Status of a Tapered Element, Oscillating Microbalance-Based Continuous Respirable Coal Mine Dust Monitor

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The Mine Safety and Health Administration, Department of Labor, requires coal mine operators to measure compliance with federal respirable dust exposure standards periodically using approved gravimetric samplers. However, the gravimetric approach, with its inherent delays, cannot provide dust concentration data quickly enough to allow on-site correction of inadequate dust control strategies or removal of personnel from harmful environments. Furthermore, alleged tampering with dust samples collected to determine compliance with standards prompted the Secretary of Labor to appoint a special Respirable Dust Task Group to study options to improve monitoring and control of respirable coal mine dust. The Mine Safety and Health Administration's Task Group recommended that the U.S. Bureau of Mines develop a fixed-site monitor that would provide continuous information to the mine worker and mine operator regarding dust levels and the status of compliance with the applicable respirable dust standard. In response to the Mine Safety and Health Administration's request, the U.S. Bureau of Mines is investigating several sensor technologies for continuously monitoring respirable coal mine dust. One of these technologies is the Rupprecht and Patashnick Co. tapered element, oscillating microbalance. The bureau is in the process of investigating the suitability of using this sensor in the high humidity and vibration environment of underground coal mines. Laboratory tests have indicated that, with modification, the sensor can meet the humidity and vibration requirements for underground coal mine use. Currently, the bureau is developing prototypes of a continuous dust monitor based on this technology. When available, these will be evaluated in underground coal mines. CANTRELL, B.K.; STEIN, S.W.; PATASHNICK, H.; HASSEL, D.: STATUS OF A TAPERED ELEMENT, OSCILLATING MICROBALANCE-BASED CONTINUOUS RESPIRABLE COAL MINE DUST MONITOR. APPL. OCCUP. ENVIRON. HYG. 11(7):624–629; 1996.

The current gravimetric approach to measurement of shift-average respirable dust concentrations in underground coal mines,[1] with its inherent delays, cannot provide dust level data quickly enough to allow on-site correction of inadequate dust control strategies or removal of personnel from harmful environments. Furthermore, in April 1991 the Secretary of Labor alleged widespread tampering with respirable dust samples taken by mine operators for compliance assessment at several hundred coal mines. These allegations of tampering and a directive from the secretary prompted the Mine Safety and Health Administration (MSHA) to appoint a special Respirable Dust Task Group to study options to improve the monitoring and control of respirable coal mine dust.

Since then, the Mine Safety Appliances Company, sole supplier of approved samplers,[1] has modified the samplers to make them resistant to tampering or accidental dislodgement of dust from the sampler's filter. Despite these improvements, MSHA's task group concluded that continuous monitoring of the mine environment and parameters used to control dust offers the best solution for improving the dust enforcement program. The task group report recommended that the U.S. Bureau of Mines (BOM) develop a continuous respirable dust monitor that can be mounted on a continuous or longwall mining machine or operated at a fixed site in a mine. The monitor would provide continuous information to the miner and mine operator regarding dust levels and the status of compliance with the applicable respirable dust standard.[2]

In response to MSHA's request, the BOM is investigating several sensor technologies for continuously monitoring respirable coal dust. To be accepted by MSHA, mine workers, and the coal companies, a machine mounted continuous respirable dust monitor (MMCRDM) must reliably monitor respirable dust concentrations in the mine with sufficient accuracy to be used as a measurement of compliance with the coal mine dust standard. Of the instruments currently on the market to measure aerosol concentration, most sense some property of the particles other than their mass. These require tacit assumptions about the relationship of aerosol mass to the property sensed to convert the sensor reading to equivalent aerosol mass. This can lead to significant error. A direct aerosol mass sensing instrument eliminates these assumptions and their potential for erroneous readings.

One direct aerosol mass sensor is the Rupprecht and Patashnick Co. (R&P) proprietary tapered element, oscillating microbalance (TEOM®) sensor. R&P has developed several commercial aerosol monitoring instruments and a variety of special purpose prototypes based on this sensor, including one intended to fly on the space shuttle. In doing this, R&P has accumulated a wide variety of solutions to difficult requirements in building custom mass measurement systems for government and industry. Mine conditions are severe, but are by no means the most severe conditions yet encountered. R&P inertial balance mass transducers now in use have operated in temperatures from cryogenic to 600°C and pressures from hard vacuum to 1200 psi. Special transducers have been designed to withstand the vibration and shock of a space shuttle launch simulation, the impact of a multikilowatt laser gun, and the magnetic field inside a super-conducting magnet. In the

TABLE 1. Target Performance and Environmental Specification for a Machine-Mounted, Continuous Respirable Dust Monitor

Performance Specification	Standard
Measurement units	Mass concentration of respirable dust (mg/m^3)
Measurement range	0.5 to 10.0 mg/m^3
Accuracy	±25% of reading with 95% confidence
Overload tolerance	100 mg/m^3 for 120 seconds 25 mg/m^3 for 60 minutes 10 mg/m^3 for 120 minutes
Measurement period	30 minutes, cumulative shift average (shift length: 8, 10, or 12 hours)
Maintenance cycle	30 days unattended, data storage for a minimum of 90 shifts
Safety certification	Must be certifiable by MSHA for use in permissible areas of coal mines
Temperature range (anticipates both underground and some surface operation)	−40° to 40°C, typically 0° to 30°C
Thermal shock range	40° to 0°C
Temperature excursion rate	10°C/min
Operational altitude/pressure equivalent Range	sea level ±10,000 ft
Humidity	0 to 100% (typical operation range 30 to 95%)
Mechanical shock (shipping)	1 m drop equivalent
Mechanical shock (operating)	11 millisecond period sawtooth impulse shock of 20 g
Vibration (continuous miner)	Sine vibration, 5 to 2000 Hz, 1.5 g
Vibration (haulage vehicle)	Sine vibration, 5 to 92 Hz, 2.5 g and 92 to 500 Hz, 3.5 g
Power fluctuation	±25%

BOM's experience, the TEOM dust monitor has exhibited excellent accuracy and stability in laboratory tests.[3] In addition, the Environmental Protection Agency has approved the Series 1400 for PM_{10} (particulate mass less than 10 μm in size) environmental monitoring.[4]

The BOM is in the process of investigating the suitability of using this sensor in the high humidity and vibration environment of underground coal mines. Laboratory tests have indicated that, with modification, the sensor can meet the humidity and vibration requirements for underground coal mine use. Currently, the BOM is developing prototypes of a continuous dust monitor based on this technology. When available, these will be evaluated in underground coal mines.

MMCRDM Requirements

This monitor would be mounted on mobile mining machines, probably continuous miners or longwall shearers, and would continuously sample dust in the vicinity of the machine operator. MSHA has not yet finalized how data from such a monitor would be used to enforce the statutory respirable dust standard. They are currently collecting data with experimental gravimetric sampling instruments that sample mine air continuously. The data obtained will help MSHA formulate an enforcement strategy utilizing the fixed-site monitor.

With the concurrence of MSHA, the BOM has drawn up the target specifications of Table 1[5] for the MMCRDM. In addition to measuring respirable dust concentration in the mine environment, the monitor is to be tamper resistant and will store the dust exposure information for later retrieval. In operation, the unit can be programmed to display for the operator both current and cumulative shift-average dust concentrations. Comparison of this with the shift average permissible exposure limit can then be used as an indicator of a dust generation problem in the mining operation.

The TEOM Dust Monitor

The TEOM sensor uses the inertial behavior of a vibrating element to measure the mass of sampled dust.[6] The active element of the system, depicted in Figure 1, is a specially

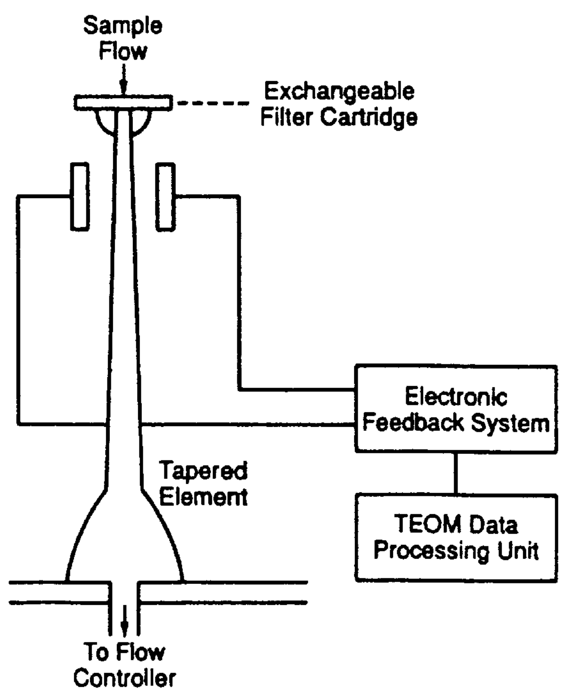

FIGURE 1. Schematic of the TEOM dust sensor.

tapered hollow tube constructed of an elastic, glasslike material. The wide end of the tube is firmly mounted on an appropriate base plate. The narrow end supports a replaceable collection medium, such as a filter, and is permitted to oscillate. Particle-laden gas streams are drawn through the collection medium, where particles are deposited. The filtered gas is then drawn through the hollow tube, typically controlled by an automatic mass flow controller. As the collection medium collects dust, the mass increases, thereby decreasing the frequency of oscillation. By measuring the change in frequency, one can determine the gain in the mass of dust on the collection medium.

An electronic feedback system initiates and maintains the oscillation of the tapered element. The details of the feedback system have evolved over the years, but typically a light-emitting diode (LED) photo transistor pair aligned perpendicular to the plane of oscillation of the tapered element detects the frequency of oscillation. The light-blocking effect of the oscillating element positioned between the photo transistor and the LED modulates the output signal of the photo transistor, which is then amplified. Part of the amplified signal is used by the feedback system to provide sufficient force to overcome any amplitude damping of the tapered element oscillation. The other part of the amplified signal from the LED-photo transistor pair is sent to a counter and data processing stage. Here the frequency of oscillation of the tapered element is calculated and stored in memory.

The equation that describes the behavior of the TEOM system derives from the equation of motion for a simple harmonic oscillator:

$$\Delta m = K_0(1/f_b^2 - 1/f_a^2)$$

where:

Δm = mass of the collected sample
f_b = frequency of the oscillating element after sample collection
f_a = frequency before sample collection
K_0 = a constant (spring constant) unique to each tapered element

Note that although the relationship is not linear, the increase in mass can be determined by measuring only the change in frequency. Although external physical influences can affect the accuracy of this mass determination, no corrections are made to the result. Instead, the tapered element is mounted in such a way as to minimize or eliminate the effects of these influences.

Benefits/Challenges

Unlike many other aerosol measurement technologies that measure an aerosol parameter correlated with mass, the TEOM technique directly measures mass inertially. With the appropriate system preclassifier, the instrument collects and measures respirable mass. The measurement range of the instrument depends strongly on the design of the tapered element. For typical commercial instruments, the range also depends on sample averaging time. Sampling at 3 L/min for 2 minutes, the 2σ mass concentration resolution is typically $\pm 15\ \mu g/m^3$. TEOM-based instruments can measure up to several grams per cubic meter. The measurement remains accurate as long as the mass on the filter remains below 10 to 15 mg. The pressure drop across the filter determines when the filter should be changed.

The TEOM aerosol monitor will initially measure any water droplets reaching the collection filter as aerosol mass. Changes in mine air humidity and temperature could also conceivably affect the response of the instrument. The commercial environmental dust monitor uses a 50°C temperature-controlled inlet conditioning system to eliminate or reduce the effect of humidity and temperature variations at the sensor. Under these sampling conditions, collected water aerosols evaporate, leaving only solid particulate on the filter.

Since TEOM instruments operate by measuring the change in frequency of a vibrating element, vibrations from external sources can also interfere with the measurement. If mounted on a mining machine, vibrations from the machine could conceivably cause it to operate improperly. It is this possibility that is the greatest challenge in using the TEOM as a dust sensor.

Status

Under a BOM contract, R&P has completed a study to determine the feasibility of using a TEOM sensor in the underground environment as a machine-mounted dust monitor. They successfully redesigned the TEOM aerosol mass sensor to meet the most critical environmental specification listed in Table 1, specifically, machine vibration. Under the contract, R&P delivered to the BOM a prototype laboratory version of this sensor. The BOM is evaluating the device in the laboratory with other candidate technologies to confirm manufacturer claims, especially with respect to vibration isolation.

TEOM Dust Monitor Modifications

Starting with an R&P model 1400 commercial dust monitor, each subsystem will be subject to review and repackaging in order to meet the more stringent requirements of underground use. The major new requirements for mine use are to maintain high resolution in the face of heavy shock and vibration and a 30-day maintenance cycle.

Other mine use requirements, such as intrinsic safety in an environment that is potentially explosive due to the presence of methane, ability to withstand rock falls, ability to work in high transients of temperature and dust loadings, ability to work in condensing humidity or water sprays, and the requirement to do all this in a reasonably small package are a challenge, but straightforward approaches have been identified for each requirement. Inherent in the basic TEOM technology are ancillary requirements such as true mass readings and real-time data reporting. Because of the real-time reporting, the monitor can potentially be made tamper resistant, since anomalies in the instrument's operation can be recorded.

The repackaging effort will include work to identify and quantify all the above-mentioned environmental and operating conditions insofar as they affect the instrument's ability to perform accurately and reliably. As monitor development proceeds, these will be combined to provide an error budget for the mass concentration measurement. Included in this as a major item will be the bias introduced by the instrument's dust sample inlet system. The budget will be used to assess monitor design tradeoffs, and will ultimately assure that the final design meets the specifications of Table 1.

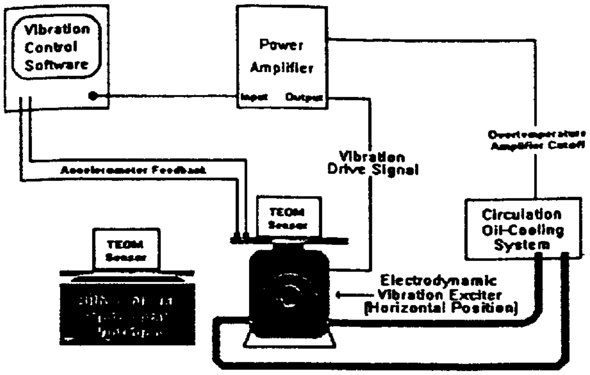

FIGURE 2. Block diagram of the BOM vibration testing facility.

The greatest challenge in the repackaging of R&P's mass monitor for mine use is thought to be ensuring the survival, proper operation, and explosion safety of the 20+-inch Hg sample pump, mass flow controllers, computer, and support electronics. There do not appear to be many off-the-shelf items suitable for these subsystems, especially in reasonable sizes. In this effort, modified or custom components will be developed that may be useful in other types of mine-ready sensors and instruments.

Laboratory Evaluation

The BOM is currently evaluating the laboratory prototype of the machine-mounted monitor based on the TEOM. The objectives of this testing are to confirm that the R&P sensor meets the specifications of Table 1 and to develop a test facility and protocols capable of evaluating other sensors for potential use in an MMCRDM. The facilities being used for this purpose are a vibration and shock test facility and a humidified dust chamber.

The laboratory evaluation of the modified TEOM sensor will be carried out in three phases. The initial phase will be an evaluation of the stability of the instrument's baseline under various vibration conditions. In the second phase, the ability of the instrument to measure aerosol mass concentrations accurately will be studied for a range of environmental vibration, shock, and humidity conditions. Instrument durability will be examined in a final phase.

Vibration Tests

A block diagram of the system used for vibration testing of the modified TEOM sensor is shown in Figure 2. The system consists of a Gen Rad 2514 vibration control computer, software, and accelerometer feedback system; a 12,000-W power amplifier (MB Dynamics, model M12K); an electrodynamic vibration table (MB Dynamics, model C-50); and an oil cooling system that cools the exciter. An oil-lubricated slip table is used for horizontal vibration. Up to four accelerometer inputs are available for feedback control of sinusoidal signals (19 are available for random vibration testing). The user can define the reference spectrum in terms of acceleration, amplitude, or velocity. This system has a usable bandwidth of 5 to 5000 Hz with minimal total harmonic distortion (<1%) and a noise specification of 60 dB below full-rated output.

Baseline Tests

During initial evaluation of the sensor, instrument baseline stability will be determined under various vibration conditions. The instrument will sample under normal operating conditions, except that a filter will be placed over the aerosol inlet so no mass will accumulate on the filter mounted on the tapered element. Deviation from the instrument baseline (i.e., any indication of a nonzero collected mass or mass concentration) will be recorded along with the input acceleration signal. Vibration frequencies for sensor resonances will be determined by sweeping through the specified range of vibration and noting any frequencies at which the indicated collected mass or mass concentration significantly deviates from zero. Subsequent tests will examine the sensor response at these frequencies by exposing the sensor to slowly sweeping sinusoidal vibration signals. The response of the instrument's baseline to random vibrations will also be evaluated by exposing the sensor to vibration spectra that would be expected for an MMCRDM.

Dust Chamber Tests

A dust chamber system, manufactured by ELPRAM Inc., has been modified to accept dust from three sources and combine these in a humidified sample air stream. Aerosol sources include two TSI fluidized-bed aerosol generators and an ONAN, model 10.OVR, 10-kW diesel electric generator set for diesel aerosol generation. The chamber has been equipped with sample flow controllers to accommodate several dust monitors simultaneously. To provide humidified sample air, the chamber is equipped with a system that can achieve stable humidities in the 30 to 95 percent range.

The ability of the instrument to measure aerosol mass concentrations accurately while challenged by a range of vibrations and humidities will be evaluated. This will be done by comparing the indicated mass concentration to concentrations indicated by concurrently collected stationary filter samplers located next to the vibrating sensor. This will be done for both vertical and horizontal vibrations. The sensor will be exposed to the expected vibration spectra of an MMCRDM. Humidity tests will be conducted separately using the dust chamber facility.

Durability Tests

The ability of the sensor to withstand extended vibration will be examined. The sensor will be exposed to extended periods of vibration and checked for instrument failures. These vibration tests will simulate the expected vibrations of an MMCRDM.

Preliminary Results

Examination of the sensor baseline response to vertical sinusoidal vibrations has been completed and the response is indicated in Figure 3. Notice that deviations from the baseline are significant at 14, 35, and about 60 Hz. These deviations are due to resonances in the spring suspension of the sensor. Smaller resonances occur at 75 and 310 Hz. At frequencies higher than 310 Hz the suspension essentially isolates the sensor from vibration. Substantial baseline deviation occurs for vibration at the tapered element oscillating frequency (~252.66 Hz). The spring suspension eliminates almost all of

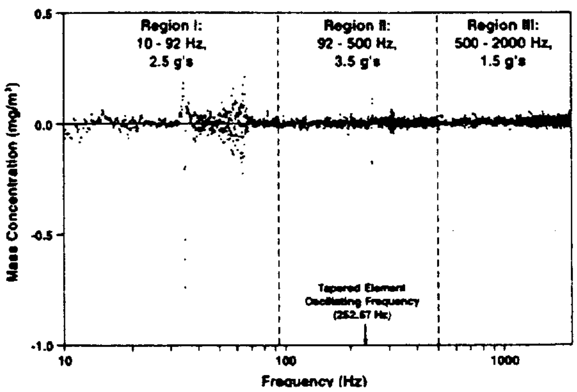

FIGURE 3. Baseline distortions caused by a vertical sinusoidal vibration sweep.

this vibration, but the small component of vibration reaching the sensor at this frequency causes significant baseline deviation. The mass concentration averaging interval used to collect the data in Figure 3 was 30 seconds. The magnitude of the baseline deviations depends on the averaging interval. Increasing the averaging interval decreases baseline deviations.

The system's resonance frequencies, indicated in Figure 3, were then examined using slow-sweep sinusoidal vibration signals. The results of a slow sinusoidal sweep across the resonance at 252.66 Hz (the tapered element oscillating frequency) are shown in Figure 4. This figure shows results from a preliminary test with horizontal vibrations. The direction of vibration in this test was the same as the direction of the oscillation of the tapered element. Initial indications suggest that horizontal vibrations in the direction of tapered element oscillation and near the tapered element oscillating frequency is the worst-case vibration scenario for the TEOM sensor. The mass concentration averaging interval for these data is 15 seconds.

Increasing the mass concentration averaging interval reduces the baseline distortions. Additional vibration tests at the tapered element oscillating frequency examined the influence of the averaging interval on the magnitude of the baseline distortion. For these tests the vibration signal was maintained at 252.66 Hz and 3.5 g, and the averaging interval was increased. The magnitude of the mass concentration distortion decreased by factors of 12 and 60 when the averaging interval was increased from 15 seconds to 5 and 10 minutes, respectively. Since the MMCRDM specifications of Table 1 require data only every 30 minutes, it appears that baseline distortions from sinusoidal vibrations can be minimized by selecting a sufficiently long averaging interval.

A preliminary coal dust concentration measurement comparison between this sensor and respirable dust samplers was conducted for sample air humidities of 30 to 90 percent and dust concentrations ranging from 0.2 to 10 mg/m³. Results from these tests indicate a measurement variance less than 10 percent at the 95 percent confidence level. Tests with diesel, diesel-and-coal dust, and diesel-coal-and-rock dust mixtures have yet to be conducted.

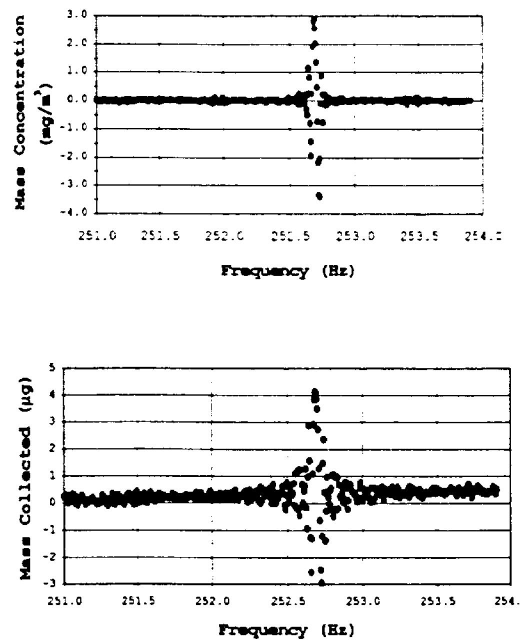

FIGURE 4. Baseline distortions from slowly sweeping sinusoidal vibration near the tapered element oscillating frequency. The mass concentration and collected mass averaging times were both 15 seconds, and the sweep rate for the test was 1 Hz every 16 minutes.

Summary and Status

In response to MSHA's Respirable Dust Task Group, the BOM is engaged in an aggressive research effort to develop mine-worthy devices to monitor respirable coal mine dust mass concentrations continuously. One of the dust sensor technologies that the BOM has chosen for development is the TEOM manufactured by R&P. This technology is desirable in that it measures collected aerosol mass directly. Preliminary results from laboratory evaluations of a TEOM sensor, modified to reduce response to environmental vibrations, indicate that the sensor will operate well within the environmental and performance specifications of Table 1.

A contract was awarded to deliver two prototype TEOM sensors in mid 1995 for in-mine evaluation. To verify the in-mine performance of the sensor without having to finalize the design of permissible electronics, these sensors will use an umbilical system for power, signal, and sample air flow. After certification by MSHA, the umbilical system will allow the prototype sensors to be evaluated underground by locating the support circuitry in a remote, nonhazardous location. MSHA will be involved in these tests as part of a joint venture with the BOM. The contract also requires fabrication of ten production prototype continuous respirable dust monitors based on the TEOM sensor developed for in-mine evaluation. After certification by MSHA, the production versions of the instruments will also be evaluated underground.

If successful, this research will foster development of a family of commercial continuous respirable dust monitors that can be mounted on mining machines, used as portable dust monitors, incorporated in mine atmospheric monitoring systems, and used as personal exposure monitors for mine workers. Such instruments could make accurate, continuous records of dust concentrations in the workplace, a significant development for occupational health and the mining industry.

Using this record, researchers, regulatory personnel, or mine personnel could evaluate specific mining practices to see immediately which ones tend to expose mine workers to excessive dust levels. This information would also permit mine personnel to take corrective action and optimize mining procedures to reduce dust exposure. It will also provide MSHA with a means to monitor dust concentrations in mines when mine inspectors cannot be present.

Disclaimer

Reference to specific companies or brand names does not imply endorsement by the BOM.

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