NEW TOOLS TO MONITOR PERSONAL EXPOSURE TO RESPIRABLE COAL MINE DUST

J.C. Volkwein
NIOSH/Pittsburgh Research Laboratory
Pittsburgh, PA

E.D. Thimons
NIOSH/Pittsburgh Research Lab
Pittsburgh, PA

ABSTRACT

The compliance sampling method for coal mine dust in the United States has not changed appreciably in the last 30 years. A call for more frequent sampling with immediately available results is leading to new instruments that may supplement or replace the existing sampler. This report discusses two such instruments that provide immediate results of dust levels. The first, called the Respirable Dust Dosimeter (RDD), is designed to supplement the existing U. S. cyclone compliance sampling method. It uses the pressure drop across a filter to provide an inexpensive screening type of measurement. The RDD has been tested in the laboratory and a limited number of coal mines. Side by side testing has compared the RDD performance with personal coal mine samplers in triplicate area sample measurements. Results show that the differential pressure of specific filtration media can be an effective surrogate for respirable mass. Data show that there is a dependence on coal type and an effect of relative humidity. There also appear to be two distinct responses related to coal type. For specific coals the coefficients of determination, R^2 , are better than 0.9. For general use the detector tube, using laboratory generated calibration curves, can be used to estimate respirable dust levels. However, a calibration to a specific coal type may substantially improve the accuracy.

Another sampler in development is called the Personal Dust Monitor (PDM). Designed to give compliance quality accuracy, the PDM uses the frequency change of a vibrating element to measure dust and give immediate feedback of results. Results of laboratory comparison of the prototype PDM sampler to personal gravimetric samplers indicate R^2 values of better than 0.99 for three different coal types. Work is in progress to package the components into a person-wearable unit combined with a cap lamp system with a total projected weight of less than 1.4 kg (3 lbs).

RESPIRABLE DUST DOSIMETER

Introduction

A prototype of the RDD concept was previously published. That work described the performance of a detector tube made from glass and brass that had good correlation between differential pressure and mass (Volkwein *et. al*., 2000; Page *et. al*., 2000). Subsequently, a new tube was manufactured from conductive plastic using similar specifications. This work describes the performance of the new dust detector tubes in the laboratory. Another paper describes the results from underground testing of the same units (Ramani *et. al*. 2000).

Description of device

The RDD is analogous to a conventional gas detector tube in that a small, low flowrate pump is used to pull a sample into a small diameter tube where measurement occurs. A uniform dust mass loading results in a proportional pressure increase across the filter. Any pressure transducer or one integral with the pump can be used to correlate with filter mass. After the detector tube has been used to make a measurement, the tube can be discarded, and a fresh tube used for the next measurement.

Dust enters the inlet of the detector tube, illustrated in Figure 1, through a 6.3 mm diameter by 8 mm length of polyurethane open cell foam (Type S, Filtercrest™ from PCF foam, Corp., Hamilton, OH) with a density of 50 pores per inch. This segment filters out oversized non-respirable particulate and protects the main classifier from plugging with over size material. The tube narrows to a 4.0 mm diameter section that contains a 25 mm length of 90 pore per inch open cell urethane foam that collects the non- respirable dust and passes the respirable fraction of the dust.

The flow path of the classified respirable fraction of the dust gradually expands in the detector tube to 6.3 mm diameter and travels 55 mm, or about 8 tube diameters, to uniformly deposit onto the collection filter. The respirable dust deposits onto an 8 mm diameter Pallflex Fiberfilm[1] T60A20 fluorocarbon-coated glass fiber filter supported by a porous fiber backup pad. The respirable classification section and the filter holder are made of conductive plastic that is ultrasonically welded together.

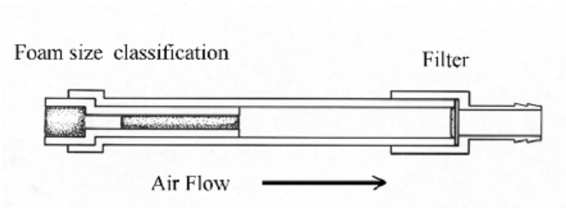

Figure 1. Dust detector tube portion of dust dosimeter

A commercially available low flowrate air sampling pump with integral pressure transducer is used to monitor the pressure increase with mass loading. Figure 2 shows both parts of a complete RDD. The increasing pressure differential across the filter created by mass accumulation is measured and correlated with respirable mass.

Figure 2. Respirable dust dosimeter showing pump with pressure readout and new plastic dust detector tube

Methods

The experimental method involved making triplicate measurements of respirable dust mass using the standard U. S. coal mine dust personal sampler unit (CMDPSU). This unit uses a Dorr-Oliver cyclone with filter mass measurement. These data were compared to triplicate differential pressure measurements made with the newly available RDD detector tube.

[1]References to commercial products are for informational purposes and do not imply endorsement by CDC

Lab testing was done in a Marple Chamber with very uniform dust flow at relative humidity levels between 15 and 70%. A fluidized bed dust generator with charge neutralization was used to aerosolize 5 different types of coal dust. A minimum of 12 triplicate pair-wise comparisons was done for each coal type at low and high humidities.

Flow controlled personal sampling pumps operated at a flow rate of 1.7 lpm were used to sample both laboratory and mine aerosols. Dust was classified using 10 mm Dorr-Oliver cyclones and deposited onto standard coal mine sampling cassette filters.

Flow controlled sampling pumps manufactured by SKC Inc. (Pocket Pump™) were operated at a flow rate of 250 ml/min to draw dust into the dust detector tubes. The pump pressure transducer was used to measure the difference in pressure with clean and dust laden detector tubes.

A direct comparison was made between dust mass collected by the CMDPSU and the differential pressure increase of the RDD. Tests compared the average response of triplicate measurements from each sampling device. Data were plotted and a least squares regression analysis was used to determine the correlation equations and coefficient of determination (R^2).

Results and discussion

For individual coal type tests, very high coefficients of determination were found. Table 1 shows correlation equations for linear and power functions for each coal type along with their respective R^2 values. Note that the power function gives a slightly better R^2 than the linear function. This may be caused by the foam classification device loading of dust with time that has the effect of reducing the amount of dust accumulating on the pressure drop filter in relation to the amount of dust reaching the gravimetric filter.

When the data from the table is plotted in Figure 3 two distinct families of responses are evident. The reasons for these different responses are not known, but may be related to the coal type and are the subject of ongoing investigation. The correlation for each grouping is quite good, R^2 for sample sizes of 36 and 24 are quite high at 0.97 and 0.96. The high R^2 for individual coal types and grouped data suggest that the dust detector tubes may provide very good estimates of dust mass when calibrated by coal family or by individual coal type.

Very low humidities produced a significantly different response in the Pittsburgh and Pocohontas coal, and a smaller difference with the Upper Freeport coal. No substantial difference was seen with the Illinois #6 or the Keystone coal. Humidities near 15% RH were generated in the laboratory by compressed air dryers would be atypical of most underground mining situations. Despite this anomalous behavior, Figure 4 shows that when both high and low humidity data are plotted, the family response function was evident.

Table 1.

	Power		Linear	
Coal Type	**Correlation Equation**	**Coefficient of determination**	**Correlation Equation**	**Coefficient of determination**
	$y=mx^b$	R^2	y=mx+b	R^2
Keystone	$4.49\ x^{0.73}$	0.99	3.32x + 0.88	0.99
Pittsburgh	$1.60\ x^{0.64}$	0.97	0.73x + 0.87	0.94
Upper Freeport	$1.77\ x^{0.61}$	0.96	0.97x + .75	0.93
Pocahontas	$3.77\ x^{0.9}$	0.99	3.10x + 1.05	0.99
Illinois #6	$3.61\ x^{0.81}$	0.98	2.58x + 1.05	0.96

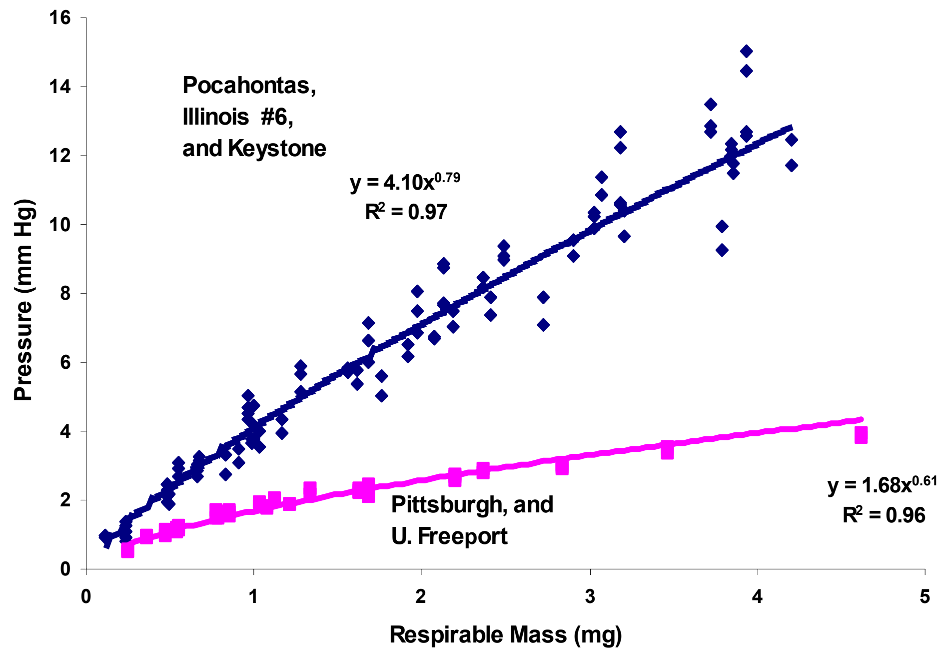

Figure 3. Dust dosimeter laboratory data for 5 coal types at humidity levels of 50 and 70% showing two distinct coal groupings

While the response of the RDD at low humidities may change the correlation of some coals, using the detector tube in mines with fairly constant environmental conditions will yield useful data. This was especially true in the region of the Permissible Exposure Limit and (PEL) of 1.4 mg (equivalent to 2 mg/m^3). Previous work also has shown that diesel particulate matter gives a much greater response than mineral particulate making correlation more difficult.

PERSONAL DUST MONITOR

Description of device

The original personal dust monitor (PDM-2) was produced under a NIOSH contract to Rupprecht and Patshnick Co. Inc. (R&P) The device is based on the highly successful tapered element oscillating microbalance (TEOM) technology that is the heart of a number of successful environmental dust monitors. Under this contract, the TEOM element was miniaturized for personal use and an electronic momentum compensation device was developed to eliminate the need for a large mass to stabilize the base of the oscillating element.

The unit was designed to be similar to the existing personal dust monitor in that a lapel cyclone inlet was maintained. Thus, the unit consists of two modules (hence the designation PDM-2). The lapel module contains the inlet to a Dorr Oliver nylon cyclone, a U-shaped air heater section, the filter connected to a momentum compensated tapered element microbalance, and a computer. The belt module contains a flow controlled pump, batteries, and data display. The inlet of the cyclone has a custom fabricated shield to protect the inlet from direct water spray action and to reduce the sensitivity of the inlet to wind direction.

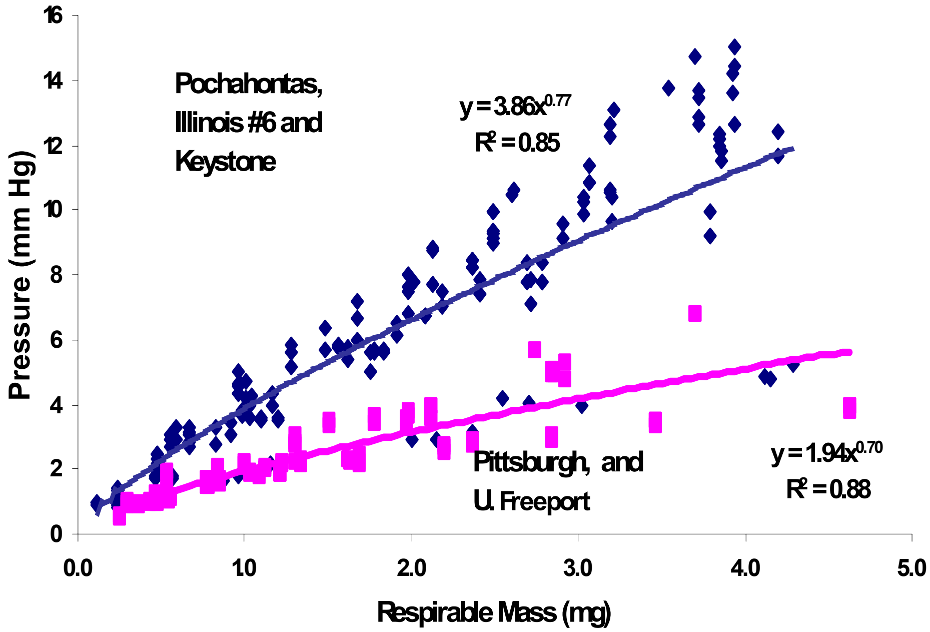

Figure 4. Dust dosimeter date for all laboratory results

A prototype PDM-2 is shown in Figure 5. The weight of the total unit is 1.95 kg. The lapel module weighs about 0.45 kg, and measures 20 cm long, 6.3 cm wide and 4 cm thick. The belt module measures 18 cm tall, 15 cm wide and 5 cm thick.

Other required components are the battery charger for the lithium ion batteries that connect through a charging port on the belt unit, and a personal computer (lap top or desk top) that accesses the lapel unit computer through a port on the side of the lapel unit. Windows based software was provided by R&P to upload and download data from the lapel unit.

Figure 5. PDM-2 showing lapel and belt pack modules

Methods

Tests were conducted in both the Marple chamber described above and in a full scale model longwall dust gallery. Two types of coal aerosols were used in the laboratory Marple chamber. Pittsburgh Seam A coal was obtained from the Pennsylvania State University and Keystone coal was obtained from a commercial source. Only Keystone coal was used in the longwall gallery testing.

Mass loading protocol

The PDM-2 was compared to the standard coal mine dust personal sampler unit (CMDPSU). The CMDPSU takes a gravimetrically determined filter sample. Filters were pre and post weighed in the PRL controlled atmosphere weighing facility according to established procedures. The filter cassettes differed from commercially available units in that the stainless steel wheel assembly and check valve were not used and mass determinations were made to ± 0.02 mg. Filter blanks were used for both Marple and longwall testing. The average of three filter blanks was subtracted from the Marple chamber data and the average of two filters was subtracted from the longwall gallery data.

Flow controlled Mine Safety Appliance (MSA) Elf Escort pumps were calibrated at the beginning of each coal type test in the Marple chamber and before the longwall testing. A Gilibrator primary standard flow meter was used to establish a flow rate 2.0 ±0.2 lpm using an equivalent pressure restriction of the cyclone and filter assembly.

The PDM-2 units were prepared for each test according to instructions from R&P. The units do not have an on/off switch and can only be started by programing the units ahead of time. A mandatory 30 minute warmup is required prior to data collection. In general, the units were programed to initiate a test the evening before a test was conducted. Prior to programing, the flow rates were checked and adjustments made to bring the flow to 2.0 ±0.1 lpm. Calibration was done with a Gilibrator flow meter attached to the bottom of a sealed inlet cyclone that was substituted for the PDM-2 cyclone. Unit start times and test duration were then programed and the units left on the chargers overnight.

On the morning of the test, the units automatically initiated warm-up. Units were then placed into the Marple chamber or transported by car to the longwall test gallery. At the conclusion of the test, final cumulative concentration data from the belt screen display was recorded and the units were returned to the laboratory. The PC was then used to download data from the PDM-2 onboard computer. This data is then translated into an ASCII text file that may be read with a spreadsheet program. Units were then cleaned, new filters installed, and prepared for the next test.

The data files were coordinated with the run times of the gravimetric data. Because the start time of the gravimetric samplers did not always match the start time of the PDM-2 units, the mass of the PDM-2 at the gravimetric start time was subtracted from the PDM-2 end time mass. Gravimetric samplers were always started after the 30 minute warmup cycle. Gravimetric start and stop times are ±1 minute and PDM-2 times are to the nearest previous minute (ie. 2 min. 59 seconds recorded as 2 min.)

Marple Chamber

Chamber testing was conducted under very controlled conditions and assessed the best performance that can be expected from the PDM-2. Chamber temperature varied between 23 and 25 degrees C. Relative humidity varied between 42 and 61% with a target of 50%. Low humidity testing was not conducted.

CMDPSU's were arrayed in a 1m diameter circle around a central point in the chamber and the two PDM-2 units placed 180 degrees apart within the array as seen in Figure 6. The table of the chamber was then slowly and continually rotated approximately 356 degrees and then reversed. A total of 19 gravimetric filters were used for each test. There were four sets of four filters for analysis and three control filters. The control filters were handled in an identical fashion to the experimental filters with the exception that the end caps were not removed. Calibrated MSA Elf Escort pumps were used to power the personal sampling cyclone filter units. The PDM- 2 units and CMDPSU'S were placed in the Marple chamber and operated under battery power as if being used in a mine.

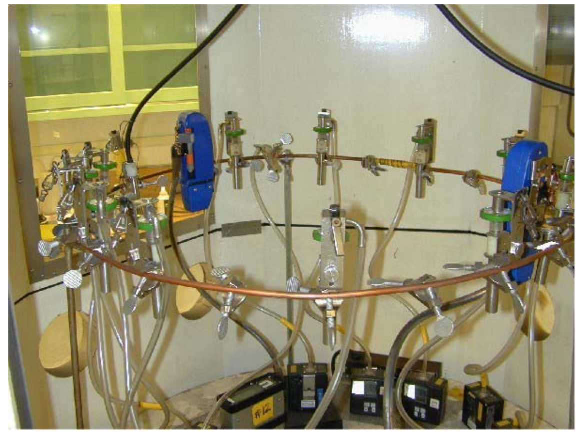

Figure 6. Marple chamber setup for PDM testing

For Keystone coal, 3 tests were conducted to achieve a range of dust concentrations from about 0.2 to 4 mg of MRE equivalent mass. Similar tests were run for Pittsburgh coal, but one additional test was conducted to address a question of possible differences in performance with low mass collection over extended sampling times.

For one test, the chamber was brought to an MRE equivalent concentration of 2 mg/m^3 for a 10 hour day. The PDM-2 was operated for 10 hours. All gravimetric filters were started at the beginning of the test but sets of four filters were turned off at intervals to encompass the desired range of mass loadings.

For a second test the chamber concentration and test time duration was controlled to achieve an MRE equivalent mass loading concentration of 4 mg/m^3. Gravimetric filters were turned off at equivalent mass loading concentrations of 1, 2, 3 , and 4 mg/m^3 .

For a third test, chamber concentration and test time duration was controlled to achieve an MRE equivalent mass loading concentration of 2 mg/m^3. Gravimetric filters were turned off at equivalent mass loading concentrations of 0.2, 0.5, 1, and 2 mg/m^3.

For the fourth test, with Pittsburgh coal, the chamber concentration was brought to a dust concentration of about 0.75 mg/m^3 and the test run for about 7 hours. Gravimetric filters were turned off at equivalent mass loadings of 0.1, 0.2, 0.3 and 0.5 mg/m^3.

Gallery

The full scale longwall gallery at the Pittsburgh Research Laboratory (PRL) enabled the assessment of the PDM-2 under less controlled conditions and in the presence of water spray mist. Performance of the device in motion was also evaluated.

To reduce spatial variability, a special portable "Lippmann" chamber (Figure 7) was constructed for this testing. This is similar in design to the multiport chamber that MSHA used to determine intersampler variability in the paper by Kogut *et. al*. (1997). The chamber contained four personal gravimetric samplers, and two PDM sampling heads. While the inlet of the Lippmann chamber did reduce the mass median aerodynamic diameter of the aerosol by about 2 micrometers, the increased precision of the four gravimetric sampling units and assurance that the PDM and gravimetric samplers were sampling a similar aerosol was considered an acceptable tradeoff.

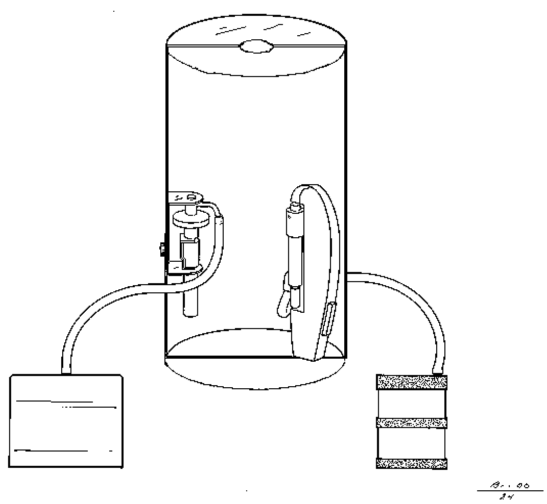

Figure 7. Cutaway view of portable lippmann type chamber used to minimize aerosol spatial variability from instrument to instrument

The gallery was operated using Keystone coal dust with constant water and ventilation flow rates. The drum water sprays on the model shearer used Spraying Systems Fulljet QPH 3.5 and 6.5 sprays. A total water flow rate of 247 lpm @ 55.1 kpa was used for each test. Ventilation air velocities in the gallery were between 1.5 m/sec. Keystone coal dust was commercially available in large quantities required for gallery testing. A powered continuous loop of chain conveyor, described below, was used in place of a person to simulate a person's movement within the tailgate area of the gallery. This caused the inlet of the Lippmann chamber to be exposed to a variety of dust and water concentration levels.

Because the Lippmann chamber can only hold a total of 6 sampling units at one time, a series of shorter tests were conducted. A total of 14 tests were conducted. Two control filters were used for each test. As with the laboratory testing, the target range of masses for equivalent concentrations ranged from 0.2 to 4 mg. One of these tests was of 10 hour duration. During three test days, two tests per day were conducted. The same setup and download protocol was followed with the exception of battery charging.

Reduced data compared the difference between the average of the gravimetric filter mass loadings to the individual PDM-2 mass loadings in a pair wise manner. All data were converted to MRE equivalent concentrations using the factor of 1.38. In the PDM-2, this conversion takes place electronically in the instrument constant that was used to convert oscillation frequency into mass. In the case of the personal gravimetric samplers, this conversion was made following the mass calculation. It makes no difference if this constant is applied to mass or concentration since it is simply multiplication by a constant.

<u>Results and Discussion</u>

Results from the Marple chamber for the two coal types and longwall gallery are presented. Marple chamber results in Figure 8 for the Keystone coal show a very high correlation coefficient R^2 of > 0.99 for both instruments and the linear correlation equations have a slope of nearly 1 with a y intercept within 0.03 mg.

Data from the Pittsburgh coal test in Figure 9 are not as good. While the scatter is low, unit #14 showed a bias of 12%.

Results from the full scale longwall gallery in figure 10 also have correlation coefficients > 0.99.

Note that the linear equations of the figure are parallel to the theoretical one to one correlation but off set by about 0.1 mg. This may be a result of the PDM-2 actually measuring the water content of the coal that is not present in the desiccated gravimetric mass data.

Use of the Lippmann chamber in the longwall testing reduced spatial variability compared to non- enclosed inlets. The average relative standard deviation (RSD) for the personal gravimetric sampler in the Lippmann chamber used in the longwall gallery was 6.1%. This value is similar to the two Marple chamber tests where the RSD was 3.0% and 6.8% for Keystone and Pittsburgh coal respectively.

Because of the potential use of this device for compliance determination, a more detailed statistical analysis of the data is warranted and will the subject of another article.

Some additional observations of this testing showed that readings were influenced by temperature changes and water sprays. Subsequent investigation by the manufacturer showed that the temperature effect was electronic in origin and may be easily corrected. The influence of water is predictable and may be addressed by increasing the temperature of the TEOM, or the addition of a dryer to the air stream if additional accuracy is required. The small differences in coal type response was noted and is subject to further investigation. The PDM-2 prototypes were not sensitive to shock or to the tilt of the unit as might be experienced when worn by a person. The zero stability of the PDM prototype is similar to the stability of gravimetric mass blank filters.

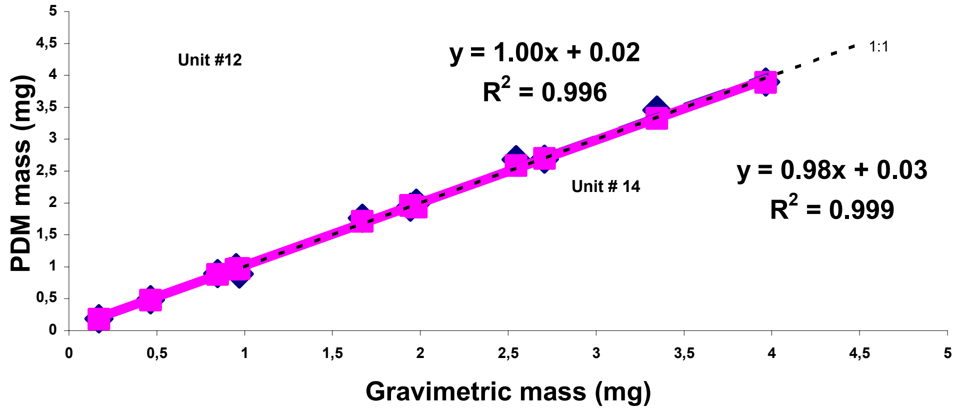

Figure 8. Keystone coal regression of Marple chamber data

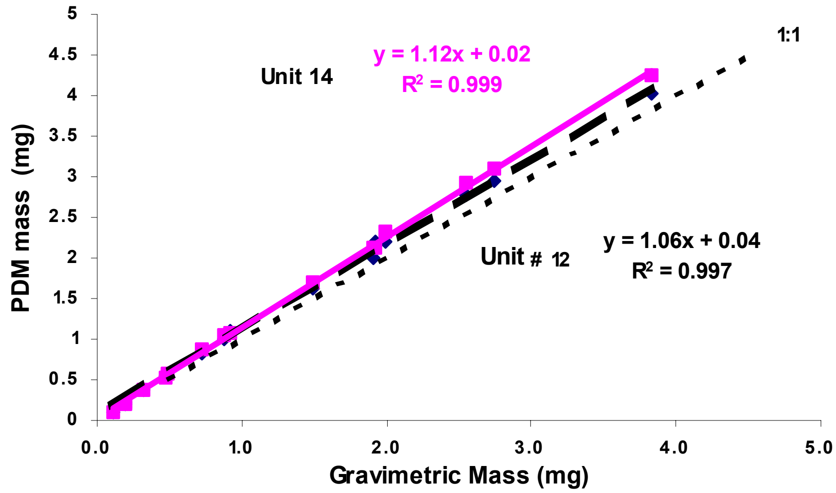

Figure 9. Pittsburgh coal regression of marple chamber data

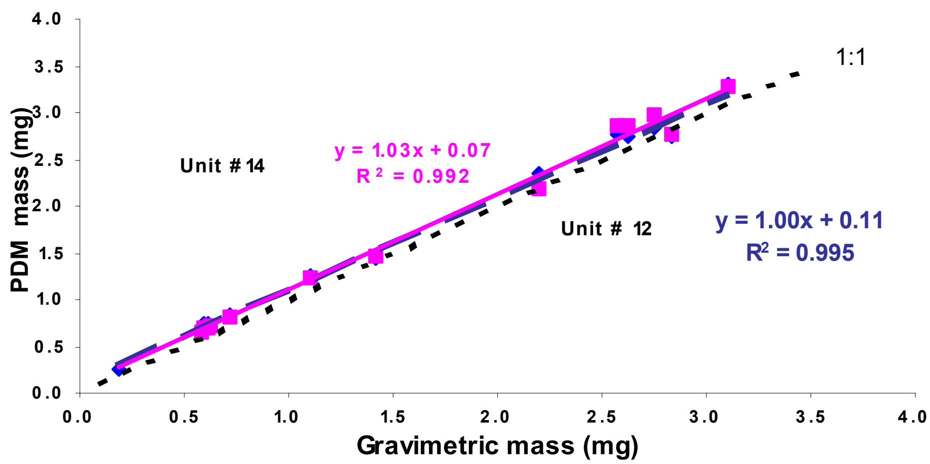

Figure 10. Longwall gallery regression using keystone coal

SUMMARY

Protection of workers' respiratory health depends on many factors. The detector tube approach to personal dust monitoring offers many advantages. Cumulative shift dust exposure estimates can be easily available at low cost in an inexpensive, small, and light-weight package. Knowledge of routine dust exposure levels can help workers' and companies focus on protection of workers respiratory health.

The PDM offers an accurate near real time assessment of worker exposure. In the present two piece configuration, preliminary findings of the laboratory evaluation of the PDM have been quite positive. The units exhibit reasonable accuracy over the mass ranges tested. There were numerous startup and debugging difficulties, however the units held up well during the entire laboratory test process. Further testing is being conducted by NIOSH in four underground coal mines to confirm the laboratory results. NIOSH hopes to build on this technology to develop a one piece dust monitor combined with a cap lamp that is even more convenient for miners to wear and will allow them to monitor their environments while working.

REFERENCES

Volkwein JC, Schoeneman AL, and Page SJ [2000]. Laboratory Evaluation of Pressure Differential Based Respirable Dust Detector Tube. *Appl. Occ. & Enviro. Hyg*. 15(1), pp 158-164

Page, S J , Volkwein JC, Baronn PA, Deye GJ [2000]. Particulate Penetration of Porous Foam as a Low Flow Rate Respirable Dust Size Classifier. *Appl. Occ. & Enviro. Hyg* 15(7), pp 561-568

Ramani R V, Mutmansky JM, He H, Volkwein JC, Marple VA, Olson B, Luna P [2001]. A Comparative Evaluation of the Differential Pressure-based Dust Detector with the Personal Gravimetric Respirable Dust Sampler in Underground Coal Mines. 7th International Ventilation Symposium, Kracow, Poland, June

Kogut JTF, Tomb, Parobeck A, Gero J, and Suppers KL [1997]. Measurement Precision with the Coal Mine Dust Personal Sampler. *Appl. Occup Envron. Hyg,* 12(12), 1997 pp.999-1006