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Patrick T. O'shaughnessy & David R. Hemenway

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Patrick T. O'Shaughnessy, David R. Hemenway

Department of Civil and Environmental Engineering, University of Vermont, Burlington, Vermont, USA

An automated system to minimize variability in an aerosol concentration over time in an animal exposure chamber was developed. This system includes a microprocessor-controlled stepper motor to regulate the speed of a dust generator, a real-time aerosol monitor to instantaneously measure chamber aerosol concentrations, and a personal computer with an analog-to-digital (A/D) converter, serial port, and relay board for signal input and output. A computer program was written to use these devices to produce a chamber concentration near a level chosen by the operator. This program was also written to start and stop an exposure after a specified time period and to continuously display the data received from the aerosol monitor on the computer screen during the exposure. A combination of operating conditions, which include a moderately high chamber flow rate (0.32 m^3/min) and high generator rotation speed while using a small scraper blade, optimized the performance of the automated system by minimizing the concentration variability (CV) seen in the aerosol monitor readings. The CV, which indicates the average difference between consecutive monitor recordings, decreased from 2.79 mg/m^3, when using the large scraper to produce a chamber concentration of 25 mg/m^3, to 0.47 mg/m^3 when using the small scraper at 25 mg/m^3. When operating with these optimum conditions, 5 consecutive trials of 180 min produced concentrations of 10.52, 10.52, 10.57, 10.37, and 10.47 mg/m^3. The system proved to be capable of calculating the appropriate generator speed needed to reach and maintain a desired concentration level after trials were performed to determine the amount of aerosol losses in the chamber. A total of 14 trials performed at 10 mg/m^3 had an average actual-to-expected concentration ratio of 1.023 (SD = 0.067). The response of the concentration level to changes in generator speed after start-up varied in relation to the magnitude of the speed change. The system proved to be more accurate when the generator speed was changed to provide a change in chamber concentration of more than 2 mg/m^3. The accuracy and reliability of the aerosol monitor were investigated by comparing the time-weighted average of the monitor recording with the average chamber concentration measured by a sample filter (M/F ratio). The average difference of the M/F ratio between consecutive trials was 3.36% when using the small scraper near 10 mg/m^3 and 9.71% when using the large scraper near 25 mg/m^3.

This study represents a novel attempt to automate the production of a dry aerosol in an inhalation exposure chamber by directly controlling the rotation speed of a Wright dust feed with commands from a personal computer. During this research, the assumption was made that any inconsistencies in generator output, or changes in the amount of dust lost in the chamber, could be compensated by manipulation of the generator rotation speed during the exposure. The system therefore was designed to allow the operator to see, and make decisions from, a graphical display of the chamber aerosol concen-

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Address correspondence to Patrick T. O'Shaughnessy, The University of Vermont, Department of Civil and Environmental Engineering, Votey Building, Burlington, VT 05405.

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tration as measured by a real-time aerosol monitor. If a change in concentration during the exposure was desired, the computer was programmed to make the necessary calculations needed to transform the change in concentration into the appropriate generator speed needed to achieve the new concentration level.

Relatively few attempts have been made to automate the production of an aerosol in an inhalation exposure chamber by means of computer-controlled equipment (Coggins et al., 1989; Crider et al., 1980; Davis & Irwin, 1982; Hirano, 1987). During two of the methods just cited (Coggins et al., 1989; Hirano, 1987), a mass flow controller was operated automatically to attain a desired aerosol concentration level. During these studies, the flow controller was used to manipulate the dilution airstream through the test chamber as the generator output remained at a stable level.

The success of the control system to regulate aerosol concentrations in each of the cases cited depended on the use of a generator that was capable of maintaining a uniform concentration level throughout the exposure period. For example, nebulizers were utilized by Hirano (1987) and Crider et al. (1980); Coggins et al. (1989) used a smoking machine; and a pulsed-air, dry dust generator was used by Davis and Irwin (1982). The development of flow-regulating instruments, such as mass flow controllers, has facilitated the precise regulation of air flow for control purposes. Therefore, of the two variables affecting chamber concentration levels, generator production rate or dilution air flow rate, the latter had been chosen as the manipulated parameter.

Research involving the production of silica aerosols (TAFQ-quartz, cristobalite, and Min-U-Sil 5) is often undertaken at our facility. A Wright dust feed has been found to be a suitable method for generating the parent silica dust into an aerosol, although problems associated with parts wear (Hinds, 1980) and inconsistent output rates (Collins, 1975; Wright, 1950) limit the effectiveness of this device. Despite these reported flaws with the dust feed, the automated system was designed to alter chamber concentrations with corrections in generator speed rather than changes in dilution air. This decision was based on results from previous trials, which revealed a dramatic shift in the aerosol size distribution with increases in chamber flow rate. A change in the size distribution was undesirable because the response of optical aerosol monitors has been shown to be a function of size distribution (Baron, 1985; Smith et al., 1987; Willeke & Baron, 1990), and also because of the need during an animal exposure to avoid aerosol size variations, which might significantly affect aerosol deposition patterns in the test animals (Phalen, 1984).

Practical use of an automated exposure system depends on the ability of the aerosol monitor to accurately measure chamber concentration levels. The need to calibrate each aerosol monitor individually for the particular aerosol measured has been well documented (Cheng et al., 1988; Gressel et al., 1987; Smith, 1987; Willeke & Baron, 1990; Willeke & Degarmo, 1988). Once they are calibrated, aerosol monitors have been found to give a linear response over as much as a 10-fold change in concentration (Cheng et al., 1988; Smith et al., 1987).

To be of use throughout the length of an exposure, these instruments must also consistently give readings that are accurate indications of the actual chamber concentration as measured by a sample filter. The wide range of values reported for these "monitor/gravimetric" ratios in the literature (Cheng et al., 1988; Smith, 1987; Page & Jankowski, 1984) indicates this factor is also specific to the instrument and sampling method used.

It was found during initial trials of this research that large variations in concentration tend to diminish the ability of the operator to distinguish the mean level of the process at any given time when viewed on a computer screen (Fig. 1). Also, if the variation in observed aerosol concentration is much greater than a proposed change in concentration, the change in concentration induced by a generator speed correction may have no apparent affect on the mean level. Therefore, the second objective of this research involved the reduction of this "instantaneous" variability of the observed aerosol concentration before attempting to utilize an automated exposure system. Various combinations of operating conditions were investigated to determine if the variation could be reduced by physical manipulations of these settings rather than by electronic or mathematical signal conditioning. After optimizing the production of the aerosol in this way, research needed to determine the response of the concentration level to changes in generator speed was initiated.

METHODS

The Exposure System

During a typical exposure, the aerosol concentration was measured on each of four shelves of a horizontal flow chamber (Hemenway & MacAskill, 1982) using gravimetric analysis of membrane filters. An average of the shelf concentrations was used as an indication of the dose administered

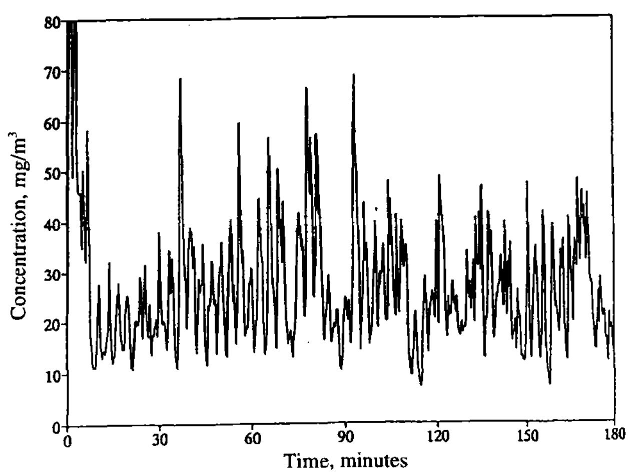

FIGURE 1. Chamber concentrations recorded by a real-time aerosol monitor during a trial set to produce an average concentration of 25 mg/m^3.

during each day of an exposure. Flow through the chamber was produced by two regenerative blowers located on both the upstream and downstream side of the chamber (Fig. 2). This system allowed the operator to manipulate both the flow rate and the static pressure of the chamber. The flow rate was indicated by a water-filled manometer connected to a Pitot-venturi flow meter located in the supply air duct.

The production of the test aerosol used throughout this study, cristobalite, a form of free crystalline silica, was accomplished with the use of a modified Wright dust feed (BGI, Inc., Waltham, MA) (Hemenway et al., 1986). This device produces an aerosol by rotating a cylinder, packed with the bulk powder, past a scraper blade. The production rate of the dust feed is thus determined by the rotation speed of the cylinder. An airstream, flowing along the base of the scraper blade, carries the scraped powder out of the generator and into the main dilution airstream entering the chamber (Wright, 1950).

The Automated Exposure System

The rotation speed of the dust feed was regulated by a microprocessor-controlled stepper motor connected to the gear drive of the dust feed as described by Hemenway et al. (1986). However, a microcontroller board with the ability to communicate with a personal computer was needed in order to change the generator speed based on commands from a computer keyboard. The microcontroller chosen for this purpose (model SIBEC-II, Binary Technology, Inc., Meriden, NH) contains the programming and digi-

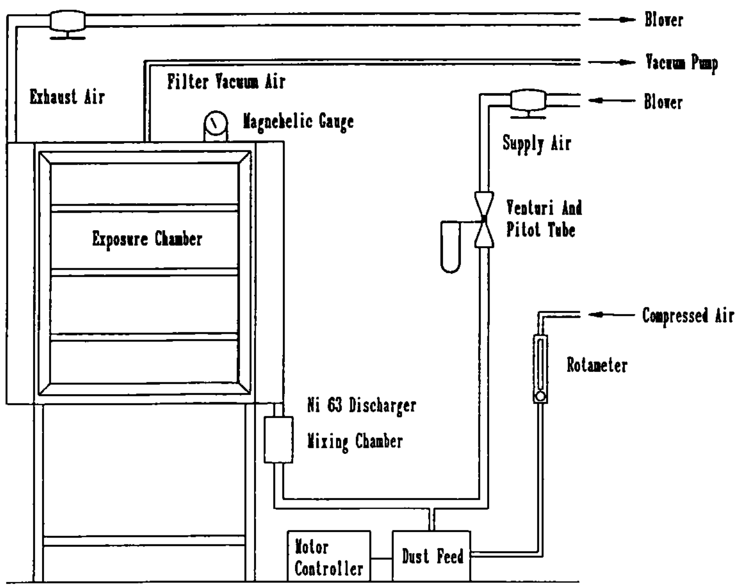

FIGURE 2. Schematic diagram of the exposure system prior to addition of automation equipment.

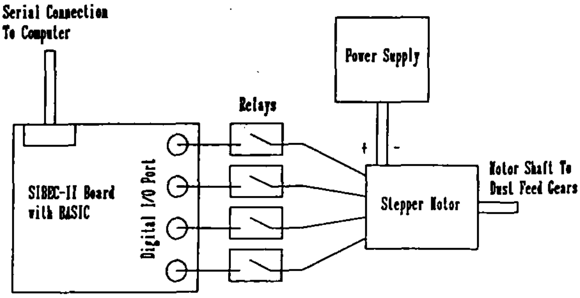

FIGURE 3. Schematic diagram of microcontroller-to-motor connections.

tal output capability to control a stepper motor, as well as a serial communications port to transfer and receive information from the host computer.

The SIBEC-II contains the Intel 8052AH BASIC CPU and an EPROM chip to store any programs written on the 8052AH. A program was written in the programming language Turbo C (Borland International Inc., Scotts Valley, CA), on the personal computer, to allow serial communication with the BASIC program on the SIBEC-II board. After accessing BASIC, a program to control the stepper motor speed was written and stored on the EPROM chip. This BASIC program was developed to perform three functions:

1. Ask for the initial time delay between "steps" of the motor.
2. Control motor speed by activating four optically isolated relays between the SIBEC board and the stepper motor (Fig. 3) in the correct sequence and with the correct time delay between steps.
3. Check the serial port of the SIBEC board for a signal from the host computer to change motor speed while the motor is running.

The particular stepper motor used (model 20-2235D200-E2.6, Sigma Instruments, Inc., Braintree, MA) requires 200 steps per revolution. Each step of the motor was accomplished by activating in the motor one of four coils, which, when activated, "instantaneously" accelerated the motor shaft to the next position. Therefore, rotation speed was established by varying the time delay between steps as mentioned above. The BASIC program listing (Fig. 4) contains a GOSUB command between each activation of a motor coil accomplished with the use of the XBY( ) command. When the program skipped to line 300 because of the GOSUB command, it performed a simple loop routine for a specified number of times depending on the amount of delay required to affect a particular rotation speed.

After the initial time delay was entered by the user on the computer keyboard, the BASIC program caused the stepper motor to rotate at the specified speed by continuously running between lines 60 and 200 of Figure 4. The command D = GET on line 70 is used to check the serial port

```
10 XBY(0F003H) = 080H
20 XBY(0F002H) = 0FH
30 PRINT "INPUT INITIAL TIME DELAY"
40 INPUT S
50 B = S
60 DO
70 D = GET
80 IF (D<>0.AND.D>10) THEN B=(50*S)/(D-10)
90 A = B * 625
100 XBY(0F002H) = 09H
110 GOSUB 300
120 XBY(0F002H) = 0CH
130 GOSUB 300
140 XBY(0F002H) = 06H
150 GOSUB 300
160 XBY(0F002H) = 03H
170 GOSUB 300
180 WHILE D <> 1
190 XBY(0F002H) = 0FH
200 END
300 FOR I=1 TO A : NEXT I
310 RETURN
```

FIGURE 4. Program written on the microcontroller to control stepper motor speed and to ask for a signal sent by the host computer to change motor speeds during a trial period.

for an ASCII character sent by the host computer once during each program loop. If one has been sent, a new time delay is calculated on line 80 and the motor rotation speed changes accordingly.

There are 256 ASCII characters available, each of which has an associated integer from 0 to 255, but only numbers 10 through 110 were made available to be sent to the SIBEC-II. During each exposure, ASCII number 60 was associated with the initial generator speed computed for the chamber concentration desired. Numbers 59 through 10 were used to decrease the motor speed to a nearly a full stop, and numbers 61 through 110 were available to increase the speed to within twice the initial speed. The BASIC program can be rewritten to narrow the range of speeds available and thus increase the resolution between speeds.

The C program on the personal computer was written to ask for the desired concentration (DC) and the chamber flow rate set by the operator. The appropriate dust-feed cylinder rotation speed (ω) needed to achieve the DC is then computed (Eq. 2) with the use of this information and an equation for nominal concentration (NC) rearranged to solve for ω (Eq. 1):

$$NC = 1000\, K \frac{\rho_c \omega}{Q_c} \tag{1}$$

$$\omega = \frac{DC}{1000} \times \frac{Q_c}{\rho_c K} \times \frac{NC}{AC} \tag{2}$$

where NC is the nominal concentration (mg/m^3), AC the actual chamber concentration (mg/m^3), DC the desired concentration (mg/m^3), K the cylinder volume constant (cm^3/revolution), ρ_c the packing density of the dust cake (g/cm^3), ω the cylinder speed (revolutions/min), and Q_c the chamber flow rate (m^3/min). The term NC/AC in Eq. 2 is needed to compensate for losses in aerosol concentrations between the generator and the center of the exposure chamber. The AC/NC ratio was determined, in relation to chamber flow rate, by a series of trials conducted at flow rates of 0.1, 0.2, 0.3, 0.4, and 0.5 m^3/min.

The NC refers to the expected chamber concentration, excluding losses, and is assumed to be constant for a given generator rotation speed. Any variability in NC would be induced primarily by variations in the packing density of the dust cake, ρ_c, in the cylinder of the dust feed. However, a separate study of packing density has confirmed ρ_c was consistent, between 0.5-in layers of the cylinder and between separate cylinders, when using a hammer and steel rod to pack the dust cake. During the packing procedure, enough dust was added to gain 0.5 in of packed dust after hitting the steel rod 3 or 4 times. The value of ρ_c obtained with this method (1.396 g/cm^3 for cristobalite) was also greater than when using a hydraulic press at loads of up to 2000 psi (1.338 g/cm^3).

The appropriate stepper motor speed needed to achieve the DC is 5 times as fast as the calculated cylinder speed because of the 5 : 1 gear ratio between motor shaft and cylinder. This speed, in terms of revolutions per minute, was converted into a value of seconds per step and displayed to the operator for insertion into the BASIC program as shown in lines 30 and 40 of Figure 4. As explained in the dust-feed operating instructions (BGI, Inc., 1989), the running time of the dust cylinder for the given rotation speed was also calculated and displayed to the operator by the computer.

Chamber aerosol concentrations were measured with a real-time aerosol monitor (HAM-DS model 1050, ppm inc., Knoxville, TN). This instrument is capable of measuring dust concentrations in ranges of 0–2, 0–20, and 0–200 mg/m^3. After the exposure trial had been initiated, the concentration measurement of the aerosol monitor was shown on an LCD display and converted into a voltage signal to be read by an analog-to-digital (A/D) converter connected to the computer. The voltage signal has an output of 0–2 V for each of the ranges mentioned. As is typical of many A/D converters, the particular one used for this research (model AD500, Real Time Devices, Inc., State College, PA) is a 12-bit converter that reads voltage in the range of 0–5 V. In order to utilize all the available bits of the converter, and therefore maximize the resolution of the aerosol monitor signal, an operational amplifier circuit was devised to increase the aerosol monitor signal by a factor of 2.5 to a range of 0–5 V. A solenoid valve, activated by a relay board in the computer, was placed in the filter sample vacuum line behind the critical orifice to allow the computer to automatically regulate the sample time during an exposure.

Personal Computer Controller

The computer program was written to serve five main functions:

1. Ask for and receive information from the user regarding the desired concentration level, the chamber airflow rate, and the length of the exposure trial.
2. Automatically initiate the operation of the generator at the proper speed, and begin reading the aerosol monitor signals.
3. Provide a continuous graphical and numerical display of the aerosol monitor readings.
4. Make the appropriate adjustments to the generator based on information received by the user.
5. Terminate the exposure after a specified period of time by turning off the sample air, dust generator, and aerosol monitor recordings.

Items 1 and 2 have been discussed previously. The graphic display on the monitor of the computer (Fig. 5) was designed to provide the user with both an indication of the current level of concentrations in the chamber and the time-weighted average.

The program was written to display 30 min of data at all times after the first half hour. This allowed the operator to see a relatively large time period of previous data in order to make a judgment as to whether the chamber concentration level was drifting off target. To accomplish this, new data points were added to the right-most portion of the screen as all other points were shifted back one time unit.

In an attempt to minimize the number of aerosol monitor readings displayed on the computer monitor without reducing the accuracy of the system, a reading was taken every second and averaged together with the next 14 readings. This average of 15 s of readings was then displayed as a single point on the computer monitor. The numerical value was also displayed on the computer monitor and "written" on a disk file for storage and retrieval into a spreadsheet (Quattro Pro, Borland International Inc., Scotts Valley, CA). The spreadsheet was used to make printed graphs and perform statistical analysis of the data.

In order to satisfy item 4, the program was written to accept a signal from the keyboard by the operator, which would terminate the graphics display and allow a new concentration level to be keyed in. At this time, the

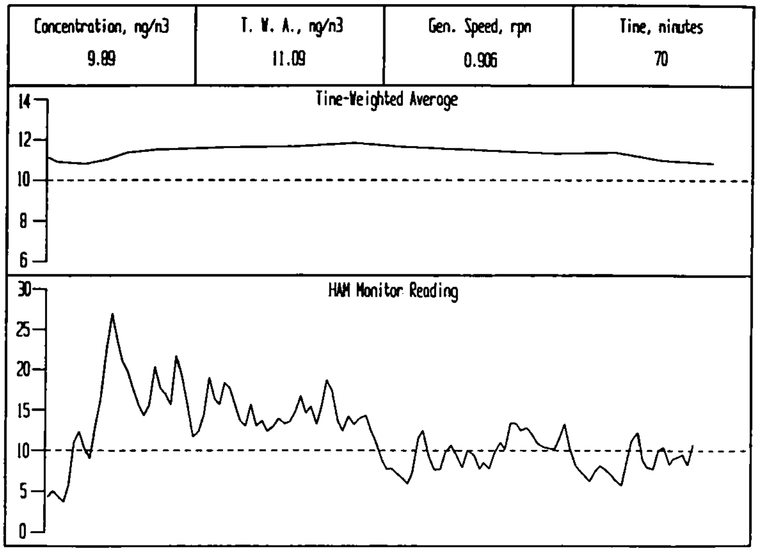

FIGURE 5. Facsimile of the computer display of aerosol monitor readings.

computer would calculate the required generator speed needed to achieve the new level and the appropriate ASCII character to be sent to the SIBEC-II board to activate the speed change.

Aerosol Monitor Calibration

As a means of examining the accuracy of the aerosol monitor, a Plexiglas collar was made to fit around the sample probe with fittings made to connect directly to a 25-mm filter cassette (Fig. 6). (A similar unit is available from the manufacturer for use with 35-mm cassettes). This "sample train" was placed in the middle of the second shelf during all trials, after a separate analysis showed this location contained dust concentration levels that approached the mean level of the entire chamber. Aerosol monitor accuracy was checked by comparing the results of the filter measurements with the time-weighted average of the aerosol monitor readings taken throughout a trial (Baron, 1985; Willeke & Degarmo, 1990).

The aerosol monitor was calibrated for the measurement of cristobalite by rotating a trimming potentiometer ("span" setting) to set the aerosol monitor display, and resulting voltage output, to a level that matches the measurement made with a sample filter. Instrument drift was tested by placing the aerosol monitor in a recently cleaned exposure chamber and allowing it to record concentration levels for 180 min. Prior to this trial, the aerosol monitor was zeroed using filtered compressed air, blown through the view volume, while rotating another trimming potentiometer until the aerosol monitor approached 0.000 in the 0–2 mg/m^3 range.

After calibrating the aerosol monitor, results of the relationship between

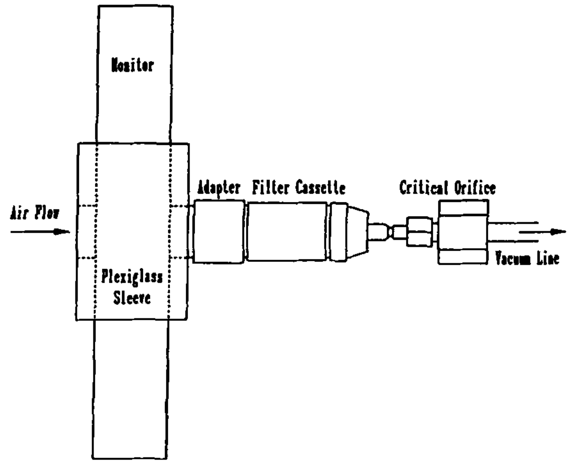

FIGURE 6. Aerosol sampling train used to verify the aerosol monitor readings with the concentration measured by a sample filter.

the time-weighted average of the aerosol monitor recordings (M) and gravimetric analysis of the filter measurements (F) were combined for all subsequent trials to determine how well the two measurements agreed from trial to trial. The actual ratio acquired depends on the span setting and the value of any correction factor used. Therefore, a true indication of the reliability of the aerosol monitor as a control sensor is determined by the amount the ratio changes from day to day when the correction factor and span setting are held constant, rather than by the actual value obtained each day. To determine the aerosol monitor reliability, the change in M/F values between successive trials was determined for a total of 31 trials.

Temporal Variation Reduction

Attempts were made to reduce the aerosol monitor reading variation by manipulating generator speed and chamber flow rate to determine which set of conditions minimized the variation. With the use of time-series analysis, successive data points in each series were found to be highly autocorrelated. Perfect autocorrelation between successive points is an indication of a "random walk" series (Box & Jenkins, 1970). This type of time series, characterized as being nonstationary, has a mean that is not constant over the time interval of the series. Therefore, the application of standard statistical methods for computing the variance of the data is not valid. A simple technique described by Schuurmans and Coops (1984) was used to make a comparison of concentration variation between trials that avoids this problem. With this method, the mean of the absolute value of the difference between successive measurements was used as an indication of concentration variability (CV) for a particular trial. This technique was also used in any case that required the comparison of variability between separate time intervals of the same trial.

Chamber CV was compared during trials in which:

1. The dilution air was varied as concentration remained constant by making the appropriate corrections to the generator speed.
2. The carrier air flow rate through the dust feed was varied as generator speed and dilution air remained constant.
3. The flow rate of the sample line was varied as generator speed and dilution air remained constant using a procedure described by Willeke and Degarmo (1988).
4. The use of a small scraper blade was compared with a larger one when producing the same concentration level.

With reference to the final investigation, the manufacturer of the dust feed supplies scrapers, and corresponding cylinders, with an ID of 1.5 and 0.5 in. Use of the smaller blade reduces the dust volume in the cylinder to 12% of the larger cylinder. To maintain the same concentration level, the small blade must therefore rotate 8.33 times faster than the large blade. Pairs of trials performed on the same day were run to produce the same concentration level of 25 mg/m^3 but using the two scraper types. Prior to this analysis, all other investigations were performed using the large scraper.

Concentration-Response Characteristics

Trials were performed to determine the response of the chamber concentration levels to step changes in generator speed. These trials were performed in anticipation of the need to alter the level based on keyboard input from the operator. In one case, the generator speed was increased to attempt a concentration increase of 5 mg/m^3 from 10 to 15 mg/m^3. This was followed 60 min later by a decrease in speed to reduce the concentration by 10 mg/m^3 to 5 mg/m^3. Another attempt was made in which progressively larger increases followed 10 min later by an equal decrease in rotation speed were induced to create theoretical increases of 0.25, 0.50, 1.00, 2.00, and 4.00 mg/m^3 from a base of 10 mg/m^3.

Procedure Summary

A summary of the standard procedure used for each exposure trial, after the automated system was initiated, involved the following:

1. Attach sample filter cassette to the aerosol monitor after cleaning view volume of the monitor with filtered air.
2. Turn on aerosol monitor, computer, and SIBEC-II board.
3. Turn on regenerative blowers, compressed air through the dust feed, and the filter sample vacuum pump.
4. Manually set the chamber and carrier airflow rates.
5. Initiate the computer program and enter the DC, chamber flow rate, and sample time.

After these preliminary steps were completed, the program activated serial communication with the SIBEC-II board, at which time the initial delay time, computed by the host computer, was entered by the user. The stepper motor was started at the appropriate speed and the solenoid valve connected to the sample line was activated. The program continued to run for the specified time period while displaying the results of the aerosol monitor recordings, or until a key was hit to change the concentration level. After completion of the trial period the generator and solenoid valve were automatically shut off. All other devices were manually turned off.

RESULTS

After all connections had been made and the computer program was written as described, the automated exposure system performed as intended. However, calibration of the dust feed cylinder rotation speed with a stopwatch revealed it to be slightly less than the computed speed. A correction factor was applied to the computer program to compensate for the discrepancy.

Aerosol Monitor Calibration

Results of the aerosol monitor calibration procedure showed the span setting had to be adjusted to give a reading of 195 mg/m^3 to allow the monitor reading to closely compare with the filter measurement. This setting, as well as a similar setting to zero the instrument, was checked during subsequent trials and found to remain relatively constant (±2 mg/m^3 on a scale of 0–200 mg/m^3) without further adjustment. However, over the 2 yr of this research, the instrument reading tended to slowly diminish in relation to the filter measurement, despite frequent cleansing with ultrafiltered air. Because the span setting was already placed near its maximum value, a correction factor was added to the computer program to increase the value of the measurement by a factor of 1.2.

The aerosol monitor drift detection trial produced a linear regression of monitor readings, which increased a total of 0.005 mg/m^3 over the 180-min trial. The magnitude of this drift was assumed to be inconsequential when measuring concentrations over 1 mg/m^3.

Temporal Variation Reduction

Changes in dilution air, when the concentration remained at a fixed level, did not appear to affect the instantaneous variation seen in the aerosol monitor readings in a consistent manner, although these changes did produce a shift in the overall aerodynamic particle size distribution as measured by an impactor (data not shown). Therefore, a flow rate of 0.316 m^3/min (11.15 ft^3/m), which represents a value near the center of allowable flows for this system, was chosen for all subsequent values.

High carrier air appeared to have an obvious affect on concentration variability. The average CV after increasing the flow to 7.67 L/min was 1.124, compared with an average of 0.236 for all data points prior to the increase.

This sudden rise in variation is thought to be due to an increase in the carving action of the carrier air against the dust cake (BGI, Inc., 1989). As the flow rate increased, the stream of air eventually left the groove of the scraper blade and channeled through the dust cake before reentering the return hole in the center of the blade.

Two trials were run to test the effects of the sample train flow rate on CV at DC levels of 10 and 25 mg/m^3. Both trials revealed a significantly higher CV ($p < .003$) at the lowest sample flow rate (Table 1), with lower CV values occurring above a sample flow rate of 4.66 L/min. The results given in Table 1 also reveal that the concentration level remained relatively constant throughout each trial (slope of a regression of flow rate vs. average concentration not significantly different than 0), indicating sample flow rate does not significantly affect the response of the aerosol monitor to the mean level of the aerosol concentration. However, Willeke and Degarmo (1988) reported results that showed changes in concentration over flow rates from 1 to 19 L/min. They attributed this variation to a change in aerosol monitor response caused by a modification of the aerosol concentration external to the instrument as it was transported to the view volume of the monitor. Our results suggest the monitor is capable of distinguishing greater variation in the concentration of the air passing through the aerosol monitor at low sample flow rates, but the average concentration over time is equivalent to monitor recordings taken with a higher flow rate and less concentration variation.

Use of the small scraper blade produced a dramatic reduction in concentration variability between successive aerosol monitor readings compared with readings taken when using the large scraper (Fig. 7). The average CV values for the trials that used the small scraper were 0.47 and 0.52 mg/m^3, compared with 2.30 and 2.79 mg/m^3 for trials using the large scraper while maintaining a chamber concentration near 25 mg/m^3. The data shown in

TABLE 1. Average Concentration and Concentration Variability (CV) for 10-min Time Periods while Sampling at Randomly Chosen Sample Flow Rates During Two Separate Trials

	10 mg/m^3 Trial		25 mg/m^3 Trial	
Flow rate (L/min)	Average concentration (mg/m^3)	Average CV (mg/m^3)	Average concentration (mg/m^3)	Average CV (mg/m^3)
1.20	11.62	0.24	23.52	0.57
2.41	11.85	0.22	22.46	0.51
3.55	12.20	0.20	22.68	0.57
4.66	12.02	0.16	23.61	0.49
5.71	11.65	0.14	23.13	0.50
6.72	12.09	0.17	23.85	0.55
7.67	11.83	0.12	23.55	0.58
8.57	11.64	0.16	23.91	0.50
9.43	11.81	0.13	23.09	0.57

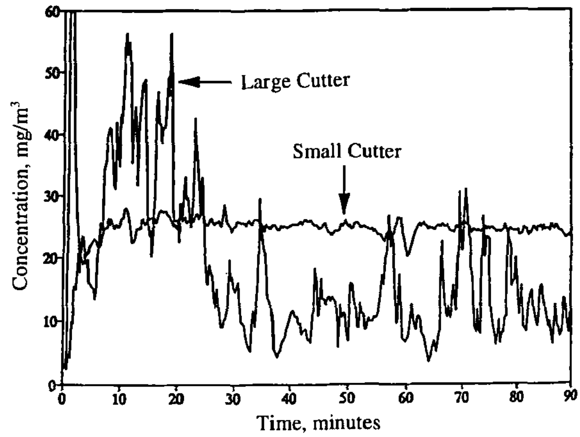

FIGURE 7. Monitor recordings for 2 trials set to produce a desired concentration level of 25 mg/m^3 when using the large and small scrapers.

Figure 7 for the first set of trials using the small and large scraper demonstrate that the small scraper reduced variation and maintained a more consistent average level compared with results when using the large scraper.

Aerosol Monitor Reliability

Of the 31 trials used to test aerosol monitor reliability, 17 were performed while using the small scraper to produce a chamber concentration of 10 mg/m^3, and the remaining 14 trials were performed with the large scraper to produce a concentration of 25 mg/m^3 with results given in Table 2. The minimum change in M/F was 0.78% between 2 trials in the first group and a maximum difference of 26.68% was produced between 2 trials in the second group.

Automation System Implementation

Based on the results presented earlier, the automated exposure system was found to be most effective when using the small scraper together with relatively low carrier air (6 L/min) and dilution air flow rates (0.316 m^3/min). This set of parameters produced the least variation in the aerosol concentra-

TABLE 2. Comparison of the Difference Between Aerosol Monitor-to-Sample Filter (M/F) Ratios Computed for Successive Trials, and the Average Concentration Variability (CV) for All Trials Within Each Group of Trials Performed under Similar Operating Conditions

Trials type	Average difference of M/F ratios between trials (%)	SD of differences in M/F ratios (%)	Pooled average CV (mg/m^3)
Small, 10 mg/m^3	3.36	1.54	0.38
Large, 25 mg/m^3	9.71	9.51	4.06

TABLE 3. Actual-to-Nominal Chamber Concentrations (AC/NC) with Respect to Chamber Flow Rate

Flow Rate (m^3/min)	AC/NC (%)
0.1	6.29
0.2	9.54
0.3	11.97
0.4	15.03
0.5	15.78

tion that was essential to achieve proper control of the aerosol generator when implementing a change in chamber concentration. In order to utilize the system to achieve an actual concentration (AC) level equivalent to the desired concentration (DC), the AC/NC ratio at various flow rates was determined (Table 3). Based on this evidence and the average AC/NC ratio of previous trials operated at the settings mentioned earlier, a value of 12.05% was used for all subsequent trials.

After determining the relationships described by AC/NC and M/F, the system was capable of producing and maintaining an AC equivalent to the DC. Typical results for two trials performed to achieve DC values of 10 and 25 mg/m^3 are given in Figure 8. Five consecutive trials of 180 min, operated at conditions as noted earlier to achieve a DC of 10 mg/m^3, produced concentrations of 10.52, 10.52, 10.57, 10.37, and 10.47 mg/m^3 without changes in speed during the trials. Aerosol monitor recordings of these trials revealed the concentration level in each case remained close to 10 mg/m^3

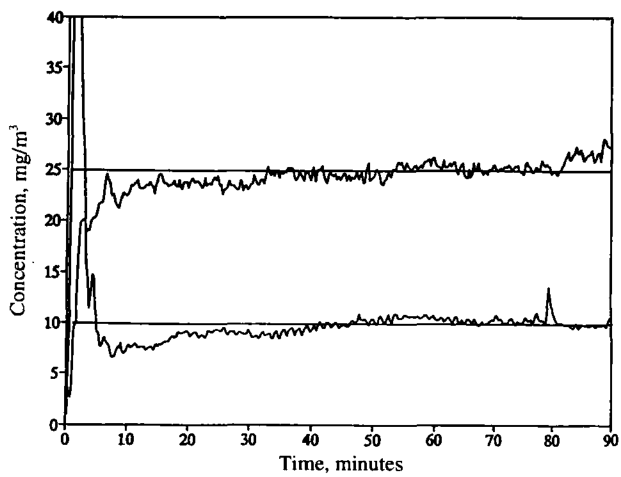

FIGURE 8. Monitor recordings of trials set to produce DC levels of 10 and 25 mg/m^3 with settings chosen to minimize concentration variation.

except for large peaks evident at the beginning of each trial (see Fig. 8), which caused the trial averages to be higher than the DC. In total, 14 consecutive trials were performed with the use of the automated system to achieve a chamber concentration of 10 mg/m^3 in which the average actual-to-expected ratio was 1.023 (SD = 0.067).

Results from trials performed to test the response of the chamber concentrations to changes in generator speed after the concentration had achieved a stable level are shown in Figures 9 and 10. The concentration changes shown in Figure 9 agree closely with the desired changes; however, the modifications shown in Figure 10, especially when small changes were required, do not coincide well with the desired levels. Initially, the average concentration level failed to reach the DC level of 10 mg/m^3, and the first two speed changes appear to have been too small to have an effect on the average concentration level. Visual inspection of the last three speed changes reveal an increase in the slope of the concentration readings after each speed change and initial delay time. These data suggest that a longer time period is required to realize the effect of a small speed change on the concentration level. A separate analysis to determine how much of the delay time and response time can be attributed to aerosol monitor performance, as described by Smith et al. (1987), was not performed. The assumption was made that an operator would allow sufficient time between adjustments for a new concentration level to become well established.

CONCLUSION

The usefulness of an aerosol exposure system depends on its ability to achieve a chamber concentration equivalent to the DC and maintain that level

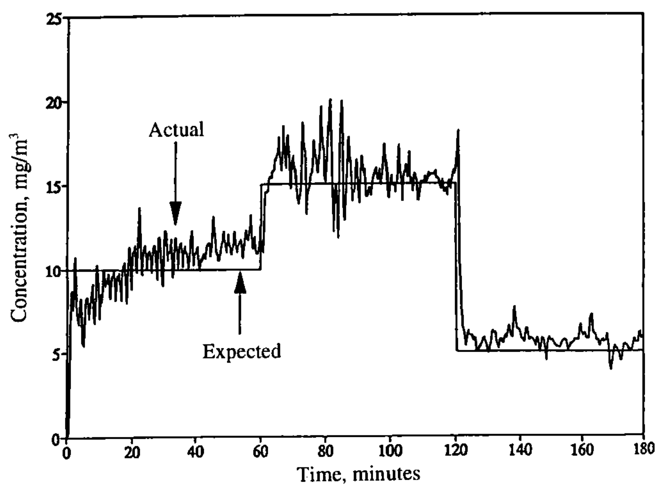

FIGURE 9. Monitor recording of a trial in which the generator speed was changed at specified time intervals to induce a change in chamber concentration to new levels.

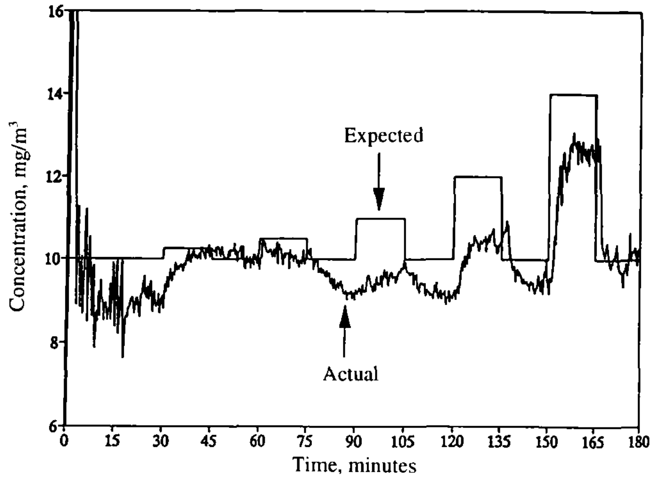

FIGURE 10. Monitor recording of periodic step increases and decreases in chamber concentration of increasing magnitude after reaching a desired concentration level near 10 mg/m³.

with a minimum of variation throughout the exposure period. Results from this research demonstrate that a Wright dust feed can be automated to produce a chamber concentration level near the desired level despite instantaneous variations. Reports that indicated the inconsistent output of this device (Collins, 1975; Hinds, 1980; Wright, 1950) appeared to be justified when using the large scraper. The variation in the daily average of chamber concentrations during actual exposures when using the large scraper initiated the development of this system. However, after determining those factors that caused the greatest reduction in instantaneous variation, the dust feed was capable of establishing and maintaining a DC level throughout each trial period. These developments shifted the utility of this system from one needing to continuously compensate for a concentration level that wandered over time to a system that was capable of establishing the correct generator speed needed to achieve a DC level and provide a visual display of chamber concentrations.

The advantage an automated system provides, in the form of offering visual feedback and control, is dependent on the ability of the aerosol monitor to accurately measure chamber concentrations. As indicated earlier, the instantaneous variation of the aerosol monitor recordings increases with an increase in the chamber concentration level and when using the large, rather than the small, dust feed scraper. Furthermore, the results shown in Table 2 indicate a positive correlation between instantaneous concentration variation and M/F variation and, consequently, less confidence can be placed in the aerosol monitor to indicate the true concentration level when operating with these conditions. The graphical display of the aerosol monitor recordings could be altered to display upper and lower confidence limits about each recording based on the relationship between monitor reliability and concentration variation.

The effect of chamber flow rate on chamber losses, aerosol particle size distribution, and, consequently, aerosol monitor response precluded attempts to change chamber aerosol concentrations by manipulating the flow rate. The greatest disadvantage to using the small scraper is the large increase in the number of times the dust cylinder must be changed during an exposure compared with using the large scraper. Therefore, a decrease in chamber flow rate, which causes a corresponding decrease in generator speed, may be warranted in cases when the small scraper is used to produce high concentrations. If an exposure protocol requires a change in the flow rate, a regression between aerosol monitor response and flow rate should be developed and incorporated in the computer program to update the monitor-reading correction factor for the new flow rate. A technique for modeling the instrument response based on the mass median diameter and geometric standard deviation of the aerosol is given by Smith et al. (1987).

If it is desired that the chamber concentration, as measured by the sample filter (AC), be as close as possible to the DC, then control of the chamber level should be based on the time-weighted average of the aerosol monitor readings. In this case, the computer program must be written to change generator speeds to a new concentration level based on the influence of readings taken during start-up conditions. For example, if the readings taken during the first few minutes of the trial show a large spike in concentration, then all subsequent readings must be less than the DC to make the time-weighted average and therefore the filter measurement equivalent to the DC at the end of the trial period.

When a change in the concentration level is desired during an exposure, an automated exposure system of this type should be capable of determining the correct generator speed and the system must respond to the new desired level as expected. Results from this research demonstrate that a large change (>2 mg/m^3) will provide a quicker response and achieve a new level more accurately than will small changes. The inconsistent response of the generator demonstrates the problem of implementing a standard feedback control methodology to this system. However, if more trials support a deterministic pattern to the response, a feasible feedback control system could be developed in which the computer program is written to automatically initiate the appropriate control action. Further work will focus on this problem and on the use of statistical process control techniques to determine the mean concentration levels "hidden" in the instantaneous variation seen in the aerosol monitor recordings and provide confidence limits about each data point as alluded to earlier.

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