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# Response Characteristics of Scattered Light Aerosol Sensors Used for Control Monitoring

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The response characteristics of scattered light aerosol monitors used in control monitoring applications were evaluated. In this report, "control monitoring" refers to continuous, fixed point monitoring used to ensure that dust controls are effective. Instruments evaluated included the following: an ATI-722, which uses a white light source; a RAM-S, which uses a LED source; and a PCAM-TX, which uses a LED source and provides a correction for particle size. The linearity of the monitors was evaluated from 0.5 - 10 mg/m<sup>3</sup> with the use of coal dust as an aerosol. This concentration range was broken up into two smaller ranges since it was not possible to generate an aerosol with a constant size distribution over the entire range. All instruments showed a linear response with concentration for constant dust size distribution. The size sensitivity of the instruments was determined by passing a test aerosol through a series of impactor stages and measuring the mass response of each instrument relative to the indicated mass response of an Aerodynamic Particle Sizer (APS). The particle size was varied from 2-14  $\mu\text{m}$ . The mass response of the instruments relative to the APS over this size range varied from as low as 0.1 to as high as about 5. The PCAM provides data that indicate changes in the size distribution of the aerosol being monitored. A simple model was developed to relate the net response of each test instrument to various log normal size distributions. The user of the instruments has to be aware of particle size changes in the aerosol being monitored since changes in the size distribution will affect the relationship between the response of the instruments and the mass concentration. Guidelines for instrument use are given in order to show how the instruments can be applied to the continuous monitoring of dust in the workplace.

## Introduction

Control monitoring of dust in the workplace is used to reduce the exposure of workers to dust and to protect their health. In this report, control monitoring refers to continuous, fixed point monitoring used to ensure that dust control measures are effective. Possible applications include monitoring of the performance of air cleaners in recirculation systems, identification of processes and work practices that produce particulate emissions, and continuous monitoring of workplace air to ensure that emission controls are working properly and that proper work practices are being followed. Among the instrumental techniques that can be used for the monitoring of particulate matter are those based on  $\beta$ -attenuation, piezoelectric vibration measurement of mass, and measurement of scattered light from aerosols.

Because of their relatively low cost, sensitivity, simplicity, low maintenance and quick response, scattered light sensors have been applied to the monitoring of particulate matter in both control monitoring and portable instruments.<sup>(1-4)</sup> A disadvantage, however, is that the response is a function of the size distribution and optical properties of the aerosol being measured. Thus, the instruments must be calibrated for each aerosol measured and the size distribution and optical properties of the aerosol must not change significantly if the calibration is to remain valid. One manufacturer has developed instruments that attempt to compensate for size distribution changes by using an approximate particle sizing method for larger particles.<sup>(3)</sup>

The present study examined the operating characteristics of commercially available scattered light particulate monitors to determine their suitability for use in control monitoring applications. The areas studied included the dust response characteristics of the sensors and the operational characteristics that could determine suitability of the sensors for use in the industrial environment. The combination of these factors will determine how successful the sensors will be in a given application.

## Experimental

The variables studied included the response linearity of the instruments over an extended range of concentrations and the size-response characteristics of the instrumentation. The first part of the study was carried out by examination of the response of the instruments as a function of concentration with the use of coal dusts as test aerosols. The second part of the study used various stages of a cascade impactor to generate different size fractions of an aerosol and thereby determined the response of the instruments to the various size fractions. The aerodynamic particle sizer (Model APS-3300, TSI, Inc.) was used to measure the concentration and size distribution of the various aerosol fractions. Throughout the study, maintenance requirements and other characteristics of the instruments that determine their suitability for use in control monitoring applications were examined. These characteristics as well as the response characteristics of the

instrumentation are included in the guidelines for instrument application.

### **Instruments Chosen for This Study**

Three scattered light aerosol measurement instruments were used for this study: a RAM-S (GCA/Technology Division, Bedford, Mass.); a PCAM-TX (ppm, Inc., Knoxville, Tenn.); and an ATI-722 (Air Techniques, Inc., Baltimore, Md.). These instruments represent a cross-section of those available commercially and were selected because of their unique features and their designation by the manufacturer as control monitors. They are all self-contained and require only data recording devices and line power for operation. The instruments are described below:

#### **RAM-S**

The RAM-S employs a pulsed light emitting diode (LED) light source and solid state detector over an angle of approximately 40 to 70 degrees. The RAM-S can be mounted in the desired location with use of the bracket provided. The packaging is rugged and compact. Concentration range changes and output range choices are done with jumpers on a circuit board inside the instrument. It is easy to operate, and the on/off switch with a purge position is easily accessible to the operator. The purge setting is used for zeroing the instrument without use of an external filter. The purge command can be accessed by an external computer or controller in addition to the on/off switch. Thus, a periodic zero check for instrument performance can be made automatically by a computer. This instrument, however, has no reference scattering device for span checks as provided by the portable version, the RAM-1. An adjustable alarm, either for concentration or for low flow, is provided.

#### **PCAM-TX**

The PCAM-TX tested is a portable version that contains considerable built-in data acquisition capability. The instrument is also available in a multipoint version in which one data acquisition system can service a number of remote sensors. The individual PCAM-TX sensors are modified somewhat, depending upon the intended application (size range and concentration range). The PCAM-TX, like the RAM-S, uses an LED light source and detects forward light scattering. It is the only instrument tested that provides compensation for changes in the particle size distribution. The instrument provides periodic automatic zero and calibration checks, with the use of filtered air and a calibrated reference scattering device. The PCAM-TX has a self-contained data system that provides average concentration measurements for intervals of 15 min, 2 hr and 8 hr. Average size distribution data also are collected over the same interval. The instrument operating parameters (such as zero and span settings) can be read out. All data are accessible from a digital display that attaches to the instrument. The instrument has a rugged carrying case for easy transport and is easy to operate. Only on/off and reset controls are accessible to the user through use of key switches. The data selected on the digital display are accessed by use of thumb switches.

The instrument tested did not have any alarm outputs, but these can be ordered as an option.

#### **ATI-722**

The ATI-722 was included in the study since it has been used in control monitoring applications and is an example of an instrument employing a tungsten light source and photomultiplier tube detector. The instrument also uses near forward light scattering for detecting the aerosol. The response characteristics, therefore, differ somewhat from the other instruments tested. This instrument is larger and heavier than the others and employs a higher flow rate. It is a rugged package and provides alarms for light source, amplifier and pump failure as well as for concentration, making performance checks of these parameters convenient. The ATI-722 is easy to operate and provides easily accessible front panel knobs for zero, gain and stray light adjustment, as well as switches for purge and alarm reset. The purge setting can be used to zero the instrument without the use of an external filter. Contact closures for external alarms or other functions can be wired with the connections provided on the back of the instrument. The alarm setting is adjusted easily with a knob on the analog meter.

### **Instrument Response as a Function of Concentration**

#### **Description of Instrument Test Chamber**

The aerosol test chamber is similar to that described by Marple.<sup>(5)</sup> It is a hexagonal box with sides 30 cm in length and glove ports and windows on three sides to permit the manipulation and observation of the chamber contents. The chamber is supported on a triangular frame. A variable speed rotating table within the chamber can rotate the contents of the chamber through an angle of 360 degrees to compensate for spatial variation in the aerosol concentration. After instruments placed in the chamber are rotated through one revolution, the direction reverses to prevent twisting of the electrical lines and vacuum connections. Appropriate vacuum and electrical connections are fed through special fittings in the side of the chamber and through the center of the rotating table. The aerosol used in the experiments was generated with a fluidized bed aerosol generator (Model 3400, TSI, Inc.).

For some of the experiments, a variable portion of the generator output was drawn off through a filter by a vacuum pump. This was necessary to generate a range of aerosol concentrations with the same generator feed chain speed. It was found that if the chain speed was changed to vary the concentration, the size distribution of the aerosol also changed. After the aerosol was generated, it was mixed with about 200 L/min of dilution air and carried through a 2.5 cm pipe into the top of the chamber. The combined flow then impinged upon a circular mixing baffle and passed through a flow straightener to produce uniform concentration distribution within the test volume. The uniformity of concentration in the chamber was measured with the use of data from the RAM-S and was found to give a pooled coefficient of variation (CV) of 5.4% over 18 runs. The air containing the aerosol was pulled out of the chamber through a coarse filter

**TABLE I**  
**General Operating Characteristics**

Instrument	RAM-S	ATI-722	PCAM-TX
Concentration Range	0-20 mg/m <sup>3</sup>	0-0.1 mg/m <sup>3</sup>	0-20 mg/m <sup>3</sup>
Voltage Range	0-10V	0-1V	0-2V
Noise (mV)	0.4	2.0	3.0
Zero Drift (24 hr)	Neg.	40mV	Compensated
Response Time(sec)			
63%	30		30
95%	57	10 <sup>A</sup>	50

<sup>A</sup>Rapid response with overshoot, final value approached rapidly.

followed by a HEPA filter by a variable speed, high-volume blower. Typically, the chamber was operated at -0.25 cm H<sub>2</sub>O pressure to prevent aerosol leaking into the room air.

#### General Operating Characteristics

Several general operating characteristics of the instruments such as a signal noise level, zero drift and time response are of interest. In order to determine noise levels, the definition of noise given by the U.S. Environmental Protection Agency (EPA)<sup>(6)</sup> was used. The instruments were exposed to filtered air for 2 hr and the outputs were recorded on strip chart recorders. The standard deviation of measurements taken at 2-min intervals from the strip charts provided an indication of the noise level. For the RAM-S and ATI-722, the internal purge mode was used for the noise determination. With the PCAM-TX, filtered air from the instrument test chamber was sampled, since the operator cannot control the purge cycle. This may have resulted in a slightly larger noise value than would have been obtained with filtered air from the instrument itself. The noise levels determined by this procedure were low (see Table I). They were not converted to mg/m<sup>3</sup> since this determination depends on the aerosol being measured.

The zero drift of the instruments (both short-term and long-term) also was determined. None of the instruments

had significant short term (e.g., 1 hr) zero drift. The PCAM-TX compensates for zero drift by automatically zeroing the instrument every hour. The zero on the RAM-S initially rose from approximately 3 mV to about 11 mV in the first two weeks of operation; however, the zero remained at about 11mV for at least the next six months. During this period, the instrument was operated continuously except for a two-week interval when the instrument was taken on a sampling trip in an automobile. Zero drift is apparently not a problem for the RAM-S when it is operated for extended periods of low dust exposure with short periods of exposures in the range of 2-20 mg/m<sup>3</sup>. Setting the zero on the RAM-S was somewhat tedious since it took about 30 sec for the output to stabilize after a change was made. The zero on the ATI-722 drifted about 45 mV in 24 hr; therefore, the zero should be adjusted daily. This is a simple procedure with the front panel accessible automatic purge mode and stray light adjustment.

For certain applications, the time response of the instruments is an important parameter. The 95% response time is defined as being the time required to reach 95% of the final response after a step change in concentration. Since it was not possible to produce a step change in concentration, the time response was measured by an indirect procedure. The RAM-S and ATI-722 were placed in the purge mode while about 5 mg/m<sup>3</sup> of coal dust were sampled. The instruments then were switched to the sample mode and the outputs were recorded. For the PCAM, a slightly different procedure was used since its purge mode is not externally controllable. The PCAM-TX was reset and the output was recorded. This resulted in the instrument being purged with filtered air for a period of time, after which the instrument automatically switched back to the measurement mode. The response time was measured from the time the output began to change until it had reached its final value. The PCAM-TX and RAM-S followed what appeared to be first order response functions and, therefore, both 63% and 95% responses are shown in Table I. The ATI-722 responded almost immediately when the purge was switched off and overshoot the final value (in fact, went off scale), but rapidly approached the final value. For the ATI-722 and RAM-S, no measurable lag time was observed (i.e., the instrument began to

**TABLE II**  
**Response as a Function of Gravimetric Concentration**

Instrument	Coal Dust I (1.4-7.5 mg/m <sup>3</sup> )	Coal Dust II (0.5-2.1 mg/m <sup>3</sup> )
RAM-S	Res <sup>A</sup> = 1.445G <sup>B</sup> +0.285 (R <sup>C</sup> = 0.999) Res <sup>A</sup> = 1.496G <sup>*(B,D)</sup>	Res <sup>A</sup> = 2.226G <sup>B</sup> +0.437 (R <sup>C</sup> = 0.997) Res <sup>A</sup> = 2.49G <sup>*(B,D)</sup>
PCAM-TX	Res <sup>A</sup> = 1.012G <sup>B</sup> +0.226 (R <sup>C</sup> = 0.999) Res <sup>A</sup> = 1.054G <sup>*(B,D)</sup>	Res <sup>A</sup> = 1.646G <sup>B</sup> +0.476 (R <sup>C</sup> = 0.993) Res <sup>A</sup> = 1.93G <sup>*(B,D)</sup>
ATI-722	Res <sup>A</sup> = 0.722G <sup>B</sup> +0.130 (R <sup>C</sup> = 0.996) Res <sup>A</sup> = 0.746G <sup>*(B,D)</sup>	Res <sup>A</sup> = 1.176G <sup>B</sup> -0.031 (R <sup>C</sup> = 0.988) Res <sup>A</sup> = 1.151G <sup>*(B,D)</sup>

<sup>A</sup>Res = Response of instrumentation (mg/m<sup>3</sup>); assumes that the median scale on the ATI is 0-10 mg/m<sup>3</sup> (the manual gives a range of 0-1 mg/m<sup>3</sup> for 0.3 μm DOP).

<sup>B</sup>G = Gravimetric concentration.

<sup>C</sup>R = Correlation coefficient.

<sup>D</sup>\* = Best fit line with zero intercept.

## RESPONSE VS. GRAVIMETRIC CONCENTRATION

COAL DUST II

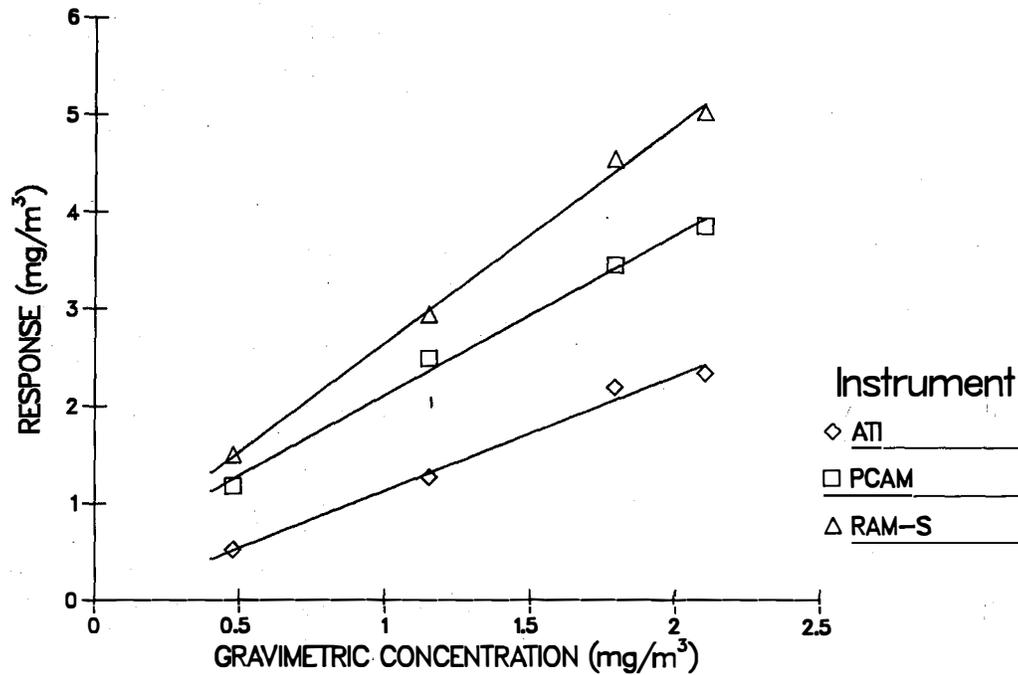


Figure 1 — Instrument response as a function of concentration — Coal Dust II.

respond immediately to the change in concentration). For the PCAM-TX, this procedure could not be used to determine lag time.

### **Instrument Response vs. Concentration**

Of the three instruments tested, only the RAM-S actually was placed inside the chamber because of space limitations.

## RESPONSE VS. GRAVIMETRIC CONCENTRATION

COAL DUST I

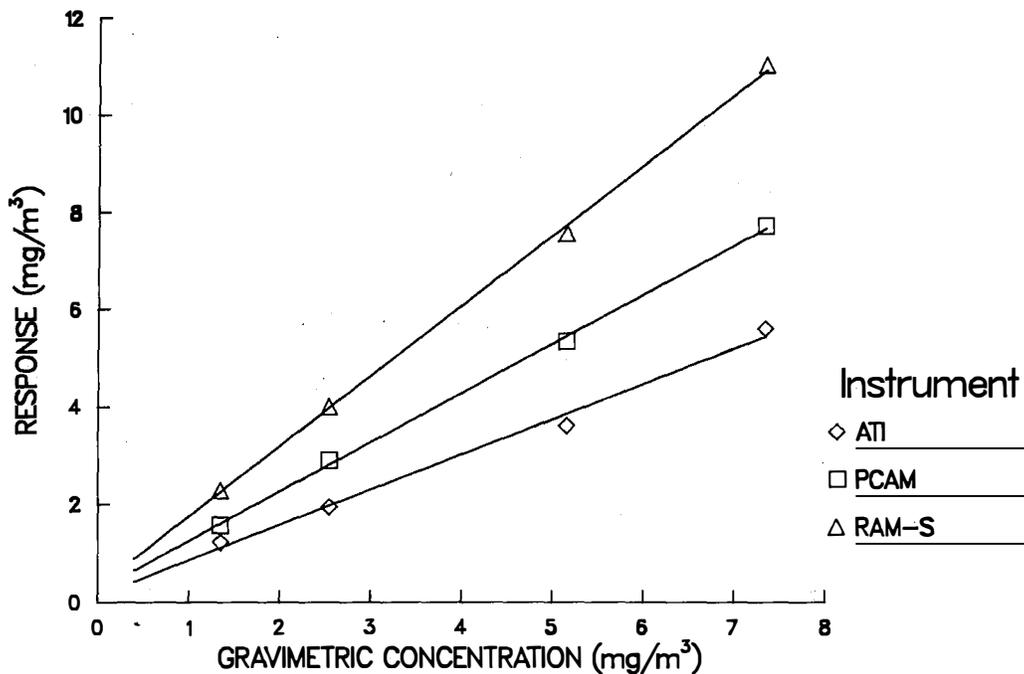


Figure 2 — Instrument response as a function of concentration — Coal Dust I.

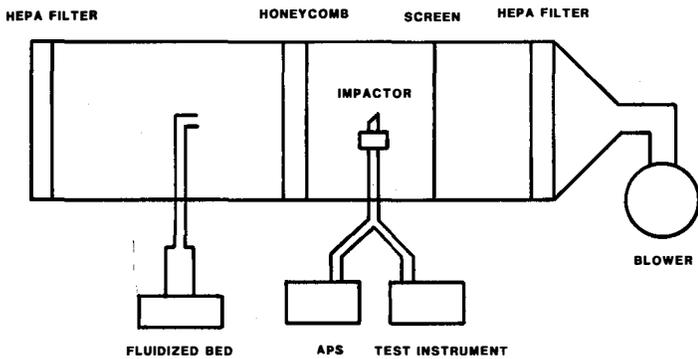


Figure 3 — Size response wind tunnel test system.

Both the PCAM-TX and ATI-722 were placed outside the chamber and sampled through probes that were inserted through a glove port. The PCAM-TX used a 0.93 cm OD sampling probe, and the ATI-722 used a 1.25 cm OD sampling probe. Both probes were approximately 75 cm long. The use of these probes probably biased the response factors of these two instruments for the dust being measured; however, in this test the linearity of response was of primary interest and should not be affected by a biased response factor. Also, there should be minimal losses for particles less than 10  $\mu\text{m}$ . For the PCAM-TX, the concentration and size distribution of the dust sampled through the probe was found to be the same as that measured with the instrument

placed inside the chamber. This was for a dust with a smaller size distribution than Coal Dust I used in this study, however.

Strip chart recorders were used to record the instrument test data. Readings then were taken manually from the strip charts and averaged. All instruments were operated without the use of any size selective devices on the inlets since the response of the instruments to the largest possible range of aerosols was desired.

The aerosol size distribution in the chamber was measured with two 6-stage Marple impactors (Sierra Model 266) operated at 3 L/min. Glass microscope slide covers coated with Apiezon grease were used as collection substrates. Apiezon L was used for Stages 1 and 2 to reduce particle bounce whereas Apiezon H was used for Stages 3-6. The final filter was a 47 mm Gelman DM-800. The substrates and final filter were weighed before and after sample collection with the Sartorius balance. The multiple impactor measurements gave a CV of 5.0% over the course of the study. The mass median diameter (MMD) and geometric standard deviation (GSD) of the coal dusts were calculated by use of the Statistical Analysis System-General Linear Model (SAS-GLM) routine.<sup>(7)</sup> This routine calculates the least squares slope of the probit transformed cumulative mass distribution data vs. the natural log of the diameter.

## MASS DISTRIBUTION

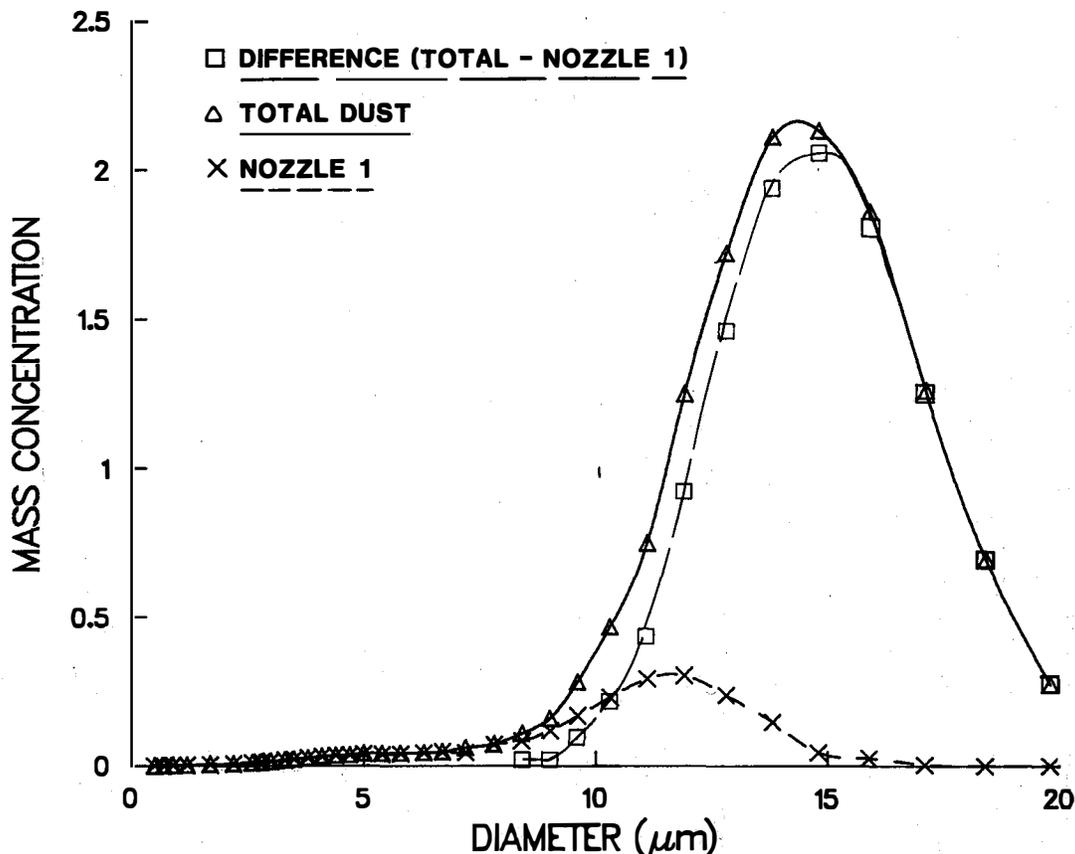


Figure 4 — Mass distribution of generated aerosols with various impactor nozzles.

## DIFFERENCE DISTRIBUTION FROM ADDITION OF IMPACTOR STAGES

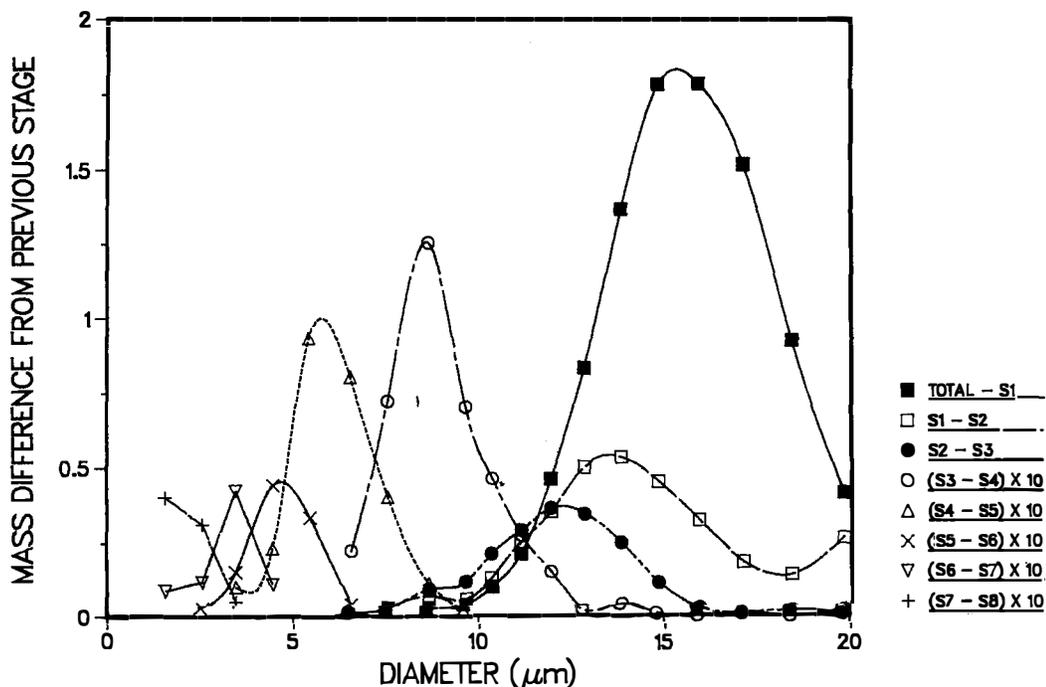


Figure 5 — Difference distributions produced by addition of impactor nozzles.

The aerosol concentration within the test chamber was measured with 37 mm, open-faced cassettes oriented perpendicular to the flow in the chamber. Gelman type VM-1 5  $\mu\text{m}$  pore size filters were used; the flows were controlled with critical orifices. The filters were weighed before and after collection with the use of a Sartorius Model 2405 balance with microgram sensitivity. Three cassettes were employed in runs where the impactor was not used. When the impactors were used, only two filter cassettes were employed. The multiple gravimetric measurements with the use of the filter cassettes gave a within run CV of  $\pm 8.4\%$  when pooled over the entire study.

For each run, the aerosol generator was started and the aerosol together with dilution air was metered into the instrument test chamber. After the concentrations had stabilized in the chamber, the rotating table was started. After a brief period of time, the sampling pump for the filter and impactors was turned on. Before a run was started, the PCAM-TX was reset so that data from the entire run could be averaged and recorded. In addition to the strip chart recording, data from the internal memory of the instrument were used. The average concentrations from the strip chart agreed with those from the PCAM-TX memory. Prior to every run, the ATI-722 also was adjusted for zero, gain, and stray light according to the procedures in the manual.

Unfortunately, a large range of concentrations could not be generated with a constant size distribution because of the change in size distribution with fluidized bed feed chain speed. The reason for change in size distribution is not clear and may have been due either to agglomeration, producing a larger MMD at high concentrations, or to increased commi-

nution of the relatively soft coal at low concentrations. Therefore, the range of concentrations was broken up into two smaller ranges over which a constant size distribution could be generated. In each of these ranges, a portion of the aerosol from the generator was drawn off through a filter to achieve the desired final concentration. The coal dust aerosols in the two ranges, having different size distributions, were designated Coal Dust I and Coal Dust II. The size distributions of these dusts were measured at the extremes in

### RATIO (RAM/APS) VS. DIAMETER

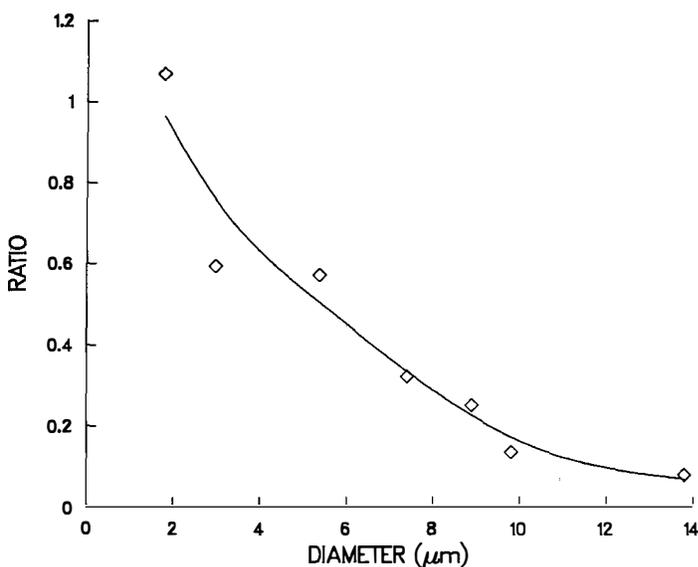


Figure 6 — Mass sensitivity RAM-S as a function of particle aerodynamic diameter.

## RATIO (ATI/APS) VS. DIAMETER

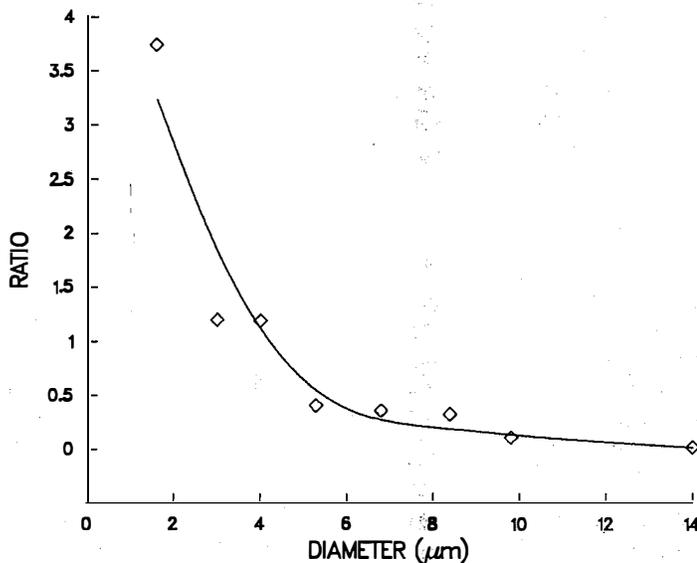


Figure 7 — Mass sensitivity ATI as a function of particle aerodynamic diameter.

concentration used in the study. The size distribution was assumed to remain the same over each of the concentration ranges studied.

The calculated MMD for Coal Dust I was  $5.4 \pm 0.6 \mu\text{m}$  with a GSD of  $4.1 \pm 0.3$  at the high concentration and  $5.2 \pm 0.6 \mu\text{m}$  with a GSD of  $3.8 \pm 0.3$  at the low concentration. For Coal Dust II, the MMD was  $3.1 \pm 0.3 \mu\text{m}$  with a GSD of  $4.3 \pm 0.2$  at the high concentration and  $2.8 \pm 0.3 \mu\text{m}$  with a GSD of  $5.3 \pm 0.2$  at the low concentration. Coal Dust II had a considerably smaller MMD than Coal Dust I. The MMDs and GSDs did not change more than 10% within each range except for the 20% change in the GSD of Coal Dust II.

The response functions of the instruments for each coal dust are shown in Figures 1 and 2. The least squares slope and intercept for each instrument are given in Table II. It can be seen that the response function for each instrument was dependent on size distribution. All of the instruments displayed better linearity for Coal Dust I than Coal Dust II. This may have been due to more accurate weighing for Coal Dust I because of a larger mass on the filters. Coal Dust I also may have had a more constant size distribution over the entire range of measurement. Since the instruments are known to indicate approximately zero response at zero concentration, the best fit line passing through zero response at zero concentration also is given in the table. The slope of this line was used to compare the response of the instruments to the calculated response for aerosols of varying MMD and GSD.

It can be seen that all of the instruments have a linear response over each range studied. It was hoped that an even lower concentration range could be examined in this study (e.g., as low as  $0.1 \text{ mg/m}^3$ ), but it was difficult to generate and measure concentrations lower than those examined. From noise considerations, the instruments can be used to detect concentrations at least ten times lower than the lowest con-

centration examined in this study or at least  $0.050 \text{ mg/m}^3$ . The linearity of response was not examined in this concentration range, however. Also, the size distribution of the aerosol being measured affects the actual limit of sensitivity. It is not known whether the instruments have the same response factor over the entire range, but they are linear over at least a factor of 10 in a given concentration range.

## Particle Size Dependent Response

### Experimental System

Figure 3 shows the experimental system used to measure the size response of the instrumentation. The experiments were carried out in a 30 cm square cross-section wind tunnel, which has been described previously.<sup>(8)</sup> The aerosol was generated by use of a fluidized bed aerosol generator (Model 3400; TSI, Inc.) and was carried 2.5 m to the test section of the wind tunnel. A honeycomb flow straightener was placed between the aerosol generator and the test section of the wind tunnel. At the test section of the wind tunnel, the generated aerosol was passed through a Marple impactor that contained two stages with zero, one or two nozzles.

In the beginning of each experiment, the Marple impactor stages were used without any nozzles in place to obtain a total dust measurement. This measurement was repeated between each of the subsequent measurements to check on the stability of the aerosol size distribution. The largest four nozzles provided by the manufacturer then were added one at a time in order of decreasing 50% cut point to the impactor stages. The use of smaller cut point impactor stages was limited by the increased pressure drop of these stages. The APS could not operate accurately under these conditions. Specially prepared impactor nozzles were machined to provide cut points between those of the commercially available nozzles. For the smaller cutoff distributions, an additional preselector stage was included to prevent overloading of the

## RATIO (PCAM/APS) VS. DIAMETER

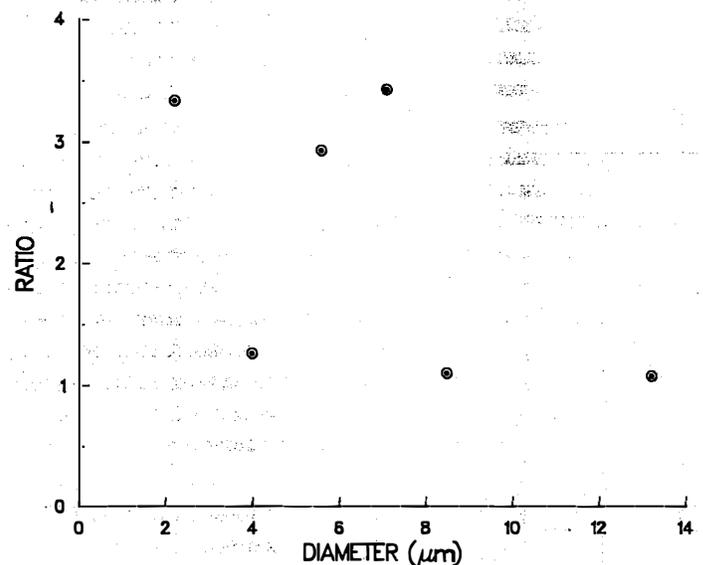


Figure 8 — Mass sensitivity PCAM as a function of particle aerodynamic diameter.

## MMD PCAM VS. MMD APS

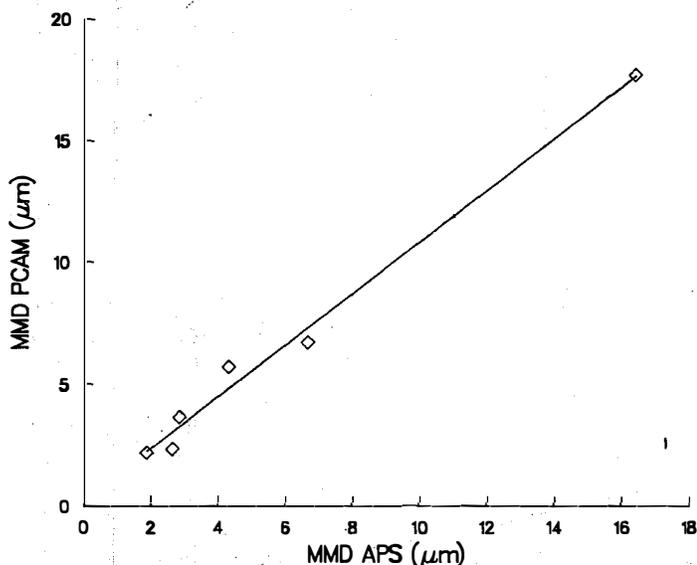


Figure 9 — MMD measured by the PCAM as a function of MMD of the APS.

subsequent stages. After passing through the two-stage impactor, the aerosol flow was split in a Y from which half of the flow went to the aerodynamic particle sizer (APS)<sup>(8)</sup> and half to the instrument under test. The flow to the APS was adjusted to match that of the instrument under test, and the tubing lengths and sizes were matched in an attempt to compensate for any losses in tubing and inlets.

The performance of comparison measurements with the APS places stringent requirements on the test aerosol being used. The presence of a large number of submicron particles can cause significant coincidence counts appearing at large particle sizes. In addition, the stability of the generated aerosol is critical in these types of measurements. The aerosol used for these studies was 10-30  $\mu\text{m}$  fraction of volcanic ash, since it had the size distribution and stability that were needed. All of the measurements from the APS are in terms of aerodynamic diameter. The mass concentration was corrected for the density of the dust being used.

### Size Sensitivity Measurement

Figures 4 and 5 illustrate the technique used to calculate the mass sensitivity of the instrument under test for various size ranges. In Figure 4, the size distribution obtained from the APS for the total dust with no impactor nozzle in place is shown. The APS can calculate the total aerosol mass ( $M_t$ ) from the measured size distribution. Figure 4 also shows the size distribution obtained with the first impactor nozzle in place. The APS can calculate the aerosol mass from the resultant distribution ( $M_1$ ) as well as the difference between the two size distributions. The difference between the two mass distributions is the value used to determine the response of the light scattering monitors, as indicated in Figure 5. During each of these APS measurements, the light scattering instrument being tested produced a total response  $R_t$  and a preselected response  $R_1$  ( $R_1$  is the response with the first impactor nozzle in place). The upper end of the size distribution was 16  $\mu\text{m}$  and the cut point of the first impactor

## RESPONSE RAM-S VS MMD

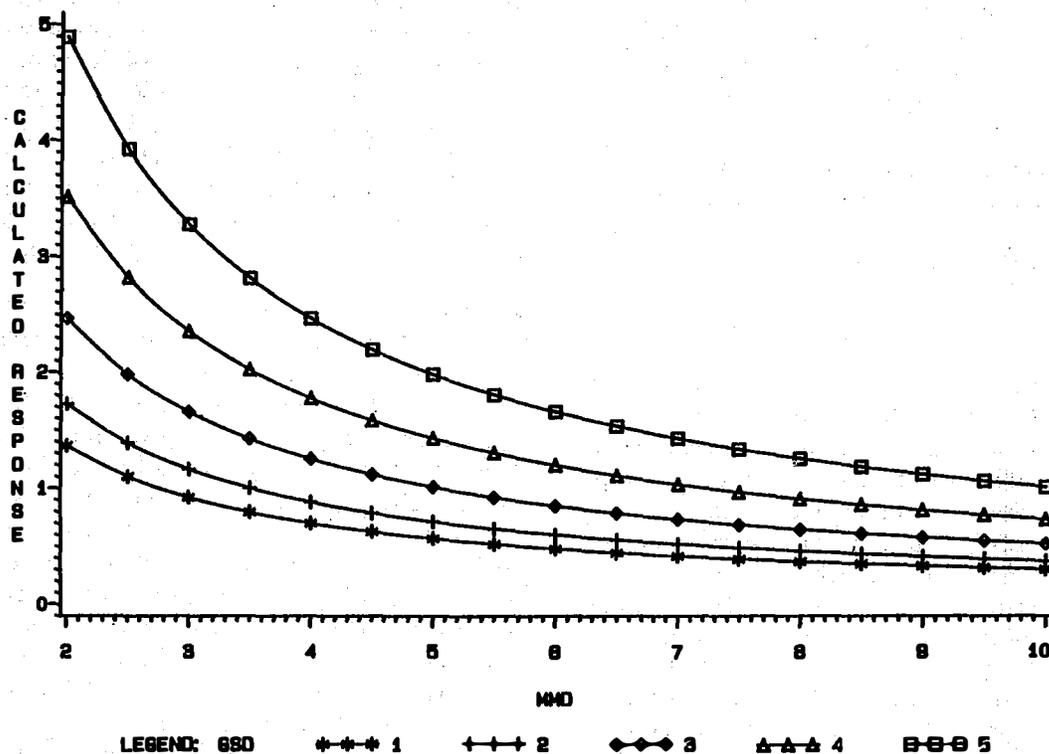


Figure 10 — Calculated response of the RAM-S as a function of MMD at various GSD values.

# RESPONSE ATI VS MMD

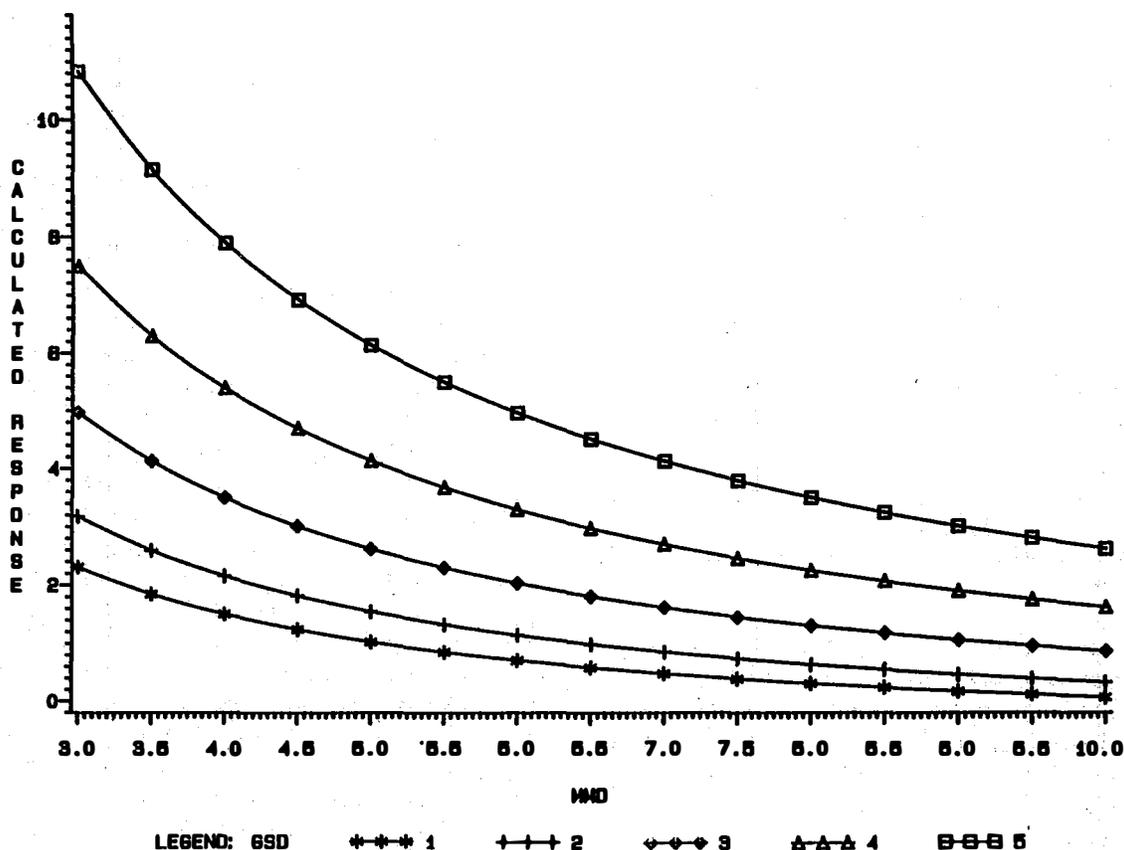


Figure 11 — Calculated response ATI as a function of MMD at various GSD values.

stage was  $12 \mu\text{m}$ , so the relative response of the light scattering monitor was calculated to be the ratio  $(R_t - R_1)/(M_t - M_1)$ . The midpoint of the size interval was chosen as representative of that relative response and is plotted in Figure 6 and 7 as the ratio at  $14 \mu\text{m}$ . This is not the arithmetic midpoint, but was chosen as a weighted midpoint because of the large concentration change in this range. The rest of the points were calculated similarly from the general function for each instrument's size dependent mass response  $(R_i - R_{i+1})/(M_i - M_{i+1})$ . Each of the instruments had a somewhat different size dependent mass response function.

## RAM-S

The mass sensitivity of the RAM-S in the various size ranges is shown in Figure 6. The mass sensitivity is low (about 0.1) for particles greater than  $9 \mu\text{m}$  and gradually increases to a value of 1.5 for the size range of 1-2  $\mu\text{m}$ . Over the size range studied, the sensitivity increased by about a factor of 10. These data were transformed as a function of  $1/D$  since response tends to go as  $1/D$  for particles greater than about  $0.1 \mu\text{m}$ .<sup>(6)</sup> The point from 3.4-4.5  $\mu\text{m}$  was left out of this transformation since its value was out of line with other values, possibly due to the very small change in mass obtained from both the RAM-S and APS over this region. The least square slope of this line produces the response function that will be used to predict the response of the instrument for aerosols of varying size distributions.

## ATI-722

For the ATI-722, the same general type of response function as the RAM-S was observed. The response for the ATI-722 is shown in Figure 7. The ATI-722 shows an even greater variation of response with particle size than the RAM-S. The sensitivity varies from about 0.1 for particles greater than  $10 \mu\text{m}$  to 5 at 1-2  $\mu\text{m}$ . These data again were transformed as a function of  $1/D$ , and the least square slope of the line was determined. The larger slope of this curve shows the greater variation of response with particle size.

## PCAM-TX

Since the PCAM-TX attempts to calculate the mass concentration by measuring the approximate size distribution of the aerosol, the technique of measuring the mass sensitivity in each size range yielded fluctuating results. This is shown in Figure 8. It should be noted that for these measurements a new size distribution chip supplied by the factory was used; thus, the sizing information was different than in runs used to determine instrumental linearity. In general, the PCAM-TX predicted a higher mass than the APS except for the total dust where the predicted masses were similar. The size distribution data for the dusts produced by the different impactor stages are shown in Figure 9. The PCAM-TX and APS show similar MMD values. The agreement is good, even though the APS measures aerodynamic diameter and the PCAM projected diameter and the data were not corrected

for the density of the dust used. This indicates that the predictive algorithm used by the PCAM-TX should be successful in compensating for changes in size distribution.

### Modeling Instrument Response

A model expressing the instrument mass response as a function of the MMD and GSD of the aerosol being measured can be used to estimate instrument response for different size distributions of the same aerosol material. In order to do this, a response function (expressing the response as a function of  $1/D$ ) was developed in terms of the particle size distribution in the following manner. The response function as a function of diameter is designated  $R(D)$  and is assumed to be a linear function of  $1/D$ :

$$R(D) = dM(\text{instrument})/dM(\text{reference}) = A(1/D) + B \text{ for } D \geq c \text{ to } \infty$$

( $c$  is the lower limit of the range in which the instrument response varies as  $1/D$ ). The mass distribution is assumed to be log-normal and is given by<sup>(9)</sup>

$$\frac{dM}{dD} = \frac{M}{D\sigma\sqrt{2\pi}} \exp[-(\ln D - \mu)^2/2\sigma^2] \quad (1)$$

where  $M$  is the total mass given by

$$M = \int_0^{\infty} \frac{dM}{dD} dD \quad (2)$$

and

$$\text{MMD} = e^{\mu} \quad (3)$$

$$\text{GSD} = e^{\sigma} \quad (4)$$

Integrating the response function with the size distribution yields the total response  $R(t)$  for an aerosol with the size distribution specified.

$$R(t) = \int_c^{\infty} R(D) \frac{dM}{dD} dD =$$

$$\int_c^{\infty} \left[ A \left( \frac{1}{D} \right) + B \right] \frac{M}{D\sigma\sqrt{2\pi}} \exp[-(\ln D - \mu)^2/2\sigma^2] dD =$$

$$AM \int_c^{\infty} \frac{1}{D^2\sigma\sqrt{2\pi}} \exp[-(\ln D - \mu)^2/2\sigma^2] dD +$$

$$BM \int_c^{\infty} \frac{1}{D\sigma\sqrt{2\pi}} \exp[-(\ln D - \mu)^2/2\sigma^2] dD = I_A + I_B \quad (5)$$

$$I_A = \frac{AM}{2} \exp \left[ \frac{\sigma^2}{2} - \mu \right] \text{erfc} \left[ \frac{\ln c}{\sigma\sqrt{2}} - \frac{\mu}{\sigma\sqrt{2}} \times \frac{\sigma}{\sqrt{2}} \right] \quad (6)$$

$$I_B = \frac{BM}{2} \text{erfc} \left[ \frac{\ln c}{\sigma\sqrt{2}} - \frac{\mu}{\sigma\sqrt{2}} \right] \quad (7)$$

The function is very sensitive to the lower limit of integration,  $c$ , and therefore was evaluated with several different values of  $c$  between 0 and 1 (0.2, 0.5, and 1). It appeared that, of the values calculated, the ones with  $c = 0.2$  and  $c = 0$  come closest to predicting the change in response factors found in this study for Coal Dusts I and II. The response

factors for  $c = 0$  are presented in Figures 10 and 11. It is not intended that these figures be used to predict exact response of the instruments, but that they be used to obtain an idea of how the response changes for dust of differing MMD and GSD. For instance, the response factors calculated for the ATI-722 (4.4 for Coal Dust I and 7.2 for Coal Dust II) are much larger than those observed for Coal Dusts I (0.746) and II (1.15), but the ratios of the calculated responses (1.6) are close to the observed response ratios (1.5). The difference in the actual response may have been due to optical differences between coal dust and volcanic ash and changes in the ATI response factors, since the optics on the instrument were cleaned before the size-response experiments were performed.

For the RAM-S, the calculated responses (1.45 for Coal Dust I and 2.32 for Coal Dust II) are much closer to the observed response factors (1.496 and 2.49, respectively). The curves cannot be used for aerosols with MMD much less than  $3 \mu$  since the functions do not model the response very well for small particles. This is because the response varies as a function of  $1/D$  starting at some value of  $D$  and falls off as  $D^3$  below this value of  $D$ . The exact value of  $D$  where this happens cannot be determined from the data obtained since the response function below about  $2 \mu\text{m}$  was not determined. If the MMD and GSD of two optically similar aerosols are known, then the relative response of the instruments to these dusts can be determined. Thus, if the response factor for one dust is known, the response factor for an optically similar dust can be determined.

### Operational Checks

There were a number of failures observed with the instruments. A pump failed on the PCAM-TX, and a light source burned out and the optics needed cleaning on the ATI-722. These were remedied easily and could be considered within the realm of normal maintenance for the instruments.

It is good practice to perform certain checks on instrument operation periodically. The zero of each instrument should be checked. The ATI-722 especially needs to have the zero checked and adjusted daily if used for low concentrations. The RAM-S zero was found to be stable over the period of the study, but it would be good practice to check its zero to ensure that the instrument is operating properly. If a computer data acquisition and control system is used, this could be done automatically on a daily basis with the external purge command. The PCAM-TX automatically adjusts its zero and calibration hourly. It would be good practice, however, to check to see that the value of the zero does not change greatly with time. The zero can be checked with the instrument read-out device.

Other instrument operating codes can be read out to check instrument operation. The data acquisition capability of the instrument is very useful for a number of purposes: to obtain the size distribution of aerosols; to obtain the average concentration data over the time period of an experiment; and to check the operating codes. The PCAM-TX reference

scattering device is a useful check on instrument operation since the instrument recalibrates itself every hour using this device. The amplifier gain value needed to maintain the calibration is stored and can be read out on the display.

The RAM-S does not have a reference scattering device, but there was no indication that its sensitivity changed during the study. A reference scattering device would be a useful feature, however. The ATI-722 did have a change in sensitivity during the study because of dirty optics. This change was not detectable by the provided instrument operating checks and was found by looking at the response to a known dust concentration. A reference scattering device is useful in detecting such a problem. Both the RAM-S and ATI-722 provided alarms for low flow, and the RAM-S has a visual measurement of flow. The PCAM-TX would benefit by having some type of flow indicator, since its pump failure was not immediately detectable except by manual measurement of the flow at the inlet.

### Conclusion

The instruments evaluated in this study are capable of providing long-term continuous dust monitoring in the workplace for a number of applications, but the user needs to be aware of the size-dependent nature of their response. The instruments functioned for the duration of this study (about six months in the laboratory with continuous operation) except for several minor failures. The scattered light instruments provide a reliable indication of aerosol mass concentration if the instruments are calibrated with the aerosol to be measured and the size distribution of the aerosol does not change. They provide linear response over a tenfold concentration range. They are especially useful in monitoring applications where time response is important and exact agreement with gravimetric mass is not important.

After the instruments are calibrated with the dust to be monitored, the possibility of size distribution changes needs to be assessed. The size response of the instruments can be important if the size distribution of the dust varies greatly. The mass response of the instruments can vary from as low as 0.1 to as high as 5 in the particle size range 2-14  $\mu\text{m}$ .

The figures developed in this study can be used to give an indication of the range of instrument responses that might be expected. The approximate sizing information given by the PCAM-TX can be useful to determine if the size distribution has changed appreciably although, in this study, the correction to the mass measurement did not agree with the reference method for all size ranges. For the RAM-S and ATI-722, the response falls off as a function of particle diameter and the developed figures can be used to assess possible changes in response.

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