Performance of a light-scattering dust monitor in underground mines

G.J. Chekan, J.F. Colinet, F.N. Kissell, J.P. Rider, R.P. Vinson and J.C. Volkwein
NIOSH, Pittsburgh, Pennsylvania

Abstract

The Thermo-MIE personal DataRAM dust monitor (pDR) is a light-scattering instrument approved for use in gassy underground mines by the U.S. Mine Safety and Health Administration (MSHA). However, the use of light-scattering monitors has been inhibited by concerns about inaccurate readings resulting from changes in dust size distribution and composition, as well as concerns about the impact of moisture in the mine air. Because of this concern, the National Institute for Occupational Safety and Health (NIOSH) evaluated the pDR using available data from laboratory tests and mine surveys. The data show that accuracy can vary widely from test to test and mine to mine. In most cases, the results can be improved by using a companion gravimetric measurement to adjust the pDR data.

Introduction

For the measurement of respirable dust, instantaneous dust monitors based on light-scattering principles have an advantage when compared to gravimetric filter samples — they offer immediate feedback on dust levels. The Thermo-MIE personal DataRAM dust monitor (pDR) can be used in underground gassy mines because it has been tested and approved by the Mine Safety and Health Administration (MSHA) for intrinsic safety in methane-air mixtures (Approval No. 2G-4126-0). It uses light-scattering principles to detect dust concentrations. Light-scattering instruments offer a relative measure of concentrations, but provide a continuous record of particulate levels so that concentrations can be evaluated over any time interval during the sampling period.

In some mines, the pDR is regarded as a useful tool for making rough relative measurements, such as those made to identify dust sources and select locations for subsequent gravimetric sampling. However, any expanded use of light-scattering monitors has been inhibited by concerns about inaccurate readings resulting from changes in dust size distribution and composition, as well as concerns about the impact of water sprays (Williams and Timko, 1984; Smith et al., 1987; Tsai et al., 1996). This concern has been reinforced by coal mine tests (Page and Jankowski, 1984) showing that light-scattering measurements could vary from gravimetric measurements by a factor of two.

Despite these findings, there is a continuing interest in using light-scattering instruments for broader applications in mining, possibly by identifying specific circumstances under which the pDR can be expected to be more accurate.

The work reported here details some side-by-side comparisons between the pDR and conventional gravimetric samplers first conducted in a laboratory test chamber, then in three different types of underground mines. The main purpose of the mine studies was to assess control technology; however these dust studies also offered the opportunity to make pDR-gravimetric comparisons under a variety of realistic mining conditions.

Two specific issues were addressed. First, what was the instruments precision? Precision is defined as the instrument's degree of agreement in a series of tests or, in other words, its repeatability. Information was collected to determine how much the precision varied from laboratory to mine and from mine to mine. Second, what was the instruments bias? Instrument bias is defined as a systematic distortion in a measurement. This would be the accuracy of the instrument when compared to the true value — in this case the Dorr-Oliver gravimetric sampler. Again, information was collected to determine how much the precision varied from laboratory to mine and from mine to mine.

Methods used

In this study, all of the tests were conducted with the pDR in the "active" sampling mode, as shown in Fig. 1. In this sampling mode, particulate was classified through a Dorr-Oliver cyclone before entering the pDR light-scattering chamber. In addition to dust measured by the pDR, reference samples were collected by conventional gravimetric samplers located within a few inches of the pDR. Each of these conventional gravimetric samplers consisted of a Dorr-Oliver cyclone, a 37-mm filter and a pump. The pDR pump and the gravimetric

Figure 1 — Active-mode pDR modified for a Dorr-Oliver cyclone.

Table 1 — Laboratory test results.

Concentration, mg/m^3	pDR #1		pDR #2	
	Precision	Bias	Precision	Bias
0.6	0.053	-0.18	0.05	-0.21
1.5	0.19	-0.49	0.19	-0.5
3	0.12	-0.23	0.098	-0.22
5	0.4	-0.66	0.39	-0.66

pumps were operated at 2 L/min in coal mines and 1.7 L/min in metal/nonmetal mines.

To calculate precision and bias for a typical mine test, a pDR and two gravimetric samplers were placed in a designated location and operated continuously for approximately six hours. When the concentration results were obtained, a ratio for that location was calculated. This ratio was the pDR average concentration divided by the average of the two gravimetric concentrations. All of the ratio values obtained at that mine were averaged, and the standard deviation calculated. The precision was obtained by dividing the standard deviation by the mean concentration ratio. A value of less than 0.25 is considered acceptable.

Bias is the relative discrepancy between the average instrument reading and the true value, with the true value defined as the average of the reference gravimetric samplers. So, the bias was calculated by subtracting 1.0 from the mean concentration ratio. A value of ±0.30 is considered acceptable.

Laboratory tests

Prior to the mine tests, a brief series of laboratory tests was conducted to assess the pDR under more ideal conditions. The tests were designed to compare the responses of two pDR light-scattering samplers to the average of three separate gravimetric samplers at four different dust concentrations at four different exposure times. These tests used Arizona road dust, which is used as a standard for calibrating dust-monitoring instruments due to its consistency in mineral content and particle size. The aerosol test chamber used to test the instruments is known as a Marple Chamber and is 1.2 m (4 ft) in diameter and 2.4 m (8 ft) high (Marple and Rubow, 1983). Dust and dilution air are introduced at the top of the chamber. The air then flows downward through a honeycomb structure to provide a low, uniform velocity flow through the test section of the chamber. A tapered element oscillating microbalance (Patashnick et al., 2002) was used to continuously monitor dust concentrations so that dust in the chamber could be adjusted and kept constant during each test-sampling period.

The three gravimetric samplers in the Marple Chamber tracked each other reasonably well. The average gravimetric sampler-to-sampler precision over all of the tests was 6%. The two pDRs also gave like readings in all of the tests, with the average difference between the two pDRs being only 1.9%. A concentration ratio was then calculated for each measurement. This ratio was the pDR average reading divided by the average of the three gravimetric results. All of the measurements at a given concentration level were averaged, and the precision and bias were calculated as previously described. The results are shown in Table 1.

As an example, for Arizona road dust at the 3-mg/m^3 level, four measurements were conducted at 53, 113, 173 and 233 minutes. With pDR #1, the mean concentration ratio for the four measurements was 0.77 and the standard deviation was 0.09. This yielded a precision of 0.12 and a bias of -0.23. Table 1 suggests that the major source of pDR error is the bias.

Mine tests – metal/nonmetal

Dust data from pDRs used in several underground limestone mines and one gold mine were analyzed in the same manner as the laboratory data. Table 2 gives the type of mine, the dust sources, the number of locations where instruments were placed and the number of shifts during which testing was conducted at each location. These mines displayed a variety of particulates, including diesel smoke, water mist, and mineral dust from blasting, roadways and crushers. In the mines, instrument packages, consisting of one pDR and two gravimetric samplers, were placed at key locations depending on the sampling protocol for the study. Because the testing was performed in metal/nonmetal mines, the pumps were operated at 1.7 L/min in accordance with MSHA regulations.

All sampling protocols consisted of area sampling and the placement of sampling packages in intake and return airways, on the outside and inside the operator's cab of haulage trucks and at locations around dump/crusher facilities. Prior to testing, a zero and internal span check, as described in the instrument manual (Thermo Andersen, 2001) was performed on each pDR to ensure that the instrument's calibration agreed with the original factory setting.

For each location on each shift, the pDR/gravimetric ratio was calculated using the pDR reading and the average dust concentration from the two gravimetric filters. The average difference between these two gravimetric samplers in the metal/nonmetal tests was 7%. Also, shift average pDR readings below 0.1 mg/m^3 were considered unreliable due to the limitations of the unit, so those tests were excluded. Overall, 4% of tests were excluded for this reason.

Precision and bias results for the ratio values were then calculated in two different ways. First, the pDR/gravimetric ratios for all locations on a given shift were averaged, and the precision and bias were calculated for that shift. Because these measurements extended over several shifts, the precision and bias values from each of the shifts were averaged to obtain a mean precision and mean bias value. This was called the "shift value." Secondly, the pDR/gravimetric ratios for all shifts at a given location were averaged and the precision and bias calculated for that location. Because the measurements extended over several locations, the precision and bias values from each of the locations were averaged to obtain a mean precision and

Table 2 — Test results for underground metal/nonmetal mines.

Mine type:	Limestone	Gold	Limestone	Limestone	Limestone
Particulate sources	Crusher dust and diesel	Load, haul, dump cycle dust and diesel	Blast dust and diesel	Blast dust and diesel	Blast dust and diesel
Number of locations	5	5	4	4	6
Number of shifts	3	3	3	3	1
Average gravimetric concentration, mg/m^3	0.88	0.48	0.58	0.41	0.69
Shift value – mean precision	0.20	0.18	0.14	0.14	0.19
Shift value – mean bias	1.30	-0.35	-0.035	-0.18	0.20
Location value – mean precision	0.16	0.087	-0.11	0.11	–
Location value – mean bias	1.30	-0.36	-0.035	-0.12	–

Table 3 — Test results from longwall mines.

Mine Location	Mine A Shield 10	Mine A Shield 160	Mine B Shield10	Mine B Shield 153	Mine C Shield 10	Mine D Shield 10	Mine E Shield 10
Number of shifts	3	3	3	3	3	3	3
Average gravimetric concentration, mg/m^3	0.26	3.20	1.00	4.50	1.10	0.79	0.80
Location value – mean precision	0.67	0.07	0.14	0.07	0.30	0.19	0.09
Location value – mean bias	0.73	-0.17	-0.059	-0.28	0.38	0.27	-0.26

mean bias value. This was called the "location value."

Shift and location values were calculated separately because there was a possibility that an instrument at a given location might show different variability in the pDR/gravimetric ratio over several shifts in comparison to instruments on a given shift over several locations.

Table 2 gives the mean precision and the mean bias values of the pDR/gravimetric ratio for each mine. The bias is actually a "mine bias," because the change in bias from one mine to another is likely a result of changes in external conditions rather than in the instrument itself. Both a shift and a location value of the mean precision and mean bias are presented in Table 2; note that the results vary widely. Like the laboratory results, the hard rock results suggest that a substantial source of error is the bias rather than the precision.

Mine tests — coal

Following the hard rock testing, the pDR was tested at longwall faces in five coal mines using the same procedure that was followed in the hard rock mines. Table 3 gives the location where the instrument package was placed and the number of shifts of testing conducted at each location. The arrangement of instruments was similar to that used in the hard rock mines, and two gravimetric samples were taken. The average difference between these two gravimetric samplers in the coal mine tests was 10%.

Table 3 gives the mean precision and mean bias of the pDR/gravimetric ratio for tests in each of the coal mines visited. At the coal mines, data were available from only one or two sampling locations. Consequently, calculation of shift values was not completed. Only location values were determined. As with the hard rock data, the results vary widely. The bias is again a major source of error.

Analysis

In the laboratory testing, the pDR values were less on average than the gravimetric values, leading to a consistently negative bias. In the mine testing, seven of the 11 bias calculations were also found to be negative. However, it was not clear what circumstances caused the bias to be positive at certain locations. In general, if the absolute value of the bias were 0.3 or less, the precision value was under 0.25, as shown in Fig. 2. However, high bias values did not automatically lead to poor precision. Moisture in the air is one likely cause of the spread in bias values. Quintana et al. (2000) called attention to a strong humidity effect on pDR readings, especially above relative humidity values of 85%. Although relative humidity values were not measured in this study, it is well known that

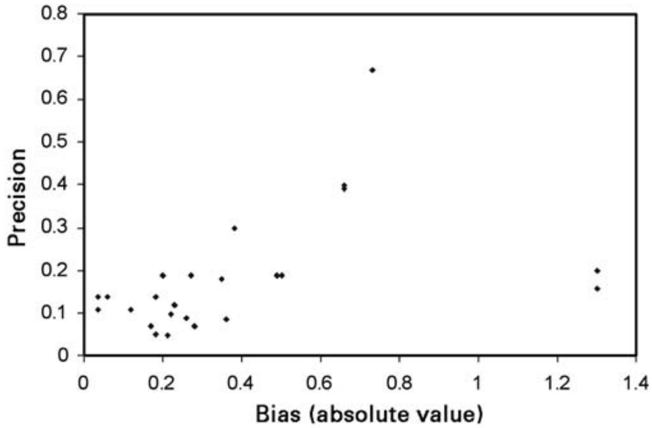

Figure 2 — Precision vs. bias for all of the measurements.

air in mines can have high relative humidity (Pappas et al., 2002) and even visible fog. Cecala et al. (1985) described a mist eliminator for use with light-scattering dust monitors. However, up to now, it has been used only when the mine air contained visible mist from water sprays.

Although the pDR continues to be a useful tool for making rough relative measurements in mines, users cannot depend on the absolute values of the numbers that are obtained. However, accuracy of pDR concentrations can be improved when the bias is corrected with a "field gravimetric calibration," as described below.

Guidelines for using the pDR in the active mode in underground mines.

It is strongly recommended that one take an accompanying gravimetric sample when using the pDR. Test the pDR to determine if the seals are tight and the case of the pDR is not drawing air through the unit under the negative pressure of the pump. When this occurs, particulate may be drawn into the unit, bypassing the cyclone. As a result particulate is being deposited on the in-line filter but not being recorded by the unit. If leakage is extreme, the concentration from the in-line filter and the average concentration from the pDR can vary greatly.

Leakage in the unit is easily determined by placing the pDR in-line when setting the pump flow rate during pump calibration with a primary standard instrument. If leakage is occurring, the required flow rate will be difficult to achieve. In this situation, the pDR may need to be resealed. If no leaks are detected, the concentrations calculated from the in-line filter on the pDR can also be used in precision and bias calculations if needed.

The accompanying gravimetric concentrations are important, because they can be used to correct the individual pDR concentrations. This "field gravimetric calibration" (Thermo Andersen, 2001) is accomplished by multiplying individual pDR data points by the ratio of gravimetric concentration to the average pDR concentration. For example, if a five-hour gravimetric sample gives a concentration of 2.0 mg/m^3 and the accompanying five-hour pDR concentration average is 1.0 mg/m^3, all of the individual pDR readings can then be multiplied by 2. If dust and environmental conditions are not expected to vary during multiple-shift sampling, there is a menu option in the pDR software so this correction factor can be directly programmed into the unit to improve sample efficiency.

In addition, the accuracy of pDR measurements is questionable when the average pDR concentration for the shift is below 0.1 mg/m^3 or when the bias is greater than 0.3 (or less than -0.3). In these instances, additional sampling should be considered.

There are many other uses for light-scattering dust monitors in mines where accuracy is not of paramount importance. Some of these include:

- calculate dust concentrations for different operations (such as characterizing dust levels during truck haulage cycles or headgate to tailgate cuts in longwall mining),
- identify and isolate high or problematic dust sources,
- use for short-term sampling to improve statistical validity,
- monitor dust movement through the mine as an estimator of air velocity for large opening mines that have extremely low air flow (Chekan et al., 2004),
- identify ambient dust concentration buildup in mines and mills and
- activate alarm feature to detect high dust concentrations so personnel can implement remedial action to lower dust levels.

References

Cecala, A.B., Volkwein, J.C., and Thimons, E.D., 1985, "Adding Steam to Control Dust in Minerals Processing," U.S. Department of the Interior, Bureau of Mines, Pittsburgh, Pennsylvania, RI 8935, NTIS No. PB 85-198885.

Chekan, G.J., Colinet, J.F., and Grau, R., 2004, Evaluating ventilating air movement in underground limestone mines by monitoring respirable dust generated from production shots," *Proceedings of the Tenth US/North American Mine Ventilation Symposium*, May 16-19, 2004, Anchorage Alaska, pp. 221-232.

Marple, V.A., and Rubow, K.L., 1983, "An aerosol chamber for instrument evaluation and calibration," *American Industrial Hygiene Assoc. J.*, Vol. 44, No. 5, pp. 361-367.

Page, S.J., and Jankowski, R.A., 1984, "Correlations between measurements with RAM-1 and gravimetric samplers on longwall shearer faces," *AIHA J.*, Vol. 45, No. 9, pp. 610-616.

Pappas, D.M., Barton, T.M., and Weiss, E.S., 2002, "Developments in sealant support systems for ground control," *Proc. 21st International Conference on Ground Control in Mining*, Morgantown West Virginia, August 6-8, 2002, pp. 344-353.

Patashnick, H., Meyer, M., and Rogers, B., 2002, "Tapered element oscillating microbalance technology," in Mine Ventilation: *Proceedings of the North American/Ninth U.S. Mine Ventilation Symposium*, Kingston, Ontario, Canada, June 8-12, 2002, E. DeSouza, ed., Balkema, Lisse, Netherlands, pp 625-631.

Quintana, P.J.E., Samimi, B.S., Kleinman, M.T., Liu, L.J., Soto, K., Warner, G.Y., Bufalino, C., Valencia, J., Francis, D., Hovell, M.H., and Delfino, R.J., 2000, "Evaluation of a real-time passive personal particle monitor in fixed site residential indoor and ambient measurements," *Journal of Exposure Analysis and Environmental Epidemiology*, 2000, Vol. 10, pp. 437-445.

Smith, J.P., Baron, P.A., and Murdock, D.J., 1987, "Response characteristics of scattered light aerosol sensors used for control monitoring," *AIHA J.*, Vol. 48, No. 3, pp. 219-229.

Thermo Andersen, 2001, "Operator Manual for Personal DataRAM Model pDR-1000AN and pDR-1200," Thermo Andersen, 500 Technology Court, Smyrna, GA, 30082

Tsai, C.J., Shih, T.S., and Lin, J.D., 1996, "Laboratory testing of three direct-reading dust monitors," *AIHA J.*, Vol. 57, pp. 557-563.

Williams, K.L., and Timko, R.J., 1984, "Performance Evaluation of a Real-Time Aerosol Monitor," U.S. Department of the Interior, Bureau of Mines, Pittsburgh, Pennsylvania, IC 8968, NTIS PB 84-199710.