The Proceedings of the 29th International Technical Conference on Coal Utilization & Fuel Systems

April 18 – 22, 2004
Sheraton Sand Key
Clearwater, Florida, USA

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WELCOME

On behalf of the Coal Technology Association, the American Society of Mechanical Engineers' Fuels & Combustion Technologies Division, the U.S. Department of Energy, and the National Energy Technology Laboratory, I welcome you to the 29th International Technical Conference on Coal Utilization & Fuel Systems. We are truly honored to have you participate in our annual conference.

I want to take this occasion to thank the many people who work so hard to make this conference the success that it continues to be each year. The Clearwater Conference Committee works diligently throughout the year to organize the panels, tutorials and technical sessions. They do this under the direction and guidance of my two co-chairmen: Dr. Lawrence A. Ruth of the National Energy Technology Laboratory, U.S. Department of Energy; and Stanley J. Vecci of The Babcock & Wilcox Company. In addition, special mention must be made of those who chair the Tutorials: Bruce Folkedahl of UNDEERC, Alan Paschedag, representing ASME-FACT, Ken Bryden of Iowa State University and Klaus Lackner of Columbia University. And the Panels: Dr. Lowell Miller of the U.S. Department of Energy, Mike Eastman of NETL, Edmundo Vasquez of RMT Alliant Energy, and last and certainly not least, Dr. Bob Romanosky of NETL who continues to bring the world's leading experts to us each year in his dynamic and exciting panel on Global Climate Change.

As we approach our 30th year of conducting these international technical conferences, those of us in this room and other leaders of our industry face an exciting, and unprecedented challenge. The need to reduce the nation's dependence on imported oil and to increase the production and utilization of domestic resources has never been greater. Coal has now taken center stage in the national quest for energy independence. Our job is an essential one: developing the technologies that will allow us to burn this valuable natural resource more efficiently and cleanly. Today there is no debate in Washington or anywhere else about the importance of clean coal technology.

I thank all of you for being with us in Clearwater, and I hope that our program meets and exceeds all of your expectations.

Barbara A. Sakkestad
Vice President
Coal Technology Association

DEVELOPMENT AND EVALUATION OF AN NEW PERSONAL DUST MONITOR FOR UNDERGROUND MINING APPLICATIONS

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ABSTRACT

An inertial mass measurement technology named the tapered element oscillating microbalance has been adapted for the measurement of respirable coal dust concentrations in underground mines. The new instrumentation called the personal dust monitor (PDM) holds the promise to provide miners and mine operators with continuous personal exposure information during a shift. The measurement methodology, also known as the TEOM® system, is unique in its ability to collect suspended particles on a filter while simultaneously determining the accumulated mass with NIST-traceability.

A number of hurdles were overcome to enable the use of TEOM technology in the underground mining application. This required miniaturization, the use of the latest battery technology to power the microbalance and miner's cap lamp operation, and the development of a new physical configuration to isolate the mass measurement system from external shocks. These advances were achieved through a multi-year project funded by NIOSH and carried out by Rupprecht & Patashnick with strong support from both labor and industry.

In early 2003, researchers at NIOSH tested the PDM response to different coal types in the laboratory. Results showed that the PDM met the accuracy criteria established by NIOSH for comparability of sampling methods. Following the successful completion of these tests, the dust monitors were challenged at four different coal mines over the summer. In these trials, the PDM successfully measured the respirable dust concentrations in 108 out of 115 shifts. Results indicate that the PDM performs similarly to collocated manual reference samplers. The underground mining tests also showed that the PDM was convenient to wear, robust, provided accurate information, and generated timely data that could be used to protect miners from overexposure to coal dust. More detailed trials of the PDM technology are planned.

INTRODUCTION

Measurement of personal exposure to coal mine dust has remained essentially unchanged since the passage of the 1969 Coal Mine Health and Safety Act. At the recommendation of The Secretary of Labor and the Federal Advisory Committee on the Elimination of Pneumoconiosis among Coal Mine Workers[1] NIOSH embarked on research to improve sampling instrumentation for use in the mining industry. 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-1). 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.

Coal Workers 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 work shift[2,3]. The Mine Safety and Health Administration (MSHA) uses a periodic method to audit compliance with this standard and to assess the effectiveness of the dust control plan. Under the current dust control strategy, MSHA primarily relies on the implementation of a well-designed dust control plan and not on sampling to prevent overexposures for individual shifts. This periodic method of audit and plan verification works well in other industries when dealing with fixed work sites 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 over 1000 annual deaths attributed to CWP in U.S. coal mines[4].

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

An essential design goal of this person-wearable dust monitor was that the device be acceptable to the miners. This was accomplished by incorporating the monitor into the existing miners' 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[5,6,7].

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)[8] has recommended that the definition of respirable dust follow the convention described by Solderholm et al.[9] 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 currently used 10-mm Dorr Oliver (DO) dust cyclone has bias relative to both the ISO and the former United Kingdom's, Mining Research Establishment (MRE) convention[10]. The cyclone chosen for use in the PDM required a configuration that could accept the tube coming from the hard hat inlet. The cyclone selected followed the Higgins and Dewell (HD) design previously shown through testing to have low bias relative to the ISO convention[11].

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 the size distribution of the dust[12,13]. Therefore, the ability of the PDM to measure a mass of respirable coal mine dust accurately 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 ascribed to the 10-mm DO cyclone when determining the respirable mass for different coal mine aerosols.

This report describes the theory of operation, description, and 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 to 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 PDM AND THEORY OF OPERATION

The PDM incorporates innovations in battery, mass measurement and information management technology to achieve its design and performance goals. The device is intended to be virtually "invisible" to the miner as a replacement for the cap lamp and battery currently employed in mines.

The TEOM mass sensor holds the key to the accurate, time-resolved measurements provided by the PDM[14]. R&P has applied this mass measurement technique in 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 on par with 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 brings new challenges. As a result of a multi-year effort, R&P invented a hardware-based compensation approach that effectively isolates the mass monitor from external shocks and holds the key to providing microgram mass resolution in challenging applications.

System Configuration

The PDM is a respirable dust sampler and a gravimetric analysis instrument that is part of a belt-worn mine cap lamp battery. Components of the device include: sample 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 these components. The enclosure of the PDM is hardened to withstand the harsh conditions found in the mine environment, with the system designed to meet MSHA intrinsic safety type approval requirements.

The PDM system also includes a docking station simultaneously used to download stored information to a PC and recharge its batteries for the next work shift (Figure 2). This module also provides the means for the user to upload the operating parameters for the next work shift into the PDM, including the starting and ending times for monitor's operation.

Sample Flow Path

A 2.2 liter per minute flow of particle-laden air from the mine atmosphere enters an inlet mounted on the bill of the miner's hard hat, and passes through conductive tubing before reaching the HD cyclone at the entrance of the PDM. The sample stream with respirable particles that exits from the cyclone proceeds through a heated section of tubing to remove excess moisture, and then enters the unit's removable mass sensor. As the air flow 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), who changes the particle collection filter and cleans the unit after the end of each work shift. The mass measurement system is based upon the tapered element oscillating microbalance (TEOM® technology) pioneered by R&P, and is described below.

Flow Measurement and Control

Downstream of the mass sensor, the filtered air stream flows through an orifice used in conjunction with a differential pressure measurement to determine the volumetric flow rate. In-line relative humidity 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 air pressure in the mine. The PDM uses these inputs, together with the sample stream 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 control the speed of the pump dynamically so that the constant 2.2 liter per minute flow rate required for proper size separation by the cyclone, under the mine's ambient temperature and pressure conditions.

Battery Configuration

The two identical battery packs inside the PDM provide power to the miner's cap lamp and the particle sampling and analysis system. The batteries can be recharged from a complete discharge in less than six hours to provide maximum use of the monitor. These 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 cap lamp and microbalance functions in a size and weight approximating those of the current battery pack. A filter-based, true mass weighing technique called the tapered element oscillating microbalance (TEOM technology) has been optimized and miniaturized to fit into the small space available in the PDM while providing a mass resolution of 1 microgram. A microprocessor-based controller collects real-time inputs from sensors and the microbalance to provide a full record of the dust loadings and mine environment to which a miner is exposed. The PDM continuously displays personal dust exposure information to the miner in numeric and graphic formats, and stores a full record of detailed data internally for downloading and analysis following the end of each work shift.

Data Handling

A microprocessor-based electronics system controls all aspects of the PDM's operation and manages the data computed by the system. The device stores the readings from its built-in environmental sensors and mass sensor internally for downloading following the end of the shift, and provides summary information on a continuous basis to the miner through a backlit screen with large characters. The display continuously shows the latest values for the cumulative mass concentration, the current dust concentration, and the miner's end-of-shift projected exposure. Through this interface, miners can gauge their current dust exposure, as well as the effectiveness of actions taken to reduce the in-mine dust concentration.

The shift-based statistics described above that are always available to miners but are protected from tampering by being accessible only to a responsible 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. The averaging time used for these readings is user-selectable prior to the start of the work shift, and can be set to a time base as short as 15 minutes for maximum instrument responsiveness. In this short term or engineering mode, the user executes two keystrokes to start and stop sampling to cover a particular period of interest. Operators may conduct these intra-shift measurements as often as desired, and data obtained during these trials are downloaded 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 that is clamped at its base and free to oscillate at its narrow end (Figure 4). The exchangeable filter cartridge mounted on its narrow end collects the respirable particles contained in the air stream that passes from the entrance of the mass sensor through the tapered element. Electronic components positioned around the tapered element 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 oscillating 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 a given period of time by the volume of the air sample that passed through the system during the same time frame. The system updates its mass concentration readings, shown in mg/m^3, every few seconds. The manufacturer uses NIST-traceable mass standards to calibrate the mass sensor of the PDM, i.e., to determine the relationship between mass change at the end of the tapered element and frequency change. Users also have the ability to verify this mass calibration of the system in the field for quality assurance purposes by using a pre-weighed filter as the means of adding mass to the end of the tapered element.

Momentum Compensation–Key to Miniaturization

In their conventional configurations, TEOM-based monitors were much too large to be used for personal exposure monitoring. The application of the TEOM technology for the mining application 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 the opposing phase to the tapered element. By applying this principal, energy loss from the tapered element oscillator to its surroundings approaches zero with the appropriate design of the momentum compensator. The tapered element effectively behaves as if it were mounted on a massive base without the use of a large mass. 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 requirements.

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 mass concentration measurements to those of side-by-side reference samplers, and determined cyclone bias.

Laboratory

Laboratory testing was conducted in a dust chamber at the Pittsburgh Research Laboratory (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[13] 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

Four identical PDM units were available for laboratory evaluation and 2 additional units were provided for the in-mine testing. Instruments were used as delivered to NIOSH 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 (BGI, Inc., Waltham, MA) dust sampler. 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 liters per minute. The device was operated according to the manufacturer's instructions, including correction factors to account for wall loss[15].

Dust Exposure Chamber

A Marple chamber provided a uniform atmosphere for the comparison of dust measuring instruments while maintaining good control of test variables[16]. The chamber was operated to produce dust concentrations nominally ranging from 0.2 mg/m^3 to 4 mg/m^3, following the NIOSH Guidelines for Air Sampling and Analytical Method Development and Evaluation. A turntable in the Marple chamber that holds the instruments was rotated at a rate of 1 to 2 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. The 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 TEOM Series 1400a Ambient Particulate Monitor (R&P Co., Inc., 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 #6 coal dusts were obtained from the Penn State University Coal Collection, State College, PA. The target median mass aerodynamic diameters of the Keystone and Illinois coals were 3 and 8 µm respectively. The Pittsburgh coal was ground at the Penn State University into three separate sizes to provide nominal median mass aerodynamic diameters of 4, 10, and 20 µm. A total of 5 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 pre- and post-weighed at the NIOSH/PRL controlled-atmosphere weighing facility using established procedures. Flow controlled, MSA Elf Escort 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 liters per minute for personal coal mine gravimetric pumps and impactor pumps and to 2.2 liters per minute ±0.022 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 liters per minute. Three filter blanks for each type of filter were also used for each day of testing.

Impactor Preparation

Model 290 Marple impactors, connected to MSA ELF Escort pumps operating at 2.0 ±0.020 liters per minute, 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 (polyvinyl chloride 34-mm diameter, 5-µm pore size). Mylar substrates were sprayed with an approximate one to ten micrometer thick layer of impaction grease (Dow Corning 316 Silicone Release Spray, Dow Corning Corp., Midland, MI). Substrates and the PVC final filters were then pre-weighed and loaded into the eight stage impactors. Three substrates and three filters were used as controls.

Experimental Design

For each of the 5 coal types or size distributions, 3 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 4 test-time interval groups of 3 samplers. Figure 5 illustrates a typical chamber test run setup.

For a typical test run, the internal computer for each PDM was implemented to automatically start at the same time, as were the manually operated gravimetric samplers. 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 monitor. The mass loading then determined the test-time interval. This procedure resulted in 4 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.

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 at the same time as the gravimetric samplers. The run time of each impactor, T_R, contained a portion of each time interval.

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 over-emphasizes the tails of the distribution. Cumulative lognormal plots often show curvature towards the tails, resulting in regression error of the distribution parameters. To account for this, data were only used if the R-squared values for the regression were greater than 0.95.

Analysis

The accuracy and precision were calculated from the laboratory 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 relative standard deviations (rsd's) 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. Bias was then calculated based on the mean concentration minus one. Accuracy was calculated based on the method provided by Kennedy, et al. Confidence limits were calculated based on the method used by Bartley[17] using a non-central Student-t distribution. These laboratory data were primarily used to judge the mass measurement capability of the PDM.

Data from all laboratory and mine 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 sets.

A second analysis determined how well the PDM compared to the currently used personal sampler. An indirect analysis was used for this 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 was used to calculate the ISO respirable fraction as defined by Solderholm (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 AIHA[18] 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 was 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 averaged. The mean bias was computed for each cyclone by coal type and overall. A 95% confidence interval was then calculated for each mean.

In-Mine Testing

In-mine testing used pair-wise testing partially to take into account the increased variability associated with personal sampling in mining conditions and to examine the mine worthiness issues of the instrument when worn by miners performing their normal duties. Limited testing was conducted for 5 shifts in each of four coal mines. This testing compared the end-of-shift gravimetric concentration measured by the PDM to the end-of-shift gravimetric concentration measured with a reference filter sampler using a 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 unit was designated as a spare to be 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. Chosen mines were located in Pennsylvania's Pittsburgh seam, Central Appalachian'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 operation, 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 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. Elf Escort flow-controlled pumps, set at a flow rate of 2.2 liters per minute, 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. Two NIOSH research technicians wore PDM and reference sampling equipment identical to those of the miners. In addition, the NIOSH personnel wore three other samplers that were used to measure cyclone bias.

Sampling was conducted for the entire shift length. The PDM was operated in program mode, with the shift length, start time and other identification data entered prior to 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 PDM's 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 PDM's finished sampling.

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

Analysis

Mine worker sampling measurements were expected to be less precise than the laboratory measurements because of the increased variability associated with personal sampling. To assess the degree of agreement between the PDM and the reference sampler, an intraclass correlation coefficient (ICC) was computed[19, 20]. 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"?

RESULTS AND DISCUSSION

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. For the laboratory experiments, the limit of detection (LOD), as defined by the mean filter blank mass value plus 3 standard deviations, for the HD and DO filters was 0.055 and 0.026 mg, respectively. The limit of quantification (LOQ), 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.

Mass Accuracy

Bias, precision, accuracy, and confidence limit calculation results presented in Table 1 are for individual instruments by coal type and for the overall laboratory experiments. For the overall data there is a 95% confidence that the individual PDM measurements were within ±25% of the reference measurement according to Kennedy's method. From the confidence interval data we can predict that 95% of future random samples will be within ±25% of a reference sampler measurement. The bias data in Table 1 are consistently negative, indicating that the PDM under-samples relative to the gravimetric standard. The instruments have high precision, indicated by the low $RSD_{x/r}$. Subsets of data for PDM serial number 105 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 was equivalent to that of the other PDM units. PDM serial number 102 also exceeded the upper confidence limit for the subset of Illinois #6 coal, presumably for similar reasons.

Cyclone Bias Results

For the combined laboratory data the bias of the HD cyclone was less than the DO cyclone using either the ISO or MRE definitions of respirable dust. Table 2 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. The precision of the size data used to calculate the equivalent ISO or MRE equivalent mass had an average rsd of 0.06 derived from the triplicate size distribution measurements of the T-4 time interval.

To compare the bias between the HD and DO cyclones, the confidence intervals were inspected to determine if they overlapped. Due to the small number of measurements for each cyclone within coal type (n=12), the confidence intervals tended to be wide, so the chance for overlap was increased. A statistically significant difference in bias was found when the two confidence intervals 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% confidence intervals are presented in the Table 3.

Mine Data

Mine testing was conducted during the summer of 2003 in 4 coal mines in different coal producing regions of the U.S. 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

The ratio of PDM to reference concentrations for all mine data was 0.98. This agrees with the laboratory observations where the PDM demonstrated a small negative bias compared to reference samplers. The regression data presented in Figure 6 show that the PDM gave a nearly equivalent response in the mine environment as it did in the laboratory. There is some decline in the r squared value due in part to the increased difficulty in obtaining good comparative samples on people in working environments.

To test for statistical agreement between the samplers from the mines, an intraclass correlation coefficient (ICC) for absolute agreement was computed for the overall mine data. The ICC between the PDM and reference sampler was found to be equal to .93 [F-value for two-way mixed effects model = 29.99, $p < .0001$; 95% CI (.90, .96)]. An ICC of .80 is considered good agreement, thus these data demonstrate excellent absolute agreement between the PDM and reference sampler. These results suggest that the two samplers could be considered interchangeable.

Durability

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

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 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. The presence of dirty mine clothing and jackets interfering with the inlet has been another unquantified potential source of error. The additional tube and pump added to the worker further interfered with their 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%[21]. 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 the mean concentrations of reference sampler concentrations. 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.

CONCLUSION

The laboratory work specifically assessed the performance of the new dust monitor by comparing the performance to currently used personal samplers in a two-step manner. The first step demonstrated that the PDM accurately measured mass according to accepted criteria. 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 considered interchangeable. 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 lead to good acceptance by mine workers.

As this technology is commercialized, further applications of the PDM data can be developed to better protect mine workers' health. 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.

Table 1. Laboratory mass measurement accuracy and confidence limits of the PDM .

Coal type	**Unit serial number**	**Bias**	**RSD x/r**	**accuracy**	**Confidence Limits**	
					Lower 5%	**Upper 95%**
Pgh 4u	101	-0.07	0.04	12.60	10.70	16.30
	102	-0.07	0.04	11.80	10.10	15.00
	104	-0.07	0.03	11.00	9.80	13.40
	105	-0.08	0.05	15.80	13.00	21.00
Pgh 10u	101					
	102	-0.12	0.06	18.40	16.00	22.90
	104	-0.06	0.06	13.20	10.80	17.80
	105	-0.13	0.08	21.70	18.40	27.80
Pgh 18	101	-0.11	0.02	14.90	13.00	22.60
	102	-0.05	0.05	11.10	9.00	15.20
	104	-0.04	0.03	7.20	6.10	9.50
	105	-0.13	0.02	16.10	14.80	18.40
Ill #6	101	0.00	0.06	10.40	7.80	15.70
	102	-0.10	0.08	20.80	16.80	28.40
	104	-0.05	0.06	13.10	10.00	19.10
	105	-0.19	0.06	25.40	22.60	31.70
Keystone	101	-0.03	0.04	7.80	5.90	11.80
	102	-0.04	0.03	8.40	6.70	11.60
	104	-0.01	0.04	6.70	5.00	10.40
	105	-0.12	0.02	15.00	14.00	17.00
Overall	101	-0.04	0.06	12.50	10.70	15.10
	102	-0.08	0.06	15.80	14.30	17.70
	104	-0.05	0.05	11.30	10.10	12.90
	105	-0.12	0.06	20.00	18.60	21.90

Table 2. Average ratio of individual cyclones to ISO or MRE definitions of respirable dust for the specific coal types tested.

(MRE) Dorr Oliver /ISO	1.27
Higgins Dewell/ISO	1.15
(MRE)Dorr Oliver/ MRE	1.11
Higgins Dewell/ MRE	1.02

Table 3. The HD cyclone used in the PDM has statistically less bias than the DO when results are compared to the International Standards Organizations definition of respirable dust.

95% Confidence Intervals for Mean DO and HD Bias by Coal Type

Coal Type	DO/ISO		HD/ISO		Significant Diff
	Mean	95% CI	Mean	95% CI	
Keystone	1.48	(1.41, 1.55)	1.16	(1.09, 1.22)	Yes
Illinois	1.22	(1.19, 1.26)	1.14	(1.04, 1.25)	No
Pittsburgh20	1.24	(1.15, 1.33)	1.06	(1.02, 1.12)	Yes
Pittsburgh4	1.37	(1.28, 1.46)	1.23	(1.14, 1.32)	No
Pittsburgh10	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

Figure 1. Major components of the PDM.

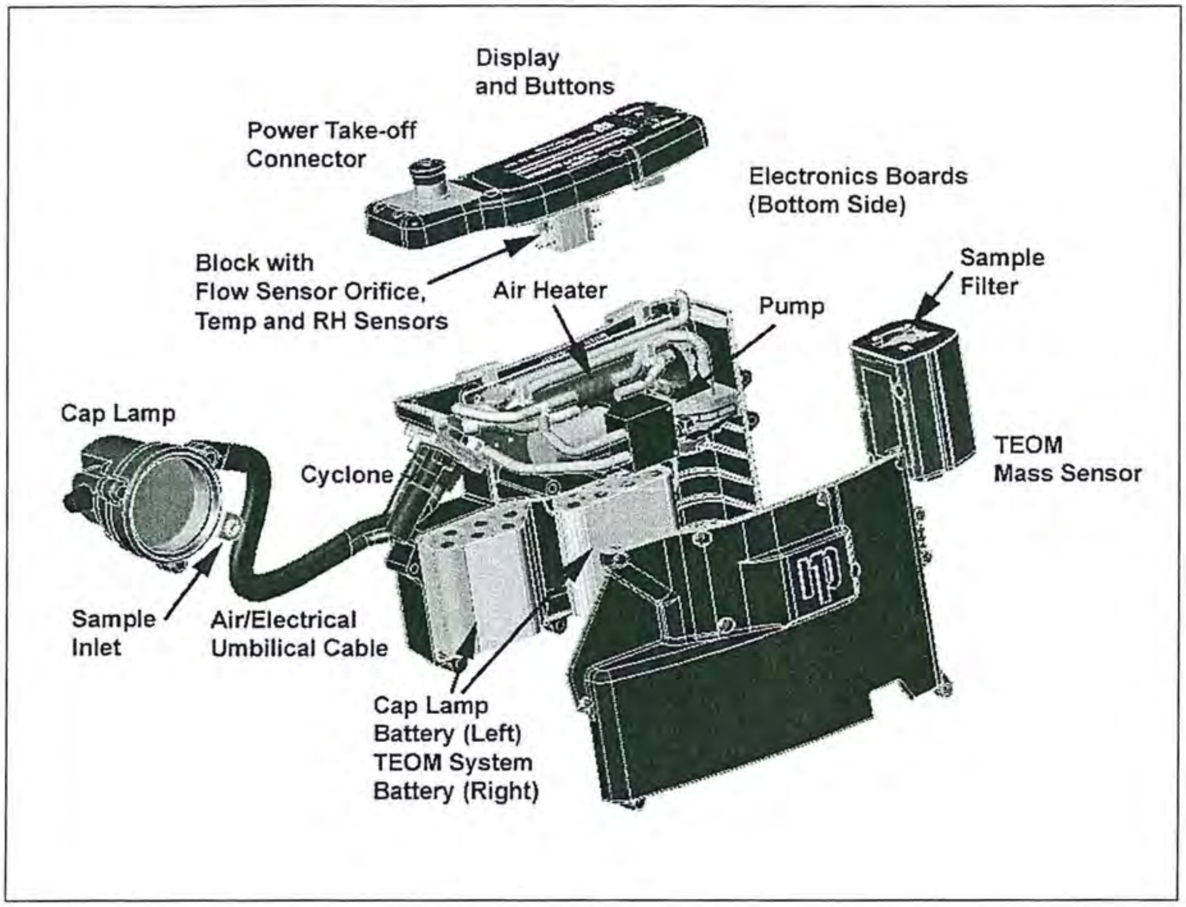


Figure 2. PDM installed on charging/communication module.

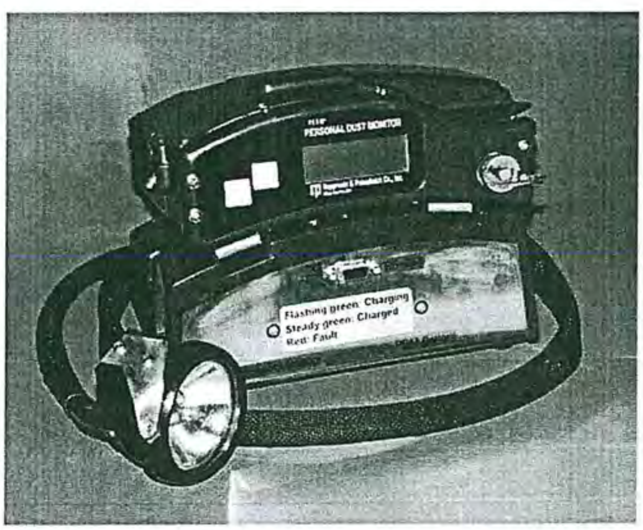


Figure 3. Installing a sample filter in the mass sensor.

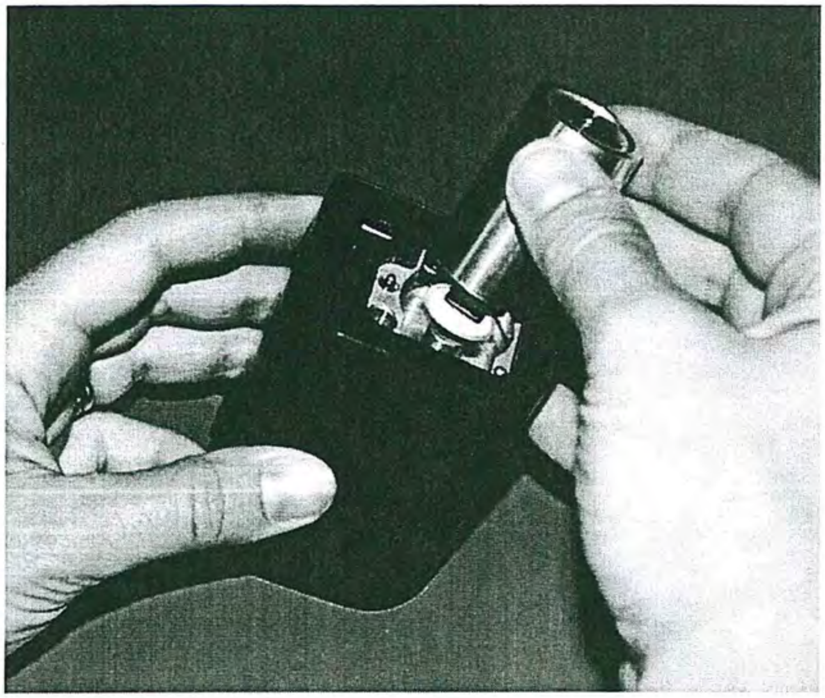


Figure 4. Tapered element with exchangeable filter mounted on narrow end.

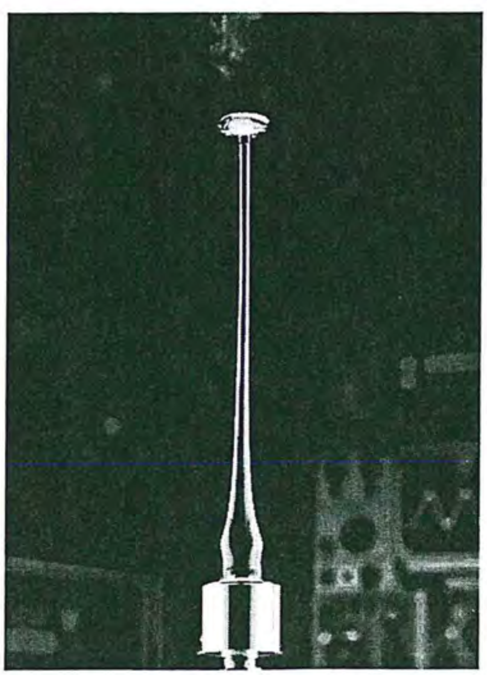


Figure 5. Arrangement of instrumentation in laboratory tests.

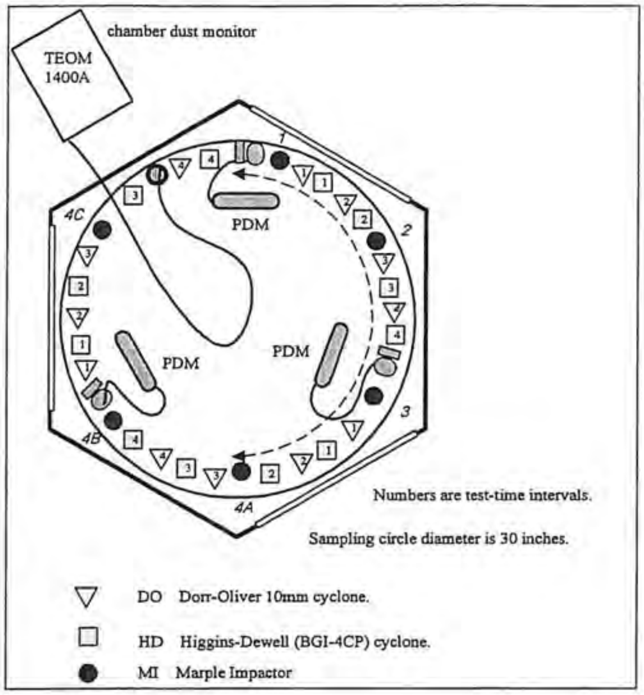
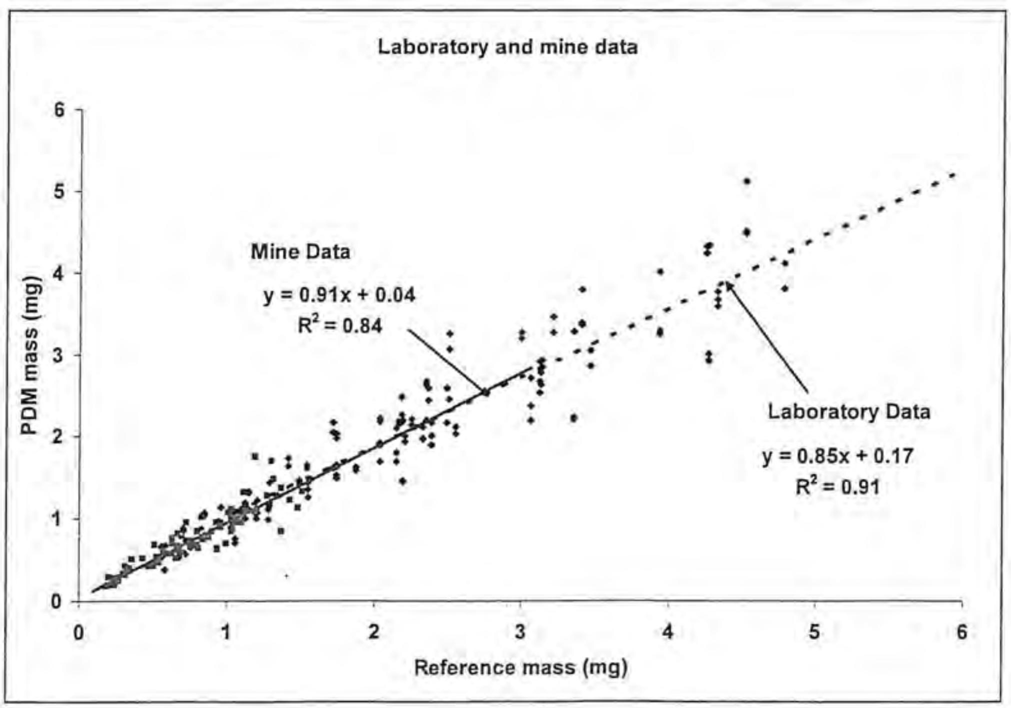


Figure 6. Comparison of PDM mass measurement to reference mass measurements in laboratory and mines.



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	PDM Left op.	PDM right op.	intake	vacuum bolter PDM Left op. adj	vacuum bolter PDM Right op. adj.	type	mist bolter PDM Left op. adj	mist bolter PDM Right op. adj.
1-Feb	1.68	1.58	1.50	0.18	0.08	v		
	0.69	0.31	0.08	0.61	0.23	v		
	1.70	1.45	1.46	0.24	-0.01	v		
	0.32	0.10	0.02	0.30	0.08	v		
	15.76	14.68				m		
	1.30	1.36	0.73	0.57	0.63	v		
	2.84	1.52				m		
	0.87	0.97	0.17	0.70	0.80	v		
	8.34	8.94				m		
2-Feb	8.51	8.26	3.93	4.58	4.33	v		
	9.25	7.25	4.20			m	5.05	3.05
	0.73	0.29	0.04	0.69	0.25	v		
	1.94	0.75	0.31			m	1.63	0.44
	1.02	2.45	0.05	0.97	2.40	v		
	8.40	9.25	4.37			m	4.03	4.88
	0.06	0.15	0.03	0.03	0.12	v		
	5.74	5.40	4.65			m	1.09	0.75
	1.00	1.71	0.01	0.99	1.70	v		
	3.22	4.04	2.29	0.93	1.75	v		
	8.48	7.91	1.99			m	6.49	5.92
3-Feb	0.28	0.28	0.12	0.16	0.16	v		
	7.28	11.61	1.53			m	5.75	10.08
	0.34	0.03	0.03	0.31	0.00	v		
	1.80	2.00	1.82			m	-0.02	0.18
	0.78	0.34	0.06	0.72	0.28	v		
	1.68	0.96	0.34	1.34	0.62	v		
	11.01	5.52	5.27			m	5.74	0.25
	9.42	7.30	5.79	3.63	1.51	v		
	0.24	0.10	0.05	0.19	0.05	v		
	3.88	2.70	1.57			m	2.31	1.13
	0.93	0.86	0.26	0.67	0.60	v		
	0.17	0.14	0.03	0.14	0.11	v		
				0.90	0.78		3.56	2.96