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An Evaluation of Fast Response Aerosol Mass Monitors

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An Evaluation of Fast Response Aerosol Mass Monitors

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AN EVALUATION OF FAST RESPONSE AEROSOL MASS MONITORS

by

C. I. Fairchild
M. I. Tillery
H. J. Ettinger

ABSTRACT

Five commercially available mass monitors were evaluated against aerosols of coal dust, silica, fiber glass, welding fume, oil shale, polystyrene latex, dioctyl phthalate, and fluorescein dye. The instruments were two identical TSI Corporation respirable aerosol mass monitors (RAMM), model 3500, and one each of GCA Corporation respirable dust monitors (RDM), models 101, 201, and 301. The RDM-201 was a long-term sampler (sampling up to 8 h), whereas the other monitors employed sampling periods generally 2 min or less. All monitors had direct readout of mass concentration in mg/m^3 with the exception of the RDM-201, which displayed the mass of dust collected in milligrams.

Each mass monitor sampled from uniform aerosol concentrations ranging from <0.1 to >10 mg/m^3. The aerosols were also sampled by three membrane filters collecting 2, 5, and 20 to 37 L/min. Mass monitor readings were compared to gravimetric concentrations of samples between 1- and 10-min duration. Statistical techniques were applied to determine significant differences between gravimetric and mass monitor results.

The RDM-201 mass monitor displayed zero mass concentration in 27 of 73 measurements and an accuracy of ±74% for 27 other measurements, when gravimetric information indicated mass concentrations ranging from 0.3 to 5 mg/m^3. Accuracy of the other monitors was better than ±25% of gravimetric concentration when four or more instrument readings were averaged; however, individual readings differed from gravimetric concentration as much as 300%. Particle size sensitivities of the monitors, indicated by the particle size of 50% measurement efficiencies, were 1.2- and 1.4-μm aerodynamic diameter for the RDM-301 and -101, respectively, and <0.3 μm for the RAMMs. The RAMMs collected particles >6-μm aerodynamic diameter with poor efficiency.

INTRODUCTION

Several semiautomatic, portable aerosol mass monitors have been developed recently for monitoring worker exposure to airborne contaminants. These instruments measure aerosol mass concentration in 2 min or less and display the results as a digital readout. If the instruments are sufficiently accurate, they represent a significant advance in the industrial hygienist's ability to measure airborne particulate concentration and provide a rapid estimate of potential worker exposure.

Although individual instruments or types of instruments have been evaluated in the literature, no direct comparison of instrument performance has been reported. Consequently, it is difficult for the prospective user to evaluate the relative advantages of a particular instrument.

We evaluated four commercially available aerosol mass monitors using 10 aerosols with various mass concentration and particle size distributions. Instruments evaluated included two Thermo Systems, Inc. (TSI) model 3500 respirable aerosol mass monitors (RAMM), one GCA respirable dust monitor (RDM) model 301, one RDM model 201, and one RDM model 101-1. Other monitors considered were either unavailable or their operating characteristics were outside the guidelines for this test program. Guidelines, based primarily on an instrument's applicability to industrial hygiene sampling, were:

- Portability: The complete instrument should weigh less than 20 kg.
- Direct Readout: The instrument should display or print out aerosol mass concentration in mg/m^3 or $\mu g/L$.
- Battery Operation: The instrument should be capable of independent operation on a self-contained power supply for a minimum of 8 h.

Each instrument is described in a later section (III, IV, and V) and evaluated for convenience of operation, ruggedness, durability, and reliability. These sections also contain performance data concerning accuracy, sensitivity, etc. Instrument performances are compared in Sec. VI. Test data for each instrument are discussed extensively in the report body and are included as an Appendix to the report.

I. TEST APPARATUS

All monitors were evaluated simultaneously by distributing test aerosols to all instruments and to three filter samplers. The instruments were arranged around a central 10-cm-diam by 20-cm-high aerosol chamber with equal length transfer lines to each instrument inlet (Fig. 1). Regardless of how the aerosol was generated, it was introduced into the top of the chamber through a 27-mm-diam pipe, past a Stairmand disk mixer, and exhausted through the bottom of the chamber. Besides the mass monitors and three filter holders, various analytic instruments were connected to one or more of the chamber's sampling ports. To obtain an adequate gravimetric sample during the minimum sampling period of the mass monitors, the entire exhaust flow was passed through a 25-mm-diam filter at up to 37 L/min. Intake probes for all the instruments and filters were identical and were arrayed in a 3-cm-diam circle concentric with the chamber aerosol inlet 8 cm below the Stairmand disk. Probe openings faced upward, and a 90° 2-cm-radius bend allowed the probes to extend horizontally through the chamber wall and connect to flexible Tygon transfer tubes. Transfer lines were 4-mm i.d. for the mass monitors requiring 1- or 2-L/min flow and were 6-mm i.d. for instruments requiring greater flow rates. Probes were 6-mm i.d. because all mass monitors and other instruments were changed randomly from one sampling position to another by moving the transfer lines from probe to probe. Flowmeters downstream of each filter holder were calibrated and adjusted to 5 L/min and 2 L/min through

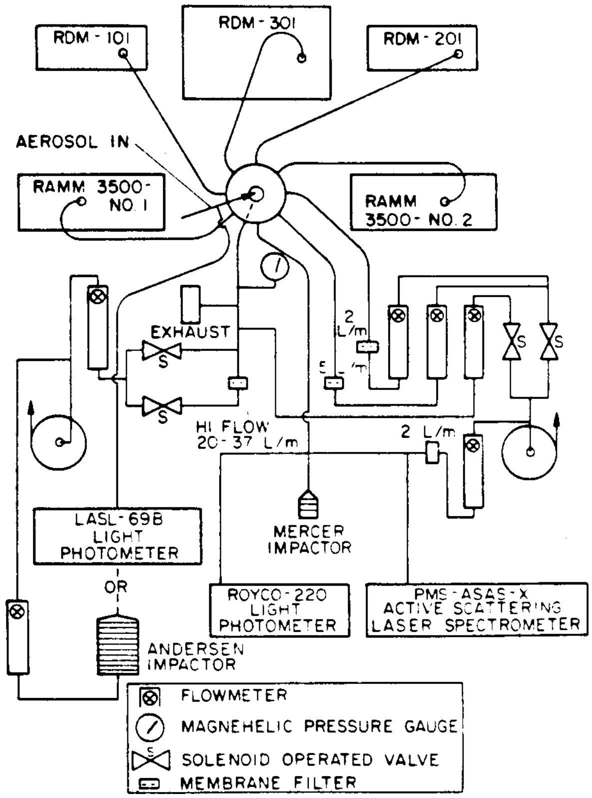

Fig. 1.
Mass monitor test unit (MMTU).

the low-flow membrane filter samplers. A magnehelic gauge connected to the chamber outlet indicated relative pressure, and a Beckman relative humidity gauge was mounted in the exhaust stream.

In addition to comparing the mass monitors against the reference filter samples, various other analytical instruments were employed. These included a Los Alamos Scientific Laboratory (LASL) 69B forward light-scattering photometer to indicate changes in aerosol concentration. For determining size distributions, a Royco 220 light-scattering photometer, a Particle Measuring System (PMS) model ASAS-X active scattering intracavity laser spectrometer, an Andersen impactor, and a modified Mercer impactor were used. Nucleopore filter samples were also taken of selected aerosols for scanning electron microscope (SEM) photomicrography and size determination.

Before testing any monitors, the uniformity of concentration within the aerosol chamber was determined with the eight sampling probes inserted various lengths into the chamber. Maximum insertion positioned each probe 1 cm from chamber center and arrayed them in a 2-cm-diam circle. Concentration uniformity at several flow rates through the chamber was determined for this configuration as well as similar arrays in 2.5-, 5-, and 7.5-cm-diam circles. Aerosol concentration differed most (12 ± 13%) when the probes were at maximum separation of 7.6 cm. When the probes were arrayed in a 3-cm-diam circle, the concentration difference between any two probes was 6 ± 4% at 0.4 mg/m^3 concentration according to the RAMM monitors. The RAMMs were used to determine concentration uniformity because, as preliminary experiments indicated, they showed smaller variation between simultaneous measurements than did even membrane filter samples. To determine chamber concentration uniformity, the difference in concentration at two positions was of primary importance, and the RAMMs were ideal for that purpose.

When all mass monitors and sampling devices were operating, they withdrew aerosol at a maximum of 60 L/min or a minimum of 30 L/min. To maintain positive pressure within the chamber (0.25-in. H_2O) and prevent significant flow fluctuations, excess aerosol was exhausted through a respirator cartridge filter (Fig. 1) at ~30 L/min. The total flow of 60 to 90 L/min produced a velocity of 13 to 19 cm/s and Reynolds numbers of 660 and 970 at the sampling probes. Velocity profiles across the chamber, measured with a TSI 1054B thermal anemometer, had a plug flow profile with a maximum velocity at the center position only 20% larger than near the wall.

Flow disruption of starting and stopping all samplers simultaneously produced considerable fluctuation in concentration, so a flow balancing system was incorporated. This system consisted of two solenoid valves and associated piping that maintained an equal flow of aerosol through the chamber whether or not the sampling instruments were operating. A double throw switch routed flow through the membrane filter samplers or bypassed them and opened another exhaust valve to preset flowmeters and pumps (Fig. 1). These exhaust flowmeters were set to allow the same total flow as that withdrawn by the sampling instruments.

II. METHODS OF ANALYSIS

A. Experimental Plan

The design of the mass monitor evaluation experiments was based upon the number of samples required to provide a statistically significant analysis of variance (AOV) and Fisher least significant difference (FLSD) analysis of sample means.

The design requirement was applied to one run randomly selected from a group of preliminary experiments. This run contained nine 1-min samples and four 2-min samples of the three filter (gravimetric) concentrations plus readings from all the mass monitors. AOV and FLSD analysis of the run data revealed that 1- and 2-min samples were different and all instruments except the two RAMMs gave significantly different readings. Based upon that information, an experimental plan was determined such that a 25% difference at the 2-σ confidence level between instrument sample means could be detected. The 25% difference was selected to correspond to the accuracy claimed for the mass monitors. The minimum number of samples required, which varied with sampling time and mean concentration, is listed in Table I. These minima were obtained by analyzing a random group of mass monitor readings using a two-way AOV followed by a FLSD test on the means; therefore, the number of samples was usually increased for instrument evaluation.

B. Analysis of Individual Runs

Each group of measurements performed in one day constituted a run. The runs were further subdivided into sets of six measurements (mass monitor readings) made in a short time period, usually <30 min. This grouping permitted weighing filters before and after each set. During each set of measurements, the aerosol concentration was relatively uniform compared to between sets, because time between sets was ~1 h. Generally, three to five sets of 1-min and one to three sets of 2-min measurements were made per run.

During each set of readings, all instruments plus three filters were sampling. The high-flow filter sampled aerosol downstream of the chamber at 20 to 37 L/min depending on aerosol concentration. This filter collected sufficient sample within 1 min to provide an estimate of concentration. The two other filters sampled at 2 and 5 L/min through probes identical to those used

TABLE I

STATISTICAL DESIGN OF EXPERIMENTS

No. Monitors	Sampling Time min	Difference in Means (%)	No. Samples Required[a] Mean Conc (mg/m³) 2	4	6	8
3	1	10	173	45	21	12
4	1	10	172	44	20	12
5	1	10	172	44	20	12
3	1	25	29	9	6	6
4	1	25	29	8	6	6
5	1	25	29	8	6	6
3 to 5	2	10	8	6	6	6
3 to 5	2	25	5	5	5	5

[a]Minimum number of samples required from each instrument at the concentration shown (2, 4, 6, 8 mg/m³) to provide detection at 95% confidence level of difference in means shown in col. 3.

for the mass monitors. The latter filters sampled until they had collected sufficient deposit for accurate weighing. Thus, the two low-flow filters provided an accurate concentration determination only over several mass monitor sampling periods, whereas the high-flow filter provided a short-term, less accurate estimate of concentration. Therefore, concentrations determined from 2- and 5-L/min samples were weighted more heavily than high-flow (20- to 37-L/min) samples; still the high-flow samples provided an indication of mass monitor reading variability. Weighting was accomplished by using as the best estimate of concentration for each sample the average of all three filter values. Each high-flow filter measurement was weighted 1/n as much as the low-flow measurements, where n was the number of measurements (readings) in each set.

The accuracy of filter weighing was estimated with 25-mm Gelman 5-μm pore size vinyl metricel (VM-1) filters, which were used in the high-flow samplers (flow rate up to 35 L/min). Six filters were weighed, subjected to a 30-L/min flow rate for 1 min, and then reweighed after a 30-min waiting period. Reproducibility of the initial weight was ±8 μg; precision of the microbalance was ±5 μg. If the same accuracy is obtainable when weighing deposited dust, the accuracy as a per cent of mass on the filter is shown in Fig. 2. Thus, to obtain a gravimetric filter accuracy of 20% or better, at least 40 μg must be collected on the filter. Further, at a flow rate of 37 L/min, this implied that the aerosol concentration should be a minimum of 1.08 μg/L. Several aerosols were below this concentration at times, increasing the probable filter weighing error to above 20% for the high-flow filter samples.

Calculations of averages and concentration ratios are illustrated in Table II, which shows analysis of the 1-min samples from all runs against coal dust. The RDM-101 and both TSI RAMMs measured respirable dust, while the RDM-301 measured total dust. The average concentration and standard deviation for the three filters are listed in cols. 4 and 5 whereas cols. 1-3 list individually measured concentration. The remaining columns list the concentration read from each instrument (C_I), and the ratio (C_I/C_G) of this concentration to the filters' average concentration (C_G). Below each set of six rows the average standard deviation and coefficient of variation (CoV) in per cent are shown for that set. The final four rows (average, standard deviation, CoV, number of samples) are the summary statistics for the aerosol. Zero values of any concentration were not calculated in the set or aerosol summary; thus, where no reading was obtained (zero in the tables), it affected the statistics only as a missing sample.

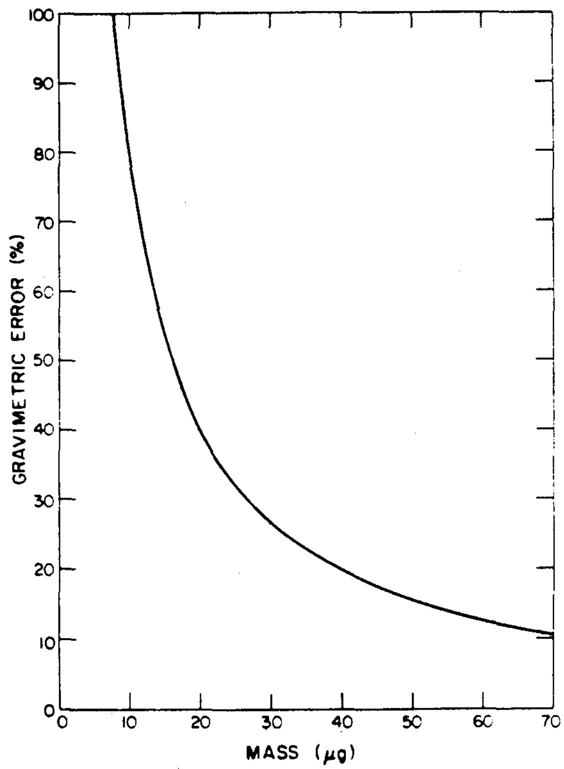

Fig. 2.
Percentage error in filter measurement as a function of deposit mass.

Data obtained from each aerosol and the calculated concentration ratios (C_I/C_G) are summarized in Appendix Table A-I, which has a format similar to that of Table II, but which contains only the grand averages for each aerosol. An average C_G is listed (col. 3) as well as the grand average of concentration ratios for each mass monitor (cols. 4-7). In addition to statistics for all samples (first row, each aerosol), statistics for particular groups of samples are shown where sufficient samples were available. For example, statistics are shown for the concentration ranges 0-4 mg/m³ and >4 mg/m³, for equal numbers of samples for each monitor, and for samples where CoV of C_G was ≤20%. The last group provides a comparison of monitor reading CoV to C_G CoV when C_G was obtained from filter samples having a CoV ≤20% for the three reference filters (high-flow rate, 5 L/min, and 2 L/min).

C. Analysis of Mass Monitor Performance

After the preceding analyses of each run were made, all data from a particular aerosol were analyzed by the following techniques. The description and data noted are not necessarily representative of results, but are provided as an example of the analytical methods employed.

1. Data Correlation Graph. The first method of analyzing mass monitor performance against each aerosol was to graph each instrument reading vs C_G for all 1- and 2-min data. Linear regression analysis of the correlated points then provided a functional relationship for each instrument. Using the regression equations, the range of C_G over which the monitor exhibited ±25% accuracy (referred to C_G) was determined. Where the aerosol concentration range was small, no analytic function was obtained. A typical correlation graph is illustrated in Fig. 3. The regression equation correlation coefficient, r, and number of samples, n, are given in the caption.

TABLE II

ILLUSTRATION OF TEST DATA

High Flow mg/m³	5 L/min mg/m³	2 L/min mg/m³	All Filters Av	All Filters Std Dev	Total RDM-301 mg/m³	Total RDM-301 Ratio	Respirable RDM-101 mg/m³	Respirable RDM-101 Ratio	Respirable RAMM #1 mg/m³	Respirable RAMM #1 Ratio	Respirable RAMM #2 mg/m³	Respirable RAMM #2 Ratio
MMEP-13AA, Coal dust, 2 min												
2.20	3.50	0.00	2.85	0.92	0.00	0.00	2.05	0.72	0.92	0.32	0.00	0.00
5.90	3.50	0.00	4.70	1.70	0.00	0.00	0.00	0.00	2.88	0.61	0.00	0.00
3.30	2.10	0.00	2.70	0.85	0.00	0.00	1.90	0.70	0.00	0.00	1.69	0.63
3.30	2.10	0.00	2.70	0.85	0.00	0.00	1.80	0.67	0.00	0.00	1.78	0.66
4.00	3.20	0.00	3.60	0.57	0.00	0.00	1.90	0.53	0.00	0.00	1.96	0.54
4.80	3.20	0.00	4.00	1.13	0.00	0.00	2.45	0.61	0.00	0.00	2.35	0.59
Av			3.42		0.00	0.00	2.02	0.65	1.90	0.47	1.95	0.60
Std Dev	for last 6		0.82		0.00	0.00	0.26	0.08	1.39	0.21	0.29	0.05
CoV			23.97		0.00	0.00	12.69	12.05	72.94	43.83	15.03	8.19
MMEP-41AA, Coal dust, 2 min												
0.80	2.70	0.00	1.75	1.34	0.00	0.00	0.50	0.29	0.48	0.27	0.00	0.00
0.80	2.70	0.00	1.75	1.34	0.00	0.00	0.84	0.48	0.81	0.46	0.00	0.00
2.80	2.70	0.00	2.75	0.07	3.19	1.16	1.30	0.47	2.60	0.95	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Av			2.08		3.19	1.16	0.88	0.41	1.30	0.56	0.00	0.00
Std Dev	for last 6		0.58		0.00	0.00	0.40	0.11	1.14	0.35	0.00	0.00
CoV			27.71		0.00	0.00	45.62	26.68	87.97	61.72	0.00	0.00
1.80	1.40	0.00	1.60	0.28	2.88	1.80	1.45	0.91	0.00	0.00	1.89	1.18
1.80	1.40	0.00	1.60	0.28	2.36	1.47	0.80	0.50	0.00	0.00	1.49	0.93
1.60	1.40	0.00	1.50	0.14	0.00	0.00	0.75	0.50	0.00	0.00	0.62	0.41
1.60	1.40	0.00	1.50	0.14	0.00	0.00	1.00	0.67	0.00	0.00	0.69	0.46
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Av			1.55		2.62	1.64	1.00	0.64	0.00	0.00	1.17	0.75
Std Dev	for last 6		0.06		0.37	0.23	0.32	0.19	0.00	0.00	0.62	0.37
CoV			3.72		14.03	14.03	31.89	29.87	0.00	0.00	52.89	49.90
Av						1.48		0.59		0.52		0.68
Std Dev						0.32		0.16		0.27		0.26
CoV	for all					22		27		52		38
No. Samples						3		12		5		8

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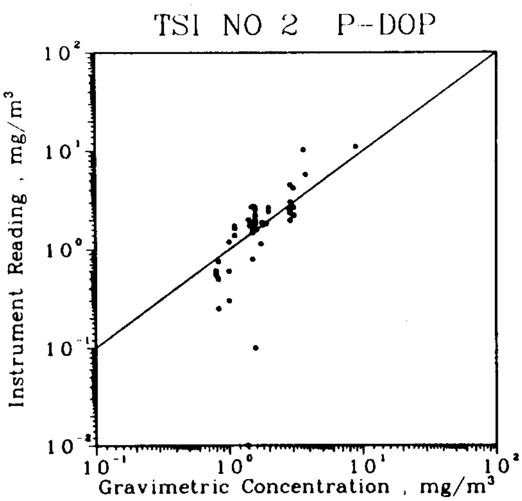

Fig. 3.
Typical data correlation showing all data for one mass monitor, one aerosol, and one sampling condition. Regression equation is $C_I = 1.32\ C_G - 0.35$, $r = 0.94$, $n = 48$.

2. Data Convergence. It is useful to the user of a mass monitor to know before sampling the optimum number of samples required. Generally, the more samples taken, the better the true concentration will be estimated; however, excessive sampling would defeat the purpose of a rapid response mass monitor. To determine the minimum number of samples required, the trend of data for selected aerosols was examined. A running average of each set of six readings, $1/6 \sum_{i=1}^{6} C_I/C_G$, was calculated for each instrument. Then the absolute difference between the grand average of all six sample ratios and each average of the 1st, 1st + 2nd, 1st + 2nd + 3rd, etc.,was calculated for all sets of concentration ratios for the aerosol:

$$N_i = \frac{1}{S}\sum_{j=1}^{j=S}\left(\frac{1}{6}\sum_{i=1}^{6} R_{ij}\right) - \frac{1}{S}\sum_{j=1}^{j=S}\left(\frac{\sum_{i=1}^{i} R_{ij}}{n}\right)_{n=i}$$

where N_i is the data trend, defined as the absolute difference between the cumulative average i^{th} sample and the grand average of samples, i the concentration ratio sequence number (1 - n), j the number of the set of six readings of S sets for each aerosol, R the ratio of instrument reading to C_G (C_I/C_G), and n the cumulative sequence number ($n \leq 6$) to obtain the average of the summed ratios R. The first summation term, from j = 1 to S, is the average of all data points, and the second term sums and averages all data points to and including the one being considered. Thus, a typical graph of N_i as a function of sampling sequence number (Fig. 4) illustrates the trend of instrument data as more readings are taken for an aerosol. The difference between each average ratio and the final ratio (N_6) must trend toward zero as the number of samples increases. but the rate at which it converges to zero indicates the number of samples (on the average) needed to obtain an average concentration close to the final concentration. Of course, even 6 samples will produce an average concentration somewhat different than 7 or 10 samples, but probably not significantly different judging from the rate of convergence to N_6.

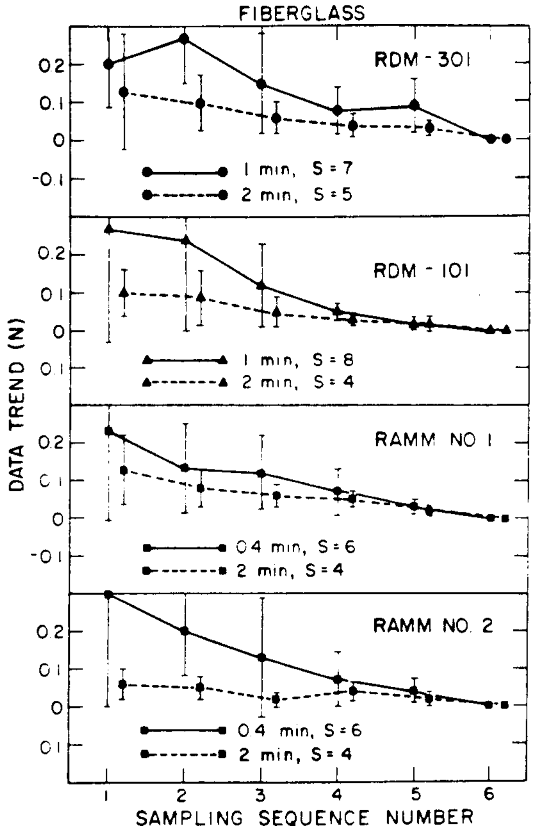

Fig. 4.
Example of data trend for mass monitors data trend illustration.

It must be emphasized that the analysis of data trend has nothing to do with instrument accuracy. N_6, which is always zero in this analysis, gives no comparison of instrument readings to gravimetric measurements. The average of all instrument readings could be in poor agreement with the C_G without affecting the convergence to N_6.

3. Statistical Analysis. The concentration means determined from all filters and instruments for equal numbers of 1- or 2-min samples were compared by AOV. If the means were statistically different, a FLSD analysis was performed to determine which instruments and filters had similar means. This analysis is illustrated in Table III for samples measuring fiber glass aerosol. The AOV statistics for a single classification problem are computed by standard procedures from filter concentrations and mass monitor readings illustrated in Table II. The computed F statistic of Table III, 7.93, indicates by comparison with a standard F value obtained from statistical tables that at 95% confidence level the hypothesis of equal means is rejected. In the following two rows the mean concentrations are ranked by source in ascending order, left to right. Finally, the lines beneath the mass concentrations (Table III) denote those sources which were found not significantly different by FLSD analysis. Neither the RDM-101 nor RAMM #2 means differ from the mean filter concentration, although these monitors are significantly different from one another. The two RAMMs and RDM-301 do not differ significantly, even though only the RAMM #2 is not significantly different from mean filter concentration.

In the appendix, Table A-II summarizes the AOV and FLSD results in a different format. AOV results are denoted in col. 2, and mean concentration ranking and FLSD grouping are listed in the remaining columns. Here again, concentrations which are not significantly different by FLSD analysis are underlined.

TABLE III

EXAMPLE OF AOV AND FLSD ANALYSIS RESULTS
FOR FIBER-GLASS, 1-MIN SAMPLES

Source of Variation	Degrees of Freedom	Sum of Square	Mean Square	F Statistic
Blocks (samples)	207	0.31082E+03		
Treatments (levels)	48	0.29692E+03		
Error	4	0.23621E+01	0.59053E+00	0.79328E+01
Total	155	0.11538E+02	0.74441E-01	$F_{95}(4,155)$ = 2.43

	RDM-101	Filters	RAMM #2	RAMM #1	RDM-301
Treatment	3.	1.	5.	4.	2.
Mean Value	0.998E+00	0.109E+01	0.122E+01	0.125E+01	0.126E+01

D. Respirable Sampling

Most testing of the mass monitors was against the entire size range of the aerosols, although the monitors were designed primarily for use as respirable aerosol monitors. Most tests were performed against the total aerosol because preliminary experiments using coal dust indicated that the preselectors (10-mm nylon cyclone for the RDMs and 3.5-μm impactors for the RAMMs) may increase sampling variation (for 1-min readings). This increase is quantitated in Secs. IV.D.1 and VI.A.

When sampling for respirable aerosol, the mass monitors should show different results if the respirable fraction of the aerosol differs significantly from 0.5. This is due to the fractionating characteristics of the preselectors. Both the nylon cyclone and the impactor have 50% collection efficiencies near 3.5-μm D_{ae}, the size of 50% collection (or penetration) of the American Conference of Governmental Industrial Hygienists (ACGIH) respirable efficiency curve.[1] However, at other particle sizes the preselectors collected different fractions of dust; their collection efficiencies differ from each other as well as from the ACGIH standard.

Figure 5 shows the ideal respirable curve (ACGIH),[2] the 10-mm nylon cyclone operated at 2.0 L/min,[3] and the TSI designed stainless steel RAMM impactor.[4] The ordinate (% penetration) represents the fraction of total challenge dust passing the preselector, which is collected downstream by a filter or mass monitor. Some controversy exists concerning the correct calibration of the nylon cyclone at 2.0 L/min, with most investigators reporting that when the cyclone is operated at 2 L/min, it underestimates the fraction of respirable dust.[3,5,6] The calibration shown for 2-L/min flow rate was taken from Ettinger, et al.[3] The curves of Fig. 5 indicate that both preselectors underestimate the concentration of respirable dust if the mass median aerodynamic diameter (mmad) is >3.5 μm, whereas below this mmad the cyclone underestimates and the impactor overestimates the respirable fraction down to about 2-μm mmad. Actual results obtained with the preselectors supplied with the monitors are discussed in Secs. IV.D and VI.A.

III. GCA RESPIRABLE DUST MONITOR (RDM-201)

The RDM-201 is intended for long-term sampling (up to 8 h) to determine time-weighted average (TWA) concentrations. It collects particles by filtration through a glass fiber filter and determines collected mass by counting the attenuation of β^- radiation caused by the collected particle mass. The count is electronically processed and displayed as mass collected in mg. The monitor operates at a flow rate of 2 L/min and collects either total dust or, by placing a 10-mm cyclone preselector on the inlet, collects respirable dust.

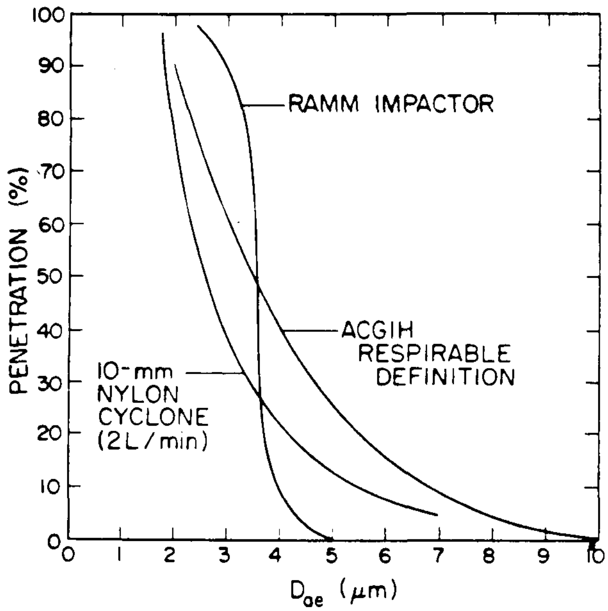

Fig. 5.
Penetration-efficiency curves of respirable dust preselectors. The nylon cyclone curve is taken from Ref. 3.

A. Qualitative Characteristics

1. **Portability.** The RDM-201 is excellent in this respect, having both lightweight (3 kg) and small dimensions (23 cm long by 8.9 cm wide by 18.4 cm high).

2. **Readout.** The LED readout in mass collected (mg) is easily read but would be more useful if the instrument displayed concentration directly, as does the RDM-101. Calculating concentration from the mass displayed and the sampling time is an inconvenience and requires the use of a stopwatch and a calculator.

3. **Reliability.** The reliability of the RDM-201 we tested was poor. It gave readings of zero concentration for more than one-third of all samples even though concentration was within the instrument's measurement range. It must be emphasized again that this assessment is based upon the performance of only one instrument. After being charged for 18 h before battery operation, the monitor pump operated for >5 h (period specified in the manual) in two of three battery-powered sampling periods. Field use of the RDM-201 is inconvenient since the collection surface (filter) should be changed after each sample. This necessitates removing the collection compartment top in the field, which may allow dust to settle in the collection chamber and could lead to misplacement or loss of the compartment top containing the ^{14}C source. A hinged top would be an improvement.

4. **Ruggedness.** A sturdy carrying case holding various accessories provides sufficient protection for transporting or shipping the instrument. However, the padded carrying case may seldom be used and the instrument would be subjected to knocks. The carrying straps likewise will not prevent the 201 from swinging against objects during field use. The 201 itself is compact and rugged with the exception of the aerosol inlet fitting, which protrudes 2 cm above the housing, and the three miniature operation switches, which are somewhat vulnerable.

The RDM-201 was packaged and shipped twice after initial receipt and suffered no damage.

5. Instruction Manual.[7]

- Component labels (list) are placed several pages from figures.
- Circuit diagram (Fig. 6, general schematic diagram) has been reduced to an unreadable size.
- Some component labels are incorrect.
- Troubleshooting information is insufficient.
- There is no discussion of the collection filter particulate filtration efficiency.
- Figure 1, "Mass concentration measurement accuracy as a function of sampling," is not discussed or explained.

B. Performance

1. Zero Check. Throughout testing the RDM-201 consistently indicated a zero or equivalent reading (reading >97.0 mg) in response to a clean air exposure.

2. Calibration. Using the factory supplied calibration disk, the instrument calibration was checked upon receipt and periodically thereafter by the prescribed procedure. For any series of seven consecutive readings, the average was within 10% of the calibration value except before the unit was returned for repair. Table IV contains calibration information for all mass monitors. The RDM-201 flow rate was within specifications until it was returned from factory repair; its flow rate of 2.7 L/min (Table IV) was corrected to 2.0 L/min again before use.

3. Performance Tests. The RDM-201 was evaluated against six aerosols at concentrations from less than 1 mg/m^3 to 85 mg/m^3. It was usually started at the beginning of a test run and it sampled for a time appropriate to the concentration. Because it was sampling constantly while

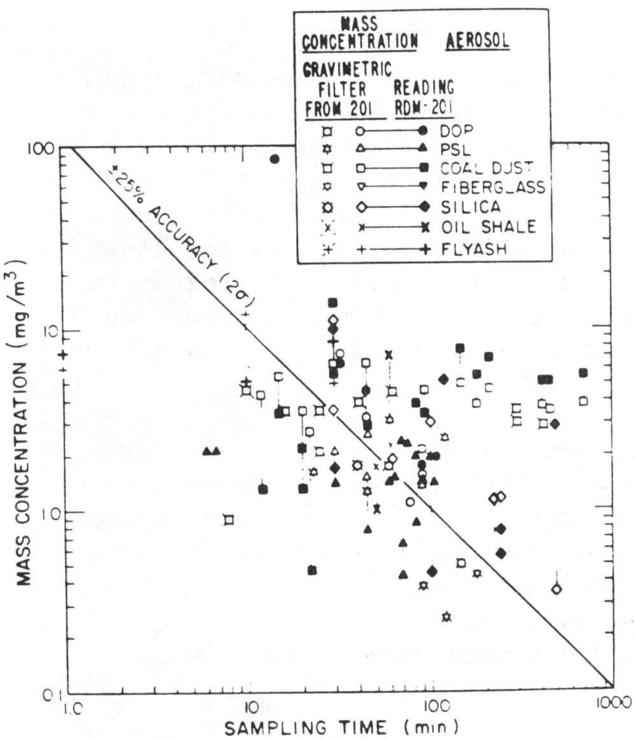

Fig. 6.
RDM-201 sampling data plotted as mass concentration vs sampling time. Solid symbols represent RDM-201 readings; open symbols represent the corresponding C_G found by the 201's filter. Vertical lines join RDM-201 symbols with corresponding gravimetric readings to emphasize that they are a data pair. Four-spiked symbols represent C_G data for which the corresponding 201 reading was zero.

TABLE IV

MASS-MONITOR CALIBRATION

	RDM-301		RDM-201		RDM-101		RAMM #1	RAMM #2
Date	Flow (L/min)	Conc (mg/m^3)	Flow (L/min)	Mass (mg)	Flow (L/min)	Conc (mg/m^3)	Flow (L/min)	Flow (L/min)
(Standard)	2.0	5.36	2.0	1.48	2.0	4.7	1.0	1.0
1-12-78	1.9±.1	6.38±0.62	2.1±0.1	1.54±0.12		4.5±0.2	1.1±0.1	1.1±0.1
2-21-78	2.0±0.1	5.94±0.39	2.0±0.1	1.46±0.10	2.1±0.1	4.6±0.3	1.1±0.1	1.1±0.1
3-21-78		6.85±0.24		1.59±0.09		4.7±0.1		
4-18-78	1.7	7.19±0.73	2.1	9.88	2.0	4.6±0.3	1.0	1.1
6-12-78	1.9±0.2	6.55±0.74			2.0±0.1	4.4±0.2	1.0	1.0
7-25-78			2.7±0.1	2.28±0.15[a]	1.8±0.1	4.6±0.3		
8-10-78					2.0	4.4±0.5	1.0	1.0

[a]After return from factory repair the RDM-201 had a calibration standard value of 2.19.

the filter and other mass monitors were sampling intermittently for (usually) shorter time periods, directly comparable C_G was not available in early runs. Although the filter was weighed before and after each RDM-201 sample, the glass fiber filters furnished with the monitor would stick to the neoprene O-ring, making the gravimetric results meaningless. This problem was later overcome by replacing the neoprene seal with a Teflon ring, which did not adhere to the glass fiber filter. Then, directly comparable C_G became available. The results of all RDM-201 sampling are shown in Fig. 6. The RDM-201 should provide ±25% accuracy for 95% of readings when operated for the recommended time against the aerosol concentration shown on the ordinate. The diagonal line, taken from the RDM-201 instruction manual, represents those sampling times that provide a manufacturer claimed accuracy of ±25% at the 95% confidence level. Although the topic is not discussed in the instruction manual, the RDM-201 should be used in accordance with this graph to provide optimum sampling. Because of the large mass of the collection filter (compared to the dust deposit), a minimum mass of dust must be collected to obtain a nonzero reading. Therefore a preliminary estimate of dust concentration is needed to determine an approximate required sampling time from Fig. 6.

Of 73 RDM-201 samples, 27 had corresponding C_G information determined directly from the 201 filter and another 27 readings, indicated by spikes on the sample symbol (Fig. 6), were zero. Thus, in 37% of all samples, the RDM-201 failed to measure aerosol concentration even though weight measurement indicated an appreciable aerosol concentration. The mean accuracy for 27 samples with both RDM-201 and gravimetric data was ±74%. Little sensitivity to aerosol material was observed.

A graph (Fig. 7) comparing data from gravimetric and RDM-201 measurements shows the scatter of measurements. RDM-201 zero readings shown in Fig. 7 were not included in a linear regression analysis of C_I on C_G, nor was one outlier at C_G = 12.0 mg/m^3. Although regression analysis indicates that on the average the RDM-201 measures within 25% of C_G over its entire sampling range, consideration of data scatter (low correlation coefficient) and number of zero readings makes this conclusion valid only for a large number of samples. Because the 201 sampling time depends on concentration and is on the order of tens of minutes for normal industrial dust concentrations, an 8-h shift is probably insufficient time to obtain enough samples to provide a valid measure of dust concentration.

It may be argued that a large proportion of our samples were displaced from the ±25% accuracy line (Fig. 6) and so should not produce accurate concentrations. This is true because we were interested in testing all conditions; however, even samples that were close to optimum (flagged, Fig. 7) showed poor correlation. Moreover, only seldom will the aerosol concentration be known closely enough beforehand to select the optimum sampling time recommended in Fig. 6.

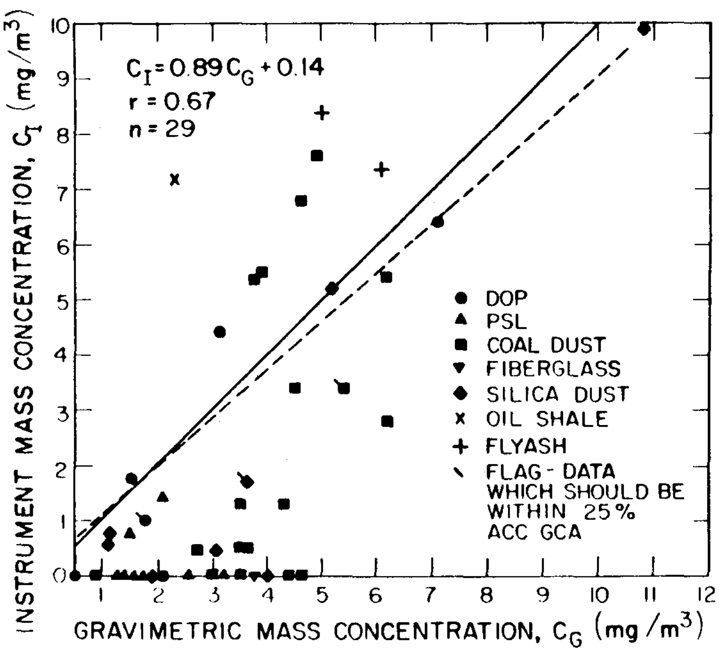

Fig. 7.
Correlation of all RDM-201 data as mass monitor concentration vs gravimetric concentration. The regression equation does not include RDM-201 zero readings.

The 201 was sent to the manufacturer once during the testing period when the instrument started giving erratic or zero readings (not included in the performance analysis). The manufacturer found the beta counter to be faulty. After return, the instrument functioned properly but still indicated ~22% zero readings, even though filter samples showed concentrations >1 mg/m^3.

IV. GCA RESPIRABLE DUST MONITORS (RDM-301 AND -101)

Both the RDM-301 and -101 collect aerosol at a flow rate of 2 L/min and measure mass by the same method. Particles are impacted onto a Mylar film in a spot beneath a ^{14}C beta source. The β^- attenuation produced by the deposit mass is measured by a counter located below the Mylar substrate. Both monitors convert the beta count to mass concentration but the RDM-301 prints the indicated mass concentration along with sampling time and collected mass, whereas the RDM-101 displays the mass concentration and retains it in memory until the next sample period is started. The RDM-301 has several distinctive features such as adjustable flow rate, preselectable sampling times up to 99 min, automatic repeat of sampling, and collection of as many as 412 samples before the Mylar substrate requires cleaning.

A. Qualitative Characteristics

RDM-301

1. **Portability.** Although it is transportable by one man, this instrument, with its large battery pack, cannot be considered a portable field instrument due to its 18-kg weight. It can collect more than 400 samples, with sample times ranging from 1 to 99 min, before the collection disk requires cleaning. Moreover, these samples can be collected consecutively if the continuous sampling mode is selected. That feature, along with printout of the results, made the 301 the most nearly automatic of the monitors evaluated.

2. **Readout.** The RDM-301 prints mass concentration, mass collected, and total sampling time onto thermal strip tape. Although the record is difficult to read because of small print and arrangement of the printer, the printed information is convenient. The printout prevented data loss several times during the tests.

3. **Reliability.** This monitor operated well on 115-V power during most of the evaluation. After ~6 months of use (~1000 readings), the unit started operating erratically. First the printer malfunctioned, then the sampling flow dropped, and finally the unit would not operate at all, so it was returned to GCA for repair. The 301 performed very poorly on battery. No more than 10 1-min readings could be obtained before the instrument stopped functioning. However, the unit had been used by another laboratory for some time before testing so the batteries may have been poor.

4. **Ruggedness.** The RDM-301 was not evaluated because the unit is not designed to be a portable monitor nor intended for extensive field use, even though one man can transport it. This monitor, like the RDM-201, was shipped to the factory for repair once. No known damage was suffered during handling and shipping.

RDM-101

1. **Portability.** The RDM-101 is outstanding in this respect with both lightweight (3 kg) and small dimensions (23 cm long by 8.9 cm wide by 18 cm high). A sturdy carrying strap is securely attached to the instrument.

2. **Readout.** The LED readout in mg/m^3 is easy to read. The display is lighted for only 10 s, but can be recalled by operating a three-position switch, provided instrument power hasn't been interrupted or another sampling action has not been initiated. Although the display switch is clearly labeled, the proximity of two other switches resulted in occasional activation of the wrong switch and consequent loss of information.

3. **Reliability.** The RDM-101 operation was outstanding. During ~1400 readings, no malfunctions occurred and few spurious readings were displayed.

4. **Ruggedness.** This instrument has qualities identical to the RDM-201 described in Sec. III.A.4. The 101 was shipped only once and no damage resulted.

5. **Battery Operation.** The monitor operated one 48-h period (including two off periods of 16 h each) with no charging. During that time samples were taken frequently without exhausting the batteries. Another time the instrument functioned for 24 h with no indication of battery exhaustion.

6. **Instruction Manual.**[8] The 101 manual is complete and is illustrated adequately, although the keyed numbers are somewhat confusing because the component list is separated from the figures. The quality of the figures makes identification of some components difficult.

Discussion of instrument theory is limited. Generally this is not a drawback, but the errors involved in the use of impactors should have been emphasized. Also, the particle collection efficiency curve for 10-mm nylon cyclone preseparators either should have been eliminated or discussed more extensively.

B. Performance

1. **Zero Check.** The 301 and 101 zeroed properly both initially and throughout the evaluation.

2. **Calibration.**

RDM-301. The 301 consistently gave readings ~20% high compared to the calibration disk value (Table IV). Although the RDM-301 calibration can be changed, it was left unchanged to check calibration drift throughout the test program. No detectable change occurred during the program.

RDM-101. Instrument readings agreed with the calibration disk value within 10% on the average. The calibration was checked upon receipt and periodically throughout testing (Table IV).

C. Size Sensitivity

Both the 301 and 101 mass monitors collect aerosol particles by impaction of particles onto a thin thermoplastic (Mylar) film. The efficiency of deposition depends upon the aerodynamic size of the particles. Large particles, because of their inertia, impact the collecting surface with greater efficiency than do small particles that follow the airflow streamlines and avoid impaction. Although large particles impact the surface quite well, they do not necessarily adhere; they may rebound and be carried off with the airstream. For this reason, some impaction surfaces, including the 301 and 101 film surfaces, are coated with a grease or adhesive to promote particle retention.

The effective cutoff aerodynamic diameter (ECAD) (particle size for which collection efficiency is 50%) of the RDM-101 impactor has been estimated by Lillienfeld to be 0.36-μm aerodynamic diameter (D_{ae})[9] while Marple[10] found it to be 0.7-μm D_{ae}. The RDM-101-1 instruction manual lists the ECAD of the monitor as 0.5 μm.[8] Marple measured penetration (aerosol passing the collector) by light-scattering techniques. Also, Volkwein[11] reported that gravimetrically measured Arizona road dust passing the GCA recording respirable mass monitor (RDM-301 prototype) indicated an impactor ECAD of 0.5-μm D_{ae}. It is important to note that in our experiments we determined the size sensitivity of the overall mass monitor rather than the impactor efficiency. No investigations of particle cutoff size for the 301 have been reported; however, its impactor is nominally the same as that in the prototype and in the 101 and should have a similar cutoff efficiency.

Challenge aerosols used for the collection efficiency tests were (1) monodisperse polystyrene latex (PSL) and (2) polydisperse dioctyl phthalate (P-DOP), both generated by a battery of Retec nebulizers, (3) monodisperse DOP (T-DOP), which was thermally generated, and (4) monodisperse Eosin-Y (E-Y) dye aerosols, which were generated by a Berglund-Liu (B-L) vibrating orifice unit. The aerosols, after neutralization, were introduced into the apparatus (Fig. 1) and sampled by all mass monitors and analytic samplers. Challenge aerosols were sized by laser light-scattering photometer and, except for the liquid particle DOP, from scanning electron microscope (SEM) photomicrographs of samples collected on 0.8-μm pore-size Nucleopore filters. Aerodynamic size was calculated from count diameter knowing the particles to be spherical, single particles (confirmed by SEM) and from densities of 1.00 g/cm^3 for DOP and PSL, and 1.45 g/cm^3 for E-Y.

The RDM-301 and -101 instruction manuals recommend that these monitors not be used against liquid particle aerosols such as DOP. We used it because it is a well characterized, spherical, unit density aerosol, that does not rebound from impaction surfaces as solid particles may. It was used to determine size sensitivity of the RAMMs simultaneously with the RDMs and to characterize the errors that arose from sampling liquid particle aerosols.

Collection efficiency was determined by comparing individual readings from each monitor to gravimetrically measured challenge concentrations. Efficiency data for each size aerosol was averaged and are presented as collection efficiency vs aerodynamic size in Fig. 8. The collection efficiency is identical to the ratio of mass monitor reading to C_G in Table A-I and discussed in Sec. II. Both 1- and 2-min concentration ratios were used to determine the curves.

Initially only monodisperse PSL and T-DOP were used to measure efficiency and no sizing information was determined; the vendor stated size distribution for PSL aerosol and the accepted size of thermally generated T-DOP were used. Thus, the majority of data, at 0.3-, 0.79-, 1.01-, and 2.02-μm D_{ae}, came from unsized aerosol. After determining the efficiency curves with these aerosols, we repeated the measurements with simultaneous sizing of the particles because the 50% cutoff size of the mass monitors differed substantially from that of the impactor alone, as estimated by GCA and reported by Marple. In Fig. 8, the size of particles at all points other than 0.3, 0.79, 1.01, and 2.02 μm was determined by the sizing techniques described. None of the points with sizing information pertains to the RDM-301 except two P-DOP aerosols collected with 44 to 55% efficiency, because it was being repaired when the other sized aerosols were used.

Only the points for the calculated mmad of P-DOP differ significantly from the efficiency curves (Fig. 8); however, they are also the only data for which only one sizing technique, light-scattering, was used. Data for the RDM-301 are not adjusted for the 20% overcalibration; if they are adjusted downward by 20% (dashed line, Fig. 8), the actual 50% collection efficiency of this monitor is at ~1.2-μm D_{ae}. Also, if we use only data for which the CoV of C_G is <20%, the ECADs are decreased slightly to ~1.2 and 1.4-μm D_{ae}. We conclude that the curves are valid for the RDM-301 and -101 and that the effective 50% cutoff size for these instruments is 1.2- to 1.4-μm D_{ae}.

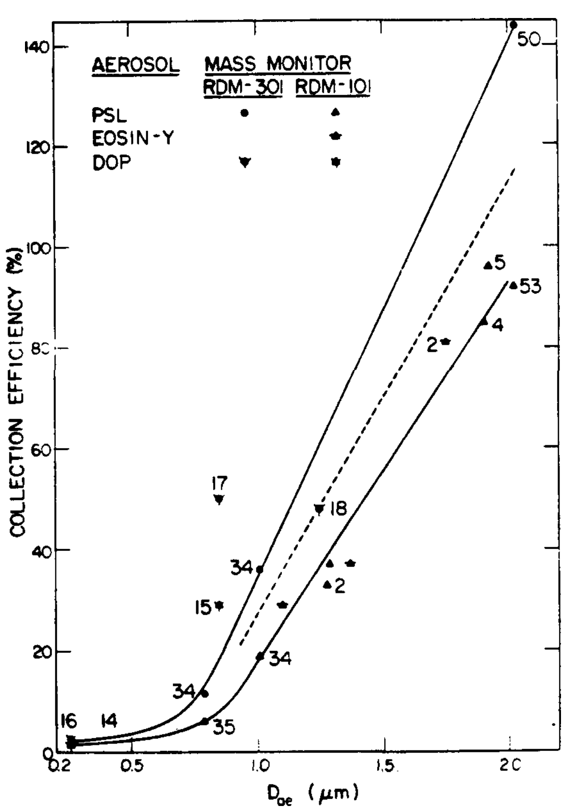

Fig. 8.
Measurement efficiency of RDM-301 and RDM-101 as a function of particle size. Data points are the mean of the number of samples shown adjacent to symbol. Dashed line is estimated RDM-301 efficiency after correction for 20% overcalibration.

D. Specific Aerosols

1. Coal Dust

RDM-301 and -101. More data were obtained from coal dust than any other aerosol; information derived from 11 runs was analyzed. All coal dust was generated with a Wright dust feed[12] which was part of a larger system[13] designed to deliver an electrically neutralized, uniform aerosol in concentrations up to 20 mg/m^3 of ~50% respirable dust.

Summarized run data are compiled in Table A-I. The runs with coal dust included measurements of respirable dust made with 10-mm nylon cyclones ahead of the RDMs and the manufacturer supplied impactor ahead of the RAMM instruments. These runs were compiled in two ways: (1) Respirable concentration readings (C_{IR}) were divided by gravimetrically determined respirable concentrations (C_{GR}) and labeled R/R data in Table A-I. (2) Respirable concentration readings (C_{IR}) were divided by gravimetrically determined total dust concentrations (C_G) and labeled R/T in Table A-I. The latter data, C_{IR}/C_G, represent the monitor indicated respirable fraction. Gravimetric respirable concentration of respirable dust was obtained independently by at least two personal coal mine samplers. Each section of Table A-I contains the average standard deviation, CoV, and number of samples for all samples or for particular concentration ranges where sufficient data exist. For example, the 1-min sample statistics are determined for all samples together, for 0- to 4-mg/m^3 and for >4-mg/m^3 concentration, whereas statistics for the 2-min total dust samples are shown only for 0- to 4-mg/m^3 concentration. Also, to provide a comparison between instruments the same statistics are tabulated for samples read by all four mass monitors. Thus for coal dust, only 37 1-min samples out of 91 provided readings from all monitors, not because of faulty operation, but in most cases because one instrument was being used for respirable or other special sampling. No statistics were provided where the number of samples was not statistically significant. Further discussion of respirable sampling will be deferred to Sec. VI.

Correlation of RDM-301 1-min readings with C_G is illustrated in Fig. A-1. The regression equation indicates that for all samples, the RDM-301 readings were within 25% of C_G in the range 1.75 to 10 mg/m^3 (highest concentration measured). Considering only the data for C_G < 4 mg/m^3 does not change the regression equation significantly except that the correlation coefficient decreases.

The regression equation for all 2-min samples (Fig. A-2) shows somewhat better agreement between C_I and C_G than was the case for 1-min samples. C_I was within 25% (on the average) for C_Gs between 1.5 and 4.7 mg/m^3 (highest concentration measured). For samples <4 mg/m^3, C_I was within 25% of C_G between 1.5 and 4 mg/m^3.

The RDM-301 readings were high for coal dust, especially at concentrations below 1.5 mg/m^3. However, as described in the physical characteristics section, the calibration was ~20% high, but could be changed to agree with gravimetric measurements. More important was the 49% CoV of the concentration ratio, which means that individual readings often differ considerably from the C_G. Even if compared with filter samples which had CoVs <20% the 301's CoV is 47% (Table A-I), more than twice the variation of C_G. For 2-min samples in the 0- to 4-mg/m^3 range, the correlation results were similar (Table A-I and Fig. A-2) to 1-min results. However, here the 301's CoV for 2-min samples was 24%, only about one-half that for 1-min samples. For 1- and 2-min samples, the RDM-101 provided concentrations within 10% of gravimetric measurements on the average. For concentrations <4 mg/m^3 this mass monitor appeared to read concentration slightly high, whereas for >4 mg/m^3 the readings were less than C_G because of expected overloading at high concentration.[10,11]

Figures A-3 and A-4 show correlation of RDM-101 readings with C_G for all 1- and 2-min samples. Linear regression equations for the appropriate conditions are included in the captions. Regression equations for all 1-min samples combined indicate that the RDM-101 overestimates coal dust concentration below about 2 mg/m^3 and underestimates above this concentration but is within 25% from <1 to >3 mg/m^3. Eliminating concentrations >4 mg/m^3 from consideration improves the RDM-101 performance somewhat. The 101 reads within 25% of C_G from 0.5 to 4 mg/m^3 on the average. The correlation is somewhat better for 2-min samples even though fewer samples were taken.

2. **Fiber Glass.** This aerosol was generated and distributed to an animal exposure chamber to evaluate aerosol uniformity within the chamber. The mass monitors were piggybacked onto this experiment to determine their performance against a fibrous aerosol. Fiber glass concentration was relatively uniform throughout the three runs of the experiment, during which aerosol to the mass monitor test unit (MMTU) flowed through a 2.2-cm-diam flexible tube at 45 L/min. The MMTU was under a negative pressure of ~0.8 in H_2O with respect to the chamber. As determined independently from personal sampler measurements, the fiber glass aerodynamic size within the chamber was ~2.2-μm mmad (~70% respirable).

RDM-301. Three runs against fiber glass provided 48 1-min samples and 12 2-min samples. Summary statistics (Table A-I) show that each group of six mass monitor readings exhibited considerable variation, which is discussed further in Sec. VI.B.

The concentration ratio, C_I/C_G for the RDM-301 was >1 in all cases (Table A-I) but was particularly high for the 2-min samples. However, after correction for the 20% overcalibration the 2-min readings are closer to C_G than are the 1-min readings.

RDM-101. The RDM-101 performed similarly to the RDM-301, although the average ratio of C_I/C_G was closer to unity than for the 301 (Table A-I). The RDM-101 average ratio value of slightly under 1 for 1-min samples and essentially 1 for 2-min samples indicates that this sampler estimates fiber glass within 10% of C_G. The CoVs of 35 and 40% for 1- and 2-min samples, respectively, indicate the poor reliability of individual readings. Graphs of RDM-101 reading (C_I) vs C_G (Figs. A-19 and A-20) show the correlation of 1- and 2-min samples.

3. **Arc-Welding Fume.** This aerosol was generated from arc-welding a mild steel plate inside an 85-L Plexiglas enclosure from which the welding fume was drawn at 25 L/min through a transfer tube leading to the MMTU, where it was sampled by all mass monitors and filters. The welding fume enclosure had openings near the welding area to permit inflow of clean air through a 100-cfm HEPA filter. Initially, sampling was performed during continuous welding; however, the fume concentration was excessive, often exceeding 100 mg/m^3. Thereafter, fume was generated for a period of 10 s, followed by a 30-s delay time before sampling was started. The result was a constantly decreasing fume concentration. By plotting sampling time vs concentration, a logarithmic decay curve was obtained. Regression analysis of the decay curves provided equations of the form $y = a - b \ln x$ fitting the filter measured concentration with correlation coefficients >0.95, where y was C_G and x was time after sampling began. Because the time of sampling by the mass monitors was recorded, an accurate fume concentration was obtained for comparison with the mass monitors' readings. One-min readings were taken during the initial 10 min, and 2-min (or longer) readings during the remaining 15 to 20 min of concentration decay.

Statistics for all arc-welding fume data for both RDMs are shown in Table A-I. Both mass monitors are considered together here because both performed similarly against arc-welding fume. The striking feature of the data summaries is the low concentration or concentration ratios indicated by the RDMs. Although the size distribution of the welding fume was not determined, it probably was a submicron aerosol, against which the RDMs have a low collection efficiency. The CoVs are large perhaps because of the large change in mass concentration for each set of samples. CoVs for samples in the <4 mg/m^3 range were 1/3 to 2/3 as large as those listed for all samples. Table A-I shows that the RDMs indicated higher concentrations for 2-min samples, giving readings about 25% of the C_G with average CoVs >100%. The ratio of monitor reading to C_G did not improve with decreasing concentration, which discounts overloading of the impaction surface, and confirms the manufacturer's statement that the RDMs should not sample fine particle fumes.

Figures A-25 through A-28 show C_I vs C_G for 1- and 2-min samples. The regression equations'correlation coefficients were poor ($r < 10^{-2}$) and the RDM readings were generally much lower than C_G at all concentrations.

4. Silica Dust. Silica dust was generated from a Wright dust feed, electrical charge neutralized, diluted, and delivered to the MMTU through a short, 25-mm-diam transfer line in concentrations up to 15 mg/m^3. Photomicrographic size analysis indicated the size parameters to be 1.7-μm cmd and $\sigma_g = 2.0$. Three runs included seven sets or 42 1-min samples and two sets or 11 2-min samples (Table A-I). The RDM-301 was being repaired at GCA during these tests, but the RDM-101 produced readings for all samples. The 1-min readings for 0 to 4 mg/m^3 averaged 89% of the C_G, whereas, above 4 mg/m^3 the readings average 59% of the C_G. These percentages are consistent with other observations using a dry dust.[13] For the 2-min readings, all at <4 mg/m^3, the average C_I/C_G ratio was insignificantly less than for 1-min samples, although the CoV for 2-min samples was about one-half that of 1-min samples.

Correlation and regression analysis of 1-min readings (Fig. A-35) also points out the relative decrease in instrument reading with increase in dust concentration (overloading). Figure A-35 indicates that individual RDM-101 readings are within 25% of C_G in the range $1.2 \leq C_G \leq 2.9$ mg/m^3 for 1-min samples, although below 1 mg/m^3 the 101 readings may correspond more closely to C_G than the regression equation indicates. For 2-min samples (Fig. A-36) the difference between C_I and C_G is less than 25% from approximately 1 to 3 mg/m^3 but from the 1-min samples and other observations, it seems probable that above a C_G of 3.5 mg/m^3 the RDM-101 readings are more than 25% below C_G. Below 1 mg/m^3, extrapolation of the regression equation would indicate that C_I is within 25% of C_G down to slightly below $C_G = 0.5$ mg/m^3. Lack of data in this concentration range precludes stating with any certainty how the mass monitor performs in this range for silica dust.

5. Polydisperse Dioctyl Phthalate (P-DOP). This aerosol was generated from a battery of RETEC nebulizers. It was used to determine the size cutoff characteristics of the RDMs because liquid droplets do not rebound or reentrain from impaction surfaces. Sizing by light-scattering followed by conversion to mmad indicated the P-DOP to range from 0.8 to 1.6 μm mmad with $\sigma_g \cong 1.5$.

The manufacturer's manuals state that the 301 and 101 are unsuitable for use against liquid aerosols. The liquid particles coalesce on the surface and spread from the impaction spot. In addition, oil particles may dissolve in the impaction surface coating, decreasing its viscosity and again spreading from the impaction area. Nevertheless, we tested the two RDMs along with the RAMMs against P-DOP. In general, the following discussion indicates the RDMs performed against P-DOP essentially as would be expected from their size cutoff efficiency. However, the P-DOP challenge concentration was generally low, perhaps lessening the effect of impaction spot spreading described in the manuals. Although the RDMs performed as expected in our tests, the results of sampling liquid aerosols with these monitors should be accepted with caution.

RDM-301. Of a total of 48 1-min and 12 2-min samples taken, the RDM-301 produced nonzero readings 45 and 11 times respectively (Table A-1). Of the zero readings, two 1-min and one 2-min readings resulted from operator error. The RDM-301 indicated from 26% (2-min readings) to 50% (1-min reading) of C_G. The low reading probably was due to the size distribution of the P-DOP.

The CoV for 1-min samples (76%) is large, but it is much lower (38%) for 2-min samples, reflecting the better accuracy of 2-min samples at low aerosol concentration and illustrating the advantage of longer averaging time.

Regression analysis of the correlation curve for 1-min readings of P-DOP (Fig. A-41) resulted in a correlation coefficient of only 0.32. The results for 2-min readings (Fig. A-42) were considerably better even though fewer samples were taken. These indicate a linear relationship ($r = 0.85$) between readings and P-DOP concentration; however, the readings average only 36% of the actual concentration.

RDM-101. Like the RDM-301 the 101 exhibited poor performance against P-DOP due to its size sensitivity. Of 46 1-min and 12 2-min samples, 40 and 6 nonzero readings, respectively, were recorded. Overall, the RDM-101 readings were 30 and 13% of C_G, respectively, for 1- and 2-min samples. Regression analysis correlation coefficients (Figs. A-43 and A-44) were essentially 0 for both 1- and 2-min samples; consequently, the trend of monitor readings with concentration change is undefined.

6. Polystyrene Latex (PSL). Three sizes of monodisperse PSL aerosol, 0.79-, 1.01-, and 2.02-μm D_{ae}, were generated by a battery of RETEC nebulizers. All monitors were tested against PSL although it was used primarily to determine the size sensitivity of the RDM-101 and -301. As listed in Table A-I and shown in Fig. 8 the response of the RDMs is size dependent, increasing as PSL diameter increases. Both mass monitors overestimate the concentration for 2.02-μm PSL, 2-min samples (Table A-I) but the RDM-101 underestimates C_G for 1-min samples. Consequently when 1- and 2-min sample results are combined as in Fig. 8, the RDM-301 overestimates concentration significantly, but the RDM-101 differs insignificantly from C_G. Correcting the 20% overestimate of the RDM-301 reduces its C_I/C_G to 1.06 for all 1-min samples and 1.33 for all 2-min samples.

Correlation data of monitor readings vs C_G for both the RDM-101 and 301 are presented in Figs. A-57 through A-60, A-65 through A-68, and A-73 through A-76 for 0.79-, 1.01-, and 2.02-μm PSL respectively. No regression analyses were made on the data because of the narrow range of concentration tested. In all cases, the C_G range was <2 mg/m^3. Thus the best indication of instrument performance is given by Tables A-I and A-II.

V. TSI INSTRUMENTS (RAMMs #1 AND #2)

A. Qualitative Characteristics

1. Portability. The RAMM is very good in this respect, weighing 5 kg and being 31.1 cm in the largest dimension. A sturdy, adjustable carrying strap is provided.

2. Readout. The large, bright LED display indicates frequency difference in Hz between the reference and collector quartz crystals as well as two ranges of concentration in mg/m^3. One range for a 2-min sampling period presents the concentration directly, but when set to the shorter sampling period of 24 s, the instrument display must be multiplied by 5. An indicator light shows when the display must be multiplied by 5, so, although inconvenient, the indirect reading is not confusing. One feature of the RAMM is its periodic display of crystal oscillation frequency that indicates the aerosol concentration even while sampling, enabling the operator to judge concentration variation. The display also has lights to indicate whether concentration or frequency is displayed and a light to indicate a negative frequency change (zero concentration).

3. **Reliability.** Neither RAMM instrument malfunctioned during ~1500 readings; however, problems with crystal cleaning occasionally delayed the tests for up to 10 min. Both RAMM instruments operated satisfactorily on their self-contained battery packs for up to 48 h with frequent sampling.

4. **Ruggedness.** The RAMMs are durable and well constructed despite protruding switches and a crystal-cleaning knob on the top surface. These are pushbutton switches and the knob is sturdy. The "flush with case" sample inlet design is rugged, although it may not be an optimum design for sampling in the presence of winds (Sec. VI.G). These monitors were shipped only once and suffered no known damage from shipment.

5. **Instruction Manual.**[4] The RAMM 3500 instruction manual is thorough and complete, but not clearly written. It is difficult to quickly locate particular information and a more liberal use of underlining, italics, or large print for important items in the operation instructions would have improved readability of the manual. Since the completion of this evaluation an improved RAMM manual has been written.

B. Performance

The two RAMMs operated reliably throughout the entire testing period. They gave zero or apparently erroneous readings fewer than six times out of well over 1400 readings taken with each instrument. Neither instrument malfunctioned a single time during operation, i.e., did not stop sampling, run too long or short a time, not display a reading, etc. Because there is no simple calibration, the RAMMs must be carefully checked against a known aerosol concentration. Checks of flow rate through the instruments are shown in Table IV. The sampling flow rate remained constant throughout the tests. The chief operational drawback noted was the inconvenience of cleaning the crystal between sampling periods. Although a simple, reliable mechanism cleans the crystal, the cleaning operation is nonetheless time-consuming and requires operator attention. Moreover, depending upon the aerosol collected and the condition of the internal cleaning sponges, several cleaning cycles were often necessary to remove deposited particles from the collection surface. As testing progressed, the base crystal oscillation frequency (see Ref. 4) gradually increased because imbedded particles were not being removed during cleaning. By the end of testing, the base (clean surface) frequency of the crystals was ~600 Hz above the initial frequency but was quite stable. Liquid-particle aerosols were most difficult to clean from the surface.

C. Specific Aerosols

1. **Coal Dust.** The introductory information for coal dust given in Sec. IV.C.1 for the RDM-301 also applies to both RAMMs.

Average results for all RAMM readings compared to C_G are tabulated in Table A-I. For all 1-min sample concentrations the ratios indicate that both RAMMs underestimated total coal dust concentration by a few per cent. The overall variability of the readings was large, being 44 and 43% of the concentration-ratio average for RAMM #1 and #2, respectively. Eliminating the ratios for concentrations >4 mg/m^3 slightly improves the agreement of monitor readings and C_G; likewise, concentration ratios >4 mg/m^3 are decreased from the overall values, indicating that overloading may have occurred in that concentration range.

Average concentration ratios, $1/n \, \Sigma \, C_I/C_G$, were slightly greater than 1 for the 2-min samples (Table A-I). The CoVs for C_I/C_G, were slightly less than for 1-min samples, judging from a comparison with gravimetric data having <20% CoVs.

Correlation of 1- and 2-min samples for the two RAMMs is shown in Figs. A-5 through A-8. RAMM #1 measures within 25% of C_G over the range $0.6 \leq C_G \leq 7$ mg/m³, whereas RAMM #2 exhibits this accuracy for $C_G > 1$. The apparent excellent performance of RAMM #2 results from one sample at 32 mg/m³ showing 1:1 correlation (Fig. A-7), but this correlation may not be valid for a larger number of samples at high concentration.

Regression equations for 2-min samples (Figs. A-6 and A-8) state that both RAMMs follow the coal dust C_G within 25% for $0.9 \leq C_G \leq 6$ mg/m³. No data were taken at concentrations >6 mg/m³. If regression equations are obtained only for concentrations below 4 mg/m³ then for this range C_I is within 25% of C_G. Sampling results for respirable coal dust are discussed in Sec. VI.A.

2. **Fiber Glass.** Summaries of run data for the RAMMs, for the concentration range used, (Table A-I) indicate that on the average the RAMMs overestimate C_G by 10 to 20% for both 1- and 2-min samples. The CoVs of the concentration ratio are low; in fact, the lowest observed for any aerosol.

The narrow concentration range adversely affected the regression analysis (Figs. A-21 through A-24); the correlation coefficient ranged from 0.52 to a maximum of 0.73. Because of the narrow concentration range, the regression equations also indicate ±25% accuracy of the RAMMs only for a small range. For this aerosol, the average of the concentration ratios, which shows the RAMMs overestimating C_G by 10 to 18%, probably gives the better indication of monitor performance.

3. **Arc-Welding Fume.** Arc-welding fume generation and analysis were described in Sec. IV.C.3. Summary statistics for both RAMMs' performance against this fume are listed in Table A-I. RAMM #1 produced, on the average, readings corresponding closely to C_G; however, the 73% CoV indicates that considerable variation occurred from sample to sample. If the samples are separated into two ranges, C_G <4 mg/m³ and C_G >4 mg/m³, RAMM #1 still indicates concentration ratios within 5% of 1 for both ranges and the CoV is reduced to 49% for <4 mg/m³ concentration.

Correlation graphs of the two RAMMs' readings vs concentration (Figs. A-29 through A-34) show that these instruments perform well against arc-welding fume.

4. **Silica Dust.** A total of 42 silica dust samples provided 41 nonzero 1-min readings by each RAMM (Table A-I). Both RAMMs read zero for an unknown reason on one sample for which the C_G was >10 mg/m³. The overall concentration ratio, C_I/C_G was 0.89 for RAMM #1 but only 0.76 for RAMM #2. The low C_I/C_G ratios probably resulted from the large mmad (~11 μm) of the silica dust. The CoVs were excessive: 81 and 66% for #1 and #2, respectively. Most unusual was the finding that the concentration ratios were closer to unity for >4 mg/m³ than for <4 mg/m³. Normally, ratios for >4 mg/m³ will be smaller due to overloading. For 2-min samples, concentration ratios of 0.97 and 0.85 and CoVs of 26 and 24% suggest that these instruments underestimate C_G by <15% in the narrow range (1 to 4 mg/m³) for which 2-min samples were taken.

Correlation of C_I vs C_G for both monitors for 1- and 2-min samples (Figs. A-37 through A-40) was similar for all data. Unfortunately, no samples at C_G <1 mg/m³ were obtained, so the RAMMs' performance against low concentrations of silica dust was not determined. Above 1 mg/m³ the monitors exhibited an unusual freedom from dust overloading to a concentration of almost 14 mg/m³, and the regression equations indicated slopes >1. Two-min samples covered only the concentration range 1 to 4 mg/m³ but linear regression equations indicated ±25 accuracy in that range.

5. **Polydisperse Dioctyl Phthalate (P-DOP).** This nebulized aerosol was used primarily to determine size sensitivity of the RDMs but the RAMMs were tested at the same time. The size distribution of the P-DOP was 0.8 to 1.6 μm, with σ_g = 1.5 to 1.8.

A total of 48 1-min readings by each monitor with no malfunctions or spurious readings, produced an average concentration ratio of 1.21 for RAMM #1 and 1.09 for RAMM #2 (Table A-I). For 12 2-min readings the RAMM concentration ratios were 1.35 and 1.15.

AOV of the 1-min samples shows that for mean concentrations only the RAMM #2 readings are not significantly different from C_G (Table A-II); for 2-min samples neither RAMM is significantly different from C_G. Although the AOV and FLSD analyses indicate different results from the average concentration ratios, there is no conflict because the variance may or may not be 25% as in the C_I/C_G analysis.

Finally, correlation graphs for P-DOP (Figs. A-45 through A-48) show that RAMM #1 estimated concentration within 25% of C_G over a small range (0.8-1.8 mg/m^3) and RAMM #2 read within 25% of C_G above 0.5 mg/m^3 for 2-min samples and 0.8 to 5.0 mg/m^3 for 1-min samples. The correlation coefficients were low for 2-min samples, reflecting the small number of samples and narrow concentration range. RAMM #2 exhibited surprisingly better performance than #1 considering that statistically no significant difference was observed between their sample means.

6. Polystyrene Latex (PSL). Generation and characterization of PSL was described in Sec. IV.C and IV.D.6. It was used primarily to determine the particle-size cutoff of each instrument. The concentration ratios, C_I/C_G, (Table A-I) indicate that the RAMMs' average reading was within 25% of C_G except for 2-min readings of 0.79-μm PSL by RAMM #2 and 1-min readings of 2.02-μm PSL by both RAMMs. The first instance where C_I/C_G for RAMM #2 was 0.67 was surprising because results from the two monitors were so different; normally they were not significantly different. The low C_I/C_G ratio doesn't appear to be attributable to size sensitivity because RAMM #1 performance was better and the RAMMs showed little decrease in sampling efficiency for 0.3-μm DOP. In the second case where both RAMMs read low (0.56 and 0.55 ratios) against 2.02-μm PSL, the monodispersity of the aerosol may have been responsible; however, both RAMMs measured within 25% of C_G against the same aerosol for 2-min samples. Although the last two sets were measured with the monitors powered by battery, this can be eliminated as a factor in the low ratios because no significant difference was observed between readings made on battery power vs 115-V AC power.

AOV and FLSD analyses of the PSL sampling runs differed from the C_I/C_G analysis because of the small variance of samples. For example, even though the mean C_I for RAMM #1 was 20% different from the average C_G for 0.79-μm, 2-min readings, it was significantly different from average C_G according to AOV. Generally, the difference between C_I and C_G had to be <10% for AOV to indicate no significant difference between the means.

No regression analyses were performed because of the small concentration range for PSL samples.

7. Monodisperse Dioctyl Phthalate (T-DOP). This aerosol was thermally generated to provide a small-particle monodisperse challenge aerosol. The particle size distribution, measured with a laser particle spectrometer, was 0.27-μm cmd, σ_g = 1.16. The concentration ranged from <1 to almost 100 mg/m^3.

The average concentration ratios, $1/n\Sigma\, C_I/C_G$ for both RAMMs sampling 1-min for C_G > 0.8 mg/m^3 indicate that they provide readings within 25% of C_G on the average (Table A-I). However, neither RAMM was within 25% of C_G when sampling for 2-min from T-DOP concentrations <1.4 mg/m^3. AOV and FLSD analyses (Table A-II) support the concentration-ratio findings, showing that 1-min RAMM readings are not significantly different from C_G but that 2-min RAMM readings may be.

The correlation graphs for T-DOP (Figs. A-53 through A-56) agree with the other analyses for 1-min samples, but agree only in a limited way with the other findings for 2-min samples. First, for both RAMMs the 1-min 25% accuracy range is moderately large [for RAMM #1, from 4.0 to 53.5 mg/m^3 (Fig. A-53), and for RAMM #2, 3.2 to 10.45 mg/m^3 (Fig. A-55)]. Second, both

RAMMs, according to regression analysis of 2-min samples, exhibit ±25% accuracy above 1.7 and 2.0 mg/m³ (Figs. A-54 and A-56). The mean concentrations are below these ranges, which is why AOV and mean concentration ratios indicate that the RAMMs do not estimate C_G within 25%. There is no known reason why the RAMMs should have done well at concentration >1 mg/m³ but poorly below this concentration during a 2-min collection cycle.

VI. COMPARISON OF MASS MONITORS

In this section all mass monitors except the RDM-201, which was discussed in Sec. III, are discussed and compared. Performance information from previous chapters is used and additional analysis of instrument data is introduced. Comparison of monitor results follows an aerosol-by-aerosol format, just as in previous sections.

A. Coal Dust

An AOV and FLSD analysis for 1-min data common to all monitors is shown in Table A-II. Only samples with all data are included in the analysis, i.e., the AOV includes only samples that contained filter concentration information and readings from all four monitors. Filter data represent the average of all filter-measured concentrations for each sample.

The computed AOV indicates that the means are significantly different. However, FLSD analysis, which compares each instrument mean with all ranked means following it using a function of the variance between each to determine their least significant difference, places RAMM #2, RAMM #1, and the RDM-101 in one group (underlined) with insignificant difference. The FLSD analysis determined that the RDM-301 has a sample mean significantly different from the mean C_G, however, if the RDM-301 mean is reduced by 20% (estimated departure from calibration), then it is probably the only monitor not significantly different from the C_G. Further, FLSD shows that although both RAMMs and the RDM-101 differ from filter values, they are not significantly different from one another.

In a similar analysis of 2-min samples of coal dust (Table A-II), it was determined that no significant difference was observed among any samplers either by AOV or FLSD analysis, even though the range of concentration of means was large.

The rate of convergence of readings toward the average of six sequential readings was determined for coal dust samples. The details of this computation were discussed in Sec. II. Both 1- and 2-min sample data trends were computed and the data trend of 2-min readings showed less variation and converged more rapidly than did 1-min readings; for example, all monitors converged to within 10% of the 6th average sample value one or two samples sooner than did the 1-min readings. In the concentration range examined (<4 mg/m³), except for the RDM-301, all monitors converged to within 10% of their final value (6th cumulative value) by the 4th 1-min sample and by the 2nd 2-min sample. It is best to take as many samples as practicable, but if circumstances are such that sampling time is limited, then sampling should be performed over a period of time in several sequential series of four or two samples, respectively, for 1- and 2-min readings. Marple[10] reported a similar convergence of short-term samples for the RDM-101.

Respirable Coal Dust. The same coal dust used for total coal dust testing was used for respirable dust testing by placing a 10-mm nylon cyclone preselector or TSI impactor ahead of each (or selected) mass monitor. Not all mass monitors sampled respirable dust simultaneously; often one monitor sampled total dust while the others were measuring respirable dust. The coal dust was determined to be 60 ± 13% respirable from independent measurements with nylon cyclones operated at 1.7 L/min.

Respirable sampling of coal dust is listed in the last four groups of coal dust data in Table A-I. Addition of nylon cyclones to the RDMs and impactors to the RAMMs increased the CoV of sampling by ~20% where 10 or more 1-min samples were taken, but no significant increase occurred for 2-min respirable samples.

The concentration ratios (C_{IR}/C_{GR}) for 1-min R/R samples of respirable dust are lower than those for total dust (Table A-I), whereas the ratios for 2-min R/R respirable samples are similar to 2-min total dust samples. The reason for the difference is not known.

Considering only the samples in Table A-I for which the CoV of C_G is <20%, a comparison of total coal-dust CoV to R/R respirable-dust CoV suggests that the sampling accuracy is better for total dust than for respirable dust. This is because the CoVs for total-dust samples are smaller than those for R/R samples in most cases where more than four samples can be compared. In several cases the CoVs for total and respirable samples are essentially equivalent. Thus it is not clear whether preselector cyclones improve precision for coal dust, although there is evidence[13] to indicate that preselectors increase sampling variation.

A summary of the information concerning monitors' performance against coal dust follows. The mean of all concentration ratios indicated that for all samples only the RDM-301 does not measure coal dust concentration within 25% accuracy (until corrected for overcalibration). However, regression analysis of C_I vs C_G for the RDM-301 indicates that it measures within 25% of C_G above C_G = 1.47 mg/m³ for 1-min samples. For 2-min samples regression analysis indicates that RDM-301 readings are within 25% of C_G between 1.5 and 4.6 mg/m³. Calculation for two ranges $C_G \leq 4$ and $C_G \geq 4$ does not improve the 25% accuracy range. The other monitors are within 25% accuracy down to C_G = 1 mg/m³ or lower. The RDM-101 2-min samples are within 25% of C_G between 0.4 and 4.45 mg/m³ (highest concentration sampled). For 1-min samples the best performance was exhibited by RAMM #1.

All data analysis considered, the RDM-101 measures coal dust concentration in the respirable size range slightly better than the RAMM instruments do.

B. Fiber Glass

AOV computation shows significant differences in the 1-min sampling data for this aerosol. Only RDM-101 and RAMM #2 means do not differ significantly from mean C_G (Table A-II). For 2-min samples AOV indicates there is a difference among the samples and FLSD analysis indicates that only the RDM-301 differs significantly (even after correction for overcalibration) from the mean C_G. These conclusions agree with the concentration ratio means for 2-min samples (Table A-I) but not with the 1-min sample means. In cases where the same number of filter and instrument samples were taken, the variability of mass concentration determined from the high-flow rate filter concentration alone indicated the overall fiber glass concentration CoV was 19.5% for all 1-min sampling sets. Approximately 33% of the variation was due to filter measurement in accuracy and the remaining 66% to change in aerosol concentration. Nonetheless, a comparison between this overall gravimetric variability and the instrument variability gives an indication of the accuracy (compared to gravimetric) of individual readings. This comparison is shown in Table V as an average of the CoV of each group of six samples. These CoVs were among the smallest observed because the large chamber served to damp concentration changes.

For 1-min samples, the RDM monitors sampled 8 sets (48 readings) and the RAMMs sampled only 6 sets, whereas for 2-min samples only the RDM-301 sampled 5 sets and the other monitors 4 sets (Table V). The ratio of instrument average CoV to filter average CoV indicates the variability of instrument readings compared to gravimetric results: the RDM-301 has more than twice the variability of filters for 1-min samples but about the same variability for 2-min samples. Note that in all cases 2-min samples vary considerably less than 1-min samples; however, this observation may be biased due to the fewer groups of 2-min samples.

TABLE V

CONCENTRATION OF VARIATION INDICATED BY FILTERS
AND MASS MONITORS SAMPLING FIBER-GLASS AEROSOL

Sample Time and No. Sample Sets	Coefficient of Variation (%)						
	High-Flow Filter						
	Total[a]	Filter	Conc	RDM-301	RDM-101	RAMM #1	RAMM #2
1 min, 8	19.5	6.6	12.9	39.4	25.9	---	---
1 min, 6	23.0	8.5	14.5			14.1	15.1
2 min, 5	11.9	1.3	10.6	11.5	---	---	---
2 min, 4	12.8	1.4	11.4	---	11.2	---	6.4
2 min, 4	12.0	1.4	10.6	---	---	7.2	---

[a]Total = $\Sigma(CoV_{filters} + CoV_{conc})$.

A convergence analysis was made on this aerosol to determine the minimum number of samples required to obtain an average value within 10% of the average of six samples (Fig. A-103). As with coal dust, the 2-min samples show less departure from the sixth average than do 1-min samples, even for the first sample. The 2-min samples are within 10% of the sixth average of samples even after the average of two samples, whereas 1-min samples are within 10% after four readings.

In summary, both the FLSD and the concentration ratio values are better than least-squares regression analysis for assessing the accuracy of the monitor readings because the concentration range is small. For 1-min samples, the RDM-101 and RAMM #2 appear to sample fiber glass better than the other monitors. The RDM-301 has a better concentration ratio than the RAMM #2 but it exhibits considerably more variability and, according to FLSD analysis, its mean concentration is higher than for RAMM #2.

C. Arc-Welding Fume

The AOV of 1- and 2-min welding fume samples confirms that significant differences exist between means of the mass monitors. FLSD analysis found that the filter concentration and RAMM #1 and #2 readings were not significantly different (Table A-II), but the RDM readings were different from filter measurements. As discussed in Sec. IV.C.3, the concentration ratios indicate that RDM readings were much lower than C_G, probably because of the small particle size of the welding fume.

Correlation graphs (Figs. A-25 through A-28) show clearly the poor performance of the RDMs against welding fume. This is not unexpected; the welding fume particle size is probably <1-μm D_{ae}, and the RDM manuals caution against the sampling of fumes. The RAMMs (Figs. A-29 through A-34) exhibit good performance against arc-welding fume with the exception of one high reading by RAMM #2. Regression equations show that for 1-min samples, RAMM #1 is within 25% of C_G from 7.4 to 22.6 mg/m^3 and if one ignores the spurious reading, RAMM #2 is within 25% of C_G over the range 10.6 to 21.7 mg/m^3. If only data points obtained from the concentration decay curves are used (Sec. V.C.3), the $\pm$25% accuracy range is 0.4 to 22.6 mg/m^3 (Fig. A-31) and 0.8 to 21.7 mg/m^3 (Fig. A-33), respectively, for RAMMs #1 and #2. The 2-min regression equations also show $\pm$25% accuracy in the range 0.3 to $>$2.0 mg/m^3.

D. Silica Dust

AOVs of filters and three mass monitors are shown in Table A-II for 1- and 2-min samples. (The RDM-301 was being repaired during silica dust testing.) For 1-min samples, AOV shows a significant difference between the sampling means, and FLSD analysis indicates that the RDM-101 readings differ significantly from C_G. Although the RAMM means are not significantly different from C_G, their CoVs (Table A-I) are large, indicating a large variability in readings. However, a comparison of filter samples with CoV <20% reduces the monitors' CoVs to expected values, and suggests that C_G varied considerably in the first (all) group. The concentration correlation for the RDM-101 (Figs. A-35 and A-36) shows that the 101 measures within 25% of C_G only for $1.2 \le C_G \le 2.9$ mg/m^3 for 1-min samples and $1.5 \le C_G \le 3.0$ mg/m^3 (1.5 mg/m^3 is lower limit of sampling concentration) for 2-min samples. The regression equations (Figs. A-37 and A-39) indicate that RAMMs #1 and #2 read within 25% from 3.6 to 14 mg/m^3 and 3.1 to 7.4 mg/m^3, respectively, for 1-min samples and 1.7 to 3.5 mg/m^3 and 2.8 to 3.5 mg/m^3 (highest concentration measured) for 2-min samples (Figs. A-38 and A-40). Judging from these results, both RAMMs are more accurate against silica dust than the RDM-101 even though the 101 follows the C_G slightly better than RAMM #1 for 2-min samples. FLSD analysis (Table A-II) shows the mean of readings of the RDM-101 differ considerably from the mean C_G.

E. Polydisperse Dioctyl Phthalate (P-DOP)

All mass monitors were tested against P-DOP, even though the RDM-301 and -101 are not recommended for use against liquid aerosols. Both the concentration ratios and correlation graphs indicate the expected performance of the RDM against P-DOP. Concentration ratios were higher for 1 min than for 2 min but were still only 0.5 (Tables A-I). Correlation graphs (Figs. A-41 through A-44) also show that nowhere in the concentration range sampled did these monitors agree consistently with C_G. The reason for the low concentration readings was, as discussed in Sec. IV.C.4, most likely the small median particle size of the aerosol.

On the average, the RAMMs read higher than C_G according to concentration ratios (Table A-I) of 1.2 and 1.1 for 1-min and 1.35 and 1.15 for 2-min samples by RAMM #1 and #2, respectively. Even though the concentration ratios of the RAMMs are high, FLSD analysis of the means determined that they are not significantly different from the filter mean concentration, probably because of the large CoV of the readings.

Correlation curves for the RAMMs are presented in Figs. A-45 through A-48. The regression equations show the #1 and #2 monitors, respectively, to be within ±25% accuracy from about 0.75 to 1.8 mg/m^3 (Fig. A-45) and between 0.75 and 5.0 mg/m^3 (Fig. A-46) for 1-min samples, and from 0.75 to 0.8 mg/m^3 (Fig. A-47) and from 0.75 to 2.4 mg/m^3 (Fig. A-48) for 2-min samples. Some of these concentration ranges are calculated to be larger, but the ±25% accuracy range was not extrapolated beyond the actual sampling concentration range. Correlation coefficients of 1-min samples were satisfactory, but those of the 2-min curves were low because of data scatter and small number of samples.

All data analyses indicate that the RDM units read low when sampling polydisperse P-DOP because the measured median particle size was near or below the effective cutoff particle size of both RDMs (Fig. 8). The manufacturer believes the poor performance against liquid droplets to be due to coalescence and spread of droplets on the surface and dissolution in the surface coating.[14] The RAMMs agreed well with C_G; in fact, they measured DOP concentration quite well, but only 12 2-min samples were obtained, so little confidence can be placed in the results for the 2-min samples.

F. Monodisperse Dioctyl Phthalate (T-DOP)

This monodisperse aerosol was generated by a Q-127 respirator filter testing unit[15] which supplied ~0.3-μm DOP at high concentration (>100 mg/m^3). The concentration was decreased for our tests by controlling the high-concentration-aerosol volume with a valve and introducing dilution air downstream of the valve. The particle size distribution, measured with an active scattering laser spectrometer, was 0.27-μm cmd with $\sigma_g = 1.16$.

Table A-I lists 1- and 2-min sampling results. This small-particle aerosol was used primarily to measure size sensitivity and response to a liquid aerosol. The 1.2- to 1.4-μm cutoffs of the RDMs caused them to display concentrations much lower than C_G when sampling thermal DOP. Even the RAMMs exhibit low C_I/C_G ratios against this aerosol, particularly for 2-min samples. The number of valid samples obtained was below normal and may have affected the concentration ratios, although the RAMMs may not sample this small aerosol with the same efficiency as larger particles. No reason is known for the 2-min sample concentration ratios to be so much smaller than 1-min samples at the C_G used.

According to AOV of 1- and 2-min samples, there are significant differences between the means. FLSD analysis shows that 1-min readings of the two RAMMs are probably not different from the mean C_G, whereas for 2-min samples none of the monitors provide average concentration values similar to average C_G.

Although FLSD showed that the average of RAMM #1 and #2 monitor readings did not agree with average C_G for 2-min samples, least-squares linear regression analysis of correlated 2-min sample data revealed that in the range of 1.7 to ~6 mg/m^3 (highest concentration obtained) for RAMM #1 and 2.0 to ~6 for RAMM #2 the monitor readings were within 25% of C_G. On the other hand, nowhere in the actual sample concentration range were the RDMs within 25% of C_G. This was expected because the RDMs are not recommended for use against liquid aerosols.

Summing up, the RDMs are unsuitable for use against thermal DOP because of its small particle size. The RAMMs perform well against T-DOP although AOV and FLSD analysis show means differ significantly from one another. The RAMMs measure C_G within ±25% for both sample times in certain concentration ranges.

G. Oil Shale Dust

A 1-wk field sampling trip was made to obtain qualitative and quantitative monitor performance data. The mass monitors were employed in conjunction with 47-mm membrane filters, Hi-Vols, and Andersen impactor samplers to determine dust levels in an underground mine and its above-ground crushing and retorting facility. Four mass monitors, mounted on a support stand with their sample inlets about 20 cm apart, were operated by battery power, with overnight charging. Considerable sampling was performed with the RDM-201 (after repair by GCA), RDM-101, and RAMMs #1 and #2, but few simultaneous gravimetric samples were obtained because of power failures, changes in schedules, and other field sampling problems. Generally, the Andersen impactor and RDM-201 filter weights provided gravimetric data. Monitor readings are compared with gravimetric information in Table A-I. The RDM-201 did not sample for 1 or 2 min as did the other monitors, but sampled for 30 min or longer while the others were sampling at intervals. It gave zero readings for one out of five samples (Sec. III.B.3) but the four good samples were within 38% of gravimetric. These results are included in the performance analysis in Sec. III and also shown in Fig. A-95 and 96.

Results from the other monitors showed generally poor agreement with gravimetric measurements, except the RDM-101 2-min samples, which were within 20% of C_G. The poor performance of the RAMMs may have been due to the inlet design. During all above-ground sampling a light breeze (up to 5 m/s) was blowing. The RAMM inlet, being flush with the instrument case and near the bottom, is probably not an optimum design for sampling during an external airflow. Another reason for poor RAMM performance may have been the large particle size of dust near the crushers and retort (3- to 7.3-μm mmad and $\sigma_g \geq 2.7$).

AOV of oil-shale data shows that all monitors readings were significantly different from filter concentration. The correlation graphs (Figs. A-95 through A-102) illustrate that the monitors did exhibit increased readings as the oil-shale concentration increased.

H. Polystyrene Latex (PSL)

This monodisperse aerosol was used primarily to determine the sensitivity to particle size of the mass monitors since it is a well-characterized standard aerosol. Performance of the RDMs against PSL was dependent upon its size as described in Sec. IV.C. Table A-I provides the concentration ratios that were used in Fig. 8 to define the RDMs' effective size collection efficiency. The CoVs for the RDMs are high, but this isn't surprising in view of the low concentration ratios for the smaller size PSL. The CoVs steadily decrease as the PSL particle size and monitor concentration ratios increase. AOV of the RDMs' response to PSL confirms that the RDM readings are significantly lower than C_G until a particle size of 2-μm D_{ae} challenges the monitors.

The RAMMs apparently are not sensitive to particle size in the range covered by PSL aerosols. They underestimate aerosol concentration, but by a factor that appears to be independent of size. For 2.02-μm PSL, the RAMMs underestimate concentration by 50% for 1-min samples, but estimate the concentration within 10% for 2-min readings. No reason is known for this behavior because the PSL concentration was neither very low nor very high.

I. Eosin-Y (E-Y)

This water-soluble, fluorescein-derivative, monodisperse aerosol was generated from a Berglund-Liu vibrating-orifice generator. It was used for size efficiency tests and for accurate determination of low concentration. The latter use was enhanced because fluorescent analysis of deposited E-Y with a Turner fluorometer provided sensitivity to 1 μg. This sensitivity provided better accuracy than weighing at concentrations <0.1 mg/m^3 (Table A-I). Because of the low concentration, the monitors were operated for longer, nonstandard sampling periods, as recommended by the instruction manuals. The particle size listed with each group of E-Y readings (Table A-I) was a nominal size obtained from light scattering only and the aerosols were grouped into the sizes shown.

The performance of the RAMMs against E-Y wasn't good, but sampling a monodisperse, large particle aerosol does not give good results according to the RAMM manual. The RAMMs estimated the concentration of 1.0 μm (~1.3-μm D_{ae}) E-Y as 0.8 of C_G (fluorimetrically determined) but for larger monodisperse E-Y the ratio C_I/C_G decreased. For particles >3.0 μm the RAMM readings averaged only ~20% of C_G.

An opposite performance was observed with the RDMs; as the aerosol size increased, the RDMs' estimate of concentration increased relative to C_G. The RDM-301 wasn't available for testing against the smaller E-Y aerosols, but for large E-Y particles its overestimate was similar to the RDM-101. The CoVs of samples are large for the large particle tests, but the overestimate of E-Y aerosol >1.5-μm D_{ae} by the RDMs is consistent. The RDMs' performance may relate to the very low concentration of aerosol.

AOV results, although shown in Table A-II, are invalid for some sizes of E-Y because too few samples were taken to observe statistical differences for the large CoVs and low concentration involved (see Sec. II.A). Qualitatively, all mass monitors estimate concentration poorly for monodisperse E-Y concentrations <0.1 mg/m^3 except possibly in the 1.2- to 1.5-μm D_{ae} range.

The E-Y concentration was always <0.1 mg/m^3 in the tests, and that may be the overriding factor in the poor performance of the mass monitors.

VII. DISCUSSION

The RDM-301 and -101 and two RAMMs performed within the manufacturers claims in general. Whenever challenged by a small particle aerosol the RDMs did not measure concentration well, and the RAMMs did not respond well to large particles when sampling total dust. Conflicting results were obtained from respirable sampling; however, the addition of preseparators increased sampling variation on the average. In view of the size sensitivity found for the monitors, respirable sampling should improve the performance of the RAMMs, particularly for coarse aerosols (mmad >3 μm); whereas respirable sampling may reduce the accuracy of the RDMs when sampling fine aerosols (mmad <3 μm).

All test results are summarized and compared in Table VI. The performance data discussed in the previous sections and contained in the Appendix are listed, including mass concentration ratio C_I/C_G, AOV and FLSD analysis results, and the range over which monitor readings were within 25% of C_G. In addition, one column gives the Appendix reference figure containing graphed, correlated data. For example, the reference showing RAMM #2 1-min samples of coal dust is Fig. A-7. All C_I/C_G values are from Table A-I, and all AOV and FLSD information is from Table A-II, but each correlation graph is a separate figure for each monitor. Finally, Table VI contains a scheme for objectively comparing the performance of the mass monitors in sampling each aerosol. A column labeled E following each column of monitor statistics (C_I/C_G, etc.) and the final four columns labeled "Evaluation" are used for that purpose. If each monitor performed within specifications, then a "1" appears in the E column; if not, a "0" is there. The Evaluation column is the sum of the E columns and provides a relative performance index for the monitors.

The specifications used in Table VI for an E value of 1 were that C_I/C_G be 1.0 ± 0.25, that AOV and FLSD analysis indicate no significant difference (NSD) between the C_G and C_I means, and that the monitor read within 25% of C_G from 1 to 5 mg/m^3. The last requirement was based on this concentration range being of most concern for common dusts.

The evaluation in Table VI indicates that the RDM-301 performs poorly in nearly all tests, but the calibration of the RDM-301 was 20% higher than C_G in the "as received" condition and was not reset. If the RDM-301 values are reduced by this amount, it is found that the 301 performs much like the 101. Consequently, in discussing Table VI, the 301 and 101 are considered equivalent.

Both industrial aerosols and laboratory aerosols are listed in Table VI. Because they were used to test the monitors in extreme conditions (very small or large particles) the laboratory aerosols are considered first. The RDM monitors, which collect by impaction, had a poor relative performance index (0 of 14) for monodisperse particles up to 1-μm D_{ae}, whereas the RAMMs had indices of 6 and 7 of 14 for this same range. The aerosols providing this size range were monodisperse DOP, 0.79-μm PSL, and 1.0-μm PSL. On the other end of the size range (6.9-μm D_{ae} E-Y aerosol) the RDMs overestimated and the RAMMs underestimated the concentration; however, E-Y aerosols used were at concentrations <0.3 mg/m^3, so the results are questionable.

Second, industrial aerosols used to compare monitors were coal dust, respirable coal dust, fiber glass, arc-welding fume, silica dust, and oil shale. The oil-shale dust was measured in field tests and the remainder were measured in the laboratory. The relative performance index of the RDMs was 14 out of 36, and was 22 of 36 and 19 of 36 for RAMM #1 and #2, respectively. If arc-welding fume, which is a fine particle aerosol and may be expected to pass the RDMs' collectors, is eliminated from consideration, then the RAMM units are only marginally better against the

TABLE VI

MASS-MONITOR TEST RESULTS

Sample	Sample Time Min	No.	Mass Monitor	C_I/C_G[a]	E[b]	AOV & FLSD Anal.[c]	E	±25 Accuracy Range (mg/m^3)[d]	E	Ref. Fig.	Evaluation RDM 301	RDM 101	RAMM #1	RAMM #2
Coal dust	1	59	RDM-301[e]	1.33	0	SD	0	1.7 to 9.5	0	A-1	0			
		59	RDM-101	1.00	1	SD	0	1.0 3.8	0	A-3		1		
		62	RAMM #1	0.94	1	SD	0	0.6 5.3	1	A-5			2	
		80	RAMM #2	0.93	1	SD	0	1.0 32	1	A-7				2
	2	20	RDM-301	1.26	0	NSD	1	1.5 5.0	0	A-2				
		17	RDM-101	1.07	1	NSD	1	0.4 5.0	1	A-4	1	3		
		19	RAMM #1	1.23	1	NSD	1	0.9 5.0	1	A-6			3	
		14	RAMM #2	1.14	1	NSD	1	0.9 5.0	1	A-8				3
											1	4	5	5
Respirable coal dust	1	16	RDM-301	0.90	1	SD	0	C_G range <2	0	A-9	1			
		44	RDM-101	0.73	0	NSD	1	0.8 1.9	0	A-11		1		
		40	RAMM #1	0.87	1	NSD	1	1.8 7.7	0	A-13			2	
		20	RAMM #2	0.79	1	SD	0	C_G range <2	0	A-15				1
	2	4	RDM-301	1.15	1	SD	0	2.5 2.9	0	A-10	1			
		17	RDM-101	1.07	1	NSD	1	0.5 2.9	0	A-12		2		
		13	RAMM #1	0.94	1	NSD	1	C_G range <2	0	A-14			2	
		6	RAMM #2	1.27	0	SD	0	1.5 2.9	0	A-16				0
											2	3	4	1
Fiber glass	1	46	RDM-301	1.14	1	SD	0	0.5 1.8	0	A-17	1			
		46	RDM-101	0.94	1	NSD	1	0.5 1.8	0	A-19		2		
		34	RAMM #1	1.18	1	SD	0	1.1 1.8	0	A-21			1	
		43	RAMM #2	1.15	1	NSD	1	0.8 1.8	0	A-23				2
	2	29	RDM-301	1.46	0	SD	0	0.2 0.3	0	A-18	0			
		24	RDM-101	1.01	1	SD	1	0.9 1.9	0	A-20		2		
		24	RAMM #1	1.17	1	NSD	1	1.1 2.0	0	A-22			2	
		24	RAMM #2	1.10	1	NSD	1	1.0 2.0	0	A-24				2
											1	4	3	4
Arc-welding fume	1	25	RDM-301	0.13	0	SD	0	None	0	A-25	0			
		29	RDM-101	0.10	0	SD	0	None	0	A-27		0		
		34	RAMM #1	0.99	1	NSD	1	0.4 22.6	1	A-29,30			3	
		35	RAMM #2	1.04	1	NSD	1	0.8 21.7	1	A-32,33				3
	2	21	RDM-301	0.27	0	SD	0	0.06 0.09	0	A-26	0			
		22	RDM-101	0.24	0	SD	0	0.04 0.07	0	A-28		0		
		23	RAMM #1	0.84	1	NSD	1	0.3 -	1	A-31			3	
		23	RAMM #2	0.88	1	NSD	1	0.3 -	1	A-34				3
											0	0	6	6
Silica dust	1	42	RDM-101	0.72	0	SD	0	1.2 2.9	0	A-35		0		
		41	RAMM #1	0.89	1	NSD	1	3.6 13.8	0	A-37			2	
		41	RAMM #2	0.76	1	NSD	1	3.1 7.4	0	A-39				2
	2	16	RDM-101	0.77	1	SD	0	1.5 3.0	0	A-36		1		
		17	RAMM #1	0.97	1	NSD	1	1.7 3.5	0	A-38			2	
		17	RAMM #2	0.85	1	NSD	1	1.9 3.5	0	A-40				2
												1	4	4

Sample	Sample Time Min	No.	Mass Monitor	C_I/C_G [a]	E [b]	AOV & FLSD Anal. [c]	E	±25 Accuracy Range (mg/m^3) [d]	E	Ref. Fig.	Evaluation RDM 301	RDM 101	RAMM #1	RAMM #2
P-DOP	1	45	RDM-301	0.50	0	SD	0	None	0	A-41	0			
		44	RDM-101	0.30	0	SD	0	None	-	A-43		0		
		48	RAMM #1	1.21	1	SD	0	0.8 1.8	0	A-45			1	
		48	RAMM #2	1.09	1	NSD	1	0.8 5.0	1	A-47				3
	2	11	RDM-301	0.26	0	SD	0	None	0	A-42	0			
		11	RDM-101	0.13	0	SD	-	None	0	A-44		0		
		12	RAMM #1	1.35	0	NSD	1	0.7 0.8	0	A-46			1	
		12	RAMM #2	1.15	1	NSD	1	5	1	A-48				3
											0	0	2	6
Oil shale	1	22	RDM-101	0.52	0	NSD	1	---		A-97		1		
		21	RAMM #1	0.19	0	SD	0	---		A-99			0	
		22	RAMM #2	0.22	0	SD	0	---		A-101				0
	2	20	RDM-101	0.81	1	SD	0	---		A-98		1		
		20	RAMM #1	0.27	0	SD	0	---		A-100			0	
		20	RAMM #2	0.27	0	SD	0	---		A-102				0
												2	0	0
0.79-μm PSL	1	23	RDM-301	0.16	0	SD	0	C_G range <2		A-57	0			
		23	RDM-101	0.07	0	SD	0	C_G range <2		A-59		0		
		24	RAMM #1	0.95	1	SD	1	C_G range <2		A-61			2	
		24	RAMM #2	0.86	1	NSD	0	C_G range <2		A-63				1
	2	11	RDM-301	0.07	0	SD	0	C_G range <2		A-58	0			
		12	RDM-101	0.06	0	SD	0	C_G range <2		A-60		0		
		12	RAMM #1	0.82	1	SD	0	C_G range <2		A-62			1	
		12	RAMM #2	0.67	0	SD	0	C_G range <2		A-64				0
											0	0	3	1
1.0-μm PSL	1	23	RDM-301	0.37	0	SD	0	C_G range <2	0	A-65	0			
		24	RDM-101	0.16	0	SD	0	C_G range <2	0	A-67		0		
		23	RAMM #1	0.89	1	SD	0	C_G range <2	0	A-69			1	
		22	RAMM #2	0.84	1	SD	0	C_G range <2	0	A-71				1
	2	11	RDM-301	0.33	0	SD	0	C_G range <2	0	A-66	0			
		10	RDM-101	0.27	0	SD	0	C_G range <2	0	A-68		0		
		12	RAMM #1	0.85	1	SD	0	C_G range <2	0	A-70			1	
		12	RAMM #2	0.87	1	NSD	1	C_G range <2	0	A-72				2
											0	0	2	3
2.0-μm PSL	1	33	RDM-301	1.33	0	SD	0	C_G range <2	0	A-73	0			
		35	RDM-101	0.82	1	SD	0	C_G range <2	1	A-75		2		
		34	RAMM #1	0.56	0	SD	0	C_G range <2	0	A-77			0	
		34	RAMM #2	0.56	0	SD	0	C_G range <2	0	A-79				0
	2	17	RDM-301	1.66	0	SD	0	C_G range <2	0	A-74	0			
		18	RDM-101	1.12	1	NSD	1	C_G range <2	0	A-76		2		
		18	RAMM #1	1.05	1	NSD	1	C_G range <2	0	A-78			2	
		18	RAMM #2	0.94	1	NSD	1	C_G range <2	0	A-80				2
											0	4	2	2

Sample	Sample Time Min	No.	Mass Monitor	C_I/C_G[a]	E[b]	AOV & FLSD Anal.[c]	E	±25 Accuracy Range (mg/m³)[d]	E	Ref. Fig.	Evaluation RDM 301	RDM 101	RAMM #1	RAMM #2
T-DOP	1	7	RDM-301	0.04	0	SD	0	None	0	A-49	0			
		5	RDM-101	0.06	0	SD	0	None	0	A-51		0		
		17	RAMM #1	0.92	1	NSD	1	4.0 53.5	0	A-53			2	
		17	RAMM #2	0.83	1	NSD	1	3.2 10.4	0	A-55				2
	2	9	RDM-301	0.04	0	SD	0	None	0	A-50	0			
		9	RDM-101	0.02	0	SD	0	None	0	A-52		0		
		10	RAMM #1	0.51	0	SD	0	1.7	0	A-54			0	
		10	RAMM #2	0.46	0	SD	0	2.0	0	A-56				0
											0	0	2	2
Eosin-Y dye (1.0-μm cmd) (1.3-μm mmad)	20	10	RDM-101	0.83	1	NSD	1	---		A-81		2		
		10	RAMM #1	0.74	0	NSD	1	---		A-82			1	
		10	RAMM #2	0.66	0	NSD	1	---		A-83				1
												2	1	1
Eosin-Y dye (1.5-μm cmd) (1.7-μm mmad)	20	9	RDM-101	1.76	0	SD	0	---	0	A-84		0		
		9	RAMM #1	0.51	0	SD	0	---	0	A-85			0	
		9	RAMM #2	0.47	0	SD	0	---	0	A-86				0
												0	0	0
Eosin-Y dye (3.7-μm cmd) (4.6-μm mmad)	10	8	RDM-301	3.53	0	SD	0	---	0	A-87	0			
		8	RDM-101	2.24	0	SD	0	---	0	A-88		0		
		8	RAMM #1	0.47	0	NSD	1	---	0	A-89			1	
		8	RAMM #2	0.19	0	NSD	1	---	0	A-90				1
											0	0	1	1
Eosin-Y dye (5.6-μm cmd) (6.9-μm mmad)	10	13	RDM-301	1.63	0	NSD	1	---	0	A-91	1			
		14	RDM-101	2.31	0	NSD	1	---	0	A-92		1		
		4	RAMM #1	0.20	0	NSD	0	---	0	A-93			0	
		14	RAMM #2	0.15	0	SD	0	---	0	A-94				0
											1	1	0	0

[a] C_I/C_G is the average of all instrument readings divided by gravimetric concentration for each sample.

[b] Evaluation of instrument performance for test in preceding column. "1" is satisfactory, "0" is unsatisfactory.

[c] Fisher least significant difference analysis (FLSD) indicated either no significant difference (NSD) or a significant difference (SD) between instrument-determined mean concentration and gravimetric mean concentration.

[d] Gravimetric concentration (C_G) range in which C_I is within 25% of C_G, calculated from linear regression equation.

[e] The RDM-301 was operated with an overcalibration of 20% which causes all RDM-301 readings to be 20% high. If corrected, the RDM-301 then performs essentially like the RDM-101.

remaining industrial aerosols. The RDMs estimated concentrations of oil shale in field experiments better than the RAMMs, but did not perform so well as the RAMMs against the other aerosols.

VIII. CONCLUSION

The evaluation of the mass monitors has shown them to represent a significant advance in aerosol measurement. However, judgment must be applied in their use because of the small volume of the samples and because the instruments do not measure all aerosols equally well.

Based upon the findings discussed throughout the report several recommendations for the use of the mass monitors may be listed:

(1) The instructions and precautions recommended by the manufacturer must be observed.

(2) A sufficient number of concentration measurements are required to obtain a valid indication of the average concentration. The number required will depend on the variation of concentration being measured. Single readings will not provide reliable estimates within a factor of 2 of the actual concentration, particularly if the concentration is <1 mg/m^3.

(3) The flow and mass concentration calibrations must be checked frequently. A change in calibration may be the first indication of an instrument malfunction.

The potential use of these instruments for compliance enforcement requires comparison with the accepted methods of measuring compliance. In general, the instruments do not provide the reproducibility that is obtainable by filter collection and gravimetric analysis. The small sample volume and short sampling period of most of these instruments require many readings to determine the average concentration under varying conditions. However, these characteristics also permit determination of variability in both time and space. In the case of the respirable nuisance dust standard (TLV = 5 mg/m^3) the instruments can clearly give reliable indications of being well below or above the TLV. However, the variability noted with these instruments results in significant confidence intervals in the determination of concentration. When concentrations close to some action concentration are encountered, it would be necessary to use more accurate sampling methods. The aerosol mass monitors could be used for surveys and to indicate the need for accurate determination of concentrations. Compliance enforcement measurements should employ the most accurate method available, one that is well established and that is related to the development of the health standard. The mass monitors should not be used for compliance enforcement measurements until considerable experience has been accumulated. Use of the instruments for surveying work environments would provide this experience.

The results of this study indicate some of the difficulties involved in trying to build a general purpose instrument for measuring airborne dusts. It is extremely difficult, if not impossible, to collect and detect all sizes of particles with equal efficiency. The variety of materials that may be encountered in working environments ranges from very small fumes to large dust particles. Thus, a variety of instruments probably will be required to meet all sampling needs. Designing instruments to satisfy specific purposes will also decrease the cost of some individual instruments. Sampling instruments that will not be used in explosive environments do not need to be intrinsically safe so this should not be a general design requirement.

The dependence of collection and detection efficiency on particle size indicates a need for performance standards with respect to particle size. The two criteria normally used with respect to work-place dusts are total dust and respirable dust. The collection and detection of all possible airborne particles with a high efficiency is an unrealistic requirement. The total dust performance requirement must relate to some particle size range. There is valid criticism with respect to any size range that might be selected. However, a size range that should include most insoluble particles of interest with respect to health effects would be particles having aerodynamic diameters ranging from 1 to 20 μm. It should not be unreasonable to require a combined collection and detection efficiency of at least 80% over this size range.

The aerosol mass monitors tested were designed to provide a rapid indication of particle size with little attempt to duplicate the concentrations measured by any compliance sampling method. The fact that these instruments sample much smaller volumes and for shorter times than is typical for compliance determination requires experience to correlate the two measurements, with respect to sampling for different types of dusts. Instruments of this type are still in the development stage. The establishment of rigid performance standards for aerosol mass meters for sampling all forms of airborne dust is unrealistic and would limit development of new instruments. The general construction requirements listed in federal regulations 30CFR29.51 and 30CFR29.52 are reasonable and should be required of instruments. The required accuracy should depend on the material being sampling, the accuracy of other sampling methods, the potential hazard of the material, the need for rapid concentration measurements, and the requirements and costs to provide a safe working environment.

The instruments evaluated in this study represent significant advances in the rapid determination of aerosol mass concentration and considerable potential for accurate assessment of working environments at a reasonable cost. However, the sampling procedures and detection methods are in many cases significantly different from those now used to determine health standards and to determine compliance. Field experience will be required to determine correlations and to develop confidence in the ability of the instruments to provide reasonably accurate measurements of the workers' environment.

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APPENDIX

TABLE A-I

SUMMARY OF MASS-MONITOR PERFORMANCE DATA

Sample Group	Statistic	Filters Conc	Mass Monitor RDM-301 Ratio	RDM-101 Ratio	RAMM #1 Ratio	RAMM #2 Ratio
Coal dust, 1-min						
	Av	2.57	1.33	1.00	0.94	0.93
	Std Dev	0.50	0.65	0.38	0.41	0.40
All	CoV (%)	20	49	38	44	43
	No. Samples	91	59	59	62	80
	Av	1.58	1.42	1.07	0.98	0.97
	Std Dev	0.21	0.69	0.38	0.43	0.42
0-4 mg/m^3	CoV (%)	13	49	36	44	43
	No. Samples	72	47	49	52	63
	Av	6.28	0.90	0.67	0.73	0.81
	Std Dev	1.47	0.18	0.07	0.17	0.30
>4 mg/m^3	CoV (%)	23	20	10	23	37
	No. Samples	19	9	10	10	18
	Av	2.57	1.54	1.06	0.98	0.94
Equal numbers	Std Dev	0.36	0.72	0.42	0.47	0.42
	CoV (%)	14.0	47	40	48	45
	No. Samples	47	37	37	37	37
	Av	1.66	1.75	1.19	1.14	1.07
Samples with	Std Dev	0.18	0.83	0.43	0.48	0.38
filter CoV <20%	CoV (%)	11	47	36	42	35
	No. Samples	27	19	24	24	29
Coal dust, 2 min						
	Av	1.17	1.31	1.06	1.11	1.05
	Std Dev	0.41	0.32	0.30	0.42	0.42
0-4 mg/m^3	CoV (%)	23	24	28	38	40
	No. Samples	55	48	34	39	44
	Av	4.60	1.32	1.06	1.06	1.01
	Std Dev	0.84	0.34	0.30	0.38	0.41
>4 mg/m^3	CoV (%)	18	26	28	36	41
	No. Samples	34	34	34	34	34
	Av	1.98	1.26	1.07	1.23	1.14
Samples with	Std Dev	0.26	0.37	0.32	0.54	0.57
filter CoV <20%	CoV (%)	13	30	30	44	50
	No. Samples	23	20	17	19	14
Coal dust, R/R[a], 1 min						
	Av	2.37	0.90	0.73	0.87	0.79
	Std Dev	0.32	0.49	0.47	0.56	0.32
All	CoV (%)	13	54	64	64	41
	No. Samples	49	16	44	40	20
	Av	2.05	0.90	0.74	0.26	0.79
	Std Dev	0.32	0.49	0.53	0.31	0.32
0-4 mg/m^3	CoV (%)	15	54	69	43	41
	No. Samples	48	16	43	39	20
	Av	2.39	0.90	0.77	0.73	0.79
Samples with	Std Dev	0.32	0.49	0.55	0.32	0.32
filter CoV <20%	CoV (%)	13	54	71	44	41
	No. Samples	24	16	31	22	20

Sample Group	Statistic	Filters Conc	Mass Monitor RDM-301 Ratio	RDM-101 Ratio	RAMM #1 Ratio	RAMM #2 Ratio
Coal dust, R/R, 2 min						
	Av	1.93	1.90	1.04	0.92	1.35
	Std Dev	0.23	1.09	0.5	0.45	0.50
All	CoV (%)	12	57	34	49	37
	No. Samples	26	7	12	16	10
	Av	2.00	1.15	1.07	0.94	1.27
Sample with	Std Dev	0.23	0.51	0.30	0.40	0.26
filter CoV <20%	CoV (%)	11	45	28	42	20
	No. Samples	19	4	17	13	6
Coal dust, R/T[b], 1 min						
	Av	4.48	0.42	0.40	0.31	0.32
	Std Dev	0.84	0.19	0.44	0.18	0.12
All	CoV (%)	19	44	110	59	57
	No. Samples	32	23	29	27	27
	Av	3.60	0.56	0.42	0.45	0.50
Samples with	Std Dev	0.40	0.11	0.25	0.24	0.25
filter CoV <20%	CoV (%)	11	19	61	53	50
	No. Samples	6	5	7	7	5
Coal dust R/T, 2 min						
	Av	2.54	1.48	0.59	0.52	0.68
	Std Dev	0.65	0.32	0.16	0.27	0.26
All	CoV (%)	25	22	27	52	38
	No. Samples	13	3	12	5	8
	Av	2.09	1.42	0.60	0.95	0.70
Samples with	Std Dev	0.25	0.32	0.17	---	0.34
filter CoV <20%	CoV (%)	12	32	28	---	48
	No. Samples	6	3	6	1	5
Fiber glass, 1 min						
	Av	1.09	1.14	0.94	1.18	1.15
	Std Dev	0.27	0.50	0.33	0.25	0.31
All	CoV (%)	25	44	35	21	27
	No. Samples	48	46	46	34	33
	Av	1.09	1.16	0.92	1.23	1.19
	Std Dev	0.28	0.52	0.25	0.22	0.29
Equal number	CoV (%)	25	45	27	18	24
of samples	No. Samples	30	30	30	30	30
	Av	1.25	1.06	0.92	1.20	1.19
Samples with	Std Dev	0.14	0.39	0.29	0.21	0.24
filter CoV < 20%	CoV (%)	11	37	31	18	20
	No. Samples	14	23	23	17	16
Fiber glass, 2 min						
	Av	1.12	1.46	1.01	1.17	1.10
	Std Dev	0.21	0.41	0.40	0.24	0.21
All samples	CoV (%)	19	38	40	21	19
	No. Samples	30	29	24	24	24
	Av	1.35	1.29	0.80	1.25	1.18
	Std Dev	0.21	0.38	0.12	0.22	0.18
Equal number	CoV (%)	16	29	15	18	15
	No. Samples	18	18	18	18	18

Sample Group	Statistic	Filters Conc	Mass Monitor RDM-301 Ratio	RDM-101 Ratio	RAMM #1 Ratio	RAMM #2 Ratio
	Av	1.28	1.37	0.97	1.13	1.12
Samples with filter CoV <20%	Std Dev	0.16	0.38	0.34	0.21	0.22
	CoV (%)	13	28	35	19	19
	No. Samples	23	21	19	17	21
Welding fume, 1 min						
	Av	15.06	0.13	0.10	0.99	1.04
	Std Dev	16.94	0.25	0.11	0.72	0.84
All	CoV (%)	113	192	110	73	78
	No. Samples	41	25	29	34	35
	Av	14.62	0.07	0.05	1.10	1.26
	Std Dev	13.56	0.07	0.05	0.77	0.84
Equal number	CoV (%)	93	100	100	70	67
	No. Samples	23	22	22	22	22
	Av	25.69	0.13	0.08	1.04	0.92
>4 mg/m^3	Std Dev	16.94	0.27	0.11	0.79	0.66
	CoV (%)	66	208	138	76	72
	No. Samples	32	21	27	24	26
	Av	14.21	0.08	0.09	1.23	1.40
Sample with filter CoV <20%	Std Dev	1.30	0.07	0.08	0.64	0.70
	CoV (%)	9	82	90	52	50
	No. Samples	24	17	19	24	23
Decay curve	Av	---	0.09	0.09	1.14	1.31
y=1.8 -0.10 log x	Std Dev	---	0.07	0.09	0.45	0.59
r=0.98	CoV (%)	---	85	100	39	45
y, conc, mg/m^3	No. Samples	21	13	14	19	18
x, time, min	Range	2.0 - 25.0				
Arc-welding fume, 2 min						
	Av	0.56	0.27	0.24	0.84	0.88
	Std Dev	0.20	0.33	0.71	0.45	0.47
All	CoV (%)	36	122	296	54	53
	No. Samples	23	21	22	23	23
	Av	0.64	0.18	0.10	0.84	0.97
Samples with filter CoV <20%	Std Dev	0.15	0.26	0.10	0.49	0.55
	CoV (%)	24	143	99	58	57
	No. Samples	16	7	8	8	8
Decay curve	Av	---	0.18	0.11	0.80	0.94
y=1.8 -0.10 log x	Std Dev	---	0.26	0.10	0.51	0.59
r=0.98 n=21	CoV (%)	---	140	89	64	63
y, conc, mg/m^3	No. Samples	7	7	7	7	7
x, time, min	Range	0.08 - 2.0				
Silica dust, 1 min						
	Av	5.03	---	0.72	0.89	0.76
	Std Dev	1.22	---	0.27	0.72	0.50
All	CoV (%)	24	---	38	81	66
	No. Samples	42	---	42	41	41
	Av	2.24	---	0.89	0.75	0.71
	Std Dev	0.36	---	0.28	0.31	0.26
<4 mg/m^3	CoV (%)	16	---	31	41	37
	No. Samples	18	---	18	18	18
	Av	7.11	---	0.60	1.00	0.81
	Std Dev	1.88	---	0.17	0.91	0.63
>4 mg/m^3	CoV (%)	26	---	28	91	78
	No. Samples	24	---	23	23	23

Sample Group	Statistic	Filters Conc	Mass Monitor RDM-301 Ratio	RDM-101 Ratio	RAMM #1 Ratio	RAMM #2 Ratio
	Av	3.08	---	0.93	0.81	0.77
Samples with filter CoV <20%	Std Dev	0.21	---	0.23	0.24	0.18
	CoV (%)	7	---	25	30	23
	No. Samples	22	---	18	18	18
Silica dust, 2 min						
	Av	2.86	---	0.77	0.97	0.85
	Std Dev	0.56	---	0.77	0.97	0.85
All	CoV (%)	20	---	14	26	24
	No. Samples	17	---	16	17	17
	Av	2.42	---	0.75	1.01	0.87
Samples with filter CoV <20%	Std Dev	0.24	---	0.07	0.22	0.18
	CoV (%)	10	---	9	22	21
	No. Samples	6	---	6	6	6
Oil shale, 1 min						
	Av	5.07	0.80	0.52	0.19	0.22
	Std Dev	4.04	0.52	0.40	0.17	0.13
All	CoV (%)	80	65	77	89	59
	No. Samples	5	5	22	21	22
P-DOP, 1 min						
	Av	2.02	0.50	0.30	1.21	1.09
	Std Dev	0.45	0.38	0.23	0.41	0.42
All	CoV (%)	22	76	77	34	39
	No. Samples	48	45	44	48	48
	Av	2.02	0.49	0.29	1.22	1.10
	Std Dev	0.47	0.37	0.23	0.39	0.40
Equal number	CoV (%)	23	76	78	32	36
	No. Samples	45	43	43	43	43
	Av	2.24	0.44	0.33	1.30	1.18
Samples with filter CoV <20%	Std Dev	0.20	0.25	0.20	0.56	0.56
	CoV (%)	9	56	61	43	48
	No. Samples	21	19	18	20	20
P-DOP, 2 min						
	Av	1.41	0.26	0.13	1.35	1.15
	Std Dev	0.45	0.10	0.15	0.85	0.82
All	CoV (%)	32	38	115	63	71
	No. Samples	12	11	11	12	12
T-DOP, 1 min						
	Av	26.34	0.04	0.06	0.92	0.83
	Std Dev	2.62	0.03	0.05	0.51	0.49
All	CoV (%)	10	75	83	55	59
	No. Samples	18	7	5	17	17
	Av	42.81	---	---	1.05	0.70
Samples with filter CoV <20%	Std Dev	3.46	---	---	0.53	0.57
	CoV (%)	8	---	---	51	63
	No. Samples	12	---	---	8	8
T-DOP, 2 min						
	Av	0.93	0.04	0.02	0.51	0.46
	Std Dev	0.38	0.05	0.02	0.32	0.29
All	CoV (%)	40	125	100	63	63
	No. Samples	9	9	9	10	10

Sample Group	Statistic	Filters Conc	Mass Monitor RDM-301 Ratio	RDM-101 Ratio	RAMM #1 Ratio	RAMM #2 Ratio
PSL 0.79 μm, 1 min						
All	Av	1.48	0.16	0.07	0.95	0.86
	Std Dev	0.23	0.16	0.06	0.38	0.36
	CoV (%)	16	97	79	40	41
	No. Samples	24	23	23	24	24
Samples with filter CoV <20%	Av	1.54	0.16	0.06	0.82	0.74
	Std Dev	0.19	0.16	0.06	0.27	0.26
	CoV (%)	12	100	95	33	35
	No. Samples	19	18	18	19	19
PSL 0.79 μm, 2 min						
All	Av	1.50	0.07	0.06	0.82	0.67
	Std Dev	0.20	0.04	0.10	0.20	0.10
	CoV (%)	13	51	160	25	15
	No. Samples	12	11	12	12	12
Samples with filter CoV <20%	Av	1.51	0.07	0.04	0.88	0.69
	Std Dev	0.14	0.04	0.07	0.19	0.10
	CoV (%)	9	56	170	21	15
	No. Samples	9	9	9	9	9
PSL 1.01 μm, 1 min						
All	Av	1.50	0.37	0.16	0.89	0.84
	Std Dev	0.34	0.17	0.13	0.17	0.20
	CoV (%)	23	46	82	19	24
	No. Samples	24	23	24	23	22
Samples with filter CoV <20%	Av	1.57	0.40	0.17	0.88	0.82
	Std Dev	0.14	0.18	0.15	0.17	0.21
	CoV (%)	9	45	91	20	25
	No. Samples	14	13	14	13	13
PSL 1.01 μm, 2 min						
All	Av	1.62	0.33	0.27	0.85	0.87
	Std Dev	0.15	0.07	0.10	0.17	0.16
	CoV (%)	9	21	37	20	19
	No. Samples	12	11	10	12	12
Samples with filter CoV < 20%	Av	1.66	0.32	0.28	0.86	0.90
	Std Dev	0.19	0.06	0.11	0.19	0.17
	CoV (%)	12	19	38	22	19
	No. Samples	10	9	8	10	10
PSL 2.02, μm, 1 min						
All	Av	1.10	1.33	0.82	0.56	0.55
	Std Dev	0.35	0.52	0.51	0.27	0.34
	CoV (%)	32	39	62	49	63
	No. Samples	36	33	35	34	34
Samples with Filter CoV < 20%	Av	1.01	1.51	0.91	0.55	0.51
	Std Dev	0.17	0.36	0.27	0.26	0.19
	CoV (%)	17	24	30	47	37
	No. Samples	13	13	13	11	11
PSL 2.02, μm, 2 min						
All	Av	0.80	1.66	1.12	1.05	0.94
	Std Dev	0.22	0.49	0.29	0.24	0.22
	CoV (%)	28	29	25	23	24
	No. Samples	18	17	18	18	18

Sample Group	Statistic	Filters Conc	Mass Monitor RDM-301 Ratio	RDM-101 Ratio	RAMM #1 Ratio	RAMM #2 Ratio
Eosin-Y, 1.0 μm, 20 min						
	Av	0.05	---	0.83	0.74	0.66
	Std Dev	0.02	---	0.62	0.27	0.22
All	CoV (%)	30	---	74	36	33
	No. Samples	10	---	10	10	10
	Av	0.06	---	0.58	0.84	0.80
Samples with	Std Dev	0.01	---	0.62	0.14	0.13
filter CoV <20%	CoV (%)	17	---	107	16	17
	No. Samples	4	---	4	4	4
Eosin-Y, 1.5 μm, 20 min						
	Av	0.11	---	1.76	0.51	0.47
	Std Dev	0.02	---	0.44	0.23	0.20
All	CoV (%)	22	---	25	45	42
	No. Samples	9	---	9	9	9
	Av	0.12	---	1.49	0.51	0.50
Samples with	Std Dev	0.02	---	0.11	0.15	0.15
filter CoV <20%	CoV (%)	15	---	8	29	30
	No. Samples	6	---	6	6	6
Eosin-Y, 3.7 μm, 10 min						
	Av	0.06	3.52	2.24	0.47	0.19
	Std Dev	0.04	2.46	1.65	0.82	0.07
All	CoV (%)	63	70	74	174	37
	No. Samples	9	8	8	8	8
Eosin-Y, 5.6 μm, 10 min						
	Av	0.07	1.63	2.31	0.20	0.15
	Std Dev	0.05	1.09	4.12	0.06	0.05
All	CoV (%)	70	67	178	28	35
	No. Samples	13	13	14	4	14

[a]R/R: Respirable concentration by mass monitor/respirable concentration by personal samplers; C_{IR}/C_{GR}.

[b]R/T: Respirable concentration by mass monitor/total-dust gravimetric concentration; C_{IR}/C_{G}.

TABLE A-II

STATISTICAL ANALYSIS SUMMARY

Aerosol Sample Time	AOV[a]	Ranking by Mean Concentration (mg/m^3), and FLSD Grouping [b]				
Coal dust 1 min	SD	RAMM #2 2.00	RAMM #1 2.13	RDM-101 2.16	Filters 2.57	RDM-301 2.95
Coal dust 2 min	NSD	RDM-101 1.61	RAMM #1 1.73	RAMM #2 1.86	Filters 1.91	RDM-301 2.27
Coal dust R/R[c] 1 min	NSD	RDM-101 1.89	RAMM #1 2.15	Filters 2.37		
Coal dust R/R 2 min	NSD	RDM-101 1.70	RAMM #1 1.75	Filters 1.93		
Fiber glass 1 min	SD	RDM-101 1.00	Filters 1.09	RAMM #2 1.22	RAMM #1 1.25	RDM-301 1.26
Fiber glass 2 min	SD	RDM-101 1.04	RAMM #2 1.10	Filters 1.12	RAMM #1 1.17	RDM-301 1.70
Arc-weld fume 1 min	SD	RDM-101 0.65	RDM-301 0.70	RAMM #1 11.64	Filters 15.06	RAMM #2 15.89
Arc-weld fume 2 min	SD	RDM-101 0.028	RDM-301 0.065	RAMM #1 0.42	RAMM #2 0.45	Filters 0.56
Silica dust 1 min	NSD	RDM-101 3.03	RAMM #2 4.07	Filters 5.03	RAMM #1 5.08	
Silica dust 2 min	SD	RDM-101 2.22	RAMM #1 2.73	RAMM #2 2.74	Filters 2.86	
Oil shale 1 min	SD	RAMM #2 1.23	RAMM #1 1.26	RDM-101 2.24	Filters 5.07	
Oil shale 2 min	SD	RAMM #2 0.77	RAMM #1 0.79	RDM-101 2.02	Filters 2.92	
P-DOP 1 min	SD	RDM-101 0.46	RDM-301 0.73	Filters 2.02	RAMM #2 2.33	RAMM #1 2.58
P-DOP 2 min	SD	RDM-101 0.15	RDM-301 0.38	Filters 1.41	RAMM #2 1.69	RAMM #1 2.09
T-DOP 1 min	SD	RDM-101 0.071	RDM-301 0.088	RAMM #2 16.34	RAMM #1 20.87	Filters 26.34
T-DOP 2 min	SD	RDM-101 0.02	RDM-301 0.03	RAMM #2 0.36	RAMM #1 0.48	Filters 0.93
PSL, 0.79 μm 1 min	SD	RDM-101 0.10	RDM-301 0.23	RAMM #2 1.25	RAMM #1 1.39	Filters 1.48
PSL, 0.79 μm 2 min	SD	RDM-101 0.05	RDM-301 0.10	RAMM #2 1.01	RAMM #1 1.25	Filters 1.50
PSL, 1.01 μm 1 min	SD	RDM-101 0.23	RDM-301 0.50	RAMM #2 1.22	RAMM #1 1.30	Filters 1.50
PSL, 1.01 μm 2 min	SD	RDM-101 0.43	RDM-301 0.56	RAMM #1 1.35	RAMM #2 1.45	Filters 1.62

PSL, 2.02 μm		RAMM #2	RAMM #1	RDM-101	Filters	RDM-301
1 min	SD	0.58	0.60	0.83	1.10	1.36
PSL, 2.02 μm		RAMM #2	Filters	RAMM #1	RDM-101	RDM-301
2 min	SD	0.75	0.80	0.83	0.86	1.26
Eosin-Y, 1.0 μm		RAMM #2	RAMM #2	RDM-101	Filters	
20 min	NSD	0.04	0.04	0.05	0.05	
Eosin-Y, 1.5 μm		RAMM #2	RAMM #1	Filters	RDM-101	
20 min	SD	0.05	0.06	0.11	0.19	
Eosin-Y, 3.7 μm		RAMM #2	RAMM #1	Filters	RDM-101	RDM-301
10 min	SD	0.01	0.03	0.06	0.17	0.19
Eosin-Y, 5.6 μm		RAMM #1	Filters	RDM-101	RDM-301	
10 min	SD	0.01	0.07	0.08	0.12	

[a]NSD = AOV indicated no significant difference at the 95% confidence level determined by filters and all mass monitors. SD = a significant difference probably exists between concentrations determined by filters and all mass monitors.

[b]Concentrations and monitors underlined are those which are not significantly different by FLSD analysis.

[c]R/R: Respirable concentration by mass monitor/respirable concentration by personal samplers.

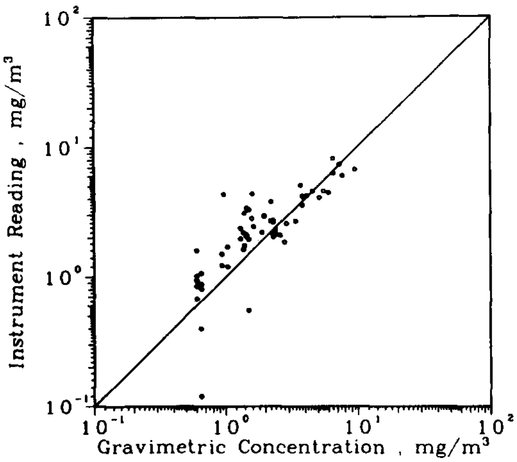

Fig. A-1.
RDM-301 measurement of coal dust, 1-min samples. Regression equations are $C_I = 0.77\,C_G + 0.83$, $r = 0.89$, $n = 58$ for all data; $C_I = 0.82\,C_G + 0.79$, $r = 0.69$, $n = 49$ for $C_G \leq 4$ mg/m³.

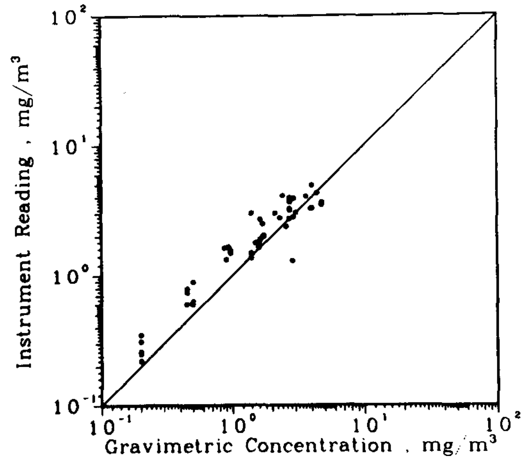

Fig. A-2.
RDM-301 measurement of coal dust, 2-min samples. Regression equations are $C_I = 0.89\,C_G + 0.53$, $r = 0.88$, $n = 51$ for all data; $C_I = 1.04\,C_G + 0.33$, $r = 0.89$, $n = 34$ for $C_G \leq 4$ mg/m³.

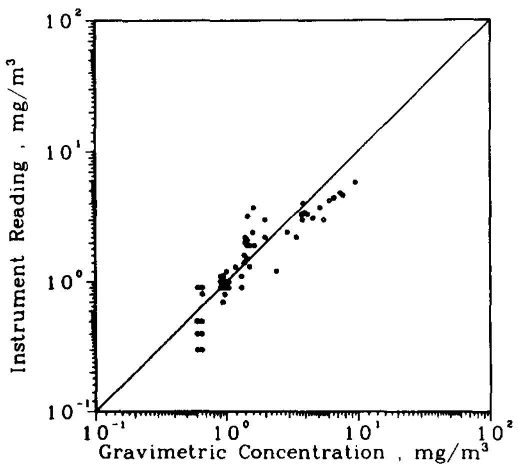

Fig. A-3.
RDM-101 measurement of coal dust, 1-min samples. Regression equations are $C_I = 0.58\,C_G + 0.64$, $r = 0.91$, $n = 59$ for all data; $C_I = 0.85\,C_G + 0.30$, $r = 0.81$, $n = 49$ for $C_G \leq 4.0$ mg/m³.

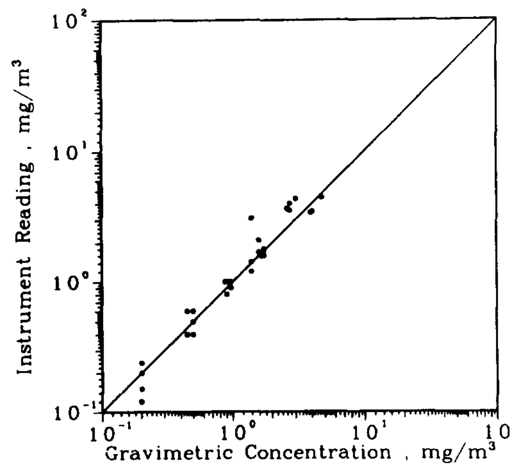

Fig. A-4.
RDM-101 measurement of coal dust, 2-min samples. Regression equation is $C_I = 1.06\,C_G + 0.07$, $r = 0.93$, $n = 34$ for all data.

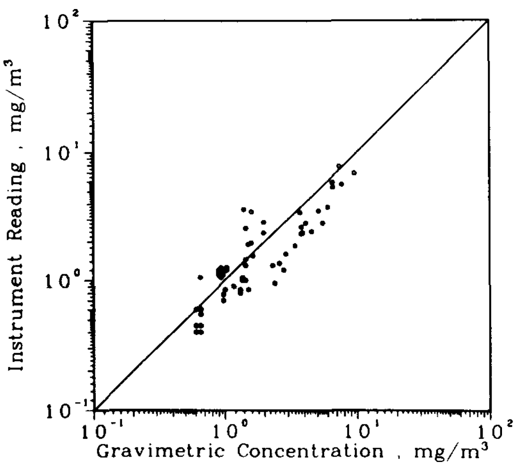

Fig. A-5.

RAMM #1 measurement of coal dust, 1-min samples. Regression equations are $C_I = 0.69\ C_G + 0.32$, $r = 0.89$, $n = 61$ for all data; $C_I = 0.54\ C_G + 0.55$, $r = 0.62$, $n = 52$ for $C_G \leq 4.0\ mg/m^3$.

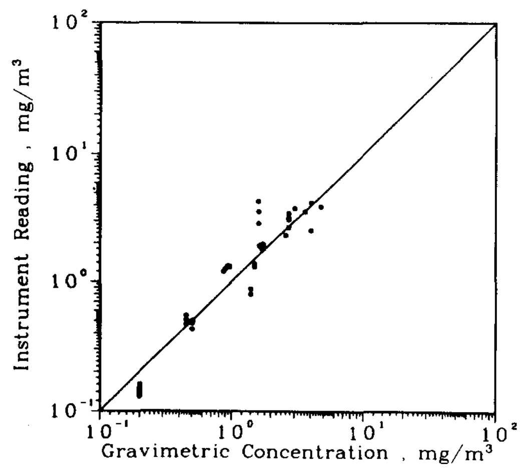

Fig. A-6.

RAMM #1 measurement of coal dust, 2-min samples. Regression equation is $C_I = 0.94\ C_G + 0.27$, $r = 0.85$, $n = 40$ for all data.

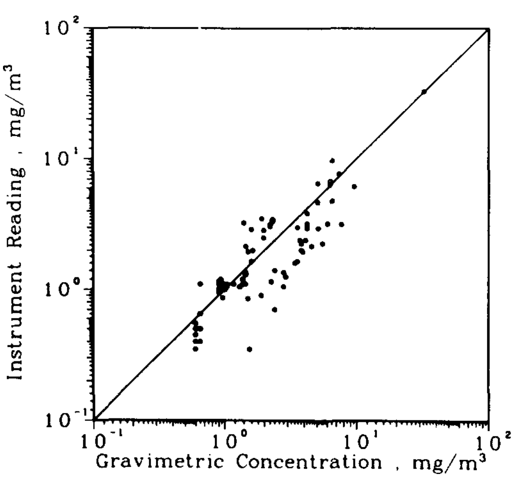

Fig. A-7.

RAMM #2 measurement of coal dust, 1-min samples. Regression equations are $C_I = 0.94\ C_G - 0.20$, $r = 0.95$, $n = 81$ for all data; $C_I = 0.54\ C_G + 0.62$, $r = 0.57$, $n = 62$ for $C_G \leq 4.0\ mg/m^3$.

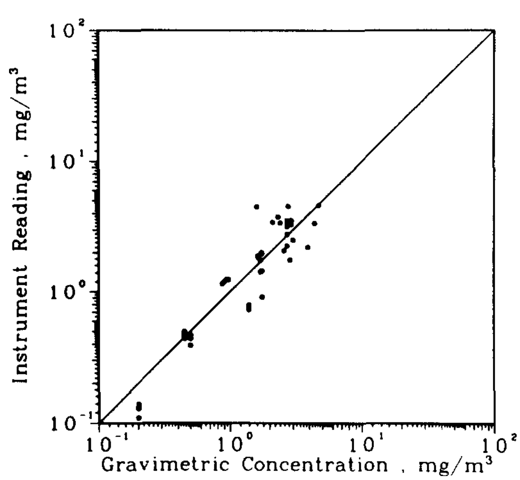

Fig. A-8.

RAMM #2 measurement of coal dust, 2-min samples. Regression equation is $C_I = 0.97\ C_G + 0.24$, $r = 0.77$, $n = 46$ for all data.

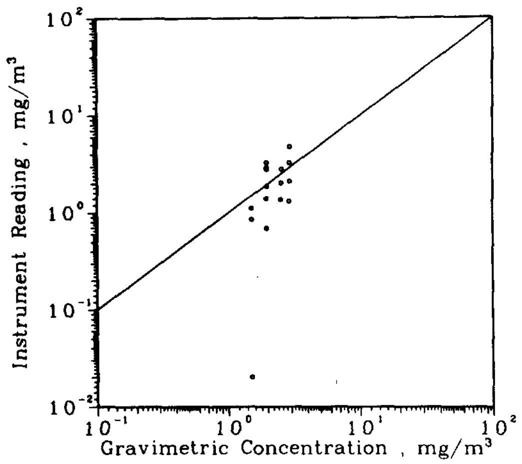

Fig. A-9.

RDM-301 measurement of respirable concentration vs gravimetric respirable concentration, 1-min samples.

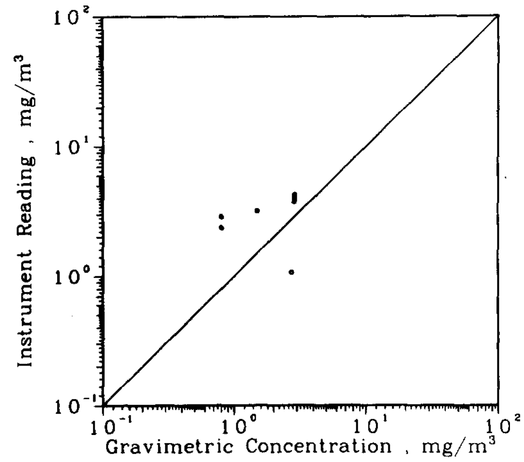

Fig. A-10.

RDM-301 measurement of respirable concentration vs gravimetric respirable concentration, 2-min samples.

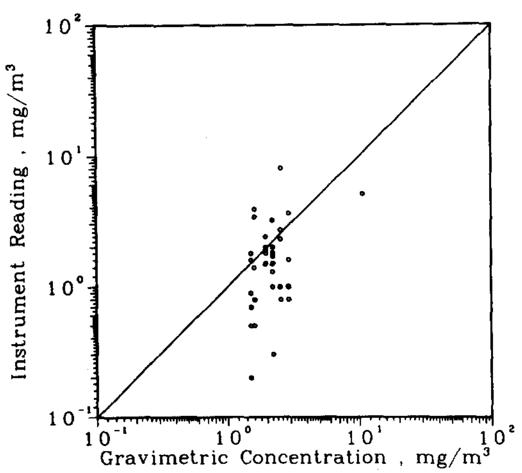

Fig. A-11.

RDM-101 measurement of respirable concentration vs gravimetric respirable concentration, 1-min samples.

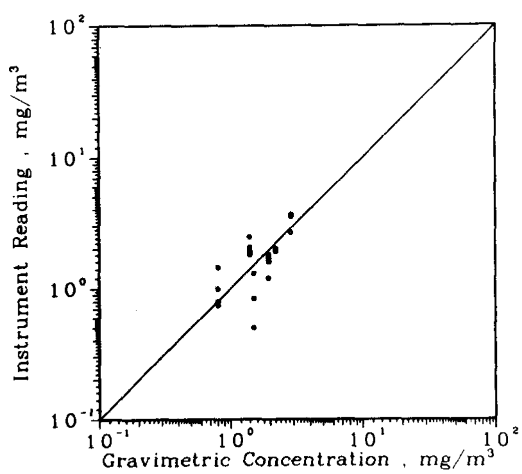

Fig. A-12.

RDM-101 measurement of respirable concentration vs gravimetric respirable concentration, 2-min samples.

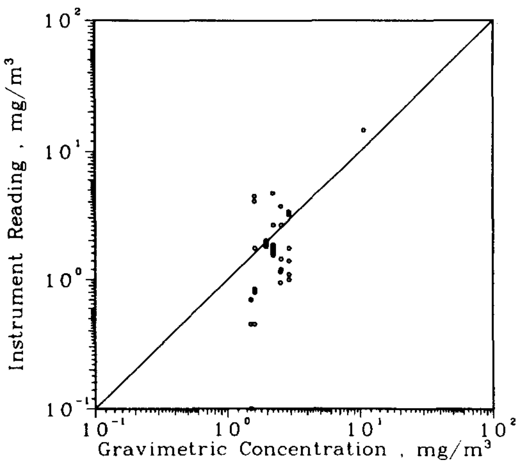

Fig. A-13.
RAMM #1 measurement of respirable concentration vs gravimetric concentration, 1-min samples.

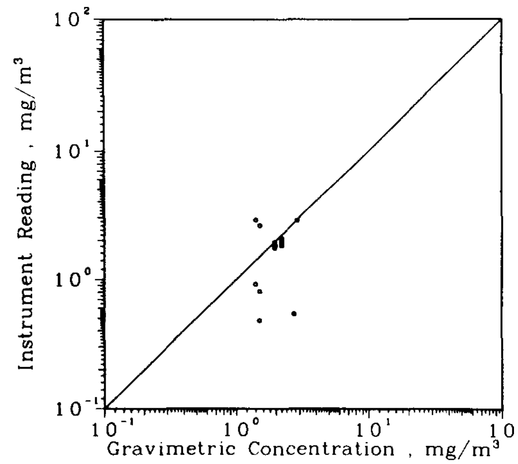

Fig. A-14.
RAMM #1 measurement of respirable concentration vs gravimetric concentration, 2-min samples.

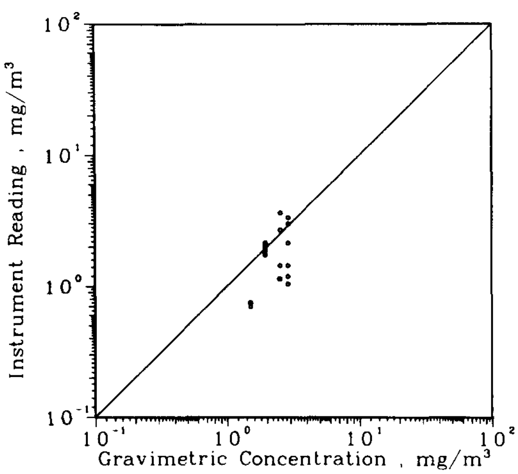

Fig. A-15.
RAMM #2 measurement of respirable concentration vs gravimetric concentration, 1-min samples.

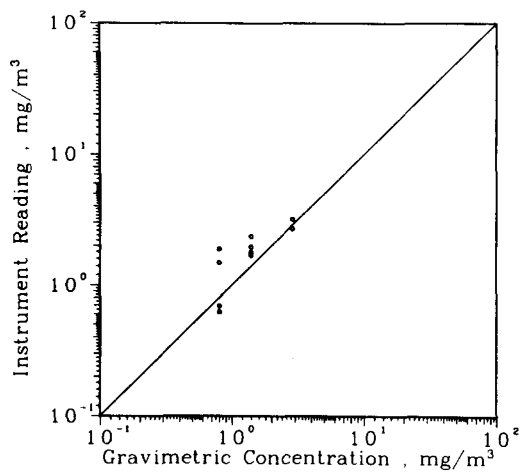

Fig. A-16.
RAMM #2 measurement of respirable concentration vs gravimetric concentration, 2-min samples.

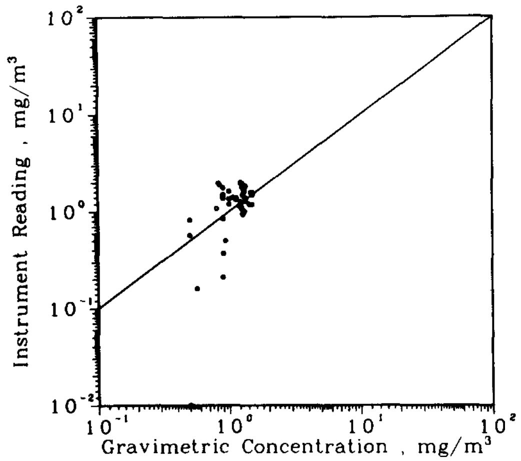

Fig. A-17.
RDM-301 measurement of fiber glass, 1-min samples.

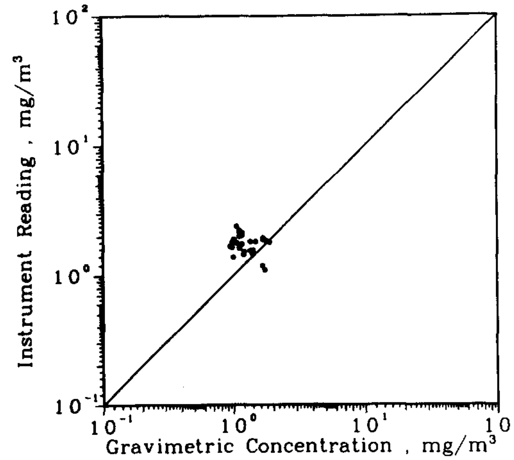

Fig. A-18.
RDM-301 measurement of fiber glass, 2-min samples.

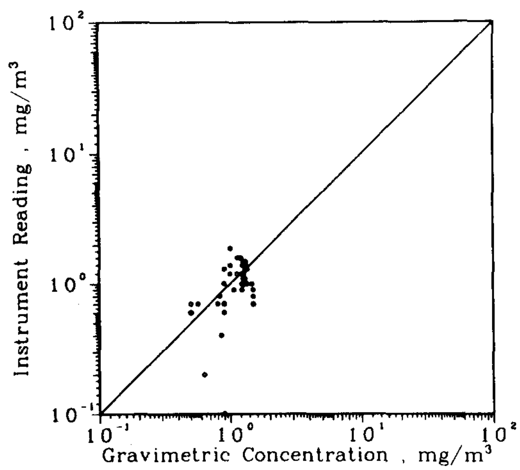

Fig. A-19.
RDM-101 measurement of fiber glass, 1-min samples.

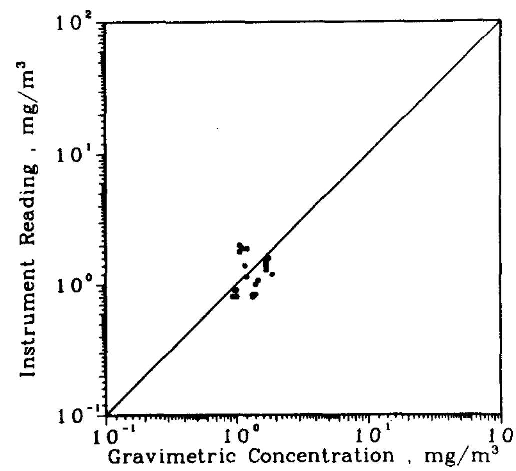

Fig. A-20.
RDM-101 measurement of fiber glass, 2-min samples.

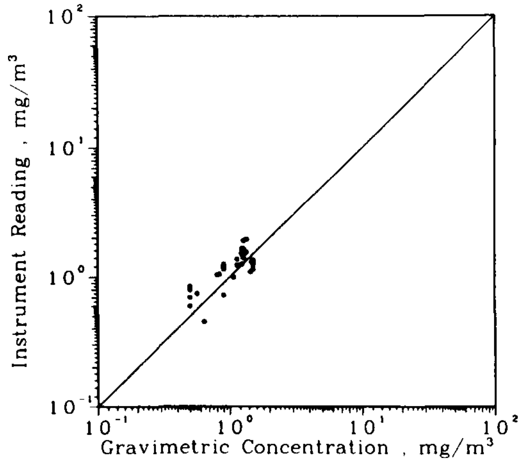

Fig. A-21.
RAMM #1 measurement of fiber glass, 1-min samples.

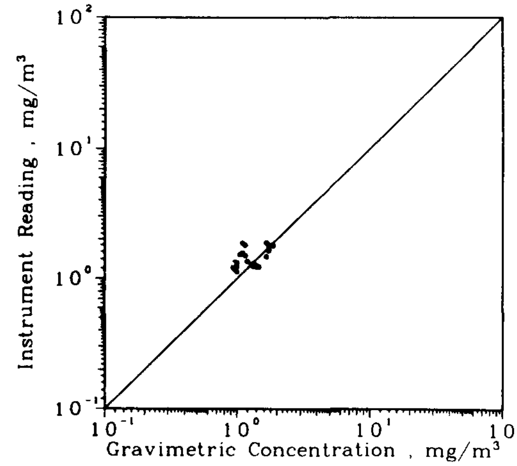

Fig. A-22.
RAMM #1 measurement of fiber glass, 2-min samples.

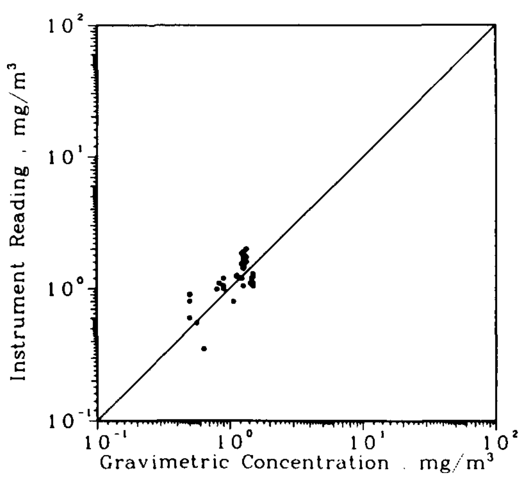

Fig. A-23.
RAMM #2 measurement of fiber glass, 1-min samples.

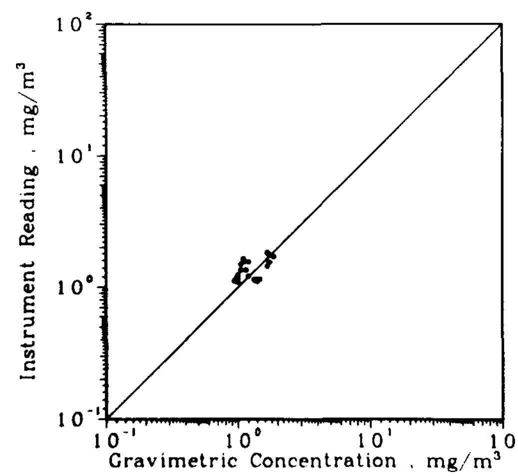

Fig. A-24.
RAMM #2 measurement of fiber glass, 2-min samples.

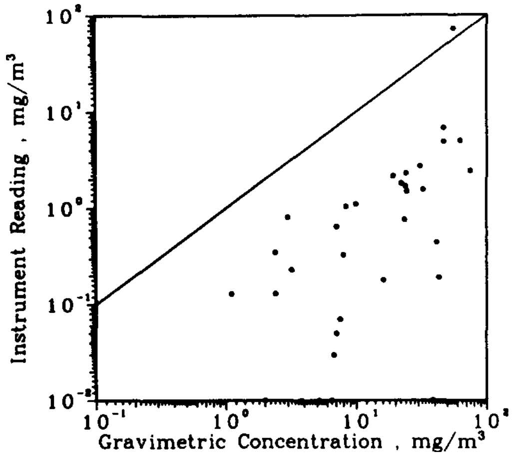

Fig. A-25.
RDM-301 measurement of arc-welding fume, 1-min samples. Regression equation is $C_I = 0.31 C_G - 5.24$, $r = 0.87$, $n = 34$.

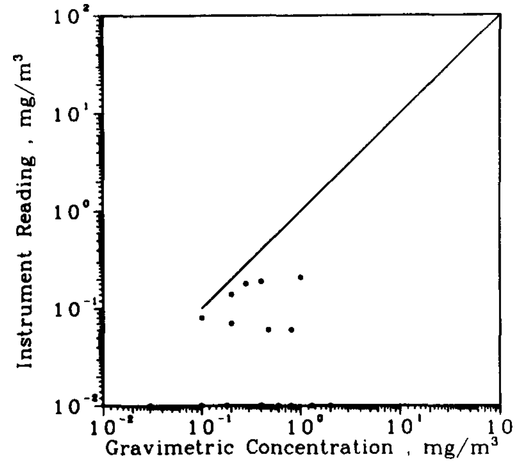

Fig. A-26.
RDM-301 measurement of arc-welding fume, 2-min samples.

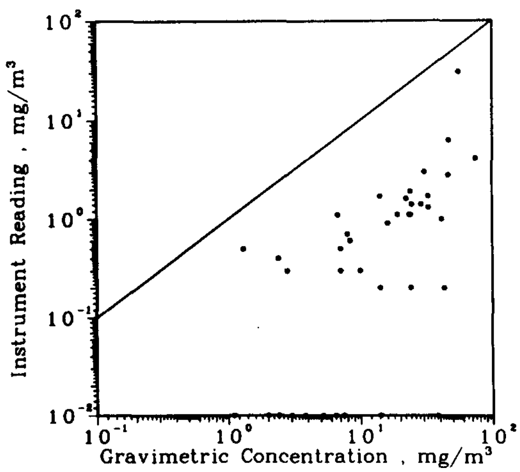

Fig. A-27.
RDM-101 measurement of arc-welding fume, 1-min samples. Regression equation is $C_I = 0.14 C_G - 1.03$, $r = 0.49$, $n = 39$.

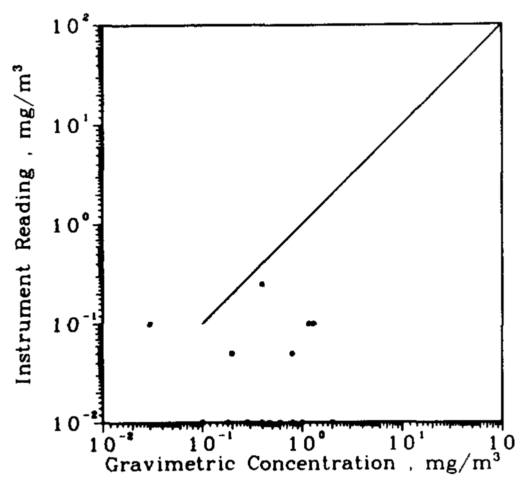

Fig. A-28.
RDM-101 measurement of arc-welding fume, 2-min samples.

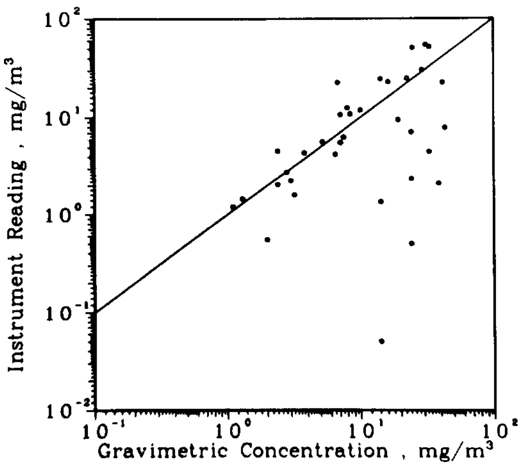

Fig. A-29.
RAMM #1 measurement of arc-welding fume, 1-min samples. Regression equation is $C_I = 0.51\ C_G + 5.44$, $r = 0.44$, $n = 35$.

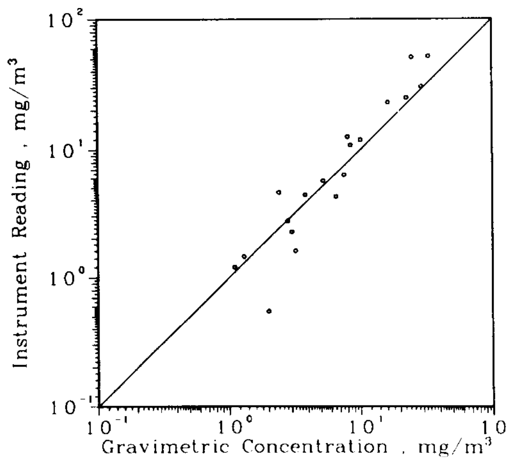

Fig. A-30.
RAMM #1 measurement of arc-welding fume, 1-min samples. Gravimetric concentration obtained from regression analysis of logarithmic decay of static aerosol concentration. Regression equation is $C_I = 1.51\ C_G - 1.91$, $r = 0.94$, $n = 19$.

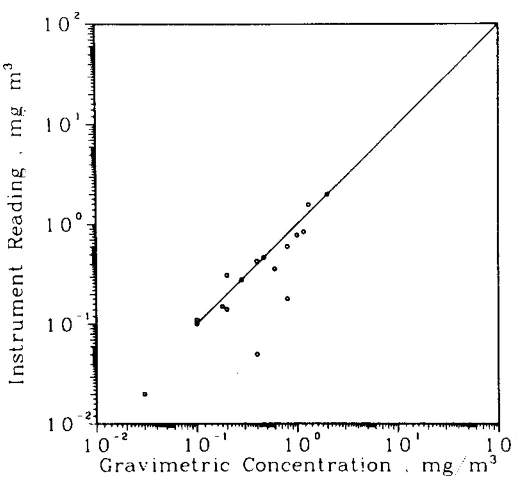

Fig. A-31.
RAMM #1 measurement of arc-welding fume, 2-min samples. Regression equation is $C_I = 0.90\ C_G - 0.05$, $r = 0.82$, $n = 23$.

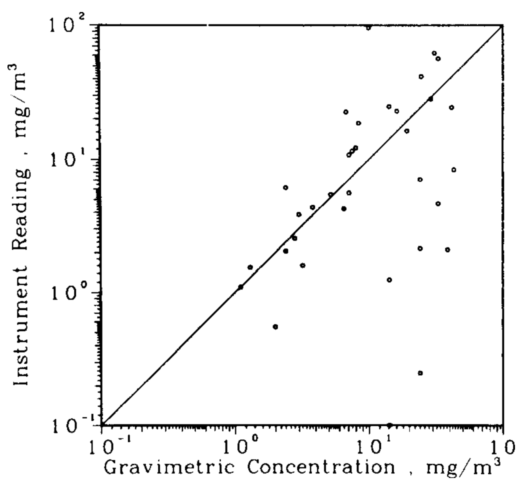

Fig. A-32.
RAMM #2 measurement of arc-welding fume, 1-min samples. Regression equation is $C_I = 0.27\ C_G + 10.39$, $r = 0.20$, $n = 35$.

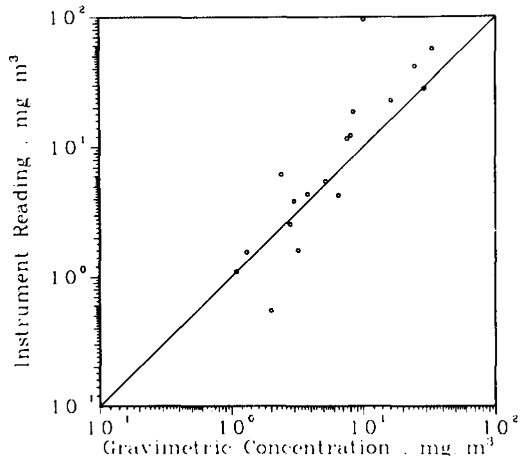

Fig. A-33.
RAMM #2 measurement of arc-welding fume, 1-min samples. Gravimetric concentration obtained from regression analysis of logarithmic decay of static aerosol concentration. Regression equation is $C_I = 1.51\ C_G - 0.58$, $r = 0.95$, $n = 18$ for all data.

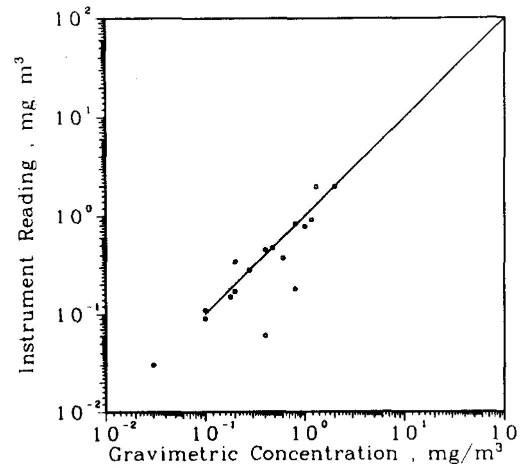

Fig. A-34.
RAMM #2 measurement of arc-welding fume, 2-min samples. Regression equation is $C_I = 0.93\ C_G - 0.05$, $r = 0.86$, $n = 23$.

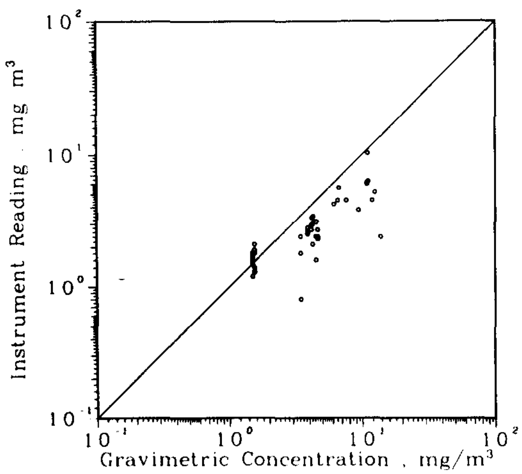

Fig. A-35.
RDM-101 measurement of silica dust, 1-min samples. Regression equation is $C_I = 0.40 + 1.03$, $r = 0.76$, $n = 42$.

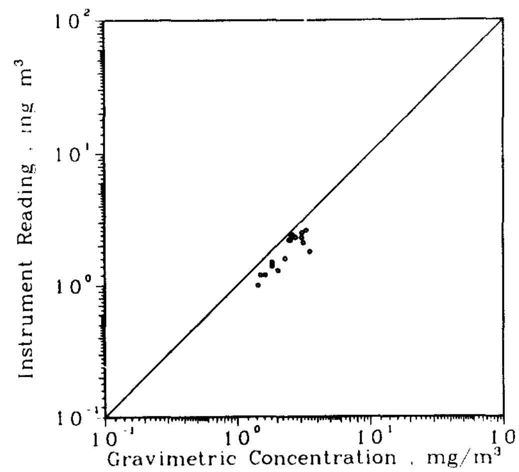

Fig. A-36.
RDM-101 measurement of silica dust, 2-min samples. Regression equation is $C_I = 0.66\ C_G + 0.27$, $r = 0.82$, $n = 17$.

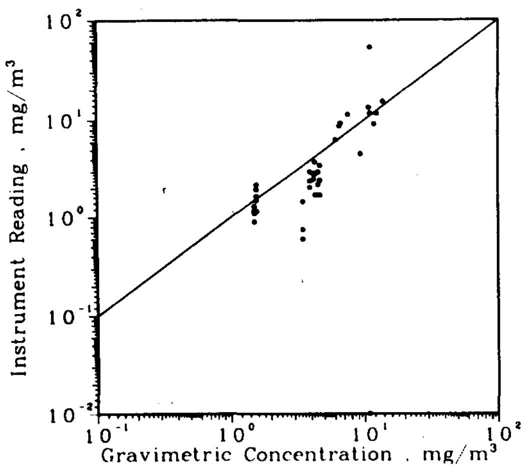

Fig. A-37.
RAMM #1 measurement of silica dust, 1-min samples. Regression equation is $C_I = 1.05\ C_G - 1.08$, $r = 0.59$, $n = 42$.

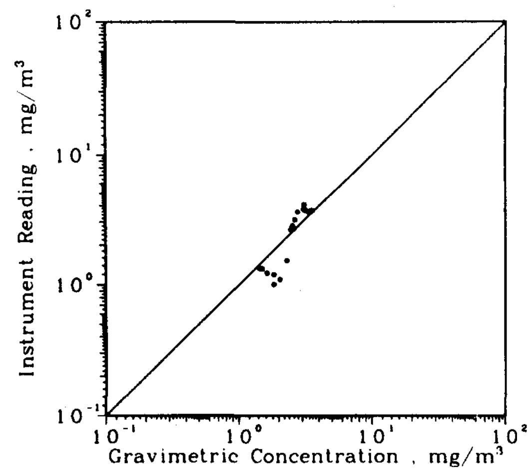

Fig. A-38.
RAMM #1 measurement of silica dust, 2-min samples. Regression equation is $C_I = 1.6\ C_G - 1.44$, $r = 0.93$, $n = 17$.

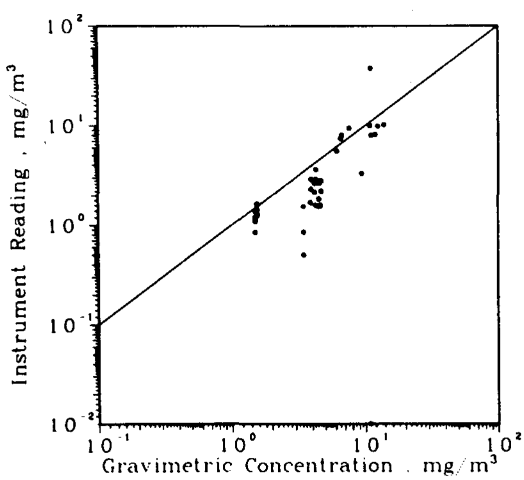

Fig. A-39.
RAMM #2 measurement of silica dust, 1-min samples. Regression equation is $C_I = 1.62\ C_G - 2.73$, $r = 0.65$, $n = 41$.

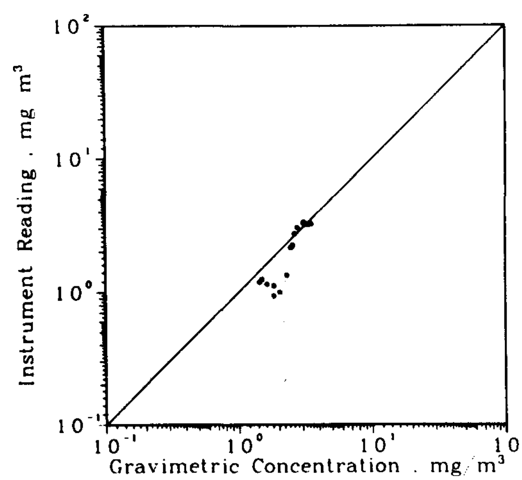

Fig. A-40.
RAMM #2 measurement of silica dust, 2-min samples. Regression equation is $C_I = 1.35\ C_G - 1.16$, $r = 0.93$, $n = 17$.

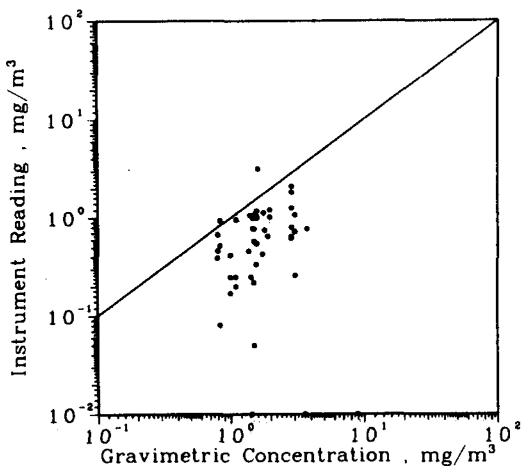

Fig. A-41.
RDM-301 measurement of polydisperse DOP, 1-min samples.

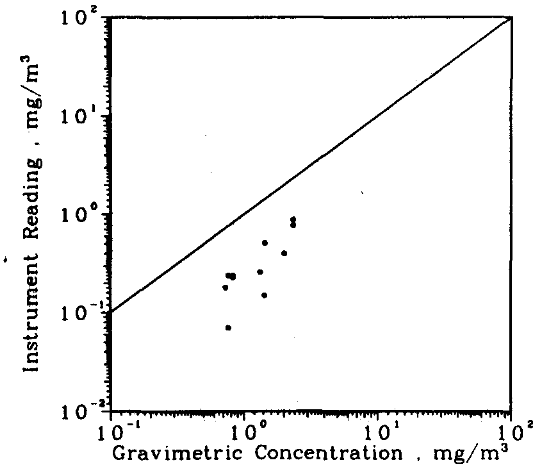

Fig. A-42.
RDM-301 measurement of polydisperse DOP, 2-min samples.

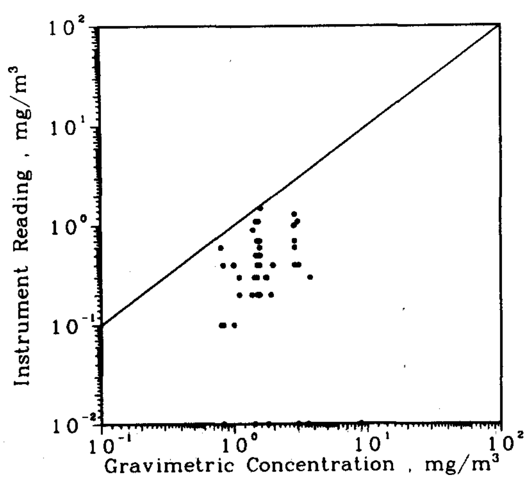

Fig. A-43.
RDM-101 measurement of polydisperse DOP, 1-min samples.

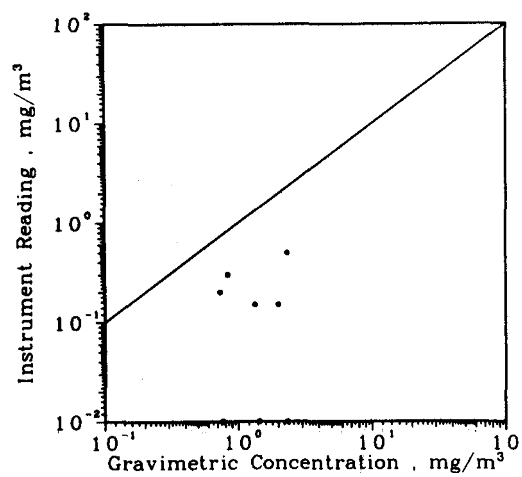

Fig. A-44.
RDM-101 measurement of polydisperse DOP, 2-min samples.

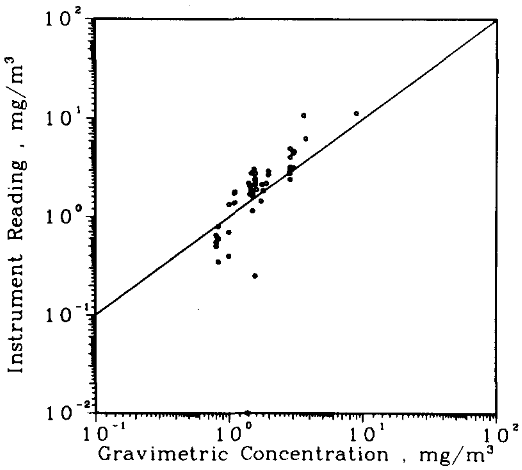

Fig. A-45.
RAMM #1 measurement of polydisperse DOP, 1-min samples. Regression equation is C_I = 1.41 C_G - 0.29, r = 0.95, n = 48.

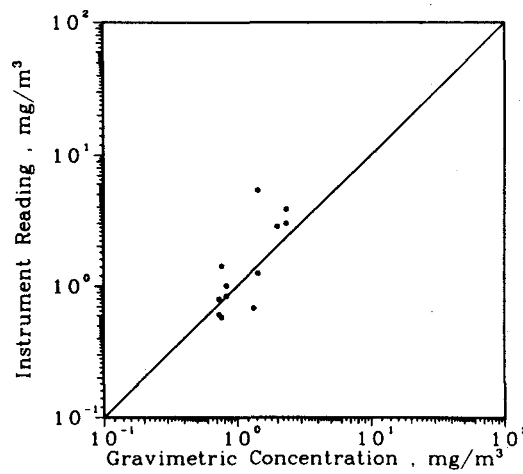

Fig. A-46.
RAMM #1 measurement of polydisperse DOP, 2-min samples.

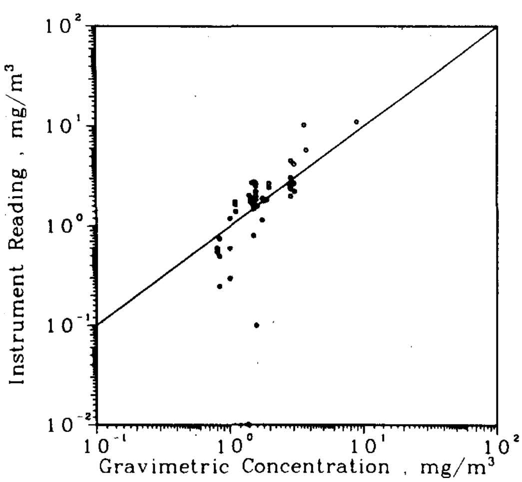

Fig. A-47.
RAMM #2 measurement of polydisperse DOP, 1-min samples. Regression equation is C_I = 1.32 C_G - 0.35, r = 0.94, n = 48.

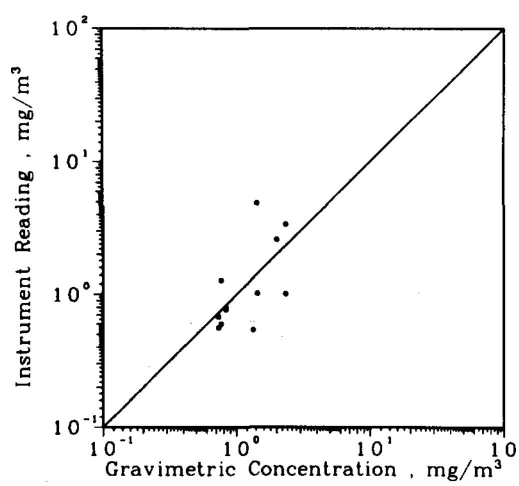

Fig. A-48.
RAMM #2 measurement of polydisperse DOP, 2-min samples.

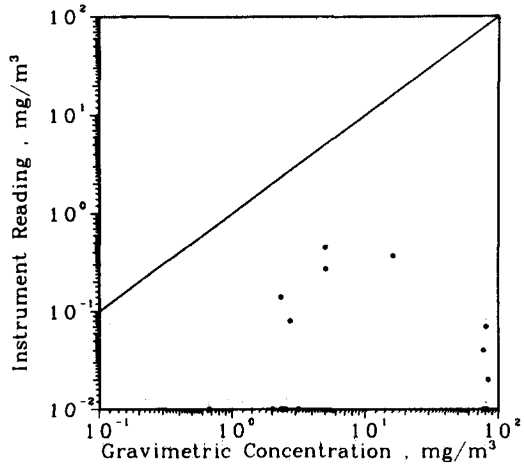

Fig. A-49.
RDM-301 measurement of monodisperse DOP, 1-min samples.

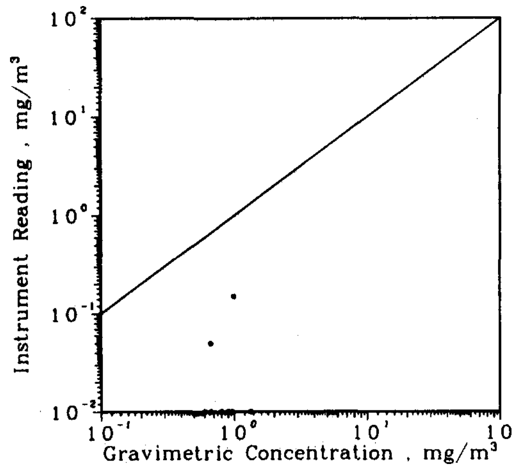

Fig. A-50.
RDM-301 measurement of monodisperse DOP, 2-min samples.

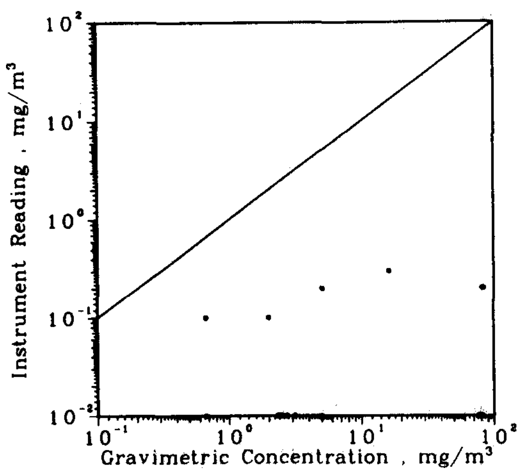

Fig. A-51.
RDM-101 measurement of monodisperse DOP, 1-min samples.

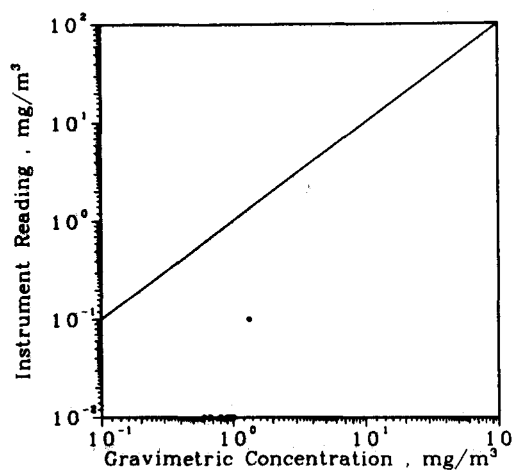

Fig. A-52.
RDM-101 measurement of monodisperse DOP, 2-min samples.

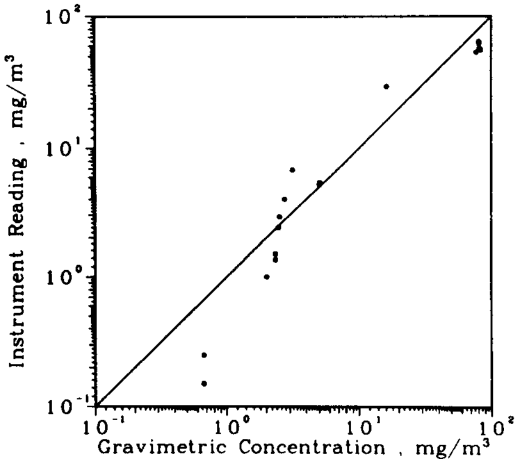

Fig. A-53.
RAMM #1 measurement of monodisperse DOP, 1-min samples. Regression equation is $C_I = 0.71\ C_G + 2.14$, $r = 0.98$, $n = 17$.

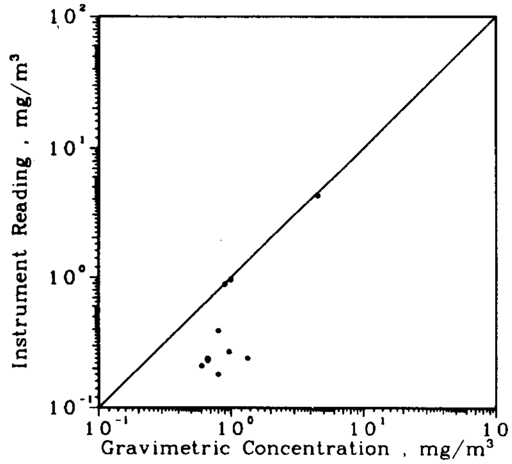

Fig. A-54.
RAMM #1 measurement of monodisperse DOP, 2-min samples. Regression equation is $C_I = 1.03\ C_G - 0.48$, $r = 0.97$, $n = 10$.

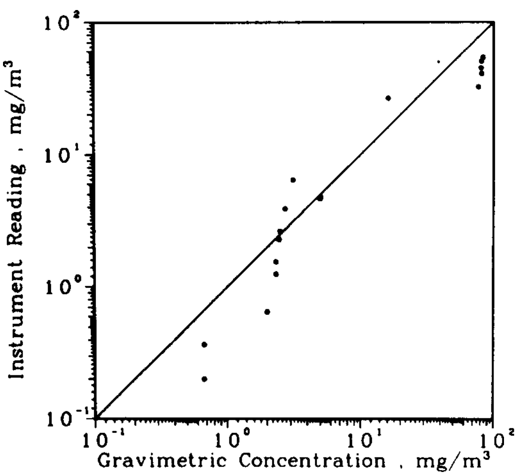

Fig. A-55.
RAMM #2 measurement of monodisperse DOP, 1-min samples. Regression equation is $C_I = 0.53\ C_G + 2.30$, $r = 0.96$, $n = 17$.

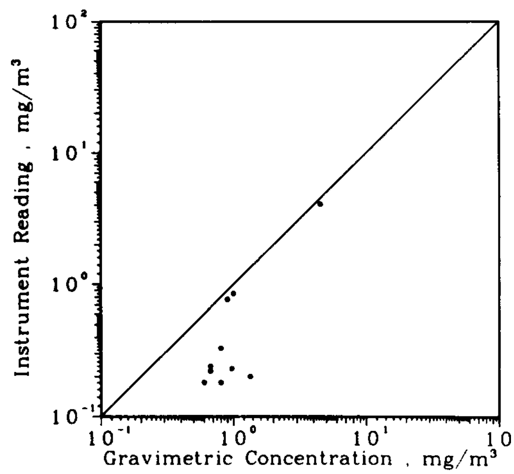

Fig. A-56.
RAMM #2 measurement of monodisperse DOP, 2-min samples. Regression equation is $C_I = 0.99\ C_G - 0.49$, $r = 0.97$, $n = 10$.

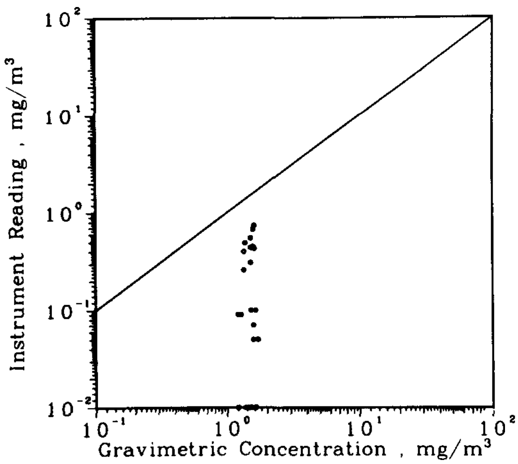

Fig. A-57.
RDM-301 measurement of 0.79-μm-diam PSL, 1-min samples.

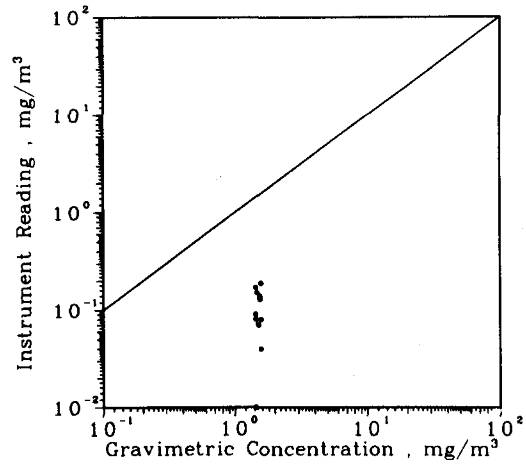

Fig. A-58.
RDM-301 measurement of 0.79-μm-diam PSL, 2-min samples.

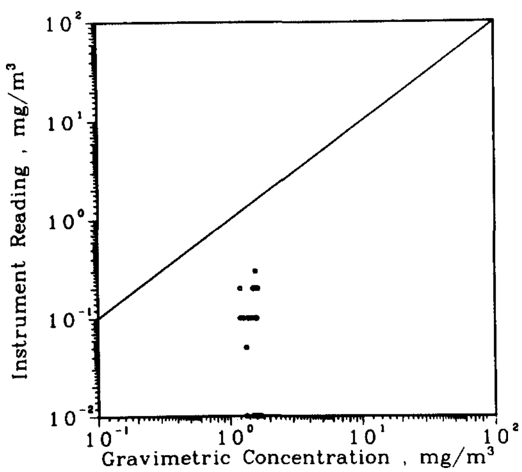

Fig. A-59.
RDM-101 measurement of 0.79-μm-diam PSL, 1-min samples.

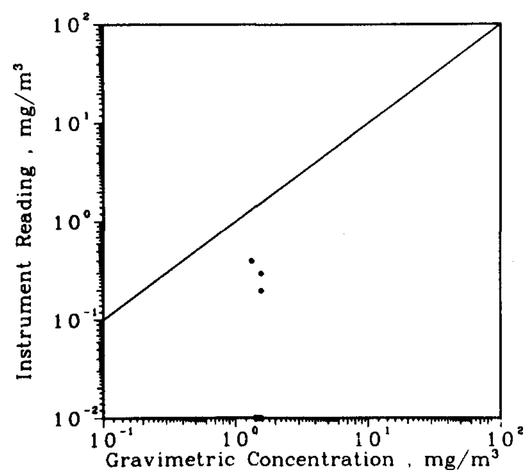

Fig. A-60.
RDM-101 measurement of 0.79-μm-diam PSL, 2-min samples.

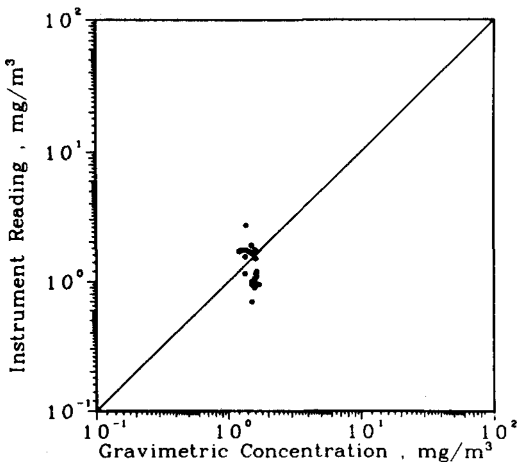

Fig. A-61.
RAMM #1 measurement of 0.79-μm-diam PSL, 1-min samples.

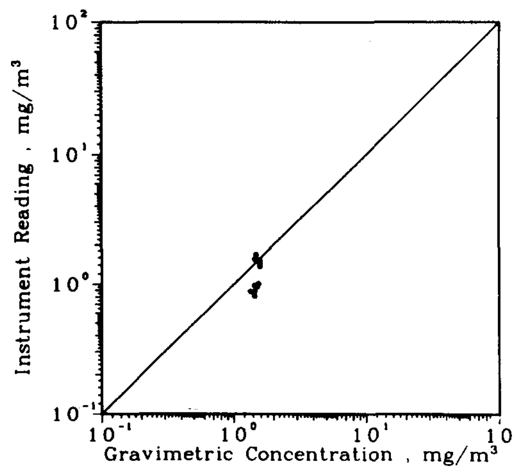

Fig. A-62.
RAMM #1 measurement of 0.79-μm-diam PSL, 2-min samples.

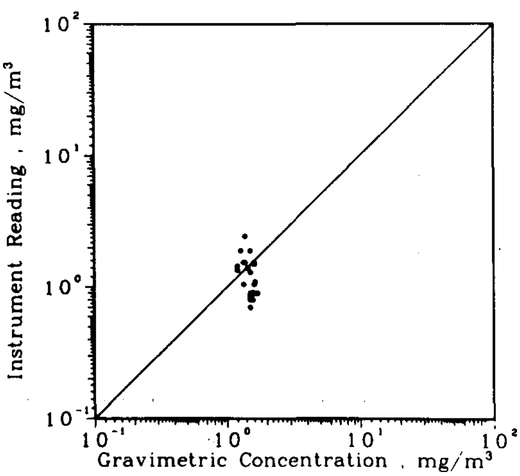

Fig. A-63.
RAMM #2 measurement of 0.79-μm-diam PSL, 2-min samples.

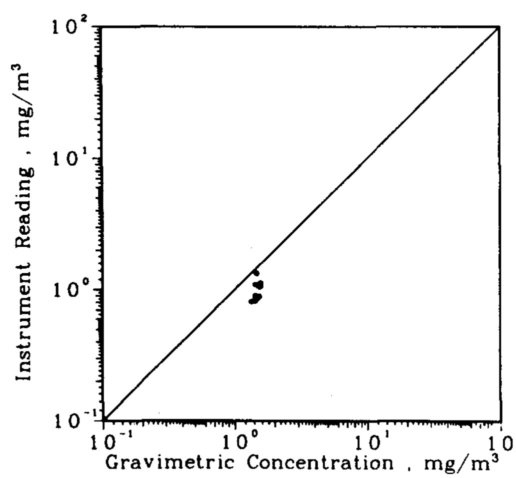

Fig. A-64.
RAMM #2 measurement of 0.79-μm-diam PSL, 2-min samples.

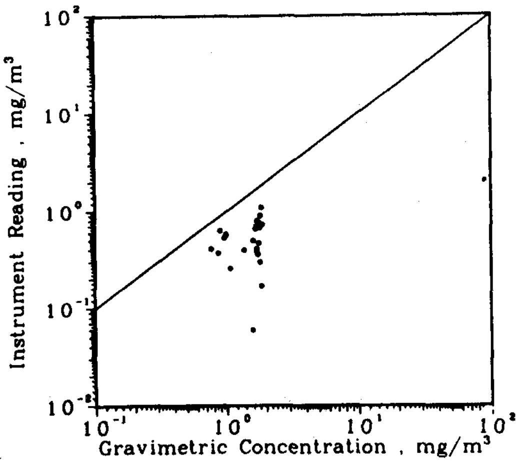

Fig. A-65.
RDM-301 measurement of 1.01-μm-diam PSL, 1-min samples.

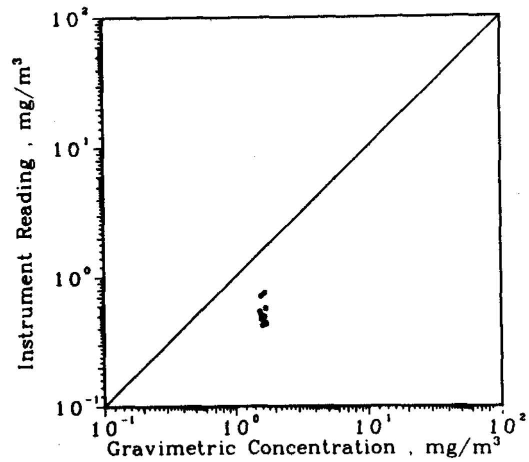

Fig. A-66.
RDM-301 measurement of 1.01-μm-diam PSL, 2-min samples.

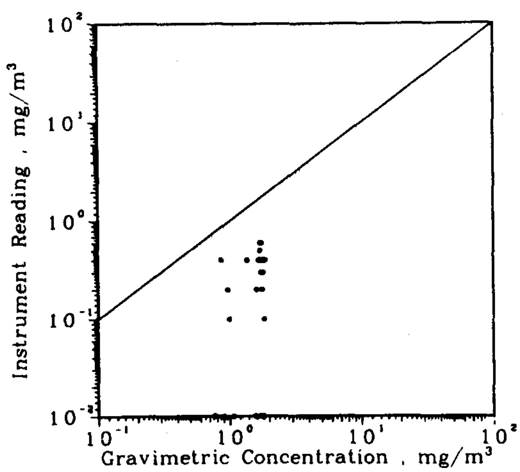

Fig. A-67.
RDM-101 measurement of 1.01-μm-diam PSL, 1-min samples.

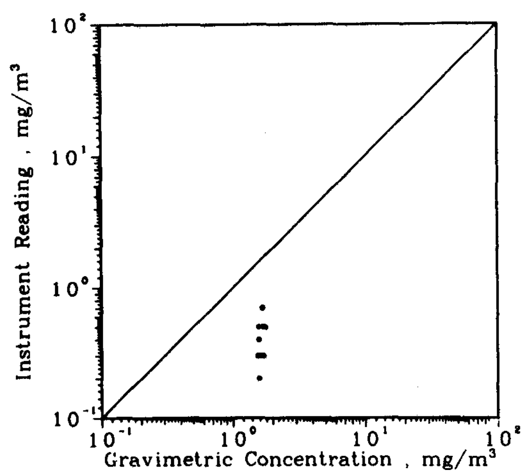

Fig. A-68.
RDM-101 measurement of 1.01-μm-diam PSL, 2-min samples.

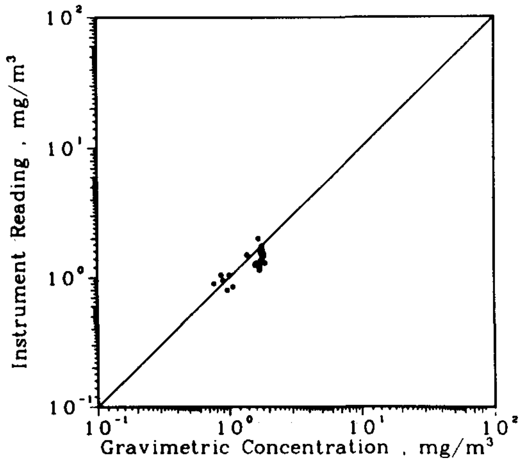

Fig. A-69.
RAMM #1 measurement of 1.01-μm-diam PSL, 1-min samples.

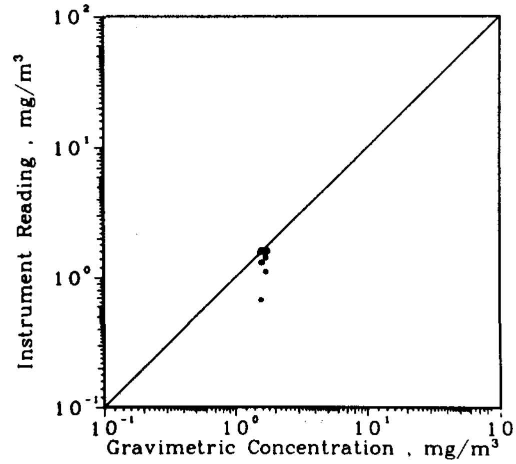

Fig. A-70.
RAMM #1 measurement of 1.01-μm-diam PSL, 2-min samples.

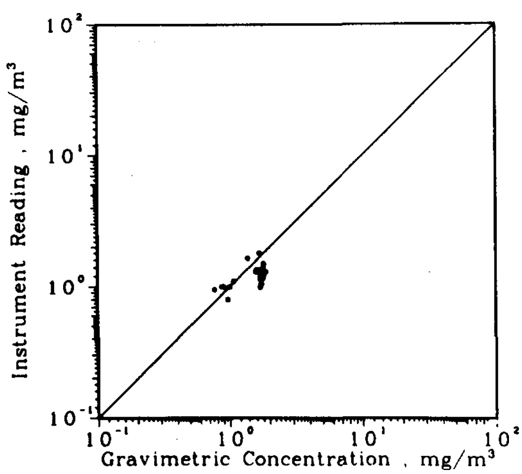

Fig. A-71.
RAMM #2 measurement of 1.01-μm-diam PSL, 1-min samples.

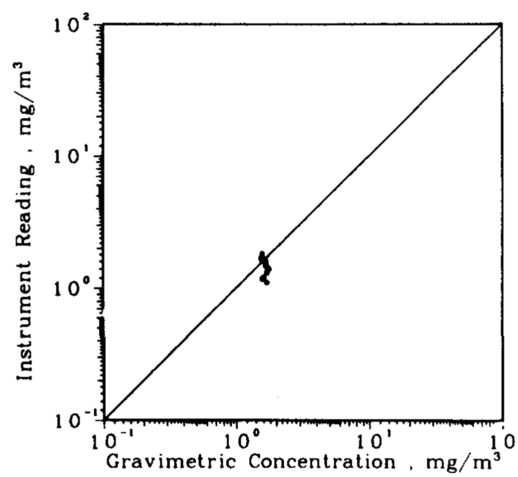

Fig. A-72.
RAMM #2 measurement of 1.01-μm-diam PSL, 2-min samples.

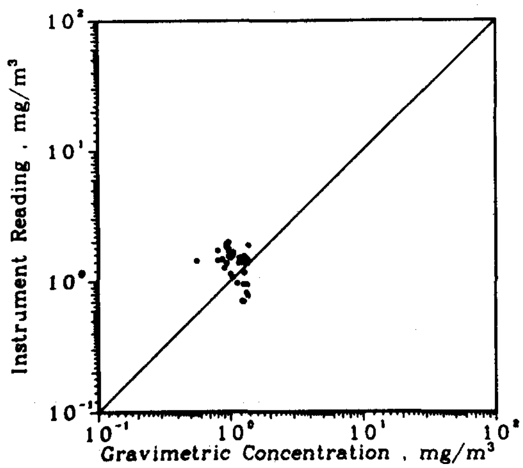

Fig. A-73.
RDM-301 measurement of 2.02-μm-diam PSL, 1-min samples.

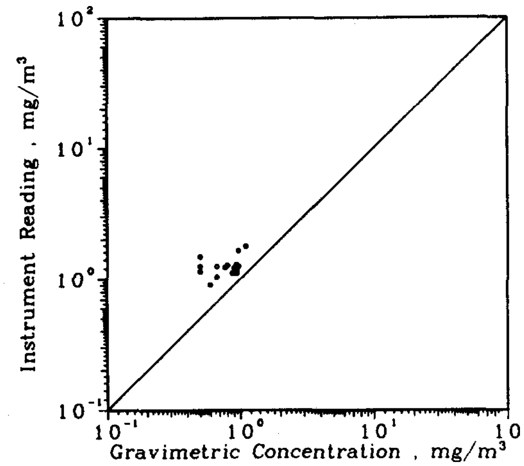

Fig. A-74.
RDM-301 measurement of 2.02-μm-diam PSL, 2-min samples.

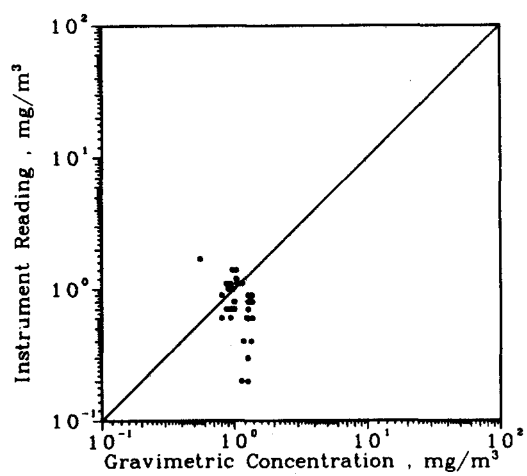

Fig. A-75.
RDM-101 measurement of 2.02-μm-diam PSL,, 1-min samples.

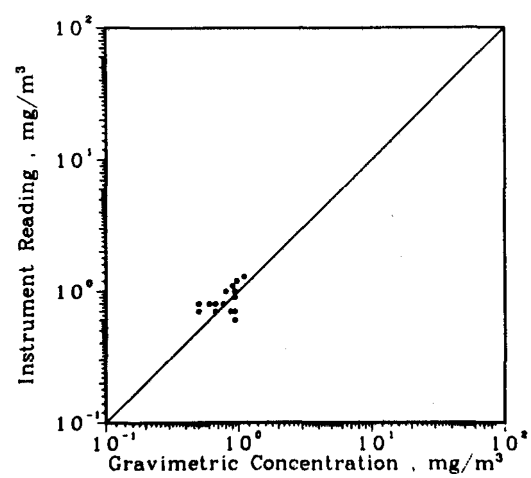

Fig. A-76.
RDM-101 measurement of 2.02-μm-diam PSL, 2-min samples.

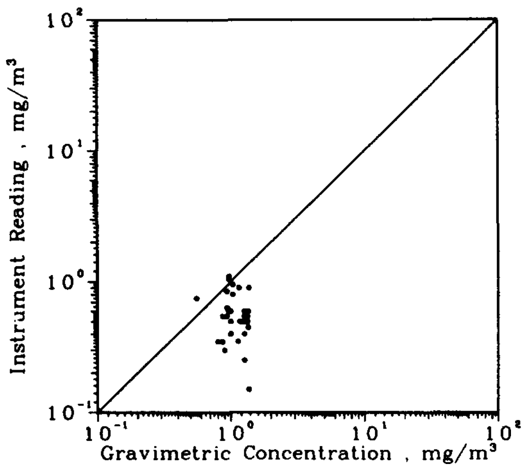

Fig. A-77.
RAMM #1 measurement of 2.02-µm-diam PSL, 1-min samples.

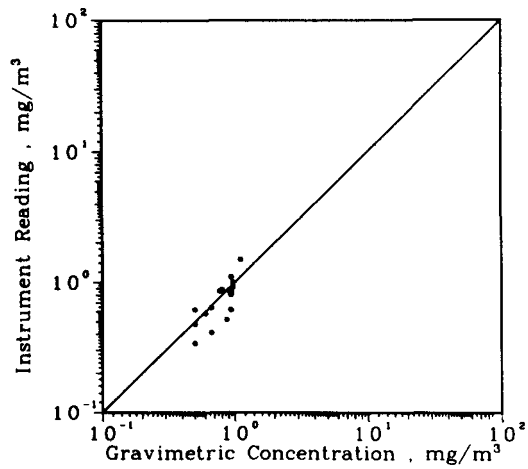

Fig. A-78.
RAMM #1 measurement of 2.02-µm-diam PSL, 2-min samples.

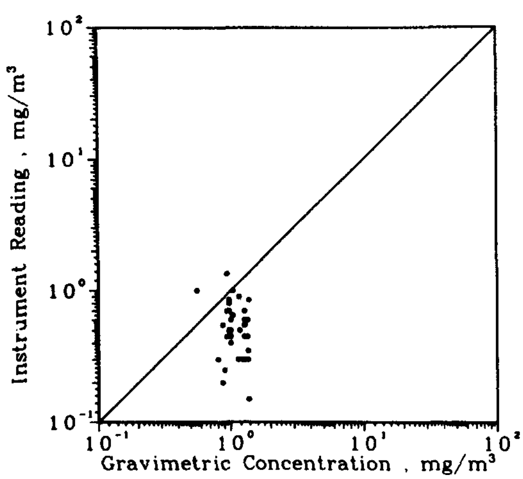

Fig. A-79.
RAMM #2 measurement of 2.02-µm-diam PSL, 1-min samples.

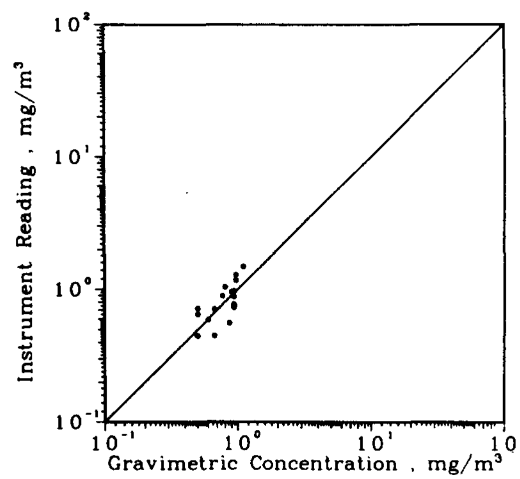

Fig. A-80.
RAMM #2 measurement of 2.02-µm-diam PSL, 2-min samples.

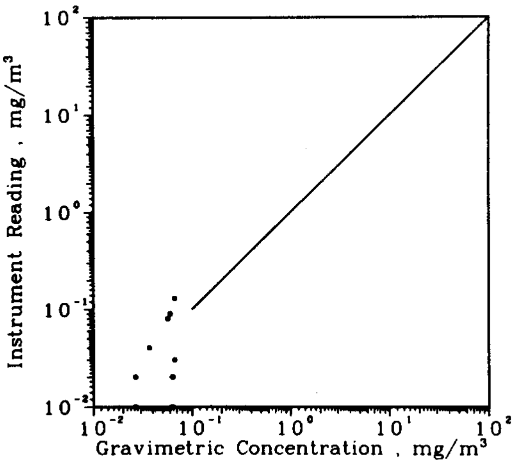

Fig. A-81.
RDM-101 measurement of 1.0-μm average diam Eosin-Y, 20-min samples.

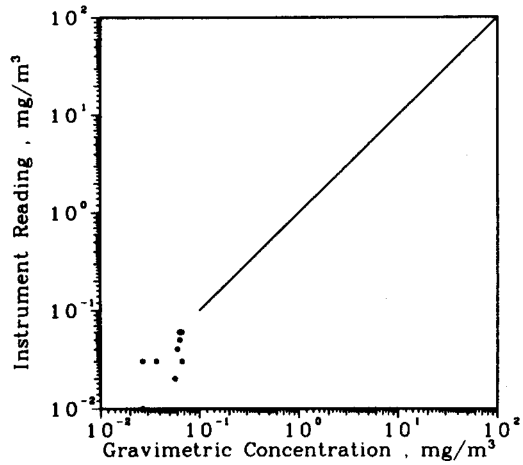

Fig. A-82.
RAMM #1 measurement of 1.0-μm average diam Eosin-Y, 20-min samples.

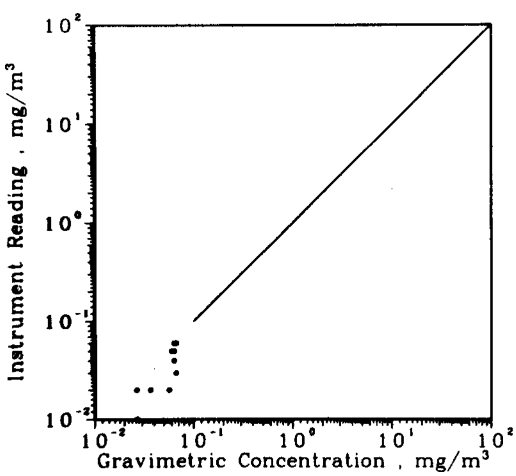

Fig. A-83.
RAMM #2 measurement of 1.0-μm average diam Eosin-Y, 20-min samples.

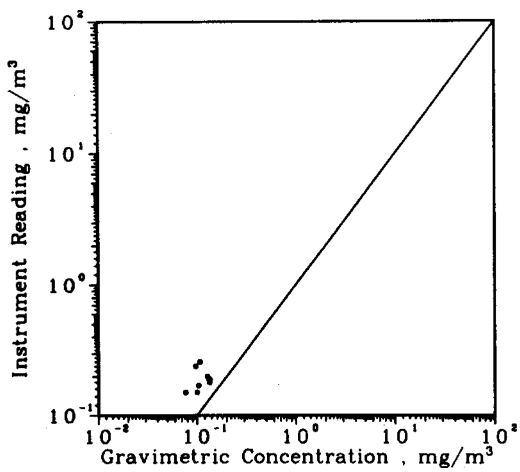

Fig. A-84.
RDM-101 measurement of 1.5-μm average diam Eosin-Y, 20-min samples.

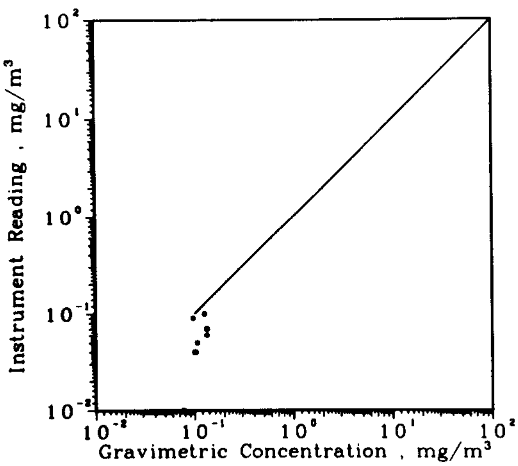

Fig. A-85.
RAMM #1 measurement of 1.5-μm average diam Eosin-Y, 20-min samples.

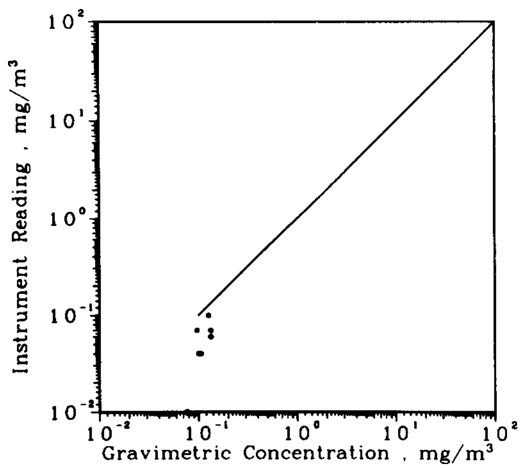

Fig. A-86.
RAMM #2 measurement of 1.5-μm average diam Eosin-Y, 20-min samples.

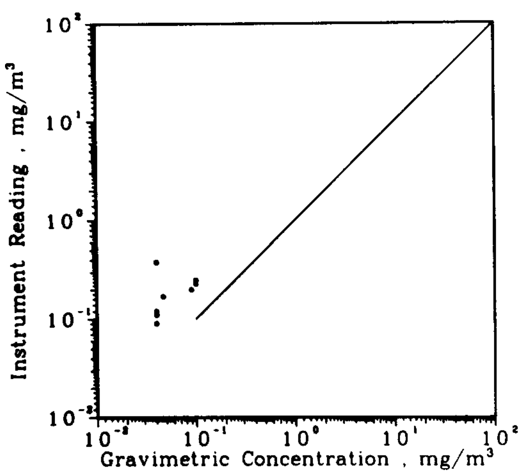

Fig. A-87.
RDM-301 measurement of 3.7-μm average diam Eosin-Y, 10-min samples.

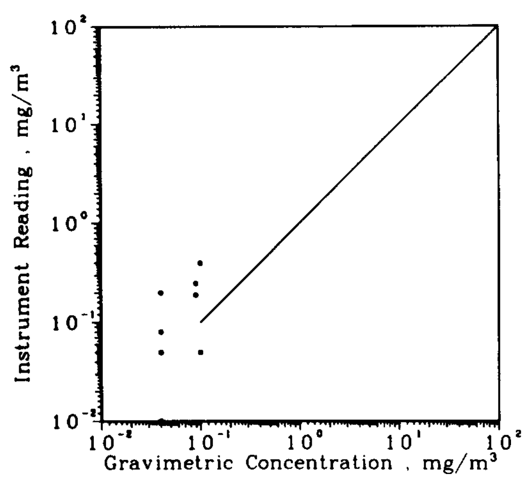

Fig. A-88.
RDM-101 measurement of 3.7-μm average diam Eosin-Y, 10-min samples.

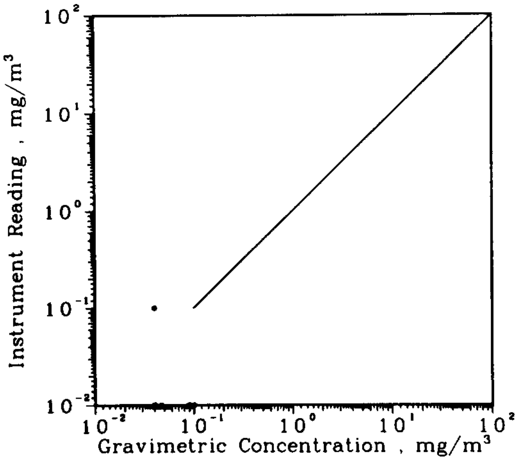

Fig. A-89.
RAMM #1 measurement of 3.7-µm average diam Eosin-Y, 10-min samples.

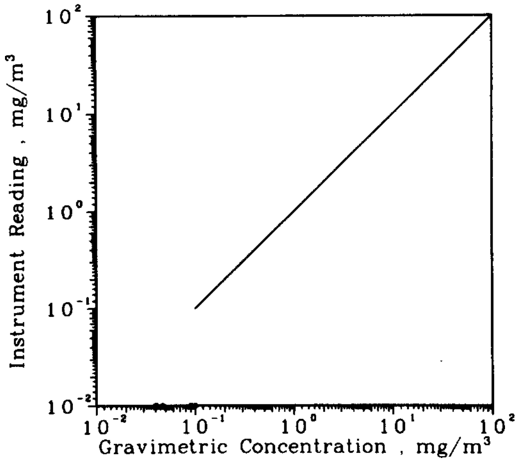

Fig. A-90.
RAMM #2 measurement of 3.7-µm average diam Eosin-Y, 10-min samples.

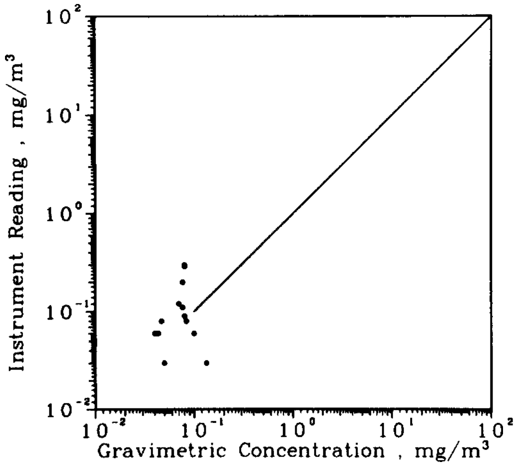

Fig. A-91.
RDM-301 measurement of 5.6-µm average diam Eosin-Y, 10-min samples.

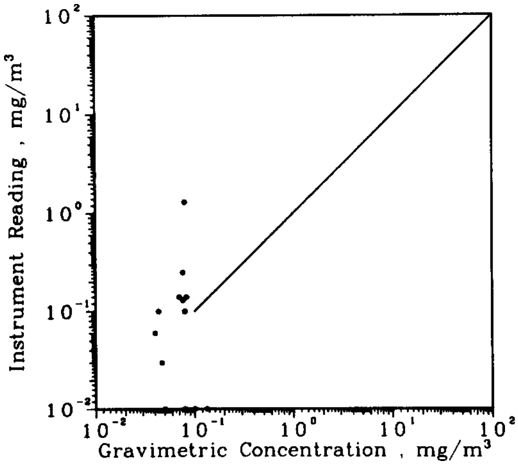

Fig. A-92.
RDM-101 measurement of 5.6-µm average diam Eosin-Y, 10-min samples.

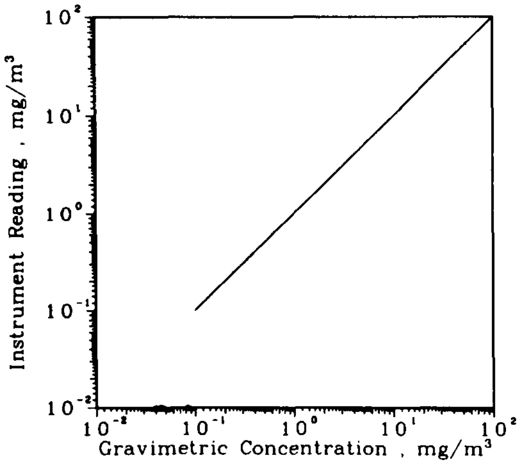

Fig. A-93.
RAMM #1 measurement of 5.6-μm average diam Eosin-Y, 10-min samples.

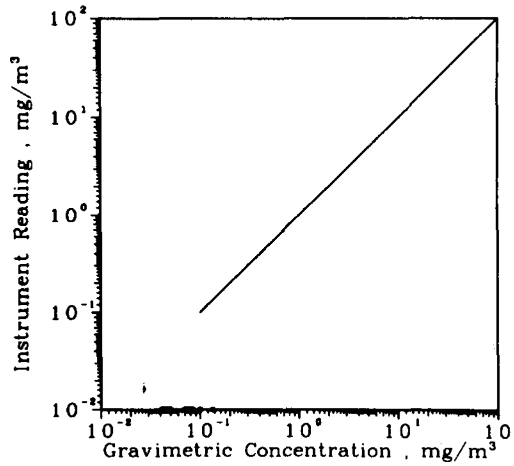

Fig. A-94.
RAMM #2 measurement of 5.6-μm average diam Eosin-Y, 10-min samples.

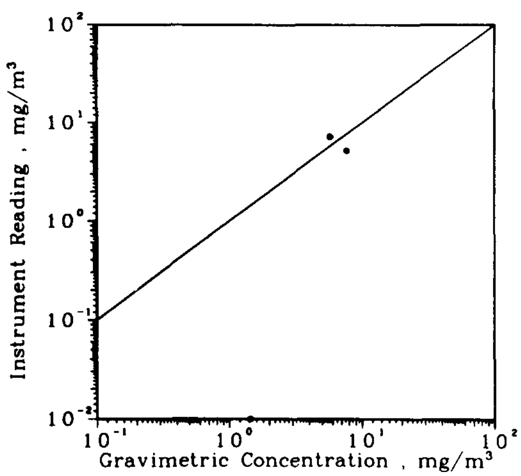

Fig. A-95.
RDM-201 measurement of oil shale.

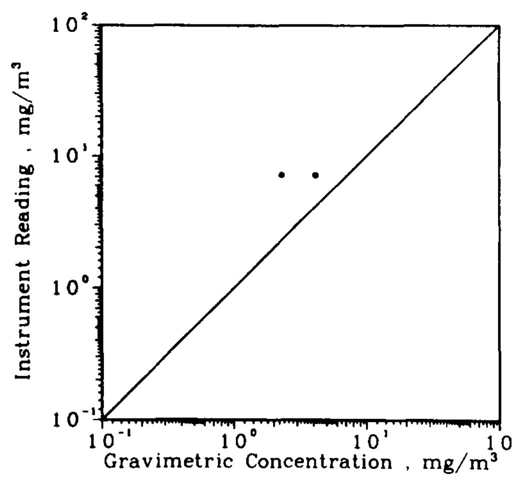

Fig. A-96.
RDM-201 measurement of oil shale.

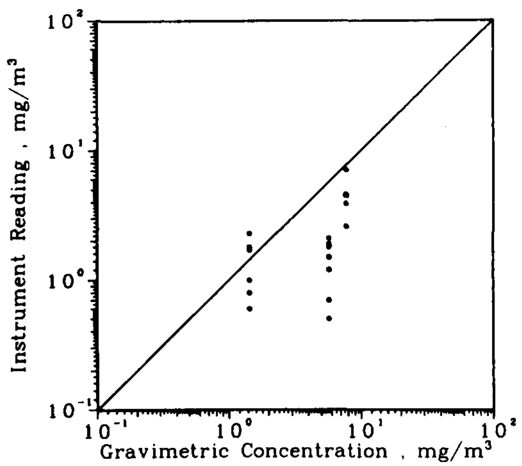

Fig. A-97.
RDM-101 measurement of oil shale, 1-min samples.

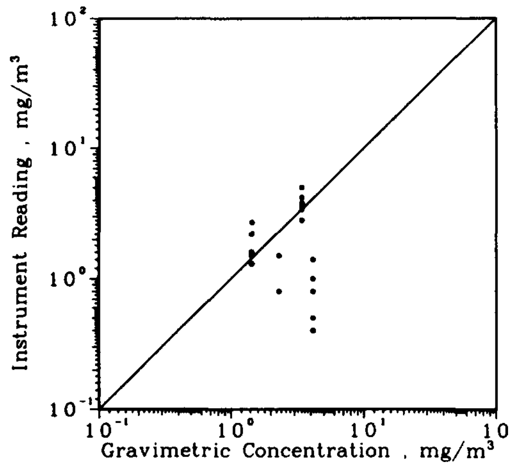

Fig. A-98.
RDM-101 measurement of oil shale, 2-min samples.

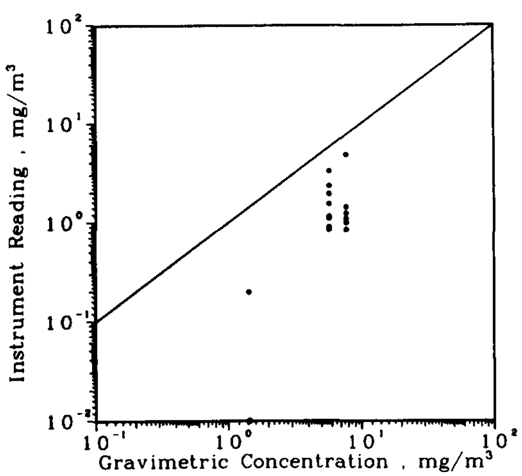

Fig. A-99.
RAMM #1 measurement of oil shale, 1-min samples.

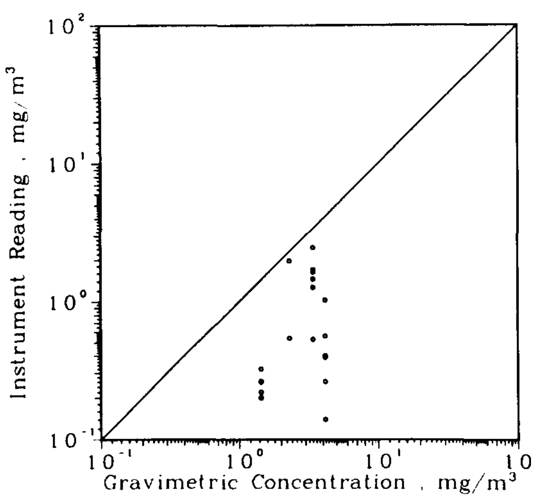

Fig. A-100.
RAMM #1 measurement of oil shale, 2-min samples.

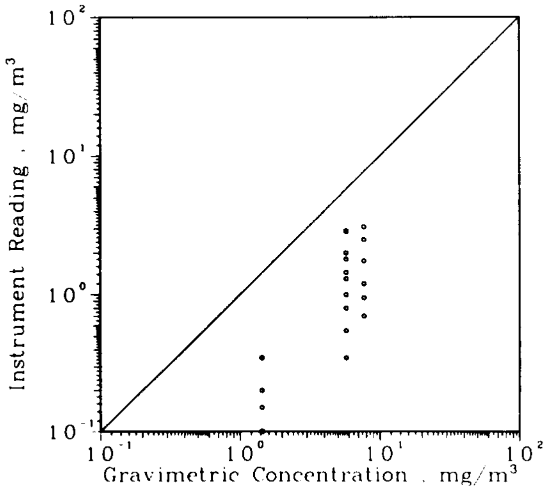

Fig. A-101.
RAMM #2 measurement of oil shale, 1-min samples.

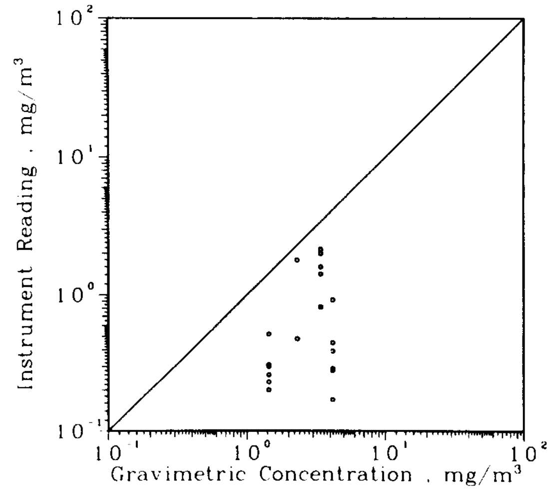

Fig. A-102.
RAMM #2 measurement of oil shale, 2-min samples.

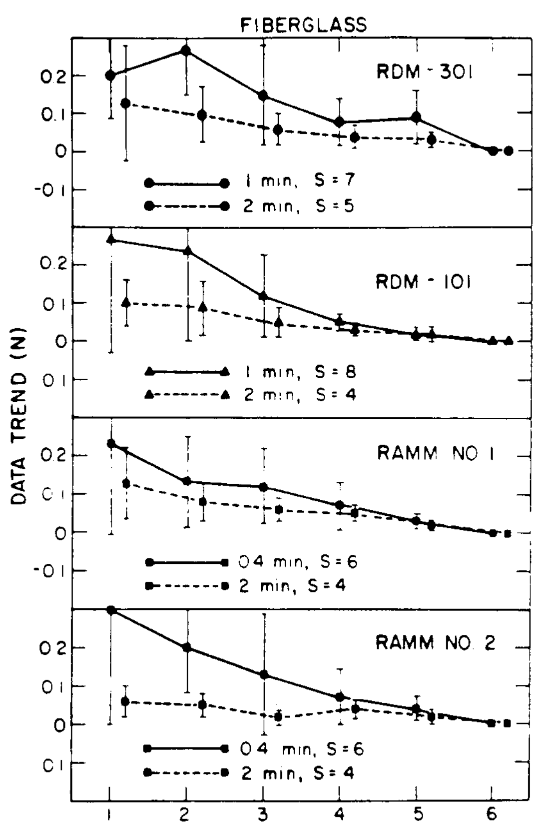

Fig. A-103.
Data convergence for all mass monitors sampling fiber glass.