4	2.169	1.953	1.760	1.948	1.23	1.11	1.11	1.00	2.68	2.16
Pgh. 10 µm Run 14	T-1	1.938	2.122	1.877	2.178	1.03	1.13	0.89	0.97	3.77	1.98
	T-2	1.816	2.058	1.717	1.957	1.06	1.20	0.93	1.05	4.38	2.14
	T-3	1.791	1.931	1.928	2.261	0.93	1.00	0.79	0.85	3.75	1.95
	T-4	1.769	2.028	1.895	2.248	0.93	1.07	0.79	0.90	5.18	2.13
Pgh. 10 µm Run 15	T-1	3.190	3.625	3.095	3.683	1.03	1.17	0.87	0.98	3.82	1.88
	T-2	3.295	3.818	3.171	3.770	1.04	1.20	0.87	1.01	4.03	2.05
	T-3	3.372	3.735	2.831	3.337	1.19	1.32	1.01	1.12	4.10	1.94
	T-4	3.357	3.989	2.972	3.492	1.13	1.34	0.96	1.14	4.30	1.98
Pgh. 10 µm Run 16	T-1	1.489	1.786	1.507	1.780	0.99	1.18	0.84	1.00	4.51	1.88
	T-2	1.656	1.770	1.496	1.715	1.11	1.18	0.97	1.03	3.91	2.08
	T-3	1.684	1.973	1.800	2.106	0.94	1.10	0.80	0.94	4.66	2.06
	T-4	1.681	2.006	1.846	2.176	0.91	1.09	0.77	0.92	4.87	2.16
					Average	1.27	1.15	1.13	1.02		

[1]Impactors not run for intervals, calculations based on T-4 data.
[2]Filter dropped.
[3]Stage filter dropped.

Table 6.—Statistical significance of cyclone bias testing against ISO and MRE definitions

95% confidence intervals for mean DO and HD bias by coal type					
Coal type	DO/ISO		HD/ISO		Significant difference?
	Mean	95% CI	Mean	95% CI	
Keystone	1.48	(1.41, 1.55)	1.16	(1.09, 1.22)	Yes.
Illinois No. 6	1.22	(1.19, 1.26)	1.14	(1.04, 1.25)	No.
Pittsburgh 20 µm	1.24	(1.15, 1.33)	1.06	(1.02, 1.12)	Yes.
Pittsburgh 4 µm	1.37	(1.28, 1.46)	1.23	(1.14, 1.32)	No.
Pittsburgh 10 µm	1.02	(0.97, 1.08)	1.16	(1.10, 1.23)	Yes.
Overall	1.27	(1.22, 1.32)	1.15	(1.12, 1.18)	Yes.
95% confidence intervals for mean DO and HD bias by coal type					
Coal type	DO/MRE		HD/MRE		Significant difference?
	Mean	95% CI	Mean	95% CI	
Keystone	1.38	(1.30, 1.45)	1.08	(1.01, 1.15)	Yes.
Illinois No. 6	1.06	(1.02, 1.09)	0.98	(0.89, 1.07)	No.
Pittsburgh 20 µm	1.12	(1.04, 1.20)	0.96	(0.91, 1.01)	Yes.
Pittsburgh 4 µm	1.24	(1.17, 1.31)	1.11	(1.04, 1.18)	No
Pittsburgh 10 µm	0.87	(0.82, 0.92)	0.99	(0.94, 1.05)	Yes.
Overall	1.13	(1.08, 1.18)	1.02	(0.99, 1.06)	Yes.

IN-MINE

Mine testing was conducted during the summer of 2003 in four coal mines in different coal-producing regions of the United States. A total of 72 in-mine comparisons of PDM to reference samplers and 40 companion determinations of cyclone bias to ISO and MRE definitions were conducted. While additional shifts of data were successfully measured with the PDM, not all were paired with valid reference comparison samples.

Concentration Comparison

Table 7 compares the in-mine PDM and the adjacent BGI-4CP reference concentration measurements for various occupations. The ratio of PDM to reference concentrations for all mine data was 0.98. This agrees with laboratory observations where the PDM demonstrated a small negative bias compared to reference samplers.

The paired t-test was used to evaluate whether the mean difference, computed as PDM minus BGI-4CP, was equal to 0. If this were the case, the two samplers would be considered to have the same reading. The data from the four mines are shown in table 7. When these data were analyzed individually by mine, the means of the four difference values did not significantly deviate from 0. In all cases, the calculated test statistic was less than the critical two-tail t-value ($p > 0.05$), so the hypothesis of no difference was accepted. These results are presented in table 8.

The data from the four mines were then combined ($N = 72$ pairs). This large sample size greatly increased the power of the test such that if this test finds a statistically significant difference, the difference would be near the LOD of the experiment, in other words, it could detect a small effect size [Cohen 1988]. The mean difference between the PDM and reference sampler was -0.024 mg/m^3. It was further noted that the distribution of the differences between the paired observations for the entire data set demonstrated a substantial deviation from normality because of the presence of two extreme outliers, one in each tail of the distribution. Because the normality assumption of the paired t-test was violated, a nonparametric, or distribution-free, test was then used. The Wilcoxon signed ranks test is analogous to the paired t-test. It is based on the ranks of the observations rather than their actual values. While this test showed a significant statistical difference from 0 ($p = 0.028$ shown in table 8), practically speaking, this difference was at the LOD of the reference samplers.

To further statistically test for agreement between the sampler readings, an ICC for absolute agreement was computed for the overall mine data. The ICC between the PDM and reference sampler was found to equal 0.93 (F-value for two-way mixed-effects model = 29.99, $p < 0.0001$; 95% CI (0.90, 0.96)). An ICC of 0.80 is considered good agreement; thus, the data demonstrate excellent absolute agreement between the PDM and reference sampler. These results suggest that the two samplers could be considered interchangeable.

Table 8 also shows that mines 1 and 4 had a high correlation between data pairs. However, the correlation is less at mine 2, a longwall mine, which had high dust gradients and airflows. Mine 3, which had a scrubber fan-equipped mining machine, also exhibits a lower correlation. High variability between dust samplers is expected when comparing single-point measurements in a mine environment due to large spatial dust gradients that may be especially prevalent in some mines.

All mine data are further compared in figure 5. Mine concentration levels were lower than the laboratory levels and did not exceed 2 mg/m^3. The lower R-squared values from the mine data are a reflection of the difficulties in obtaining precise side-by-side measurements in the mine rather than any imprecision of the instruments.

Durability

Mine testing of the PDM demonstrated successful durability. A total of 115 unit shifts of data were available for data collection, and only 7 shifts of data were lost due to the PDM's failure to record the end-of-shift mass concentration. This is an availability rate of 93%, compared to an availability rate of 88% for the reference samplers. Reasons for sample losses are included in table 7. Overall, the PDM was somewhat more successful than the reference samplers in measuring dust levels in the underground sampling environment during these tests.

Table 7.—Mine data results

Occupation	Shift 1		Shift 2		Shift 3		Shift 4		Shift 5	
	PDM conc. mg/m^3	BGI-4CP conc. mg/m^3	PDM conc. mg/m^3	BGI-4CP conc. mg/m^3	PDM conc. mg/m^3	BGI-4CP conc. mg/m^3	PDM conc. mg/m^3	BGI-4CP conc. mg/m^3	PDM conc. mg/m^3	BGI-4CP conc. mg/m^3
Miner operator	0.79	flow fault	0.36	0.44	0.56	0.6	0.44	0.57	0.32	battery fault
Loader operator	0.26	flow fault	0.32	0.29	0.17	0.21	0.18	battery fault	0.16	0.18
Left bolter	1.30	battery fault	0.60	0.55	0.96	0.9	0.60	battery fault	0.94	0.98
Foreman	1.07	battery fault	0.15	0.17	0.56	0.66	0.52	0.60	0.56	0.59
Tail shearer operator	1.50	flow fault	([1])	flow fault	1.20	1.21	1.40	1.25	1.40	1.48
Head shearer operator	1.10	flow fault	0.90	0.92	0.80	flow fault	0.90	0.89	0.80	1.30
Jack setter	1.20	1.271	1.30	1.30	0.90	1.045	1.00	0.98	0.85	0.91
Guest	2.06	NR	0.70	NR	0.40	NR	0.30	NR	0.16	NR
NIOSH 1	0.79	0.86	0.90	1.010	water in sensor	1.23	[2]0.6	0.89	0.80	0.77
NIOSH 2	0.64	0.49	0.90	0.69	0.80	0.98	0.66	0.95	0.60	0.77
Operator/helper	0.77	0.81	0.92	1.09	lost grit pot	0.96	0.51	0.61	0.82	0.90
Helper/operator	0.54	([3])	1.33	0.91	0.81	0.77	0.77	0.64	0.99	0.85
Bolter	lost grit pot	0.17	[4]0.85	1.12	lost grit pot	([1])	0.45	cracked cassette	0.57	0.64
Guest	0.54	NR	2.37	NR	0.76	NR	0.26	NR	4.28	NR
NIOSH 1	pump stop	0.71	pump stop	0.69	0.59	0.67	0.35	0.42	0.46	pump not run
NIOSH 2	0.66	0.79	0.58	cracked cassette	0.47	0.52	0.37	0.40	0.61	0.512
Miner helper	0.27	0.26	0.23	0.24	0.48	0.46	0.22	0.21	0.31	0.28
Bolter	0.63	0.54	0.22	0.21	0.41	0.35	0.22	0.19	0.19	0.22
Shuttle car	0.45	0.45	0.18	0.19	0.40	0.29	0.23	0.17	0.33	0.25
NIOSH 1	flow fault	([1])	0.32	0.36	0.53	0.53	0.45	0.51	0.46	0.56
NIOSH 2	0.18	0.21	0.20	0.19	0.40	0.43	0.45	0.49	0.56	0.61
Guest	0.64	NR	0.64	NR	0.25	NR	1.73	NR	0.15	NR

NR No reference sampler used.
[1]Sample prematurely terminated due to loss of PDM sample.
[2]End-of-shift flow rate = 2.69 L/min.
[3]Tube disconnected from reference sampler.
[4]Water in cyclone.

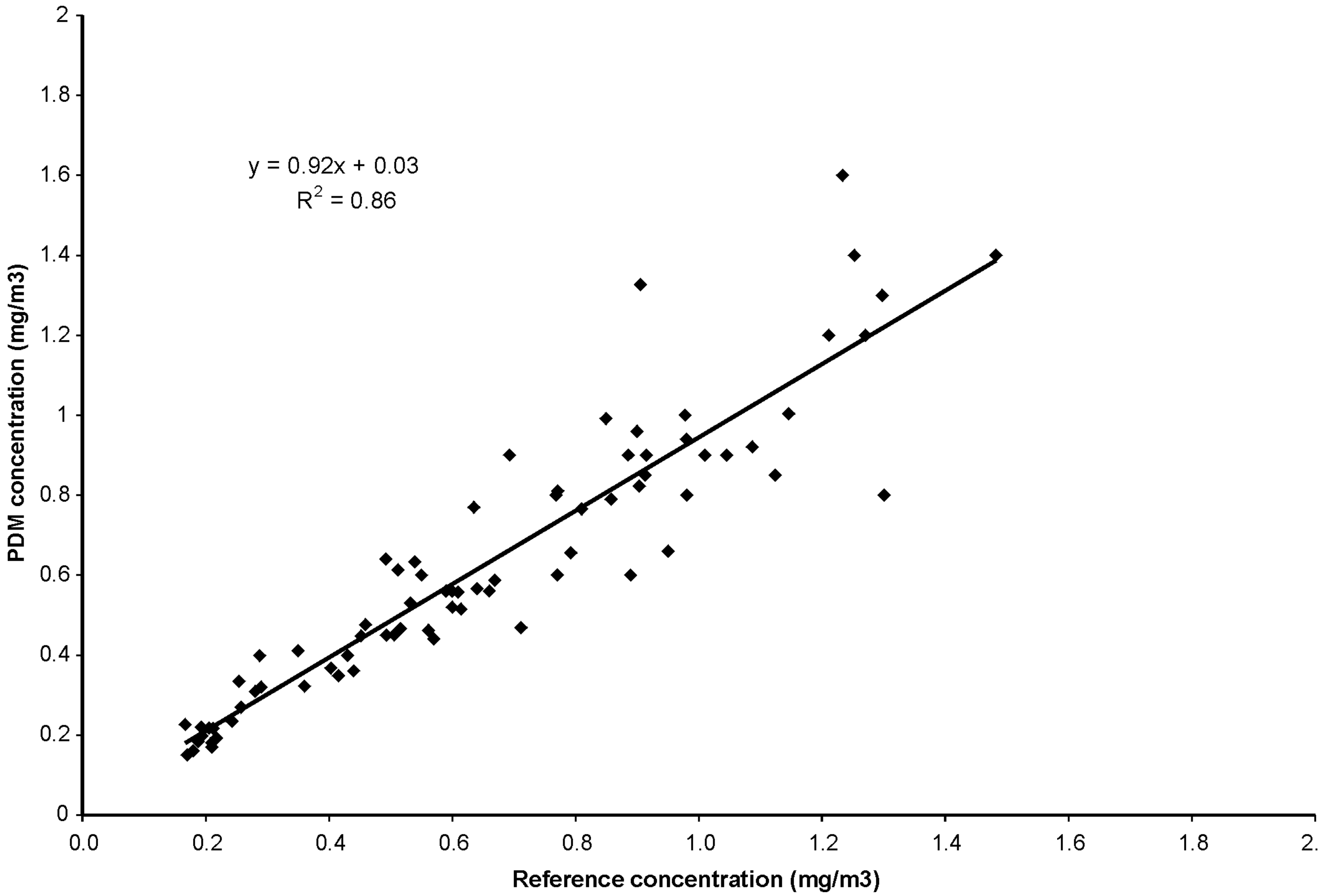

Figure 5.–Regression analysis of all mine data.

Table 8.—Paired t-test for mine data (testing mean difference equal to 0)

	n	Pearson Correlation Coefficient	Mean difference (PDM minus Ref.), mg/m^3	t	p-value
Mine 1	13	0.98	-0.034	-2.16	0.052
Mine 2	19	0.78	-0.060	-1.61	0.12
Mine 3	16	0.78	-0.017	-0.43	0.68
Mine 4	24	0.94	0.005	0.48	0.64
Overall	72	0.94	-0.024	[1]-2.19	0.028

[1]z-statistic for Wilcoxon signed ranks test (nonparametric test for two paired samples).

Table 9.—Mine cyclone bias compared to impactor-defined ISO and MRE respirable mass concentrations and size distribution data

Mine	Reference cyclone to impactor defined respirable concentrations				Size distributions	
	DO/ISO	HD/ISO	DO/MRE	HD/MRE	MMAD	GSD
Mine 1	0.94	1.04	0.83	0.91	9.62	2.94
Mine 2	1.01	1.13	0.89	1.00	8.08	2.75
Mine 3	1.25	1.09	1.14	1.00	9.90	5.15
Mine 4	1.08	0.96	0.96	0.85	11.27	3.96
Average	1.07	1.06	0.95	0.94		

Cyclone Bias Results

In the mine, the average biases of the DO and HD cyclones to the MRE and ISO standards were determined. Table 9 contains averaged results for the 10 samples from each mine and the overall average for all test mines. The average ratio of the sampler to the impactor-defined respirable mass fraction was quite similar. Note, however, that compared to the ISO standard the DO ratio ranged from 0.94 to 1.25, a difference of 0.31, whereas the HD ratio had a range of 0.17. We see similar results when the ratio is compared to the MRE standard, with a DO range of 0.31 and an HD range of 0.15. The HD cyclone had lower variability between mines than the DO cyclone when compared to either the ISO or MRE standards. This trend was also observed in the laboratory data, but given the large RSD and small sample size of the mine data set, statistical significance of the data was not established.

DISCUSSION

Over the past 35 years, accurate measurement of the workplace respirable dust exposures of miners has been difficult. During that period, the mining industry has made the best use of existing sampling technologies. The development of the PDM to provide timely, accurate on-shift and end-of-shift data on worker exposure to dust concentration levels enables heretofore unavailable approaches for labor, management, and Government to avoid overexposure to coal mine dust on any given shift.

FUNCTIONALITY

Development of a truly functional sampler has involved technical compromises in several areas. These include changing the inlet location, addition of a tube to conduct the sample to the sampler, and adoption of a different cyclone. These changes, when taken as a whole, do not impair the measurement of respirable dust within an accuracy criterion of ±25%.

Mine workers have complained to the authors for years that the current personal sampler inlet hanging from their lapel interferes with their ability to work in the tight confines of a coal mine. Dirty mine clothing and jacket interference with the inlet have also been unquantified potential sources of error. The tube and pump added to the worker further interfered with his or her job. To improve the ergonomic acceptability of the unit, the sample inlet was relocated from the lapel to the bill of the hard hat, and the tube and pump were made a part of the cap light system. The inlet is still within the breathing zone, but we lose some comparison to historical lapel sampling.

To minimize the profile and weight of an inlet on the hard hat, conductive rubber tubing was used to move the sample to the cyclone and sampler located on the belt. Dust loss to the walls of the tubing was inevitable, but careful design kept the loss of smaller respirable dust to less than 3% [Peters and Volkwein 2003]. This change also meant that a cyclone that could accept a tubing inlet was required.

In the final analysis, despite the compromises in design that intentionally traded a little accuracy for functionality, the PDM still accurately measured coal mine dust in the laboratory within ±25% of reference samplers. In mines, the PDM mean concentrations were equivalent to those of the reference samplers. In addition, the data show that the HD cyclone defines the respirable coal dust fraction as well as or, in many cases, better than the currently used DO cyclone.

Mine workers reported that the PDM was comfortable to wear despite the extra burden of the reference sampler that most wore. On occasion, when the reference samplers were not worn, most workers reported no difference between their existing cap lamp batteries and the PDM. When a dust monitor is easy to wear, it also becomes a more functional tool to encourage mine workers to control dust exposure levels.

TIMELY DATA

The concept of a rugged, lightweight dust monitor that provides the cumulative dust exposure of an individual at any time during the shift is a powerful tool that can be used to prevent overexposures. An example of the type of data available is illustrated in figure 6. The cumulative exposure reading is a good estimate of the average workplace dust levels. The cumulative exposure evens periods of high and low exposures to provide an averaged exposure number. This value can be reduced, for example at 13:00 in this figure, by breaking for lunch where little dust exposure occurred and caused the cumulative exposure levels to decline. The projected exposure reading, however, never declines because it is calculated based on the mass of dust to a given point in time divided by the sample air volume projected for the entire shift. Another way to look at this is to say that if the worker receives no additional dust exposure, this would be the shift exposure. Note that the projected exposure becomes the shift exposure at the end of the sampling time period.

During mine testing, both miners and management were able to use the real-time data to identify dust levels higher than normal and, using the PDM-provided information, locate the problems or devise strategies to minimize the miners' exposure. In one case, high intake dust levels on a longwall were traced to a defective dust control on a roof bolting machine operating in the intake. In another instance, high levels in another intake location were traced to an improperly sealed brattice near a face fan. Miners commented that the screen displays were difficult to see and suggested that an illuminated display would be preferable. The next generation of instruments is planned to include a larger and illuminated display.

DATA TRENDS

Figure 7 illustrates how the data from PDM units may be used to examine trends in dust exposures. This type of analysis can be used to spot anomalous readings, keep track of typical exposure data, and identify where in the work cycle exposures occur. The mine engineer, wearing the guest unit in this example, was intentionally trying to increase his dust exposure, which created large spikes in his cumulative concentration. This is atypical when compared to the exposures of others on the section.

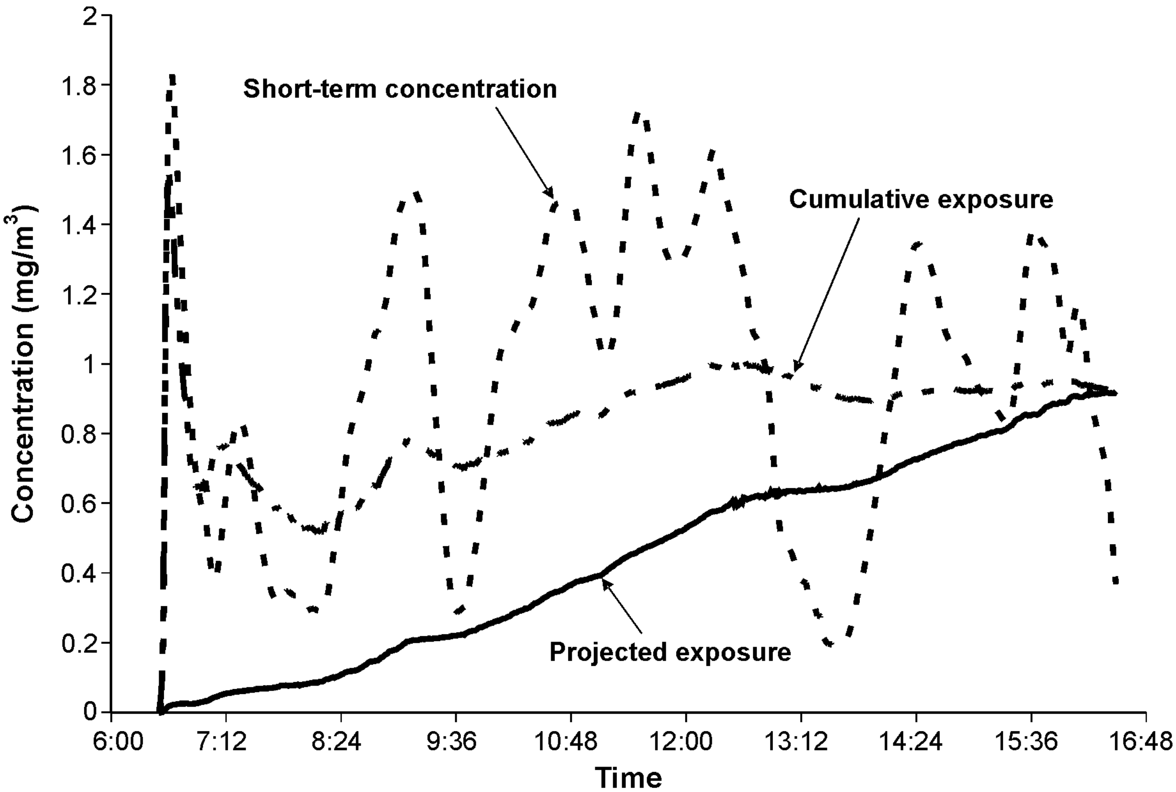

Figure 6.–Example of individual PDM data results.

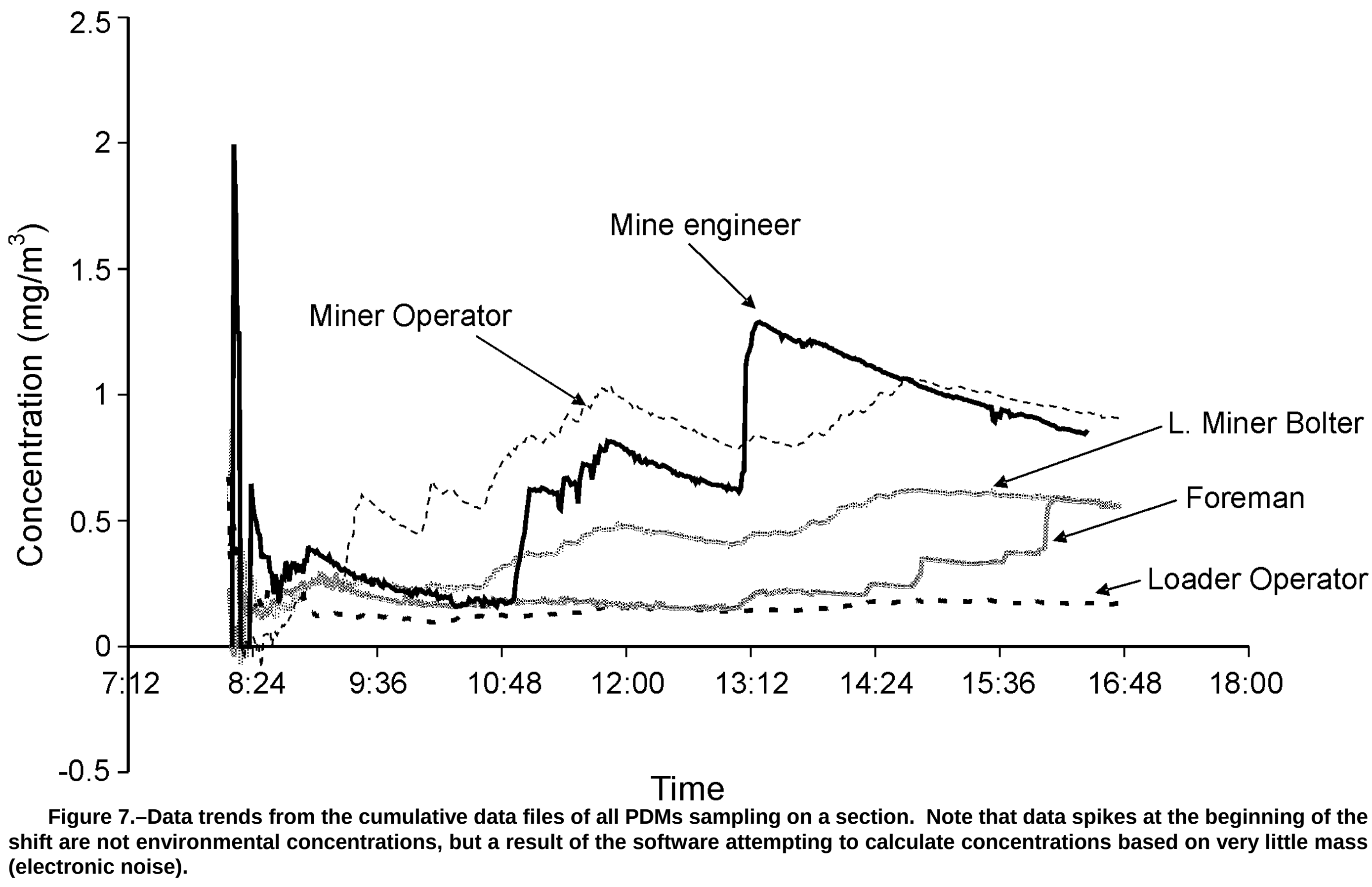

Figure 7.–Data trends from the cumulative data files of all PDMs sampling on a section. Note that data spikes at the beginning of the shift are not environmental concentrations, but a result of the software attempting to calculate concentrations based on very little mass (electronic noise).

As expected, these trends show the relative ranking of dust exposure by occupation, where the loader operator has the lowest exposure and the miner operator has the highest exposure on the section. We also can see that the foreman's exposures were not gradual like those of the other occupations, but occurred in steps as he would enter very dusty areas to take measurements or adjust ventilation devices.

This type of information is not available with conventional filter sampling. As additional experience is obtained with the PDM, other data trend analyses should help miners understand, control, and prevent overexposure to dust.

BIAS

The negative bias of the PDM determined in the laboratory study was an expected result from this testing. In the PDM, the dust sample from the HD cyclone passes through a transition and heater section before being deposited onto the filter for mass measurement. This additional sample flow path is not present in the reference sampler, where dust is deposited directly onto the filter as it leaves the cyclone. The bias, however, was minimized through empirical testing and design choices of the internal flow path.

Bias in the cyclone tests resulted from differences in coal size and type being sampled. To minimize bias, Bartley et al. [1994] had recommended that cyclones be operated at flow rates that produce the lowest bias in the region of most commonly sampled dust sizes and types. The PDM cyclone was operated at the flow rate recommended to produce minimum bias, resulting in good agreement with the ISO definition of respirable dust in this work. Attempts to correct for bias through use of a correction factor (the current practice with the personal coal mine sampler) will inevitably result in some coal types being over- or undersampled. This results from the wide standard deviation of the data set from which the average correction factor was computed. Selecting appropriate cyclone flow rates to minimize bias should result in more accurate dust measurements.

CONCLUSION

Six PDM prototype units were successfully tested in the laboratory and in four underground coal mines. Results showed that the units provide accurate readings of a miner's dust exposure, were rugged enough to survive the underground mine environment, and provided data on instrument faults or potential tampering.

The laboratory work specifically assessed the performance of the new dust monitor by comparing the performance to that of currently used personal samplers in a two-step manner. The first step demonstrated that the PDM accurately measured mass according to accepted criterion. The second step showed that the HD cyclone was better than the DO cyclone in meeting both the ISO and MRE definitions of respirable dust. The combination of these two results leads to the conclusion that the PDM is equivalent or better than the currently used personal sampler in measuring coal dust in the laboratory.

In-mine concentration data measurements taken by PDM or reference samplers suggest that the two samplers could be used interchangeably. Use of the HD cyclone in mines also demonstrated good agreement to ISO and MRE definitions of respirable dust. The durability and comfort of the PDM led to good acceptance by mine workers.

The timely PDM dust exposure data provided information that resulted in quicker recognition of the failure of engineering dust controls. This type of information enables both miners and management to prevent overexposure to coal mine dust. The information also shows how actions and equipment affect a miner's dust exposure. Miners can quickly learn how to better reduce their dust exposures by minimizing certain actions and by better positioning themselves during given activities.

As this technology is commercialized, further applications of the PDM data can be developed to better protect mine workers' health. Minor shortcomings of the prototype PDM units were discovered and are being corrected by R&P. Overall successes documented in this work have led to an early commercial version that promises to correct many of the minor problems identified in the prototype. Further in-mine trials will determine the long-term durability, stability, and maintenance requirements for this new dust monitor.

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