CONTINUOUS RESPIRABLE MINE DUST MONITOR DEVELOPMENT

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ABSTRACT

In June 1992, the Mine Safety and Health Administration (MSHA) published the "Report of the Coal Mine Respirable Dust Task Group, Review of the Program to Control Respirable Coal Mine Dust in the United States." As one of its recommendations, the report called for the accelerated development of two mine dust monitors: (1) a fixed-site monitor capable of providing continuous information on dust levels to the miner, mine operator, and to MSHA, if necessary, and (2) a personal sampling device capable of providing both a short-term personal exposure measurement as well as a full-shift measurement.

In response to this recommendation, the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Center, initiated the development of a fixed-site machine-mounted continuous respirable dust monitor. The technology chosen for monitor development is the Rupprecht and Patashnick Co., Inc. tapered element oscillating microbalance. Laboratory and in-mine tests have indicated that, with modification, this sensor can meet the humidity and vibration requirements for underground coal mine use. NIOSH is continuing that effort by developing prototypes of a continuous dust monitor based on this technology. These prototypes are being evaluated in underground coal mines as they become available. This effort, conducted as a joint venture with MSHA, is nearing completion with every promise of success.

The immediate benefit of this effort will be to researchers, regulatory personnel, and mine personnel, by permitting evaluation of specific mining practices to see which expose mine workers to excessive dust levels. Using this information, mine personnel can optimize mining procedures to reduce dust exposure. MSHA and the operators will also be able to use the dust concentration data to judge whether dust plan parameters are adequate to continuously maintaining environmental dust levels below the applicable standard.

The second development recommended by the Dust Task Group was a person-wearable version of the continuous dust monitor. It will be a monitoring system designed to provide a measurement of worker exposure to respirable dust, both during and at the end of the shift.

INTRODUCTION

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 quick enough to allow on-site correction of inadequate dust control practices. Furthermore, in April 1991, the Secretary of Labor alleged widespread tampering at several hundred coal mines with respirable dust samples taken by mine operators for compliance assessment. These allegations and a directive from the Secretary prompted MSHA to appoint a special Respirable Dust Task Group to study options to improve monitoring and control of respirable coal mine dust.

In June 1992, MSHA published the report of the dust task group (2). This report called for the accelerated development of two mine dust monitors: (1) a fixed-site monitor capable of providing information on dust levels to the miner, mine operator, and to MSHA, if necessary, and (2) a personal sampling device capable of providing both a short-term personal exposure measurement as well as a full-shift measurement.

In response to MSHA's request, the former U.S. Bureau of Mines (USBM) investigated several sensor technologies for continuously monitoring respirable coal mine dust. Most instruments currently on the market for measuring aerosol concentration sense some property of the particles other than their mass. Converting the sensor reading to equivalent mass requires tacit assumptions about the relationship between aerosol mass and the property sensed. These assumptions can lead to significant error. A direct aerosol mass sensing instrument eliminates the potential for error that is associated with converting sensor measurements to equivalent mass concentrations.

One such technology is Rupprecht and Patashnick Co., Inc. (R&P) proprietary tapered element oscillating microbalance (TEOM®) sensor. In USBM laboratory tests of sensor response to vibrations and humidity (3), the TEOM® dust monitor exhibited excellent accuracy and stability. Consequently, the TEOM® dust sensor has been chosen for use in the high humidity and vibration environment of underground coal mines. Prototypes of a fixed-site machine mountable continuous respirable dust monitor (MMCRDM) based on this sensor are currently being developed, and evaluated in underground coal mines as they become available. The first such evaluation was completed in 1995; the second is scheduled for mid 1996. A commercial version of the monitor is due in early 1997. An effort to use the technology developed, for this monitor in the design of a person-wearable version is being planned. It will provide short-term personal exposure measurement as well as end-of-shift dust exposure measurement.

MMCRDM REQUIREMENTS

This fixed-site monitor will be mountable on mobile mining machines, most likely continuous miners or longwall shearers, and will continuously sample dust in the vicinity of the machine operator. While MSHA has not finalized how data from such a monitor would be used, it would provide more complete and immediately available information regarding how well dust control practices are working.

With the concurrence of MSHA, the USBM formulated target specifications (Table I) for the MMCRDM (4). At the request of MSHA, the sample preclassifier was designed to pass size selected aerosol to the tapered element filter based on the international standards organization (ISO) definition of respirable dust (5). In addition to measuring respirable dust concentration in the mine environment, the monitor is to be tamper-resistant and store dust exposure information for 30 days. In operation, the unit will be programmed to display dust concentrations in real time and indicate whether the shift average permissible exposure limit will be exceeded during the work shift.

TAPERED ELEMENT OSCILLATING MICROBALANCE

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 tapered hollow tube constructed of metal or an elastic, glass-like 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 air is drawn through the collection medium, where particles are deposited. The filtered air is then drawn through the hollow tube. Airflow is controlled by an automatic mass flow controller. As the collection medium collects dust, its mass increases, causing a decrease in 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.

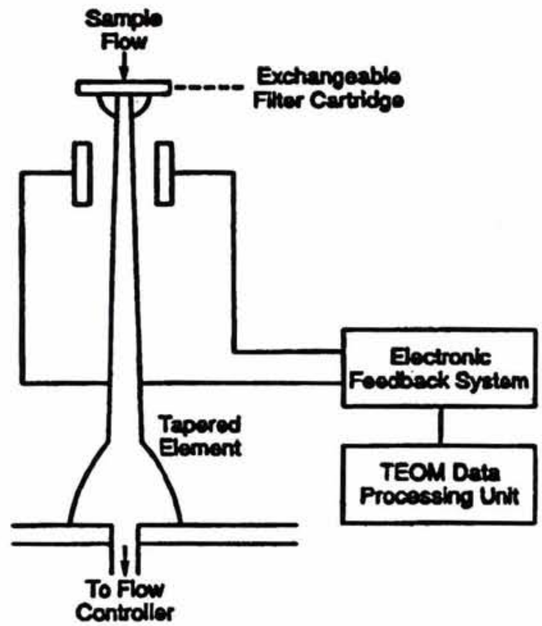

Figure 1. Schematic of the tapered element oscillating microbalance (TEOM) dust sensor.

Benefits/Challenges

Unlike many other aerosol measurement technologies that

Table 1. Target Performance and Environmental Specifications for a Fixed-site MMCRDM

Performance Specification	Standard
Measurement units	Mass concentration of respirable dust, mg/m^3
Measurement range	0.5 to 2.0 mg/m^3 ± 25%
Accuracy	± 25% of reading with 95% confidence
Overload tolerance	100 mg/m^3 for 10 sec 25 mg/m^3 for 30 sec 10 mg/m^3 for 120 sec
Measurement period	30 min cumulative shift average (shift length: 8, 10, or 12 hrs)
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 ms period sawtooth impulse shock of 20 g
Vibration (continuous miner)	Sine vibration, 5 to 2,000 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%

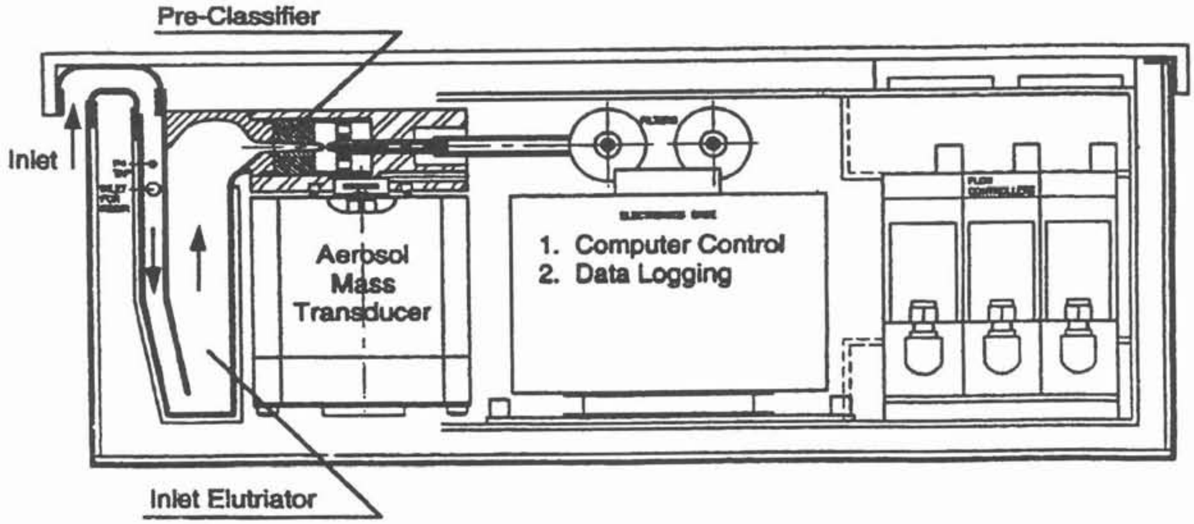

Figure 2. Cross-section view of machine mounted, continuous respirable dust monitor.

measure an aerosol parameter correlated with mass, the TEOM® technique measures mass directly. With the appropriate preclassifier, the instrument collects and measures respirable mass. Sampling at 2 L/min for 30 min, the typical measurement accuracy is ± 15 µg/m³. The measurement remains accurate as long as the mass on the filter remains below about 5 to 10 mg.

The TEOM® aerosol monitors would measure any water droplets reaching the collection filter as aerosol mass. Changes in mine air humidity and temperature could also affect the response of the instrument. However, the monitor uses a 50°C temperature-controlled inlet conditioning system to eliminate or reduce humidity and temperature variations of 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 interfere with the measurement. In the machine-mounted unit, however, vibrations from the machine are damped using vibration isolation mounting of the monitor sensor.

CONTINUOUS RESPIRABLE DUST MONITOR DEVELOPMENT

Under a USBM contract, R&P Co., Inc. embarked on a program to design, build and test ten production MMCRDM's based on the TEOM® aerosol mass sensor.

Three phases are required to complete this work:

Phase 1

Phase 1 has two parts:

(a) Design a research proof-of-concept prototype MMCRDM to be tested using tethered electronics. The prototype must be certifiable by MSHA for an Experimental Permit for use in permissible areas of coal mines. Two of these prototype MMCRDM's were evaluated by PRC and MSHA in laboratory and field tests, primarily for response to machine vibration. Field evaluation was conducted in a continuous miner section of an operating coal mine.

(b) Begin design of two pre-production prototypes. The pre- production prototypes will include prototypes of all the components that will be included in the production models.

Phase 2

Complete the design and construction of the two pre-production prototype MMCRDM's. The design was to incorporate tamper-resistance. The prototypes are machine mountable and certified for experimental permits by MSHA. These prototypes will be evaluated during laboratory and field tests. During the field test, one unit will be mounted on a continuous miner and the other unit will be used in a longwall mining section.

Phase 3

Delivery of ten production model MMCRDM's built to commercial production specification.

PHASE 1 FIELD EVALUATION

Phase 1 laboratory and in-mine evaluation of the prototype of the machine-mounted monitor was conducted as a joint venture with MSHA. Laboratory tests of the monitor sensor were conducted by the USBM in mid 1995. The protocol followed has been detailed elsewhere (7). Field evaluations were conducted in a continuous miner section from August 10 to 24, 1995.

The monitor configuration tested in the Phase 1 field evaluation is illustrated in figure 2. As designed, this configuration measured 0.3 x 0.55 x 0.2 meters. During the tests, however, the computer control, data logging, sample flow control, and sample pump were removed from the case and placed at a remote location. Only the sample inlet, sample preclassifier, and TEOM® aerosol mass transducer/sensor were attached to the canopy of the continuous miner. This arrangement placed the sensor assembly within 1 m inby of the machine operator while leaving his view of the face unobstructed. As indicated in figure 3, a 215-m umbilical cable containing instrument power, signal, and vacuum lines, connected the sensor through a group of electrical barriers to the electronics located at a data and control center near the

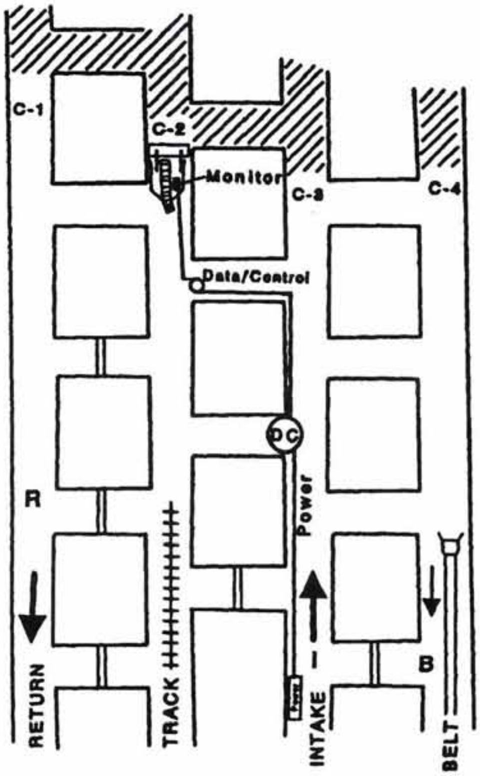

Figure 3. Location of MMCRDM sensor (Monitor) and auxiliary electronics (DC) during phase one evaluation.

section's power center. In this way, the intrinsically safe sensor assembly could be operated at the face, while the nonintrinsically safe equipment was operated in fresh or intake air.

During the field tests, measurements were also taken of machine vibration and respirable dust levels at the position of the monitor. The accelerometers used to measure machine vibration were also connected through a 300-m umbilical cable and electrical barriers to signal amplifiers and a power supply at the data and control center. Data logging for both dust monitor concentration and vibration measurements was done using personal computer-based data loggers. Gravimetric respirable dust measurements were collected for comparison with the continuous monitor measurements using Mine Safety Appliances (MSA) personal respirable dust samplers operated at a flow rate of 1.7 Lpm. This flowrate was used to better approximate the ISO respirable dust criteria used by the continuous monitor.

Table II displays the measurements made during the field evaluation of the continuous monitor. Measurements were taken for seven days over a two-week period.

Comparison of continuous dust monitor and personal dust monitor measurements of dust concentrations were made for three of the four sample days. The data from the fourth day were not used due to monitor data control damage during the measurement period. A pre-filter (PF) was placed on the monitor on the other three days to explore the effect machine vibration had on the instrument's baseline. Vibration measurements were taken on all sampling days.

RESULTS

During the Phase 1 test, the continuous monitor measured respirable mass concentration in mg/m³ every 1.7 sec. A 30-sec moving average was applied to these data. As shown in figure 4, this average was displayed graphically in real time by the computer data acquisition system. The figure shows typical results during two coal cutting cycles and one bottom cleaning pass by the continuous miner. Mass concentrations drop to background levels between periods of activity, suggesting that the measurement process is not severely affected by machine vibration. Also, total collected mass values and trends indicated no dependence on water or humidity.

Table II. Primary measurements conducted during the field evaluation of the MMCRDM

Date (August 1995)	Continuous Monitor	Measurement Vibration	Personal Sampler
15	[1]PF	Yes	No
16	Yes	Yes	Yes
17	Yes	Yes	Yes
18	Yes	Yes	Yes
21	[2]No	Yes	Yes
23	PF	Yes	No
24	PF	Yes	No

[1]Continuous monitor operated with pre-filter.

[2]Continuous monitor data/control cable damaged; data not valid.

On the last two days of the study, a pre-filter was inserted into the sample path of the continuous monitor. The monitor was otherwise operated normally. At the end of this period, which in-

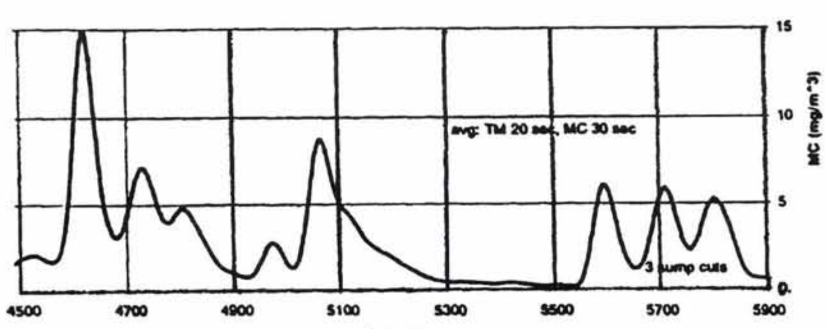

Figure 4. Dust concentrations measured by the MMCRDM on 21 August 1995.

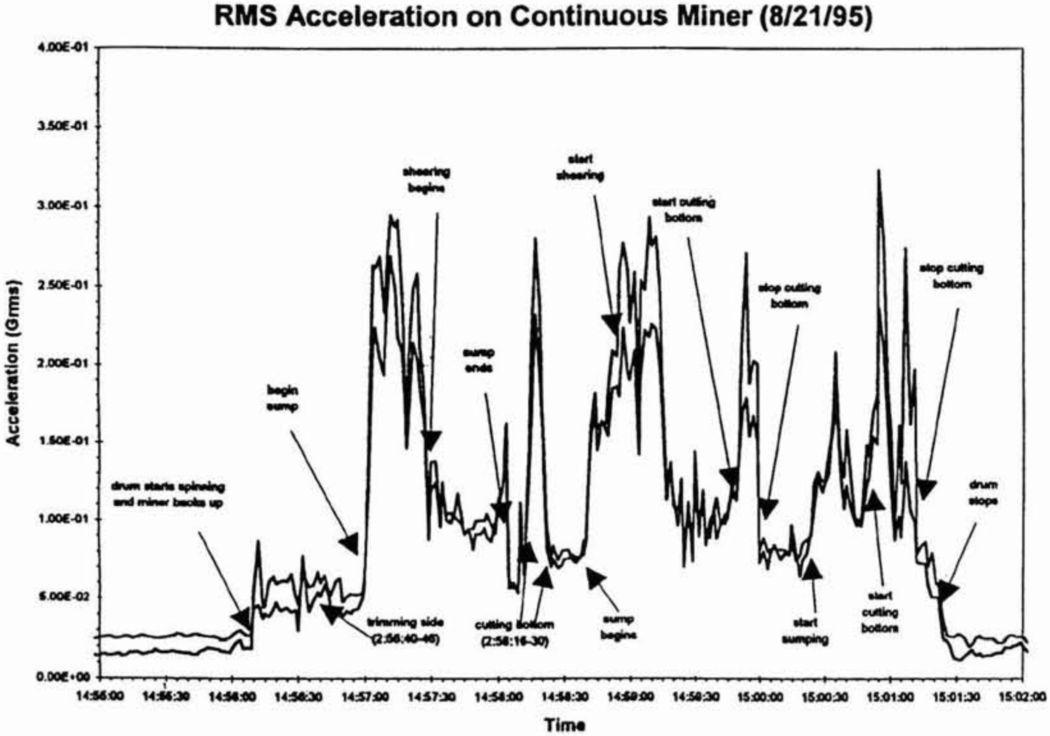

Figure 5. Vibration measured at the MMCRDM on 21 August 1995.

cluded one overnight shutdown of the monitor and a cold start half-way through the period, baseline drift for the unit was less than 1 µg of collected mass. This indicates that the sensor is not sensitive to environmental factors such as vibration and humidity.

Typical results for vibration measurements, in units of the gravitational constant (G, rms), made during the last part of the period illustrated by figure 4, is shown in figure 5. These data, collected during the three sump cuts, show in detail the machine operations during the cuts. In general, accelerations were an order of magnitude less than those cited in the target specifications of Table I.

Table III includes collateral respirable dust measurements made during the sensor evaluation. The comparison points to a positive bias in the TEOM® results, an average of 20 ± 13%. This bias can be partially explained by the difference in the preclassifiers used in the TEOM® sensor and the personal respirable dust sampler. Using the measured penetration efficiency of the monitor's preclassifier and the published penetration efficiency of the Dorr-Oliver cyclone used with the personal sampler in combination with an assumed particle size distribution for the collected mine aerosol, a net bias of 12% is predicted. Although not determined, the remaining bias has been attributed to the position of the inlet on the side of the sensor box. With this inlet position, the monitor samples from a volume where air may recirculate, concentrating aerosol mass in the TEOM® sample and producing the noted bias.

PROJECT STATUS

Phase 2 of the project to produce and test a redesigned, self-contained monitor is now underway. Using the results of the Phase 1 evaluation, the MMCRDM has been redesigned. The insensitivity of the unit to vibration and the lower than expected vibration levels permitted a modification in the vibration isolation member that has reduced the size of the sensor assembly. Because of the success using the umbilical configuration, the MMCRDM will be installed in two parts: (1) an intrinsically safe unit containing the sensor and a filter changer, and (2) an explosion-proof enclosure (XPE) containing the computer, pump, power supplies, and electrical barrier circuits. This arrangement will permit a smaller profile sampling unit in front of the machine operator.

Also, the use of an XPE preserves the ability to install the monitor components in the existing miner XPE.

The inlet bias problem has been solved by moving the inlet from the side to the top of the sensor assembly, thus putting it in the unrestricted sample airstream. Referee sampling will be done using a newly designed personal respirable dust sampler that incorporates the same inlet configuration and preclassifier as that used on the MMCRDM. This will eliminate the need to correct one of the measurements to obtain a valid comparison of respirable dust mass concentration.

The completed monitor, as shown in figure 6, is scheduled for laboratory and in-mine evaluation on both a continuous miner and a longwall section in late 1996. Laboratory evaluation of the monitor will follow the protocol followed in Phase 1 of the project. During the in-mine evaluation, the monitor will be mounted on the mining machine or, as an option in the case of the longwall tests, on a shield. The monitor will derive electrical power from the miner. It will provide the machine operator with graphical and numeric information on dust concentrations as illustrated in figure 7. A series of collateral measurements, like those performed in the Phase 1 evaluation, will be made during the evaluation. These will include measurements of machine vibration, referee shift average respirable dust concentration collected with personal samplers, face ventilation, water usage, and for a portion of the personal samples, determination of silica fraction of the collected mass.

Table III. Comparison Between Integrated Continuous Dust Monitor Mass Concentrations and Those Obtained Using the MSA Personal Respirable Dust Sampler

Date (August 1995)	TEOM® mass concentration, mg/m^3	Personal sampler mass concentration, mg/m^3	Difference %
16	1.26	1.19	6
17	3.09	2.10	32
18	0.40	0.29	23
21	([1])	0.46	NA

[1]TEOM® data not used because of cable break during test day.

NA Not applicable.

The data developed during this phase of the project will be used to finalize the design of the machine-mounted monitor. Following delivery of ten production units in Phase 3, MSHA will use them in in-mine evaluations to develop use strategies for the monitor and will explore its use in MSHA's respirable coal mine dust control program.

SUMMARY

In response to MSHA's Respirable Dust Task Group report, the USBM initiated an aggressive research effort to develop mineworthy devices to continuously monitor respirable coal mine dust mass concentration. The dust sensor technology chosen for development is the TEOM® manufactured by R&P Co., Inc. This technology is desirable in that it measures collected aerosol mass directly. Results from laboratory and initial in-mine 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 I.

Two pre-production prototype MMCRDM's will be fabricated in mid 1996. After certification by MSHA, this MMCRDM system will be evaluated in both continuous miner and longwall sections of an underground coal mine. MSHA will be involved in these tests as part of a joint venture with NIOSH-PRC. As a final phase in this development, ten production prototype continuous respirable dust monitors based on the TEOM® sensor will be fabricated for in-mine evaluation. The production versions of the instruments will be used underground to develop use strategies for the monitor.

If successful, this NIOSH-PRC 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 perhaps even be 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 which ones expose mine workers to the least dust. This information would permit mine personnel to optimize mining procedures to reduce dust exposure. It will also provide mine personnel with an immediate record of daily dust concentration levels, enabling dust exposures to be maintained below federally mandated levels.

FUTURE WORK

MSHA has endorsed the development of a personal version of the continuous dust monitor. This project will be a contract re-

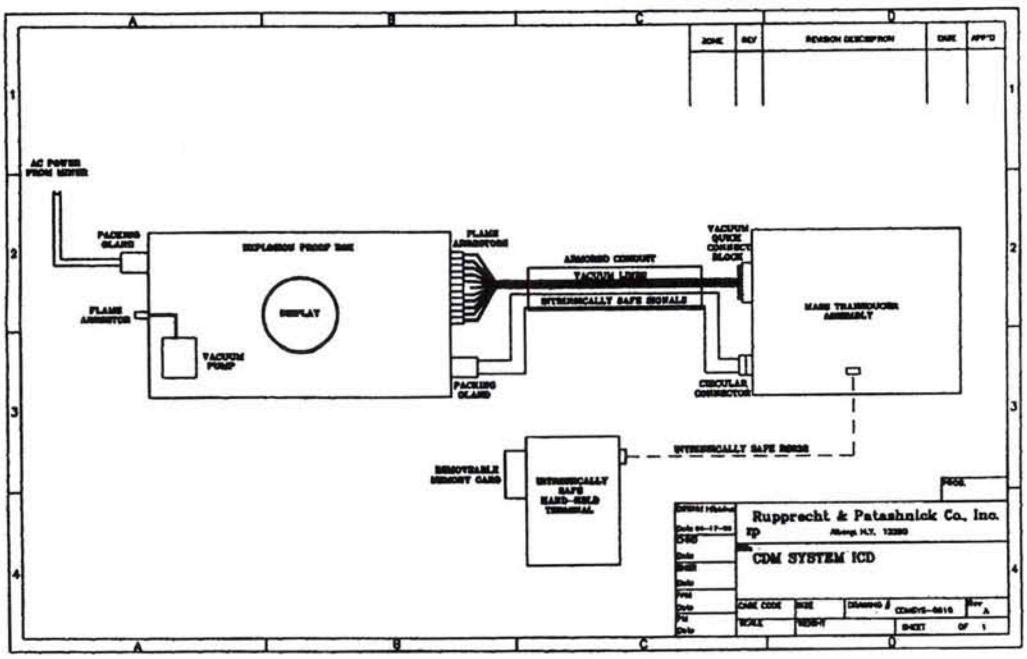

Figure 6. Design of MMCRDM for phase two in-mine evaluation.

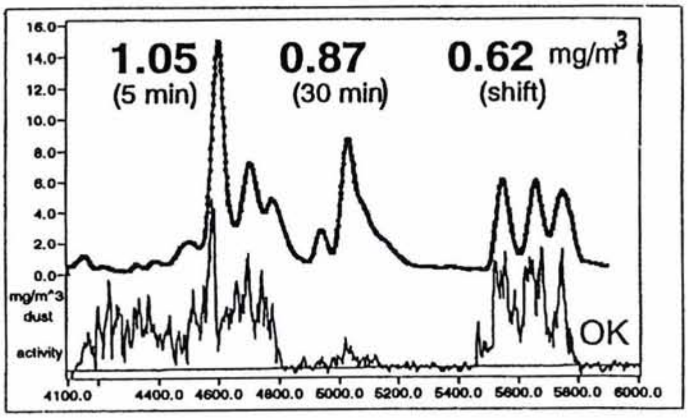

Figure 7. Real-time MMCRDM data display.

search effort with in-house evaluation of the research product by NIOSH-PRC. The personal monitoring system would be designed to operate in two modes. The first would be in the form of a personal dust dosimeter that can be interrogated underground or at the end of a shift using a portable reading system. The second configuration will provide continuous monitoring of respirable dust concentrations and would be used as a portable monitor. The system will provide immediate dust exposure information for the user and permit the mine operator to evaluate his dust control system and take effective measures to correct problems as they arise. These efforts would be part of the expanded FY96 MSHA/NIOSH joint effort and would continue through FY97 into FY98.

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