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Feedback Control of Particles in Fluid Media

04/01/94 - 03/31/96

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5 R03 OH03185-02

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LIST OF ABBREVIATIONS

A/D . . . . . Analog-to-Digital
AC/NC . . . . . Actual-to-Nominal Concentration ratio
AC . . . . . Actual Concentration
AR . . . . . Autoregressive
ARIMA . . . . . Autoregressive Integrated Moving Average
CAD . . . . . Computer-Aided Design
CSTR . . . . . Continuously-Stirred Tank Reactor
CV . . . . . Coefficient of Variation
D/A . . . . . Digital-to-Analog
DC . . . . . Desired Concentration
EPC . . . . . Engineering Process Control
EWMA . . . . . Exponentially Integrated Moving Average
LCL . . . . . Lower Control Limit
M/F . . . . . Monitor-to-Filter ratio
MA . . . . . Moving Average
MSE . . . . . Mean Squared Error
NC . . . . . Nominal Concentration
PC . . . . . Personal Computer
PID . . . . . Proportional-Integral-Derivative
PLC . . . . . Programmable Logic Controller
PRBS . . . . . Pseudo-Random Binary Sequence
SA . . . . . Sum of (controller)Adjustments
SPC . . . . . Statistical Process Control
UCL . . . . . Upper Control Limit

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SIGNIFICANT FINDINGS

During this research, the feasibility of applying a computerized feedback control system to maintain uniform concentrations of an aerosol in an environmental test chamber was studied. Prior to application of a feedback control system to automatically adjust a process output variable, an analysis of the response behavior of the system to a change in input level should be performed. Therefore, many preliminary trials were performed to determine whether concentrations responded to a change in either generator output rate or dilution air flow rate in a predictable manner regardless of operating condition.

Results from the trials indicated above showed no significant difference in the mean values of parameters (concentration steady-state level after change, time to reach steady-state level, delay time after change in input and start of change in output) used to describe the response of concentrations to a step-change in generator output rate. However, individual trials results indicated a broad range of responses about mean levels even when operating with the same conditions (starting concentration level, dilution air flow rate). Therefore, attempts to model and simulate the response prior to application of the control system were possible but with the understanding that variations will exist on a trial by trial basis. Individual system models were developed for each of five flow rates ranging from 0.1 to 0.5 m^3/min to compensate for changes in response due to flow rate. Furthermore, feedback control of very high concentrations (>25 mg/m^3) was found to be completely unpredictable.

Because of the large amount of variation in the series of samples taken with a real-time aerosol monitor, a novel technique for disregarding much of the instantaneous variation was devised. This method, based on the exponentially-weighted moving average (EWMA) of the measurements, was compared with a commonly implemented feedback control method that utilized a proportional-

integral-derivative (PID) algorithm. This method proved to be capable of maintaining chamber concentrations near a desired level in a manner similar to that of the PID controller when using the aerosol generator to control concentrations. Furthermore, this method significantly reduced to both the total magnitude and number of corrections required to maintain concentrations near a desired level. In addition, the EWMA method may be applied without an understanding of the step-response characteristics of the process. ~~This fact was especially important for systems as~~

A major emphasis of this research was concerned with the application of a feedback control system to automatically adjust the dilution air flow rate to adjust chamber concentrations. Again, the EWMA and PID control methods were tested when manipulating flow rate. Results from these trials indicated that large changes in flow rate resulted in a more predictable response in concentrations than did low changes flow rate. However, when large changes in flow were induced, the response of the concentrations was relatively consistent and allowed for an identification and estimation of a system model for simulation of the PID control method prior to actual application. Furthermore, the PID method was able to accurately produce small corrections in concentration with changes in flow rate than did the EWMA method.

Constantly changing the flow rate to control concentrations also significantly increased the overall variation in the measurements about a mean level. However, application of either of the control methods produced concentration measurements with an average near a desired level to a greater extent than when no feedback control was applied. In general, control of chamber concentrations was feasible by manipulating dilution air flow rate but with less accuracy than when controlling the aerosol generator at a constant flow rate.

USEFULNESS OF FINDINGS

There are numerous areas in the Occupational Health and Industrial Hygiene fields where the concepts and results developed in this investigation should prove very useful. There is a current interest in using dilution air for controlling concentrations of contaminants in confined spaces. As a result of this research it is clear that the use of dilution air flow rates will not always follow the precise predictions made by mathematical models and that the use of an appropriate sensor coupled with computer feedback control can be used to minimize exposure concentrations without requiring workers to enter the workplace to periodically monitor and adjust the dilution system. Such methodology, however, requires, as demonstrated in this research, a detailed knowledge of the sensor/controller interactions.

Another area of potential application would be in the use of such a system to control buildup of contaminants in rooms in buildings associated with Sick Building Syndrome. While the actual source(s) of SBS are not always clearly delineated, many of the symptoms appear to be related to providing adequate airflow in the office space. Parameters such as CO_2 or other gases could then be used as surrogate contaminants for monitoring purposes with the implementation of an appropriate sensor and feedback control system on a room by room or area by area basis. By adjusting the flow rates in anticipation of human occupancy significant cost savings might be realized in the amount of air to be processed for the building and yet provide a comfortable working environment.

ABSTRACT

This research was concerned with the investigation of issues related to two specific aims: (1) to investigate the response of concentration levels in an environmental chamber to various changes in aerosol generator output rate and chamber air flow rate, and (2) to investigate the use of a novel control method based on theory associated with statistical process control techniques to implement automatic feedback control of the instantaneous concentration levels by manipulation of either the generator output rate or the chamber air flow rate.

An environmental chamber was used as the test device for this research. A personal computer (PC) was connected to an aerosol monitor to take and record chamber concentration measurements on a real-time basis. The PC was also connected, via the serial port, to a microprocessor controlling the output rate of an aerosol generator and to a valve positioning device to control air flow rate through the chamber. This apparatus allowed the application of a computerized feedback control system for control of the chamber aerosol concentrations.

Initial trials were performed to establish the relationship between measurements made by the aerosol monitor (M) and those made by gravimetric analysis of a sample filter (F). This M/F ratio was shown to be linear and decreasing with an increase in flow rate. These trials were also used to establish the relationship between losses of the aerosol in the chamber and flow rate. A curvilinear, upward trend was obtained between losses and flow rate.

Many trials were performed in which a step-increase in either generator output rate or a step-decrease in flow rate were instigated to establish a mathematical relationship between the magnitude of the step-change and the resulting response of the chamber concentrations. In general, the response was not significantly different in relation to operating condition but large variations in response were seen about some average response pattern. A model estimation procedure that utilized a pseudo-random binary sequence (PRBS) and a computer-aided design program was used to determine the model that described the average system response and for simulation of the feedback control system.

The novel control method investigated in the second specific aim relied on a formulation of the exponentially-weighted moving average (EWMA) of the concentration measurements and the establishment of control limits based on an estimation of the concentration standard deviation at each sample period. This method was designed to make corrections only when the concentration level was high or low enough to cause a control limit to cross the desired concentration level. This method was compared with a commonly used control method that involved the formulation of a proportional-integral-derivative (PID) control algorithm.

Results from this research demonstrated that both control methods significantly improved the "tracking" ability of the chamber system to maintain concentrations near a desired level when using either the generator ($p = 0.012$) or the flow rate ($p = 0.017$) to control concentrations. An analysis of the total adjustments required to perform each control method revealed that the EWMA method required significantly less total adjustments than did the PID method ($p = 0.010$ and $p = 0.009$ for generator and flow-rate control respectively). When controlling concentrations with adjustments in flow rate, large changes in flow produced a more predictable response in concentration than did small changes. Furthermore, both control methods significantly increased the mean squared error between measurements and an average level over trials that did not employ feedback control ($p = 0.003$). The PID method was more effective at producing small corrections than did the EWMA method under flow control.

BACKGROUND

Airborne Contaminant Control

Automatic control of building ventilation systems is a well developed science (Letherman, 1981). These systems are typically designed to provide the occupants of the building with a comfortable environment and, therefore, control of temperature and humidity are often the two most important design considerations. Ventilation for contaminant control in occupational settings has been accomplished by either dilution ventilation or local exhaust ventilation with the major emphasis of research on the development of local exhaust systems (McDermot, 1985). These systems have a high collection efficiency and require less airflow than dilution ventilation systems and are, therefore, generally more cost effective. However, there are many cases where control of contaminants can only be accomplished with the use of dilution ventilation. When industrial and commercial exhaust air is recirculated for energy conservation, safeguards against employee health hazards may be controlled by the proper mix of recirculated and fresh air (Decker and Parker, 1975). Other applications of dilution air for contaminant control include the control of dust levels in coal mines (Courtney et al.,1986), control of carbon monoxide levels in road tunnels, and radon gas levels in homes and office buildings (Cavallo, 1992).

Despite the need for contaminant control based on dilution air flow rates, no journal articles were found which describe a feedback control system to automate this process. (The term "feedback control" is used here in terms of a computerized system designed to measure the concentration of a contaminant and activate an appropriate mechanism capable of changing the concentration to some desired level.) The development of an automated dilution air system may be possible, however, by combining ventilation control theory with the present knowledge of aerosol and gas monitors used

to measure particulates or gases in industrial settings on a real-time basis (Edmonds et al., 1993; Gressel et al., 1988; Gressel et al., 1992; O'Brien et al., 1992; Smith, 1987; Smith et al., 1987).

Control of exhaust fans and building environmental factors frequently rely on the use of static pressure, temperature and humidity sensors for the information needed to make control decisions to activate the appropriate mechanisms (actuator) which govern air flow. They are relatively easy to control automatically because input signals from the pressure sensors are directly proportional to an output signal sent to an actuator. These types of sensors are also manufactured to be accurate and dependable over long periods of time.

Control of air flow based on particulate concentration levels, or particulate numbers, may be complicated by a non-linear relationship between sensor input and the air-flow rate needed to affect a desired concentration level or number. A number of reports have been written which indicate optical aerosol monitors are not always accurate, especially when sensing an air volume which contains a variety of dust types or when the particle size distribution of the aerosol changes over time (O'Brien et al., 1989; Smith et al., 1987; Willeke and Baron, 1990). Furthermore, a recording of monitor readings often exhibits a random, or "stochastic" tendency because of incomplete mixing of aerosols in air. This type of sensor data complicates the ability of a computer control algorithm to make appropriate control decisions because of the uncertainty associated with individual readings to indicate the actual concentration level at any given time.

This research was instigated with the purpose of determining whether ventilation systems can be automated with the use of a feedback control system based on information received from a real-time aerosol monitor for control of airborne particulate contaminants. However, our understanding of the interactions of the control and sensing elements suggested that development of a system of this type first be tried on a pilot scale model such as an environmental chamber used for inhalation

toxicology research. This procedure allowed for an investigation of the feasibility of automatically sensing airborne particle concentrations and the subsequent control action required to maintain those concentrations near a desired level within a space with simple geometry and laminar air flow. Added complications associated with applying this methodology to a building ventilation system, for example, would require further research.

Chamber Control Systems

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 and Irwin, 1982; Hirano, 1987). During two of these studies (Coggins et al., 1989; Hirano, 1987), a mass flow controller was operated automatically to attain a desired aerosol concentration level. The flow controller was therefore used to manipulate the dilution air stream 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 studies cited above depended on the use of a generator which 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, have 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 by these researchers as the manipulated parameter. However, due to the high cost of mass flow controllers, these devices are not typically used in industrial settings.

Feedback Control Methods

During this research, two different approaches were taken when applying a computerized system to control aerosol concentrations in the test chamber. The first method utilized feedback control theory established by mechanical and electrical engineers (sometimes referred to as engineering process control (EPC). The second control method represented a novel approach based on theory associated with statistical process control (SPC). A description of each method and a comparison between the two is given below.

Engineering Process Control. A mathematical description of the relationship between the input (desired concentration) and the output (actual chamber concentration) of a process requires the use of differential equations. These equations, in their simplest form, include a variable for the input, u, and output, y, together with constants and an expression for the derivative of the output (Eq. 1).

$$\frac{dy}{dt} = ry + bu \tag{1}$$

The derivative term is necessary in the equation above because one is trying to express the change in the output over time due to some constant change in the input.

A direct relationship between the input and output variables cannot be obtained when expressed in this form because of the differential term. Therefore, the equation must be "transformed" from an expression in terms of time, t, to one in terms of "s" as defined by the Laplace transform (Eq. 2).

$$sY(s) = rY(s) + bU(s) \tag{2}$$

A direct (algebraic) relationship between input and output can now be obtained (Eq. 3.)

$$Y(s) = \frac{b}{s - r} U(s) \tag{3}$$

As with Eq. 1, Eq. 3 represents the simplest expression for an input/output relationship in the Laplace domain. More complex relationships between input and output will involve numerator and denominator polynomials (in "s") of higher degree. In general, the numerator can be designated as the polynomial "B" and the denominator as "A". A block diagram can then be made to illustrate the relationship between u and y (Fig. 1).

When a control system is connected to a computer, a digital input and output signal results from the operation of the analog-to-digital (A/D) and digital-to-analog (D/A) converters, respectively, used to measure and send these signals. The mathematical representation of a digital signal is given by the *z*-transform. The z "operator" essentially denotes a discrete time interval equivalent to the time between samples taken by the A/D converter. The development of a transfer function in the *z* domain is analogous to that in the s domain. The relationship between the Laplace transform and z-transform is given in the Appendix.

Regardless of the type of control system, when a measure of the output of the process, y, is used to affect a change in the process, a closed-loop or "feedback" system is employed (Fig. 2). The goal of a feedback control system is to compare the input with the output level and automatically adjust the process, or "plant", to compensate for the error, e, between the two levels. In

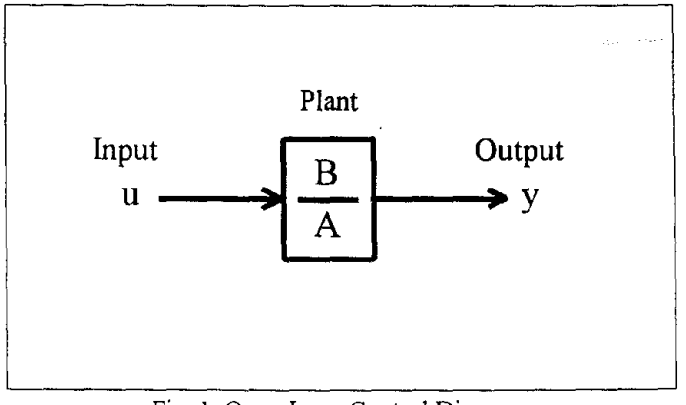

Fig. 1. Open-Loop Control Diagram.

practice, after a change in input level, the output eventually reaches some steady-state level which is less than the reference level. Furthermore, the behavior of the measured response in the output when adjusting to the new level may oscillate to a large degree prior to reaching a steady-state level. To solve these problems a "controller" is added in series before the plant to manipulate the input to the plant to reach the desired level with a minimum of oscillations (Fig. 3). In this situation, the initial input is referred to as the "reference" input, r, equivalent to the desired level. The plant input, u, is now the "corrected" input to the plant to obtain an output equal to the reference input.

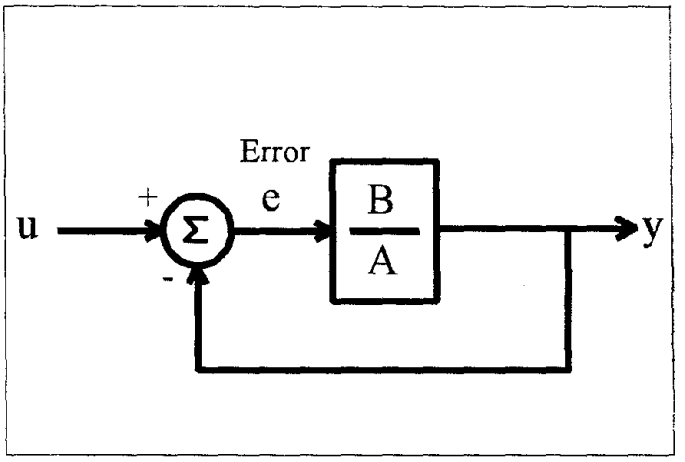

Fig. 2. Closed-loop control diagram.

A proportional-integral-derivative (PID) controller is one method for correcting the input to the plant to obtain the desired output. The proportional term sets the magnitude of the input signal but does not help to achieve a steady-state level near the desired level. The integral term ensures a steady-state level that is equal to the desired level. Furthermore, the derivative term tends to decrease oscillations in the measured response. Each of these terms has an associated constant which can be manipulated (tuned) to achieve the desired output response. This tuning process can be done "off-line" for a system which does not have a known dynamic model. However, if the dynamic model has been properly identified then a computer-aided design (CAD) program may be used to simulate

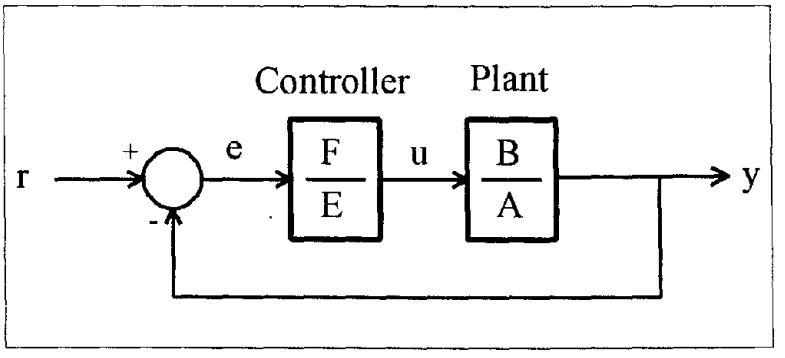

Fig. 3. Feedback control with controller.

the response of the system and appropriate P, I, and D constants chosen prior to operating the actual control system.

As an example of the concepts discussed above, the response of a closed-loop system is given in Figure 4. The response does not oscillate but the resulting steady-state level is well below the desired level as alluded to above. Therefore, a controller, containing at least an integrator, is required to ensure a steady-state level at the desired (reference) level. Other curves in Figure 4 indicate the theoretical response of the chamber system when using PID control with different tuning constants as listed in the figure (K_P, K_I, and K_D refer to the P, I, and D constants respectively). These simulated curves serve to demonstrate the large change in response that can occur with a slight change in only one of the constants. An inappropriate choice of constants may even result in a completely unstable system with oscillations that have amplitudes that grow exponentially over time.

The simulations shown in Figure 4 were performed with the use of the CAD program, MATLAB™ (Natick, Mass.), after other techniques had been followed to estimate the plant transfer

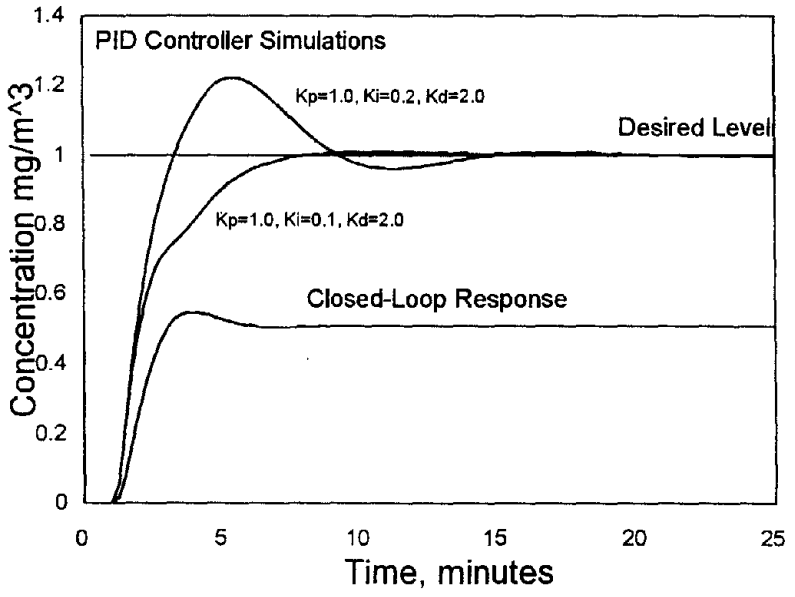

Fig. 4. Open and closed-loop simulation of the aerosol generating system.

function polynomials B and A for the test chamber system. These "system identification" techniques will be discussed in a subsequent section.

Model Development. As alluded to above, proper identification of a dynamic model of the control system is advantageous prior to application of the system. However, a typical data series from an aerosol monitor used during a chamber trial contains a significant amount of noise in relation to the level of the measurement (O'Shaughnessy and Hemenway, 1994). In addition to the large amount of noise, time series analysis of the data reveals it to be highly autocorrelated. A consequence of high autocorrelation is a tendency for the data series to "wander" about a mean level. Therefore, in regards to the discussion above, the output (concentration) has a natural tendency to change even when the input (generator output rate) remains constant. Difficulties arise, then, when trying to establish a relationship between a change in the input and its corresponding change in the output level. This relationship is apparently "hidden" within the dynamics associated with the autocorrelated nature of the aerosol measurements. Techniques are therefore needed to separate the dynamics of the output influenced by both the inherent noise and changes in the input level.

To solve the problem posed above, the "system identification" methods given by Ljung (1987) are useful. These methods incorporate statistical theory developed for time series analysis. The primary goal of time series analysis is to develop a mathematical model of measurements taken sequentially in time that reduces the data to pure white noise (Box and Jenkins, 1992). White noise is a series of normally distributed, random numbers with a mean of zero and constant variance, σ^2. The model relates the present data value with weighted functions of previous data and noise, and if formulated correctly, accounts for any correlation between data points and noise values. The two basic models associated with time series analysis are known as the autoregressive (AR) (Eq. 4) and moving average (MA) (Eq. 5) models. These models are given below in their most elementary form

where y_t is the data value; a_t is a component of the white noise process at the present time, t; and ϕ and θ are weighting constants.

$$y_t = \phi y_{t-1} + a_t \tag{4}$$

$$y_t = a_t - \theta a_{t-1} \tag{5}$$

It may be necessary to combine these models (ARMA) and/or remove any trends in the values by first taking the difference of each successive value (ARIMA, where the "I" stands for "integration". This differencing is an integration procedure if one builds the model from white noise toward the data series.)

It is common practice to make use of a back-shift operator, "q^{-1}", where:

$$q^{-1} y_t = y_{t-1} \tag{6}$$

With this notation, it is possible to develop a transfer function y_t in terms of a_t where, for the AR and MA models respectively:

$$y_t - \phi y_{t-1} = (1 - \phi q^{-1}) y_t = a_t \tag{7}$$

$$a_t - \theta a_{t-1} = (1 - \theta q^{-1}) a_t = y_t \tag{8}$$

Therefore, the transfer function of the ARMA model is:

$$y_t = \frac{1 - \theta q^{-1}}{1 - \phi q^{-1}} a_t \tag{9}$$

In actual practice, the AR and MA components of the model may be more complicated, containing weighted values of several time points into the past instead of just one as shown here. A general expression for the transfer function can be written as:

$$y_t = \frac{D(q)}{C(q)} a_t \tag{10}$$

The transfer function given in Eq. 10 describes the relationship between the input as white noise and the resulting output. As described earlier, a control system also contains an inherent relationship between the physical input to the process and the resulting output. The relationship between the output and both the noise and physical inputs may be described in its simplest terms as shown in Eq. 11.

$$y_t = G(q)u_t + v_t \tag{11}$$

where:

$$G(q) = q^{-nk} \frac{B(q)}{A(q)} \qquad v_t = \frac{D(q)}{C(q)} a_t \tag{12}$$

The resulting expression is given in Eq. 13.

$$y_t = \frac{B(q)}{A(q)} u_{t-nk} + \frac{D(q)}{C(q)} a_t \tag{13}$$

The polynomials A and C have the general form:

$$A(q) = 1 + A_1 q^{-1} + \ldots\ldots + A_{nA} q^{-nA} \tag{14}$$

The polynomials B and D have the general form:

$$B(q) = B_1 + B_2 q^{-1} + \ldots\ldots + B_{nB} q^{-nB+1} \tag{15}$$

where, nA and nB are the orders of the respective polynomials and nk is the number of delays from input to output. Most ventilation systems will exhibit some time delay between a change in the input level and a corresponding change in the output as indicated by the number of delays, nk.

The input/output relationship shown in Eq. 13 is referred to as an autoregressive-integrated-moving-average model with exogenous inputs (ARMAX) when the polynomials A(q) and C(q) are equivalent (Ljung, 1987). This mathematical representation of the aerosol generating system therefore satisfies the need for separate dynamic models for both the physical system and the measurement noise as mentioned above. Methods used to acquire an ARMAX model for the aerosol generating system will be given in a subsequent section.

Statistical Process Control.

Statistical process control (SPC) is a collection of techniques useful for improving product quality by allowing an analyst to locate and remove root causes of quality variation (Vander Weil et al., 1992). When implementing SPC, the data being analyzed is plotted on a chart relating

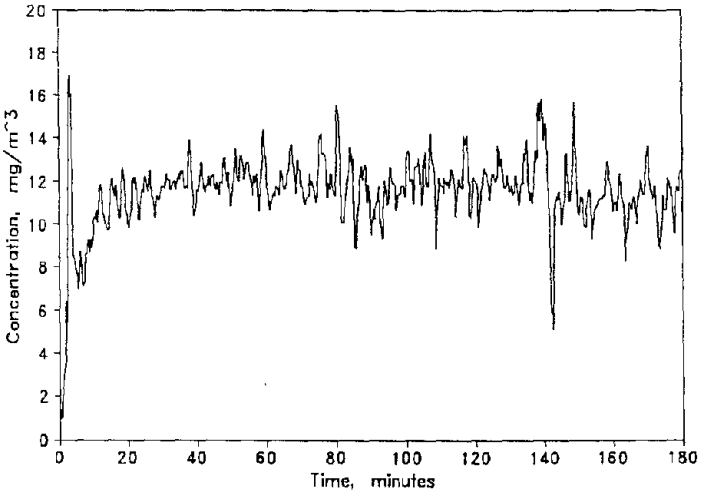

Fig. 5. Typical aerosol concentration measurements.

the process characteristic with time. The charted points are then compared to upper and lower control limits which are statistically derived from previous data. The control limits are normally set at 3 standard deviations on either side of the mean and referred to as the upper control limit (UCL) and lower control limit (LCL). When a new data point falls outside these bounds, some action may be taken to correct the process. This particular method of process monitoring is referred to as a Shewhart or "x-bar" chart (Shewhart, 1931).

Although the concept of using SPC in feedback control systems has been discussed in the past, most notably by Box and Jenkins (1970), the idea has only recently reappeared in the literature (Badavas, 1993; Box and Kramer, 1992; Harris and Ross, 1991; Montgomery and Mastrangelo, 1991; Vander Weil et al., 1992). The utility of incorporating SPC with engineering control theory is related to the limits bounding the mean of the process. If the process, with its inherent white noise, remains within the control limits no action is taken. This approach allows the process to fluctuate within a certain range without the control system making corrections to disturbances attributed only to the noise of the system.

Given the noise qualities inherent to the continuous measurements of many processes, monitoring data may be interpreted more easily if they are mathematically smoothed to reduce the variations caused by the measurement and/or process. One SPC technique, referred to as the exponentially weighted moving average (EWMA), can be applied to monitor data for both control and data smoothing applications (Eq. 16).

$$Z_t = \lambda Y_t + (1-\lambda) Z_{t-1} \tag{16}$$

where:

Z_t = EWMA value at time t,
Z_{t-1} = EWMA value at time t-1,
Y_t = the actual data value at time t,
λ = a weighting constant ($0 < \lambda < 1$).

The value given to λ determines the "memory" each EWMA derived number will have for previous EWMA numbers. As the value for λ approaches 0, the influence of previous numbers becomes greater, and the plotted line becomes smoother. Likewise, when λ approaches 1, previous numbers become less significant to the current EWMA number and it begins to approximate the actual process data values. The EWMA statistic can be used to enhance the underlying process level while diminishing the relative amount of total variability recorded by the monitor. This technique has been evaluated recently as a means of applying SPC to time series which exhibit a high degree of autocorrelation of successive data points (Harris and Ross, 1991; Montgomery and Mastrangelo, 1991). High autocorrelation in a time series, for example, would be indicated by a large value ϕ in Eq. 4 where, $0 < \phi < 1$.

A novel EWMA process control method was developed as part of this research to maintain a process within limits and minimize the number of control actions. The control chart for correlated measurements developed by Montgomery and Mastrangelo (1991) uses an EWMA of the process measurements to indicate the average value of the process at any time. These values are then plotted with control limits that continuously change in relation to how well the EWMA predicts the process average. If, for example, the process is "in control", the EWMA is a good predictor of the average and the measurements stay within the control limits. However, if a sudden disturbance causes the process to shift, the EWMA will no longer adequately predict the mean and the measurements will subsequently fall outside the limits.

As alluded to above, The EWMA statistic is a prediction of the process level over time. The error between the calculated EWMA and the actual measurement is known as the "residual". As developed by Montgomery and Mastrangelo (1991), an EWMA of the residuals, e_t, can be used to estimate the standard deviation of the process and establish control limits for charting a correlated

process as given below:

$$\Delta_t = \alpha|e_t| + (1 - \alpha)\Delta_{t-1} \tag{17}$$

Like the EWMA of the measurements, the EWMA of the residuals, is a good predictor of the standard deviation of the measurements at any sample time. Control limits are then established by multiplying Δ_t by 3.75 and added to the EWMA of the measurements. (A value of 3.75, rather than 3, is needed to obtain limits of ± 3 standard deviations from the mean because of a bias in the distribution of Δ_t from that of a normal distribution (Montgomery and Mastrangelo, 1991)).

As described above, the EWMA control chart was designed to allow an autocorrelated process to "wander" over time. Corrective action only occurred when an "outside" disturbance was great enough to cause the measurements to become greater or less than the control limits. However, one of principle goals of a feedback control system is to maintain a process near a desired output level. Therefore, a novel approach was taken to incorporate this EWMA control chart into an algorithm for automatically determining when corrective action was needed in relation to the desired level. This control method was designed with control limits based on the EWMA of the residuals as described above with the exception that corrective action would take place whenever either control limit crossed the desired (reference) line. An example of this procedure is given in Figure 6.

Control Method Comparison. The two control methods discussed above will be referred to as the "PID" method and the "EWMA" method throughout this text. In the first case, the controller consists of a set of three algorithms that act together to modify the response of the system to a change in the input level. A set of constants associated with the three PID algorithms will result in a certain response pattern for a given process dynamic model. If the physical qualities of the process change, the same PID constants will result in a different response pattern. Therefore, the PID

method is dependent on a good knowledge of the process model. Furthermore, the process qualities cannot change significantly over time once a set of constants has been chosen that result in a favorable system response.

The dependence of the PID control method on the values of the controller constants and on the process dynamic model results from the fact that a correction is made at each sample period. For example, when a correction is required, the control system reacts to the relatively large difference between the present process level and the desired level and makes a correspondingly large change in output signal. One sample-time later, the comparison is made again except the system has not risen to the new level in the short time span between samples. Therefore, a second correction is made in addition to the first one. This process can result in over-corrections, for example, if the proportional constant, K_P, is too large. Therefore, the PID constants must be chosen in relation to the dynamic response made by the process to a change in input level.

When applying the EWMA control method, a single correction is made sufficient to bring the process level to a new desired level. Enough time is then allowed for the process to reach a steady-state level prior to making further comparisons of the control limit "locations". This method essentially "ignores" the dynamic response of the system after a correction and, therefore, can be applied to a system in which the dynamic model is not known. This method only requires a knowledge of the proportional

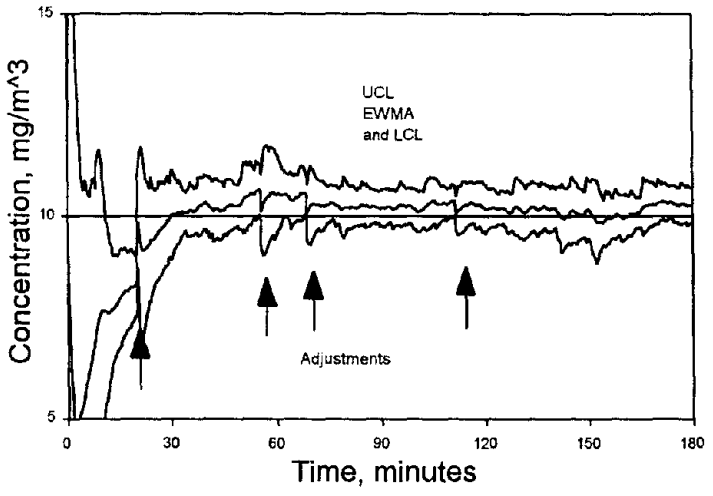

Fig. 6. EWMA control applied to chamber aerosol concentrations.

relationship between a change in the input and the eventual process level resulting from that change.

Another difference between the two methods is related to their reaction to noise in the system. The PID method will react to small changes in the measured variable caused by noise as well as to large changes caused by some outside disturbance. The EWMA method, however, only reacts to large disturbances, or drifts, that eventually cause a significant shift from the desired level.

The PID method was chosen for analysis during this research because it is a well known and commonly implemented feedback control method. Many commercially available programmable logic controllers (PLCs) used in industry contain the PID algorithms. However, a new method capable of disregarding the noise often seen in aerosol monitors was deemed desirable for maintaining a controlled ventilation system with a minimum of corrections.

System Identification

As mentioned above, an identification technique was needed that could separate the dynamics of the output that are a result of the noise inherent to the measurements from those that result from a change in the input level. Typically, an aerosol production system is run with a constant generator output rate determined from past experience to produce a chamber concentration near some desired level. A series of data can be collected from such a trial with an aerosol monitor connected to a computer via an A/D converter. Time series analysis techniques can then be used to develop a noise model as given in Eq. 10. However, if feedback control is to be implemented to compensate for either the natural drifting behavior of the chamber concentrations and/or other variables which affect concentration (e.g., aerosol loss rate, changes in dilution air flow rate), then the relationship between a change in the input level and its corresponding effect on the output level must also be understood. Therefore, attempts must be made to change the input level (generator output rate) in some fashion

during a trial run to determine the corresponding response in output levels (chamber concentration).

Establishment of a suitable system dynamic model as given in Eq. 13 involves first the identification of the proper model in terms of the order of the transfer function polynomials, and secondly involves an estimation of the coefficients that make up the polynomials. The identification method chosen for this research involved the application of "pulses" of dust to establish the subsequent response of the chamber aerosol concentration in terms of a reactor model. The coefficient-estimation process employed the use of a pseudo-random binary sequence (PRBS) of inputs to the plant (Astrom and Wittenmark, 1984; Ljung, 1987; Davies, 1970).

A PRBS is a random sequence of 1's and -1's which, in this case, was used to generate random step-changes in the chamber concentration level to satisfy the requirements stated above. After performing such a trial, a CAD program can be used to perform the necessary least-squares identification procedures to compute the transfer functions given in Eq. 13. In general, this identification procedure involves a regression analysis between the measurements and a dynamic model of a given polynomial order (to obtain B/A) followed by a time series analysis of the residuals (to obtain D/C).

SIGNIFICANCE

Results obtained from this research will have immediate relevance to investigators involved in inhalation toxicology research. In order to more accurately determine dose-response relationships, future inhalation protocols will demand greater precision in the level of the dose administered which may be met with the proposed system. There may also be a need to make a sudden change in the level of the dose during an exposure, as when using animal studies to test the validity of short-term exposure limits. The same is true for studies involving the testing of respirators, and active and passive industrial hygiene monitors of contaminants (Yao, 1993). In these cases, the relevance of the study depends on the ability of the test chamber to produce and maintain a desired concentration (DC) level despite inconsistent generator output rates and/or chamber losses. The proposed automated system would aid these researchers by providing controlled levels of the contaminant under investigation.

Other uses for the methodology developed during this research are related to ventilation control as implied in the sections above. We believe the technology applied to aerosol and other airborne contaminant sensors has improved to the degree in which these devices can be utilized to automatically control ventilation rates. However, a great deal of research, beyond the scope of this study, would be needed prior to implementation. The actuators needed to control ventilation rates, and the computers and related equipment required for an automated system, have been available for over a decade. It is our intention that results from this research will allow the combination of the devices mentioned above, with a computer algorithm based on either the PID or EWMA technique, to allow the removal of airborne contaminants from the workplace by dilution ventilation.

SPECIFIC AIMS

The proposed studies are concerned with the development of an automatic feedback control system to maintain aerosol concentration levels in an animal exposure chamber near a desired value. Although all research was carried out with the use of an inhalation exposure chamber, and will have obvious significance to the field of inhalation toxicology, this work was conducted in a way that will also benefit the design of ventilation systems needed to protect workers from exposures to airborne particulates and gases, as well as other occupational settings where control would benefit from the use of feedback control concepts.

The overall hypothesis for this research implied that an inhalation chamber could be used as a test vehicle for the study of aerosol concentration levels on a real-time basis. The central portion of the chamber was designed to facilitate the laminar flow of air across shelves normally occupied by animal cages. With the ability to make fine adjustments in chamber flow rate and aerosol generator output, aerosol concentrations can be maintained at a uniform level for extended periods. Therefore, the chamber provided a controlled environment for the production and manipulation of aerosol concentration levels by either generator production rate or chamber flow rate.

Our preliminary studies have been concerned with the development of a computerized system to automatically control the dust generator output rate and a valve actuator needed to control chamber flow rate. These devices, together with a real-time aerosol monitor to "instantaneously" measure concentration levels, have been connected to a personal computer to allow the operator to change concentration levels during an exposure trial based on a display of the aerosol sensor reading on the computer monitor. This research extended this system to include the development of the proper computer algorithm needed to properly control concentration levels without operator

intervention.

The proposed studies were approached through the following Specific Aims:

Specific Aim 1: Investigate the response of chamber concentration levels to various changes in generator speed and chamber air flow rate.

Specific Aim 2: Investigate the use of statistical process control techniques to implement automatic feedback control of the instantaneous concentration levels by manipulation of the generator speed and dilution air flow rate.

The research associated with "Specific Aim 1" involved the determination of the underlying dynamic model and investigating whether the chamber aerosol concentrations respond in a linear manner (is the model correct for all operating conditions?). The second specific aim involved research associated with the establishment of a novel control method and the comparison of that method with a well established control method. Furthermore these control techniques were investigated in relation to their performance when controlling chamber concentrations by manipulating either the aerosol generator or the chamber dilution air flow rate.

MATERIALS

Chamber Specifications and Operation

Research in inhalation toxicology initially involves the exposure of test animals to an aerosol. During a typical exposure at this department's inhalation facility, the aerosol concentration is measured by gravimetric analysis of membrane filters placed on each of four shelves of a horizontal flow chamber (Hemenway and MacAskill, 1982). An average of the shelf concentrations is typically used as an indication of the dose administered during each day of an exposure. Flow through the chamber is produced by two regenerative blowers located on both the upstream and downstream side of the chamber. This system allows the operator to both manipulate the flow rate between 0 to 0.5 m3/min and the static pressure of the chamber (normally set to -1" H_2O).

The flow rate is indicated by a Magnehelic® gauge connected to a Pitot-venturi flowmeter located in the supply air pipe (Fig. 7). The flowmeter was used to indirectly measure the chamber flow rate by indicating the velocity pressure of the air in terms of inches of water deflected in a manometer (as indicated by the Magnehelic® gauge with units of inches of water). The flow rate is related to the velocity pressure by the following equation:

$$Q_C = AK\sqrt{\frac{\Delta P}{d}} \tag{18}$$

where:

Q_C	=	flow rate
A	=	cross-sectional area of pipe
K	=	conversion constant
ΔP	=	velocity pressure in inches of water
d	=	density of air.

An air flow rate meter (Model 1.5M125 - Dresser Industries, Houston) was used to calibrate

the relationship between manometer deflection, ΔP, and chamber flow rate. With this relationship, an indication of chamber flow rate could be made by noting the position of the needle in the Magnehelic® gauge. Chamber flow rate was then set by manually turning a valve until the desired needle position was reached.

The production of the test aerosol, cristobalite (a form of free crystalline silica), used throughout this study was accomplished with the use of a Wright dust-feed (BGI Inc., Waltham, MA). This device produces an aerosol by rotating a cylinder, packed with the bulk powder, past a scraper blade. An air stream, flowing along the base of the scraper blade, carries the scraped powder out of the generator and into the main dilution air stream entering the chamber. The production rate

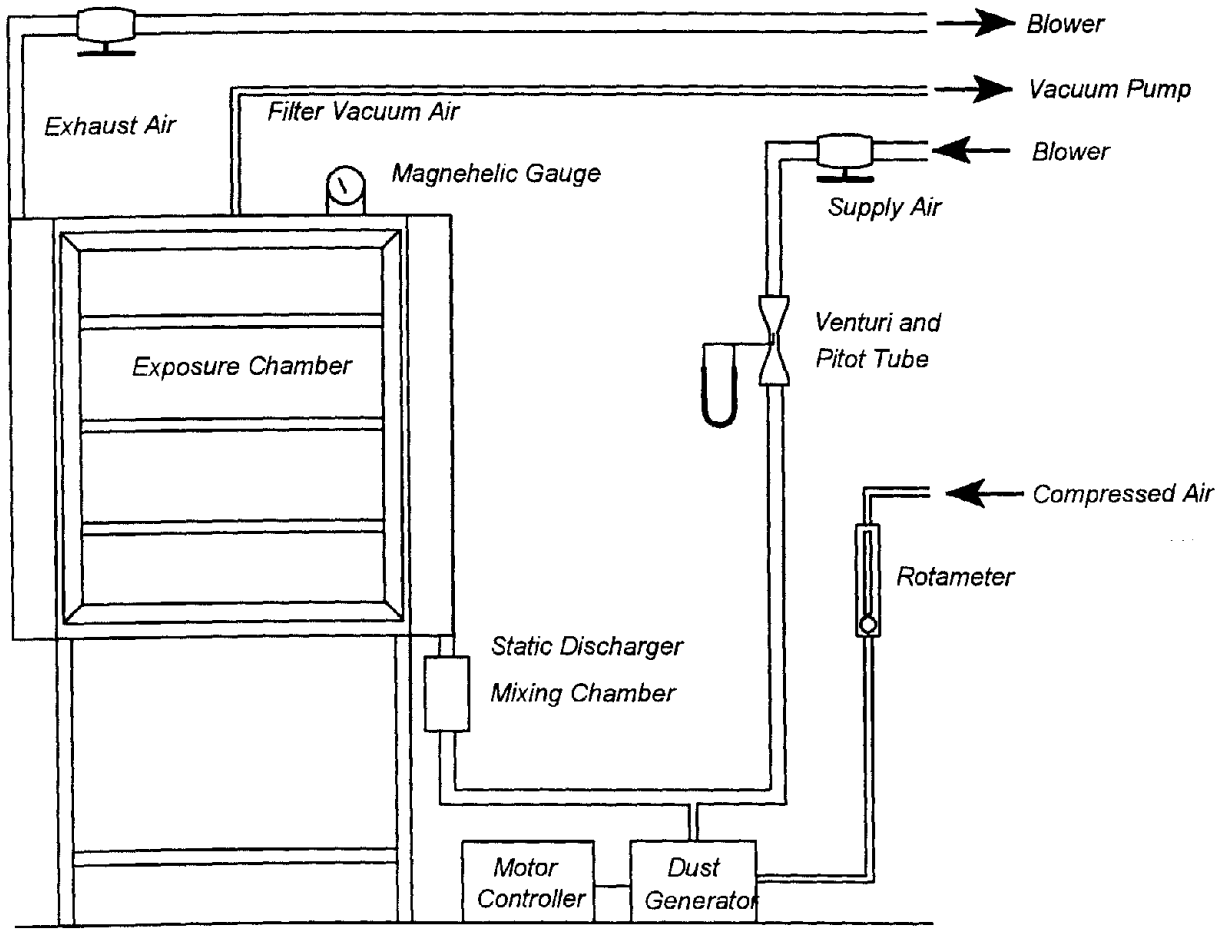

Fig. 7. Schematic diagram of the exposure system prior to addition of automation equipment.

of the dust feed (and subsequent chamber concentration level) is, therefore, determined by the rotation speed of the cylinder. In addition to changes in generator rotation speed, chamber concentrations can also be manipulated with changes in the flow rate of the dilution air stream through the chamber where an increase in flow reduces concentration.

Chamber Automation

Aerosol Monitor. In addition to the filters used for gravimetric analysis, chamber concentrations can be measured with an electronic aerosol monitor on a real-time basis. A voltage output from the sensor (HAM-DS model 1500, ppm inc., Knoxville, TN) was connected to a personal computer (PC) through an analog-to-digital (A/D) converter for data storage and display on the PC monitor.

The electronic aerosol monitor is capable of measuring dust concentrations in ranges of 0 - 2, 0 - 20, and 0 - 200 mg/m^3. The voltage signal has an output of 0 to 2 volts for each of the ranges mentioned above. 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 to 5 volts. In order to utilize all the available bits of the converter, and, therefore, maximize the resolution of the aerosol monitor signal, an op-amp circuit was devised to increase the aerosol monitor signal by a factor of 2.5 to a range of 0 to 5 volts. 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.

A plexiglass cowl was made to attach the sensing probe of the aerosol monitor directly to a filter cartridge used for the determination of the chamber concentration by gravimetric analysis. Therefore, all dust passing through the view volume of the monitor was subsequently deposited on

the filter. 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 which approached the mean level of the entire chamber.

An estimate of the chamber concentration throughout the time period of a trial can be calculated by dividing the integrated area under successive monitor readings by the total time of the trial. In this case, discrete (not continuous) measurements are made, and computing the average of all readings is equivalent to the procedure mentioned above. Therefore, chamber concentration was determined by averaging all monitor readings and by gravimetric analysis of the filter. The ratio of monitor to filter-derived measurements (M/F) was subsequently used as a measure of the monitor performance.

Aerosol Generator. A modification was made to the original Wright dust-feed by attaching a stepper motor rather than clock motor to maintain the rotation speed of the dust cylinder (Hemenway et al., 1986). Furthermore, the stepper motor rotation speed was controlled by varying the position of a thumb wheel switch on a dedicated microprocessor. However, in order to manipulate rotation speed with commands from a PC, a microprocessor with the capability of serial communication with other computers was obtained (Model SIBEC-II, Binary Technology Inc., Meriden, NH). Computer code was written on the BASIC program supplied with this microprocessor to ask for the initial rotation speed and activate the stepper motor with the proper sequence and delay-time between "steps" needed to achieve the desired rotation speed. To allow for a change in rotation speed after initial start-up, code was written to check the serial port of the microprocessor on a continuous basis. If a change in speed was required, the computer code in the PC would send an appropriate number to the microprocessor to activate the speed change. This modification, together with the use of the real-time aerosol monitor, allowed the development of PC

software for feedback control of the aerosol concentrations.

The initial rotation speed, ω (rpm), was calculated by code in the PC after entering the desired concentration (DC, mg/m^3) level and the flow rate through the chamber, Q_C (m^3/min) A theoretical, or "nominal", chamber concentration (NC, mg/m^3) can be calculated knowing the generator rotation speed, the packing density of the dust in the cylinder, ρ_c (g/cm^3), the volume of dust removed per revolution, K (cm^3/rev), and the chamber air flow rate (Eq. 19).

$$NC = 1000K\frac{\rho_c\ \omega}{Q_C} \tag{19}$$

The equation above can be inverted to solve for ω, however, the NC is never realized due to losses of the aerosol that take place in the chamber between the generator and the aerosol monitor. Therefore, an expression for chamber losses in terms of an "actual" concentration (AC, mg/m^3) and the NC must be added to an equation for ω (Eq. 20).

$$\omega = \frac{DC}{1000} * \frac{Q_C}{\rho_c\ K} * \frac{NC}{AC} \tag{20}$$

The ratio NC/AC represents the reciprocal of the chamber loss ratio as described above. (For further clarification, in terms of a feedback control system, the DC represents the reference input level to the system and the AC is the measured (output) concentration.)

Prior to application of Eq. 20 for determining the generator speed required to produce a desired concentration, trials were performed to determine the chamber loss ratio under various operating conditions (O'Shaughnessy and Hemenway, 1994). Part of the research described in this report included trials to validate those results.

A diagram of the (open-loop) automated aerosol generating system is given in Figure 8. This diagram represents the automated process for controlling chamber concentrations by manipulating the aerosol generator output rate. In the case of open-loop control, the "Control Algorithm" shown in Figure 8 represents code that can be accessed when a key is pressed to allow for a change in the desired concentration by entering the new concentration level via the computer keyboard. When closed-loop control is employed, the "loop" would be connected within the computer program code written to compare the desired with the actual concentrations and automatically adjust the generator speed.

Air Flow Control. To automatically adjust the chamber dilution flow rate through the chamber, a pneumatic positioner (765 series, H.D. Baumann Assoc. Ltd., Portsmouth, N.H.) was attached to a control valve (24000 series, H.D. Baumann Assoc. Ltd., Portsmouth, N.H.) placed in the piping leading to the chamber from the regenerative blower. The positioner is capable of making a proportional adjustment to a pressure regulator after receiving a milliamp (ma) signal from a digital-to-analog (D/A) converter (PCI-20093W-1, Burr-Brown, Tucson, Az.) connected to the PC. The air pressure acts against a diaphragm attached to the control valve which in turn pushes the valve

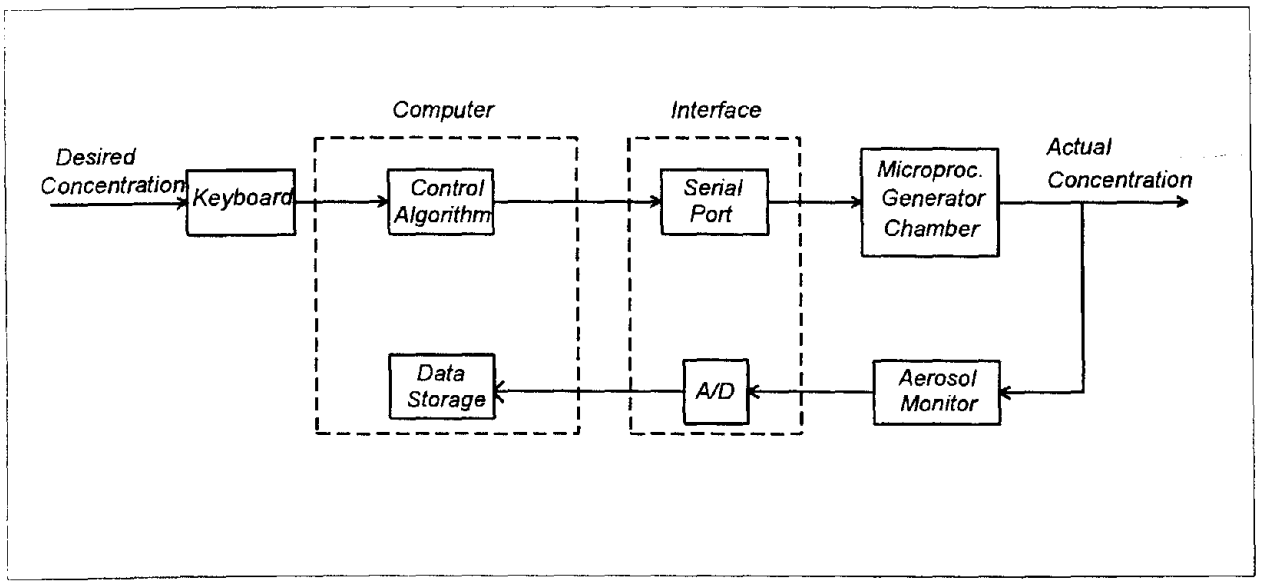

Fig. 8. Block diagram of an open-loop aerosol generating system.

stem down. Therefore, the signal from the D/A converter is proportional to valve position and hence flow rate through the chamber.

The D/A converter contained a 12-bit analog output board capable of producing an output signal of 0 to 20 ma. The positioner is capable of using 4 to 20 ma to regulate the air pressure to the actuator diaphragm between 3 and 15 psi, which corresponds to the valve changing from completely closed to completely open.

To automate the measurement of the chamber flow rate, a pressure transducer (Model PX170, Omega Engineering, Inc. Stamford, Conn.) was acquired and attached to the Pitot-venturi meter to read velocity pressure. The velocity pressure measurement was then converted to chamber flow rate as discussed above.

A feedback control algorithm was employed when using the positioner to automatically set the chamber air flow rate. The code was written to establish the flow rate at the beginning of a trial to a desired rate and to continuously check this rate and make the proper adjustments to the valve if necessary. When chamber concentrations were controlled by adjustment of the chamber air flow rate, the aerosol monitor was used to indicate concentrations and a 4 to 20 ma signal was sent to the valve positioner to automatically adjust the chamber flow rate.

Personal Computer Controller. Regardless of the feedback control method, programs for the PC were written to perform five initial functions:

1. ask for and receive information from the user regarding the desired concentration level, the chamber air flow 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 and/or control algorithm and,

5. terminate the exposure after a specified period of time by turning off the sample air, dust generator, and saving all aerosol monitor recordings to a file.

Items "1" and "2" have been discussed previously in relation to the determination of the proper generator rotation speed to achieve the desired concentration level (Eq. 20). The graphic display on the monitor of the computer was designed to provide the user with both an indication of the current level of concentrations in the chamber and the time-weighted average (Fig. 9). Furthermore, the program was written to display 30 minutes 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 judgement 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 seconds of readings was then displayed as a single point on the computer monitor. The numerical value was also displayed on the computer monitor and saved on a disk file for storage and retrieval into a spreadsheet (Quattro Pro, Borland Int. 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" above when the system was operated manually, programs were 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 entered. At this time, the required generator speed

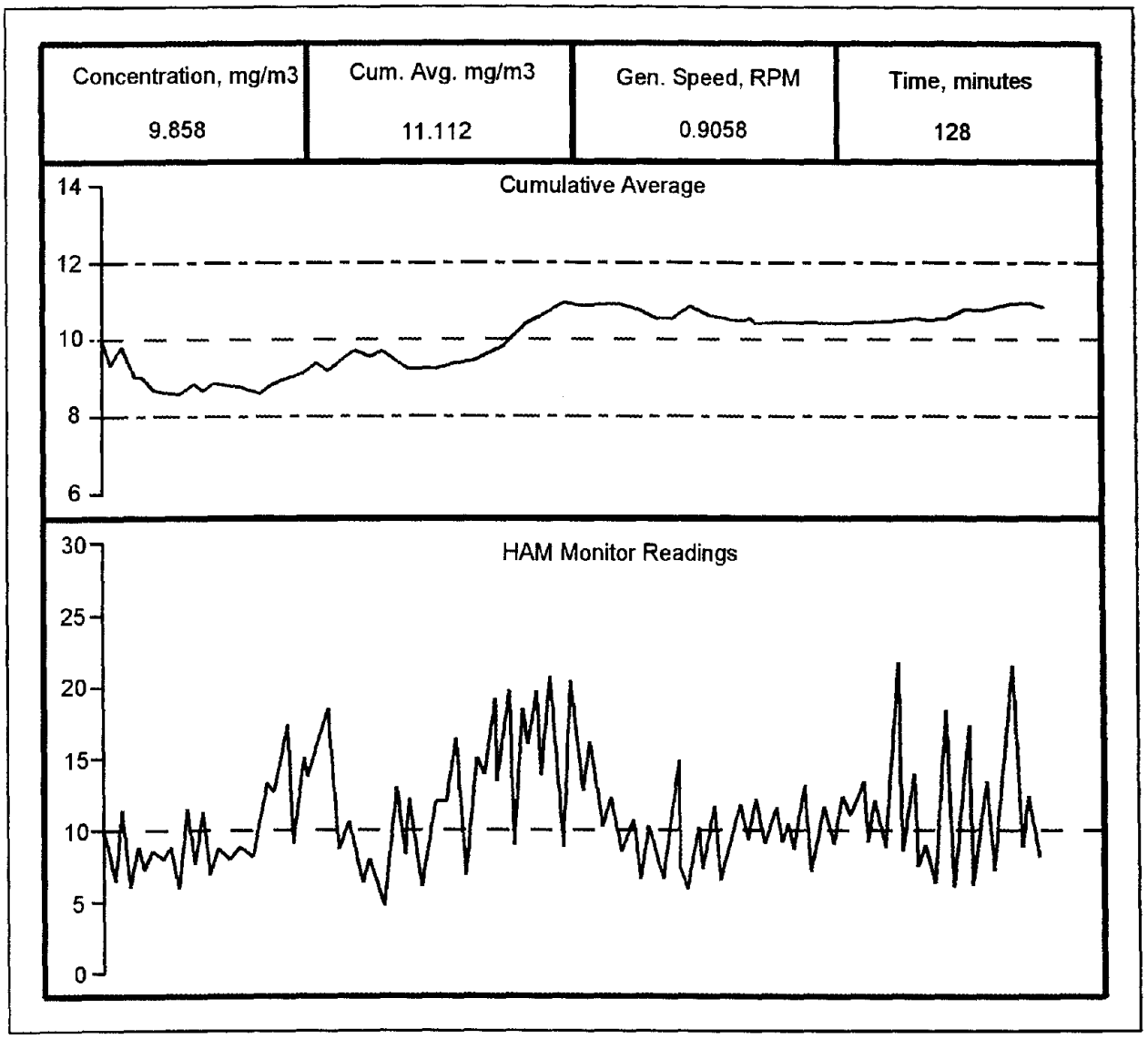

Fig. 9. Computer screen display of chamber concentrations.

needed to achieve the new level would be calculated and the appropriate number sent to the microprocessor to activate the speed change.

PROCEDURES

As described on the previous pages, this research was concerned with the automatic control of aerosol concentrations by either manipulating the generator output rate or changing the flow of air through the chamber. In general, the effect of changes in generator output rate on chamber concentrations was investigated to determine whether the concentrations responded in a consistent manner. Furthermore, previous work revealed the concentrations changed in a more predictable manner with changes in generator rate than with changes in dilution air flow rate. Therefore, preliminary work involved the manipulation of generator rate prior to the more difficult task of controlling concentrations with changes in flow rate.

Whether controlling concentrations with the generator or chamber flow rate, the following procedures were implemented:

1. perform trials to aid in the identification of a suitable process transfer function,
2. simulate the response of the system to a step-change in desired concentration,
3. simulate the response of the system when feedback control is applied, and
4. apply feedback control to the aerosol generating system to validate system performance.

Prior to application of the procedures listed above, many other trials were performed as part of this research to determine the relationship between flow rate and monitor response, flow rate and aerosol loss rate, and the step-response characteristics. Procedures associated with these objectives will be discussed in the following sections.

Calibrations

As described above, the aerosol monitor was attached directly to a filter cartridge used for the determination of the chamber concentration by gravimetric analysis. Therefore, all dust passing

through the view volume of the monitor was subsequently deposited on the filter except for minor losses in the aerosol monitor. Chamber concentration was determined by averaging all monitor (M) readings and by gravimetric analysis of the filter (F). The ratio of these two measurements (M/F) was used as a measure of the monitor performance. It is well known that aerosol monitor response is a function of the particle size distribution of the measured aerosol (Baron, 1987) and previous work (O'Shaughnessy, 1993) has verified that the chamber flow rate affects the size distribution. Therefore, these trials were performed to determine the relationship between monitor response and flow rate. Results from these trials were especially useful for maximizing monitor accuracy when changing flow rates to control chamber concentrations.

To establish the relationship between chamber flow rate and monitor response a series of 180-minute trials at flow rates of 0.1, 0.2, 0.3, 0.4, and 0.5 m^3/min were performed. An actual chamber concentration near 10 mg/m^3 was maintained for all trials. During each trial, the time-weighted average of the monitor readings over the length of each trial was compared with the concentration as measured by a sample filter and gravimetric analysis. The resulting relationship between monitor response and flow rate was then incorporated into a computer algorithm to automatically compensate monitor readings when a change in flow rate occurs.

As given in Eq. 20, the loss of dust between the aerosol generator and the aerosol monitor in the middle of the chamber is important for determining the appropriate generator speed required to produce a desired concentration. Many trials were performed to determine this loss ratio in relation to chamber flow rate. This information was originally generated during previous research (O'Shaughnessy, 1993), however, a new relationship was established as trials associated with this research were conducted.

As explained above, the loss ratio (AC/NC) was expressed in terms of the actual

concentration (AC) measured in the chamber to the nominal concentration (NC) calculated from Eq. 19. After each trial, this ratio was calculated and tabulated in relation to the chamber flow rate used during the trial. A regression relating the loss ratio to the chamber flow rate was determined from this information for use in subsequent trials to establish an initial concentration near the desired level.

System Identification and Estimation

As previously mentioned, two methods for the identification and estimation of the dynamic portion of the model represented in Eq. 13 were performed during this research. The first method involved an identification of the dynamic model based on the response of the chamber concentrations to a so-called "pulse" input of silica dust followed by estimation of the transfer function coefficients based on the response of the system to a "step" input of silica dust. The second method relied on a least-squares estimation technique to determine the values of the transfer function coefficients when using a pseudo-random binary sequence (PRBS) as input.

Impulse Response Trials. To accurately simulate the chamber control system when changing generator output rate, trials were performed to identify the proper transfer function describing the chamber system as given in Eq. 3. The identification technique used during this research involved the analysis of the system response to a "pulse" input. The pattern of the resulting chamber concentration can then be used to identify a proper reactor model that characterizes the system.

To create a pulse input, an aliquot of silica dust weighing 0.1 g was introduced into the main air-stream. The dust was placed behind a valve connected to a separate airline entering the main air-stream. The flow of air into the chamber was 0.3 m^3/min. The A/D converter was activated to read a sample every second and a stable concentration reading near 0 was acquired prior to opening the valve. The pressure of air behind the dust was sufficient to nearly instantaneously inject the dust into

the main air-stream. Measurements were taken until the resulting "spike" in concentration receded back to the base level. This trial was performed 3 times and an average response was computed by averaging the 3 samples taken at coincidental times throughout the 3 trials. This procedure was performed without the use of the aerosol generator but was assumed to give a similar response to that of the generator when quickly turned on and off.

The concentration response resulting from the procedure described above, was modeled as a "continuously-stirred tank reactor" (CSTR). (Other reactor types, such as "plug-flow" were also investigated but were not found to characterize the system response pattern.) The material balance for a CSTR is (Tchobanaglous and Schroeder, 1985)

$$\frac{dC_t}{dt}V = QC_{ti} - QC_t + r_tV \tag{27}$$

where C_{ti} is the initial tracer concentration, V is the reactor volume, Q is the volumetric flow rate, and r_T is the rate of tracer generation. In general, no reaction takes place with the non-reactive silica tracer making $r_t = 0$.

If the initial concentration, C_{ti}, of Eq. 27 is 0, then Eq. 27 represents a variation of the first-order dynamic system given in Eq. 1 without an input (Eq. 28).

$$\frac{dC_{Tt}}{dt} = -\frac{Q}{V}C_{Tt} \tag{28}$$

The quantity, V/Q, is the hydraulic detention time, τ, of the vessel. The solution to the application of a pulse-input to a first-order system is given below (Eqs. 29-30) (Palm, 1986)

$$C_{Tt} = M(1 - e^{-t/\tau}) \quad 0<t<T \tag{29}$$

$$C_t = -M(1 - e^{T/\tau})e^{-t/\tau} \quad t \geq T \tag{30}$$

where, M, is the magnitude of the pulse input and time, T, occurs when the system output reaches a maximum. Values for τ and M were determined with the use of spreadsheet that minimized the difference between the first-order model and the actual measurements.

Step Response Trials. The procedure described above was performed to identify a correct dynamic model. Further experimentation was then required to estimate the values of the coefficients associated with the numerator and denominator of the transfer function given in Eq. 3. As mentioned above, the estimation procedure consisted of either "step" response trials or application of a PRBS signal as described below.

To estimate the dynamic transfer function using step response methods, a series of trials were performed in which the chamber concentration was increased 5 mg/m^3 from starting levels of 1, 10, and 25 mg/m^3 while operating at 5 flow rates ranging between 0.1 and 0.5 m^3/min. Three trials were performed at each starting level and flow rate and an average response was computed for each set of 3 trials. A spreadsheet was then used to determine the value of the parameters, τ and M, assuming the system response is first-order as described below. A variety of starting levels and operating flow rates were chosen to determine whether the response of the system after a step-change in input level varied significantly over a broad range of operating conditions. This information was necessary for determining whether a single transfer function was suitable for describing the system or whether several were needed depending on the operating condition.

The solution of Eq. 8-6 to a step input is given in Eq. 8-9 (Palm, 1986).

$$C_t = C_{ti} e^{-t/\tau} + M(1 - e^{-t/\tau}) \tag{31}$$

A non-linear optimization routine in the spreadsheet (Quattro Pro, Novell Inc., Orem, Utah) was used to minimize the mean-squared error (MSE) between the actual step response and the modeled response as given in Eq. 8-9. During this routine, the parameters C_{ti}, τ, M, and the delay time (time between initiation of a change in input and the start of a change in output) were updated until the MSE was minimized. This procedure was followed for all trials performed. The parameters derived from an average response at a given flow rate were then used as the best estimate of the dynamic transfer function when operating at the various flow rates.

When Eq. 3 is expressed in terms of τ, the constant, r, is replaced with $-1/\tau$, and the constant, b, with $1/\tau$. In terms of a unit-step response, the value of M must be divided by 5 (because the step trial involved increases of 5 mg/m^3) to make it unitless and then applied to the numerator of the transfer function. Finally, the delay time, T, must be converted to its equivalent number of samples and applied to the transfer function in the form of e^{-Ts} (Palm, 1986). The resulting transfer function is given in Eq. 8-10.

$$Y(s) = e^{-Ts} \frac{M\tau^{-1}}{s + \tau^{-1}} U(s) \tag{8-10}$$

The corresponding discrete transfer function is given in Eq. 8-11

$$Y(z) = z^{-T} \frac{M(1 - e^{-1/\tau})}{z - e^{-1/\tau}} U(z) \tag{8-11}$$

Another series of trials were performed as part of this research to determine whether the chamber concentrations increased in a uniform manner with different changes in generator output rate. To perform these trials, 3 sets of trials were conducted to obtain a series of desired increases of 0.5, 1, 2, and 4 mg/m^3 when using proportional control. These trials were performed at base concentration levels of 1, 10, and 25 mg/m^3 and a constant flow rate of 0.3 m^3/min. After initiating a trial, the process was run for 30 minutes to equilibrate the concentration before the first change in generator speed. The generator speed was then held at the new rate for 30 minutes and then brought back to the original rate for another 30 minutes before the next speed change. A similar procedure was followed when changing the chamber flow rate to affect step increases above a starting level of 10 mg/m^3.

PRBS Signal Trials. In addition to the step-response trials, a separate identification method used during this research employed the use of a pseudo-random binary sequence (PRBS) of inputs to the plant (Astrom and Wittenmark, 1984; Ljung, 1987; Davies, 1970). This procedure allowed for the simultaneous estimation of both the dynamic and noise transfer functions associated with Eq. 13. To obtain the input/output relationship required for modeling the system, the following steps were taken:

(1) a computer text-file containing a PRBS sequence was created,

(2) the process was initiated to produce a chamber concentration associated with a specified generator output rate and chamber concentration of 10 mg/m^3,

(3) the PRBS file was automatically read by the personal computer controlling the generator output rate every 5 minutes where; a "-1" represented a step down in generator output rate, resulting in a chamber concentration of 5 mg/m^3, and a "1" resulted in a step increase to 10 mg/m^3, and

(4) a file was created during the trial that recorded the input (desired concentration) and output level (actual concentration) at every sampling time (15 seconds).

This procedure was performed once with chamber flow rates of 0.1, 0.2, 0.3, 0.4, and 0.5 m^3/min.

With the information provided by the procedure given above, a program was run in a computer-aided engineering (CAE) program (MATLAB™, The MathWorks, Inc.) that evaluated the relationship between the input and output together with an evaluation of the output and any noise in the data in order to obtain a model as given in Eq. 13 (Ljung, 1991). To begin the estimation procedure, the transfer function polynomial orders, nA, nB, nC, nD, and delay, nk, in Eqs. 13-15 were entered into a routine supplied by the CAE software. An iterative procedure was then performed by the CAE software to estimate the parameters associated with the transfer function polynomials while minimizing the error between the predicted and actual output values. The user may supply other values for the polynomial orders to determine which combination minimizes the prediction error. During this research, the polynomial orders for the dynamic transfer function (B/A) were based on the system identification results. Polynomial orders for the noise transfer function (D/C) were manipulated during this procedure to minimize the prediction error.

A similar procedure to that described above was also performed to estimate the system model when using dilution air to control chamber concentrations. In this case, the PRBS sequence was used to indicate when a change in chamber flow rate should take place in order to affect a change in concentration between 5 and 10 mg/m^3. Because no prior identification procedures were performed, transfer function polynomial orders were arbitrarily chosen and examined when using the CAE software to determine a combination of orders that minimized the prediction error.

Generator Controlled Concentrations

The following sections include descriptions of procedures followed when applying feedback control to the chamber system when using the aerosol generator to control concentrations. In general, these procedures involved:

(1) numerical simulations to obtain information on system response under feedback control,

(2) writing the appropriate computer code required to implement the feedback control algorithm under investigation, and

(3) performing actual trials with the aerosol generating system to validate the effectiveness of the control system.

The actual trials involved either single-step, multi-step, or constant level control of the chamber concentrations. In general, these trials were performed to compare the relative effectiveness of applying feedback control to that of an uncontrolled process. Furthermore, to perform a manageable number of trials, the assumption was made that performance at one level would be indicative of performance at other levels as well. Therefore, these trials were restricted to certain operating conditions rather than to all conditions examined in the previous procedures.

PID Control Trials. As explained in the "Background" section, various response patterns may be obtained when using the PID control algorithm by changing the values of the constants associated with the proportional, integral, and derivative terms. With the dynamic model formulated from the PRBS signal estimation trial, numerical simulations of the chamber system under PID control were conducted to determine the set of constants that gave a favorable response pattern to a change in the input signal. The response was evaluated in terms of minimizing:

(1) the "overshoot" typically seen after an initial increase in which the concentrations rise above the desired level, and

(2) the time required to reach a steady-state level after a change in generator rate.

After determining a valid set of PID constants by numerical simulation, computer code was written to implement the control algorithm as applied to the aerosol generator. The PID control algorithm can be generalized as given below.

(1) Compute the error between desired and actual concentration (error = DC - AC)

(2) Compute proportional (P) term (P_output = error * K_P)

(3) Compute integral (I) term (I = error * K_I)

(4) Perform the integration (I_output = I_output + I)

(5) Compute the derivative (D) term (D_{new} = error * K_D)

(6) Perform the subtraction equivalent to taking the derivative (D_output = D_{old} - D_{new})

(7) Update the previous derivative term (D_{old} = D_{new})

(8) Combine the P, I, and D output values (C_output = P_output + I_output + D_output)

(9) Compute the new generator output rate using Eq. 20 (replacing "DC" with C_output)

Notice, in the algorithm above, that all variables have units of mg/m^3 because they represent concentrations. Once a concentration has been computed by the algorithm, a conversion must be made to determine the appropriate generator speed required to produce that concentration. One then assumes that the computed generator will give the desired concentration. Hence the need to validate the relationship between generator speed and chamber concentration as performed during the procedures described in previous sections of this report.

After testing the computer code, three, 270 minute, trials were conducted when using PID control and three when using PI control. These trials were then compared with the uncontrolled trials of the same type in which concentrations were allowed to increase and decrease in a step-wise fashion between concentrations of 0.5 and 4 mg/m^3 above a starting concentration of 10 mg/m^3 and flow rate

of 0.3 m^3/min. Further trials were also conducted in which PID control was applied to maintain concentrations near a desired level for the entire length of the trials (180 minutes) and when a single increase in the middle of the trial was induced. These trials were compared with similar trials conducted without feedback control and trials performed with the EWMA control algorithm.

EWMA Control Trials. The procedures described above were followed to satisfy the goal stated in "Specific Aim 1", specifically "to investigate the response of chamber concentration levels to various changes in generator speed and chamber air flow rate". Development of that goal during this research included the response of chamber concentrations when controlled by either changes in generator output rate and changes in chamber dilution air flow rate.

The goal of "Specific Aim 2" was to "investigate the use of statistical process control techniques to implement automatic feedback control" of the chamber concentrations. Because the method used during this research has not previously been tested, comparison of the proposed method with that of a well known control method (PID) was incorporated into the second goal of this research.

As described in the "Background" section of this report, the statistical process control (SPC) technique used in this research was based on the use of the exponentially weighted moving average (EWMA) for measurements that are serially correlated. As applied to this research, the EWMA feedback control algorithm consisted of the following algorithm.

(1) Compute the EWMA, upper control limit (UCL), and lower control limit (LCL) during each sample period with Eq. 16 and multiply the result of Eq. 17 by both 3.75 and -3.75 for the UCL and LCL respectively. (A value of 0.1 was used for both λ and α in Eqs. 16 and 17 respectively.)

(2) Check if at least 20 samples (5 minutes at 15 seconds between sample) have been taken since the last correction.

(3) Check if either the UCL or LCL have crossed the reference line (equivalent to the desired concentration).

(4) If conditions are met:

(4a) Compute the error between the reference and the EWMA.

(4b) Integrate the error and compute the new generator speed required to offset the error by making a proportional change in generator speed relative to the size of the error.

(4c) Reset the EWMA to the reference level.

Although feedback control was employed when using this method, only one correction was made when required by the conditions stated above. This correction was assumed to be of sufficient magnitude to eventually bring the concentrations near the reference level. Sufficient time (5 minutes) was allowed for the concentrations to reach the new level before a subsequent correction was allowed. In relation to this procedure, the PID method makes a comparison and correction at each sample as explained previously. By only applying one proportional adjustment, application of the EWMA method did not require a knowledge of the dynamic response of the system after a correction since enough time was allowed for the system to reach a new steady-state level prior to initiating another correction (if needed).

To test the effectiveness of the EWMA control method, three trials each were performed at target levels of 1, 10, and 25 mg/m^3. These trials were performed for 180 minutes during which the generator was manipulated as described above and with constant dilution air flow rates of 0.1, 0.3, and 0.5 m^3/min for a total of 27 trials. These trials were performed without the addition of step-changes in the desired concentration level. To compare the performance the EWMA method, similar trials were performed when using the PID control method with a flow rate of 0.3 m^3/min. A series of trials were also performed with no feedback control to compare with those in which feedback

control was employed. During these trials, the chamber dilution air was automatically regulated to maintain a constant flow rate (but not to adjust for changes in concentration as performed in subsequent trials).

Step-Induced Control Trials. A series of trials were conducted in which the desired concentration (DC) level was increased after half of the trial period. This step-change was similar to that made in trials described earlier to investigate the response of the system. During these trials, however, the sudden change in concentration was induced to determine how well a given control method reacted to the change and increased the concentrations to the new DC. The step changes were made between 1 and 6; 10 and 15; and 25 and 30 mg/m^3 while operating with a chamber flow rate of 0.3 m^3/min.

Three control methods were applied during this portion of the research, EWMA, PID, and a combination of EWMA and PID. The "combination" approach involved using the EWMA-derived control limits to detect when a change was required, then using the PID method to make the necessary correction. If a correction was necessary as determined by the control limits, 20 samples (5 minutes) were then used to adjust the concentrations to the new level using the PID algorithm. The concentrations were then allowed to stabilize for another 20 samples before checking the control limits again, as when using the EWMA method. This approach was taken to determine whether a "controlled" set of adjustments would bring the concentrations to a new desired level in a more accurate manner than when just applying a simple proportional change in generator speed.

Increased Noise Trials. The effectiveness of the EWMA control method was evaluated under operating conditions that resulted in a significant increase in the noise aspect of the concentration measurements. All previous research was performed with a dust cylinder associated with the Wright dust feed with an inside diameter of 1.27 cm. A larger cylinder with a diameter of 3.81 cm is also

available for this instrument. Previous research (O'Shaughnessy, 1993) demonstrated that the aerosol concentrations produced with the large cylinder were far more erratic when measured over time with an aerosol monitor. Furthermore, average concentrations varied widely from trial to trial when using the large cylinder with the same operating conditions. Given those results, the present research was conducted to determine whether the EWMA method could maintain a relatively stable concentration despite large perturbations in the measured concentrations during a trial. Three trials were performed with a desired concentration level of 10 mg/m^3 and a dilution air flow rate of 0.3 m^3/min. These were compared with 2 trials of the same type performed with no EWMA control to compare with those described above.

Dilution-Air Controlled Concentrations

The procedures described in the previous section were related to control methods applied to the aerosol generator. Although specific to the generation of an aerosol with the chamber system described previously, these procedures were undertaken to establish methods applicable to the control of aerosol concentrations by manipulation of the dilution air flow rate as well. The assumption was made that control of concentrations with the aerosol generator would be a simpler problem than when using flow rate to control concentrations. However, this second design problem is more generally applicable to other needs in field of occupational health as described in the opening section of this report. Therefore, once control methods were established for controlling aerosol concentrations with a generator, the same methods were also applied to the automatic control of the dilution air with the necessary additions required to complete this more difficult goal. The "difficulty" of controlling aerosol concentrations with dilution air flow rate is a consequence of three factors.

(1) Monitor response is affected by flow rate because of a change in the size distribution of the

aerosol at different flow rates.

(2) The loss of aerosol between generator and the center of the chamber is affected by flow rate with greater losses at higher flows.

(3) The possible range of concentrations caused by changes in flow rate for a given generator output rate is much less than when changing the generator output with a set flow rate.

PID Control Trials. Given a transfer function model estimated from PRBS trials while using chamber air flow to manipulate aerosol concentrations (see Eq. 28 in "Results"), a CAD program was used to simulate concentration response under PID control. A set of P, I, and D constants were chosen that gave a satisfactory response to a step-increase in desired concentration. These constants were then applied to computer code needed to regulate the actual control system as described above. when controlling with the generator.

To offset the first problem listed above, additional code was written to update the monitor-to-filter (M/F) ratio when flow rate was changed. Furthermore, code was added to compensate for a change in the loss fraction with a change in flow rate. A complete description of the relationships between M/F and loss ratio with flow will be provided in the "Results" section.

The first eight steps outlined above for application of the PID control algorithm were also applicable when controlling the dilution air flow rate with the following additions after Step 8.

(9) calculate the new flow rate to achieve the new concentration level (this equation is discussed in the "Results" section).

(10) Calculate the new M/F ratio (this equation is discussed in the "Results" section)

(11) Calculate the current (mA) from the D/A converter to the valve actuator required to achieve the new flow rate. (The non-linear relationship between current applied to the actuator and the resulting flow rate was determined during a separate analysis).

Given the PID control algorithm described above, a set of trials was conducted in which the chamber concentrations were allowed to increase and decrease in a step-wise between 0.5 and 4 mg/m^3 when using the dilution air to control concentration levels. These trials were then compared with similar ones produced when using the generator to control concentrations.

EWMA Control Trials. A set of nine trials were performed when using the EWMA algorithm to control concentrations with dilution air. Three trials each were performed at concentration levels of 1, 10, and 25 mg/m^3 and an initial flow rate of 0.3 m^3/min. The EWMA algorithm was similar to that described above when controlling with the generator except for the additions given above to compensate for changes in the loss fraction and monitor-to-filter ratio. These trials were conducted for 180 minutes each with no intentional step-increase during the trial. A separate set of trials were also performed in which a step-increase in the desired concentration was induced during the trial. Three trials incorporated a step between 10 and 12 mg/m^3 and 3 trials produced a step between 25 and 27 mg/m^3. Smaller steps than those described earlier were required because of the valves limited ability to produce a range of concentrations above or below an initial concentration.

RESULTS

Chamber and Monitor Calibrations

Results from trials performed to establish the relationship between flow and the monitor-to-filter (M/F) ratio are given in Figure 10. Except for the M/F value measured for a flow rate of 0.4 m^3/min, all other values plotted in a straight line. Therefore, a linear regression was determined to relate the M/F ratio with flow rate (Eq. 21).

$$M/F = 0.755 - 0.287 * Flow \tag{21}$$

The regression given in Eq. 21 represents the "most probable" value of this ratio for a particular flow rate. Previous work (O'Shaughnessy and Hemenway, 1994) has shown that the M/F ratio can vary even between consecutive trials run with the same settings (flow rate, desired concentration). This

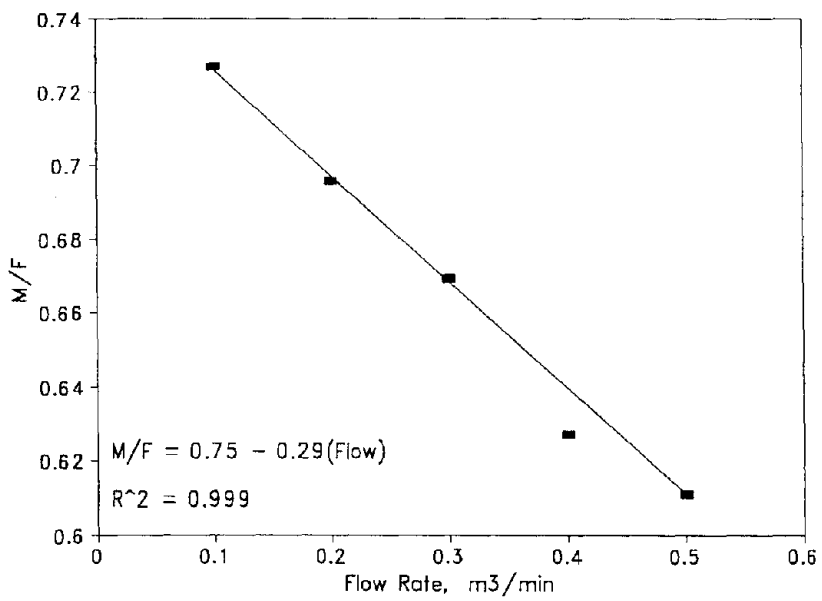

Fig. 10. Monitor response expressed as the ratio of monitor reading to filter measurement as affected by chamber flow rate. Data values and linear regression.

work revealed that, of 17 trials performed at 10 mg/m^3, an average change in the M/F ratio of 3.36% was seen between successive trials. These results, however, implied a relatively high level of confidence in the regression estimate. The relationship described in Eq. 21 was incorporated into code used to determine the chamber concentration at a specified flow rate from the aerosol monitor measurements.

As described above, the chamber loss ratio is the ratio between the actual concentration (AC), as measured by gravimetric analysis, and the calculated nominal concentration (NC). Recall, the reciprocal of this ratio (NC/AC) was used to determine the generator speed to achieve a desired concentration (Eq. 20). A graph of the loss ratio in relation to flow rate is given in Figure 11. The data values plotted in Figure 11 display a curvilinear trend which was linearized by plotting on log-log paper. A linear regression was then applied to the log of all values, except that associated with a flow rate of 0.5 m^3/min. The resulting equation is:

$$AC/NC = 0.295\sqrt{Q_C} \tag{22}$$

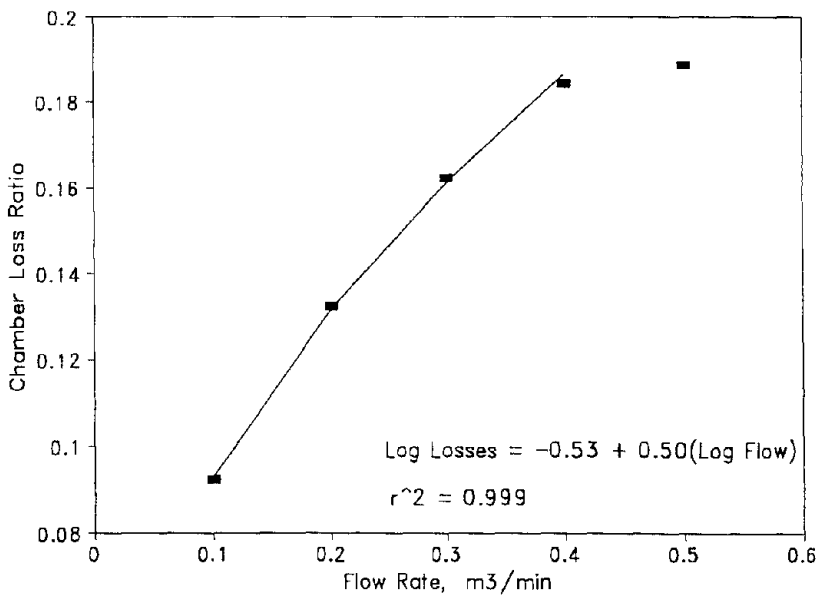

Fig. 11. Data values and regression relating the loss ratio to chamber flow rate.

From Figure 11, the loss ratio was seen to insignificantly increase above a flow rate of 0.4 m^3/min. Therefore, the loss ratio for any flow rate above 0.4 m^3/min was assumed to be the value given for a flow rate of 0.5 m^3/min.

This research was not directly concerned with the physical aspects of the chamber aerosol/flow interactions, however it may be hypothesized that the losses increased with flow rate because of an increase in impaction of the dust in the pipes leading to the chamber. In theory, an increase in flow rate should decrease the residence time of the aerosol in the plenum of the chamber. The decreased residence time will decrease sedimentation of the aerosol and result in a lower loss ratio. However with this system, the increase in losses due to impaction must greatly exceed the gain in aerosol from less sedimentation when operating at higher flow rates.

As with the estimate of the M/F ratio, an estimate of the loss ratio using Eq. 22 was also made knowing the resulting number was not exact. The amount this ratio varied from trial to trial was not investigated but was assumed to be less than 5% based on the systems' ability to approach a desired concentration relatively accurately from trial to trial.

The relationship between flow rate and the loss ratio given in Eq. 22 has significant consequences when attempting to determine the proper flow rate for maintaining chamber concentrations near some desired level. Given Eq. 20 for determining the proper generator speed, if the flow rate is constant throughout a trial, then the loss ratio is also constant. Furthermore, the packing density of the dust in the cylinder, ρ_c, and the volume of dust removed per revolution, K, are also constant. Therefore, Eq. 20 can be reduced to a simple 3-term equation to compute the initial generator speed where K' represents the combined constants, ρ_c, K, and the reciprocal of the loss ratio, NC/AC (Eq. 23). (The loss ratio was first calculated with Eq. 22.)

$$\omega = K'(DC)Q_C \tag{23}$$

If a change in generator speed is required when operating at a constant flow rate, a simple proportional adjustment can be made as shown below because K' and Q_C are constant (Eq. 24)

$$\omega_{new} = \omega_{init}\frac{DC}{AC} \tag{24}$$

However, when changing flow rate to affect a change in concentration, a more complicated procedure must be followed to estimate the new flow rate because the loss ratio is no longer constant.

As developed during this research, a trial performed to manipulate flow rate for concentration control was initiated just as described above when changing generator speed to control concentration. This procedure established a constant generator speed and initial estimate of the loss ratio. Any further adjustments to correct the concentration level were then made by changing the flow rate by solving Eq. 25.

$$Q_{C,new} = \frac{1000K\omega}{C_{new}}\frac{AC}{NC} \tag{25}$$

However, both the desired flow rate and hence the loss ratio (AC/NC) at that flow rate in Eq. 25 are unknown. Therefore, a method was devised in which Eq. 22 was substituted into Eq. 25 and solved for the remaining variable, $Q_{C,new}$ (Eq. 26)

$$Q_{C,new} = \left(\frac{295K\omega}{C_{new}}\right)^2 \tag{26}$$

Furthermore, when using dilution air to manipulate chamber concentrations, Eq. 21 was also used to update the M/F ratio and resulting concentration estimate from the monitor at each change in flow rate.

System Identification and Estimation Results

Impulse Response Trials. Values for τ and M were determined that minimized the difference between the first-order model and the actual data with results shown in Figure 12. The resulting close comparison between model and actual measurements verified use of the first-order CSTR reactor model to describe the chamber system when using the generator to control concentrations.

Step Response Trials. Step response trials were performed to estimate the transfer function coefficients. Results from the application of this procedure to the average response of one set of 3 trials operated at 0.3 m^3/min are given in Figure 13. Similar results were obtained from all other step

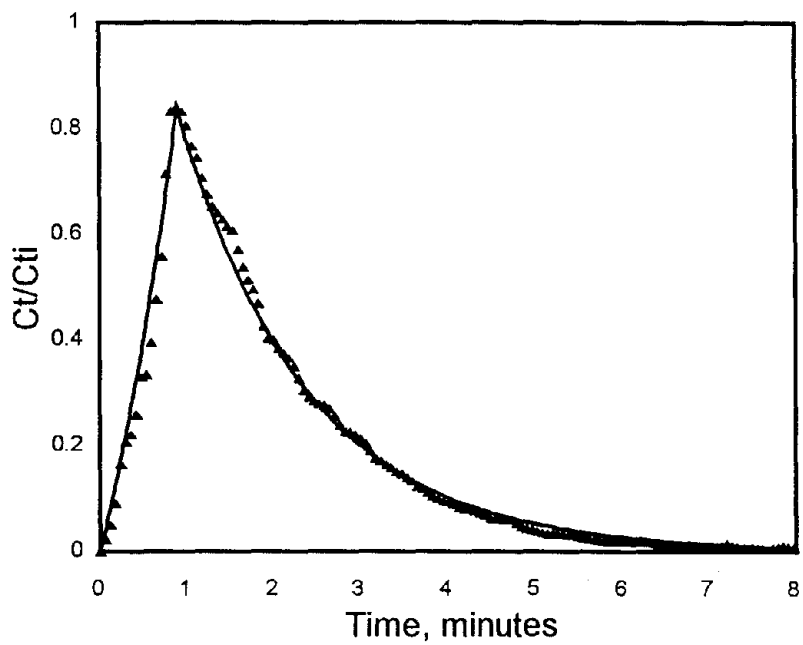

Fig. 12. CSTR flow model from impulse response and actual measurements (triangles).

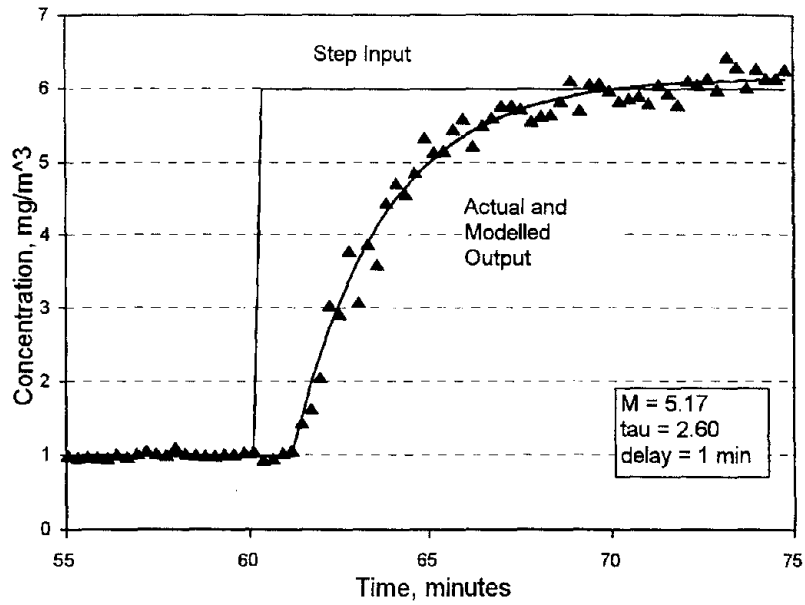

Fig. 13. Typical step-response behavior, model curve, and parameter values.

trials. To demonstrate the variability seen in step responses, plots of responses obtained from trials conducted at 0.3 m^3/min are given in Figure 14 after normalizing to a base level of 0 for all trials.

A table of results for all step-trials is given in the Appendix. A graph relating the average

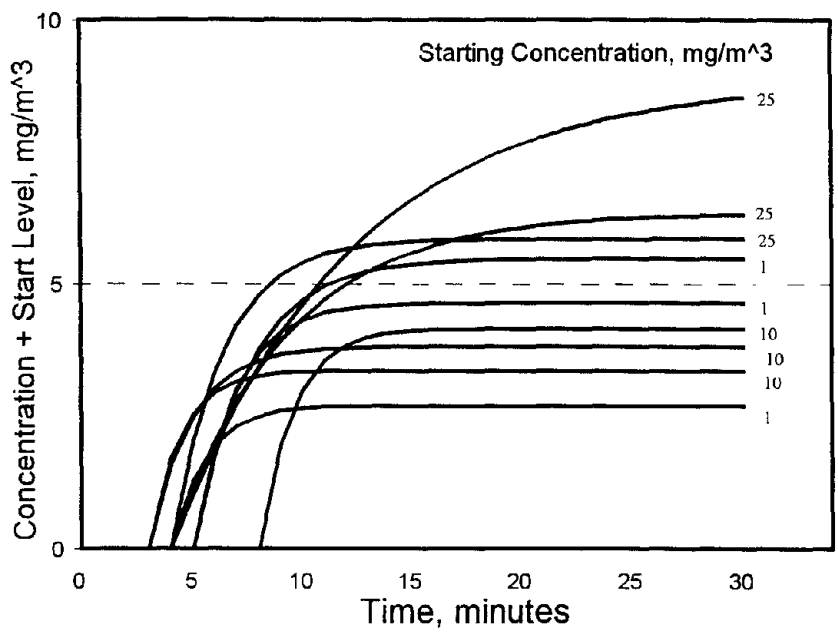

Fig 14. First-order step response of 9 trials performed at the indicated starting level and a flow rate of 0.3 m^3/min.

values for M, τ, and delay for all trials at a given flow rate is given in Figure 15. Despite the apparent dissimilarity between these parameters in relation to flow rate, a one-way ANOVA gave p-values of 0.161, 0.643, and 0.376 for M, τ, and delay versus flow rate respectively. These p-values indicate that there was no significant difference among these parameters caused by changes in flow rate. A similar analysis was performed to compare the effect of starting level on these parameters (Fig. 16). Again, a statistical comparison resulted in no significant difference among mean levels as grouped by starting concentration (p-values of 0.662, 0.340, and 0.162 for M, τ, and delay versus starting concentrations respectively).

The results given above indicate that mean values for the 3 parameters were not significantly influenced by operating condition. However, the results shown in Figure 14 indicate a large amount variability about those mean values. Based on this information, average values for M, τ, and delay were calculated and used for control system simulation and design when using the PID control method. This decision was made with the knowledge that the average parameter values may not be

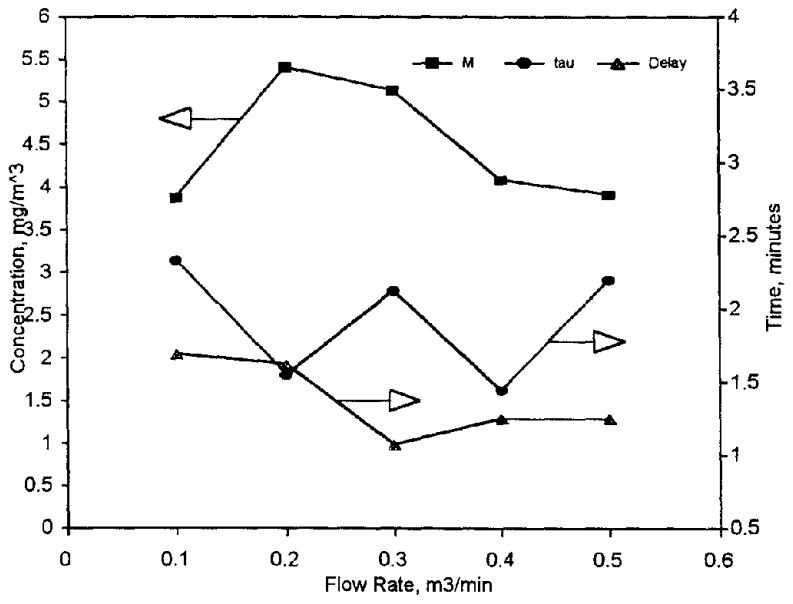

Fig. 15. Changes in dynamic model parameters caused by chamber flow rate.

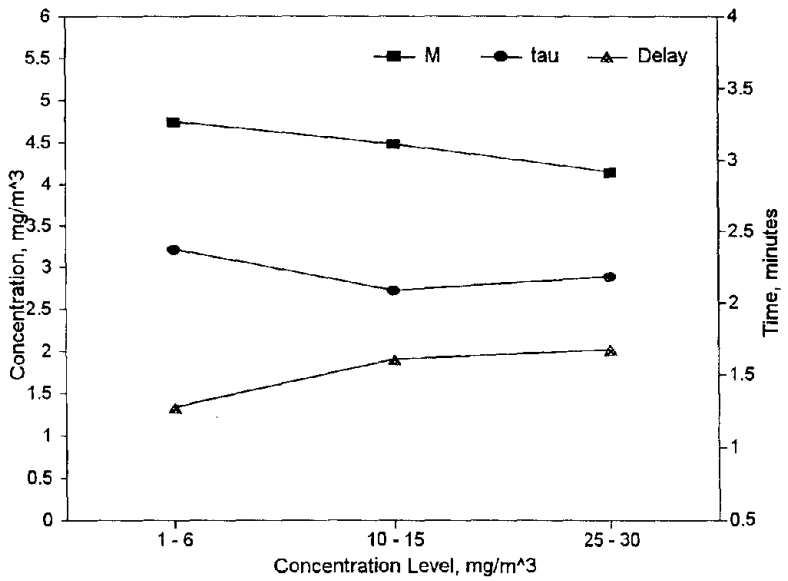

Fig. 16. Changes in dynamic model parameters caused by starting level.

representative of the system during any particular actual trial.

Trials were also performed to indicate whether the same proportional increase in concentrations can be expected regardless of the magnitude of the increase. These trials were important for determining whether a constant "gain" in concentration can be applied regardless of the increase desired. As stated above, a set of 3 trials was performed at starting concentration levels of 1, 10, and 25 mg/m^3. The 3 trials per set were averaged together to create a series of data that was representative of the response of the chamber of system at the concentration level under investigation (Figs. 17, 18, 19).

The first two trial sets (1 and 10 mg/m^3) produced concentration values which followed the expected levels. The final trials however, run near 25 mg/m^3, did not track the expected levels. As can be seen in Fig. 19, the time frame of these trials was shortened to allow the use of only one canister of dust during the length of each trial. Initially 30 minutes was given to equilibrate the initial concentration level then steps were taken every 12 minutes.

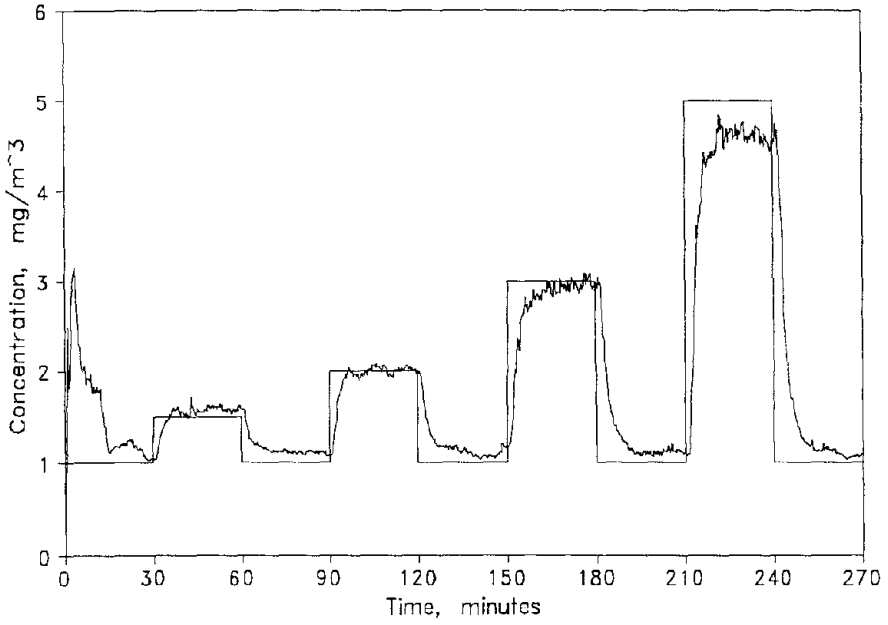

Fig. 17. Step changes in chamber concentration when operating near 1 mg/m^3.

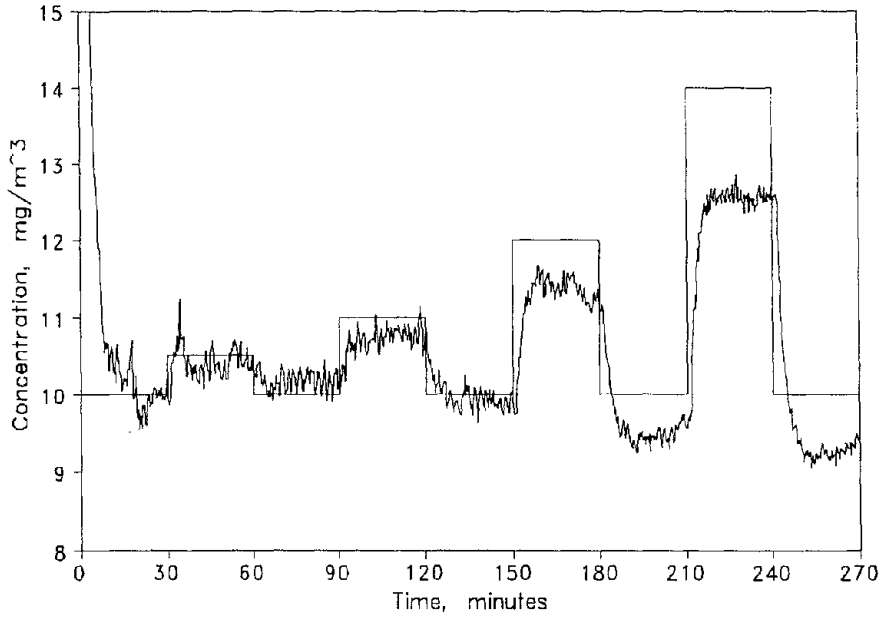

Fig. 18. Step changes in chamber concentration when operating near 10 mg/m^3.

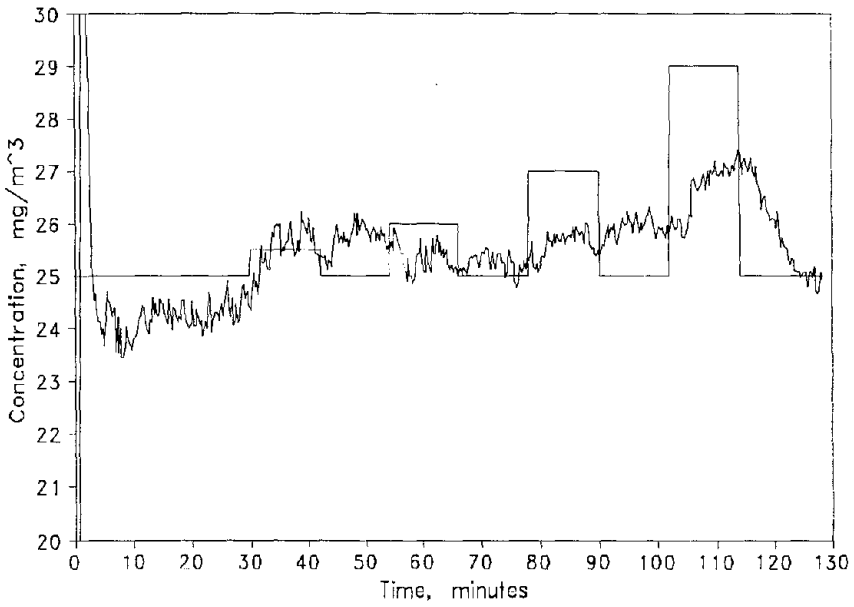

Fig. 19. Step changes in chamber concentration when operating near 25 mg/m^3.

The changes made in generator speed at each step were calculated using Eq. 20 with no feedback from the monitor readings. Therefore, the concentration level after a step-change reached a new level with no attempts to "force" it near the expected level. The next step-change then originated from whatever level was achieved during the previous step-change. This steady-state level was calculated by averaging all readings taken 15 minutes before the next step-change. The subsequent change was then assumed to be $\pm$ 0.5, 1, 2, or 4 mg/m^3 of the previous steady-state level, not the expected level.

Graphs were made which depict the actual and expected concentration changes for each step taken when operating at 1 and 10 mg/m^3 (Figs. 20 and 21). (An evaluation of the data taken at 25 mg/m^3 was ignored for reasons stated above.) The slope of the regression line associated with the data generated near 1 mg/m^3 (Fig. 20) was 0.90 whereas a slope of 0.80 was produced when operating near 10 mg/m^3 (Fig. 21). These results indicate the system achieved an actual concentration that was 90% of the desired concentration when operating at lower concentration levels. This ratio

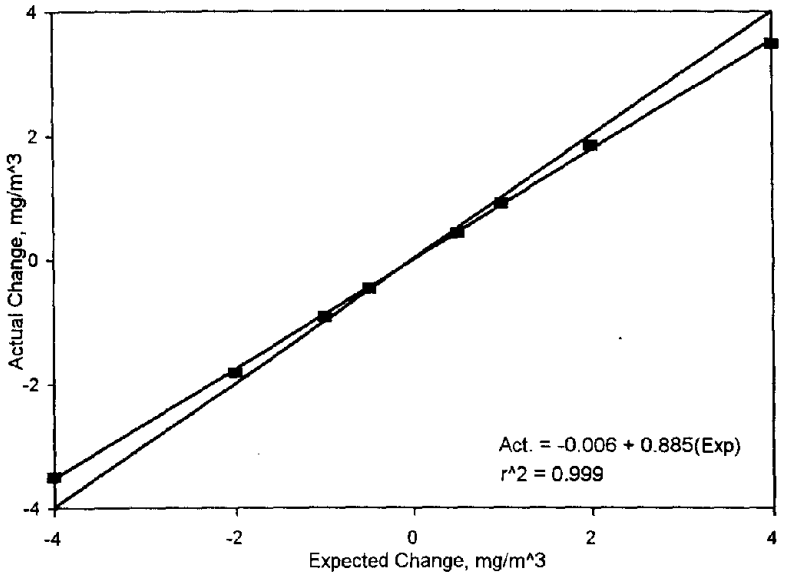

Fig. 20. Actual step increases in relation to expected increases when operating near 1 mg/m^3. Lines indicate linear regression and 1:1 line.

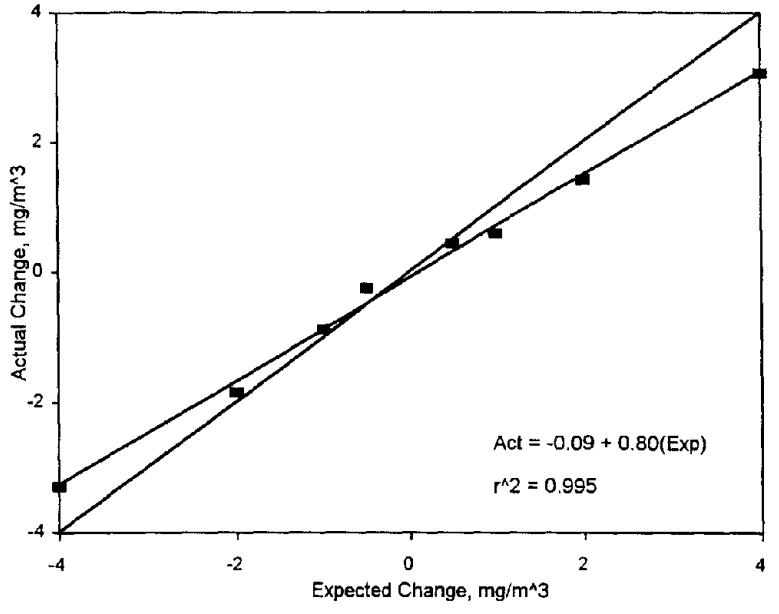

Fig. 21. Actual step increases in relation to expected increases when operating near 10 mg/m^3. Lines indicate linear regression and 1:1 line.

changed to 80% when operating at higher concentrations. Therefore, some adjustment to the gain constant applied to the control system may be necessary when operating at different concentration levels.

Results from a similar trial conducted to test the response of the chamber system when applying various changes in dilution air flow rate is given in Figure 22. It should be noted that this trial was conducted prior realizing that corrections for a change in the loss ratio with a change in flow rate need to be made as explained previously (Eq. 26 was not used). Hence, chamber concentrations were much less responsive to changes in flow rate than for changes in generator speed. However, this figure reveals that relatively small changes in flow rate had little effect on the level of the aerosol concentrations. Further work, as reported below, was performed to validate this assumption.

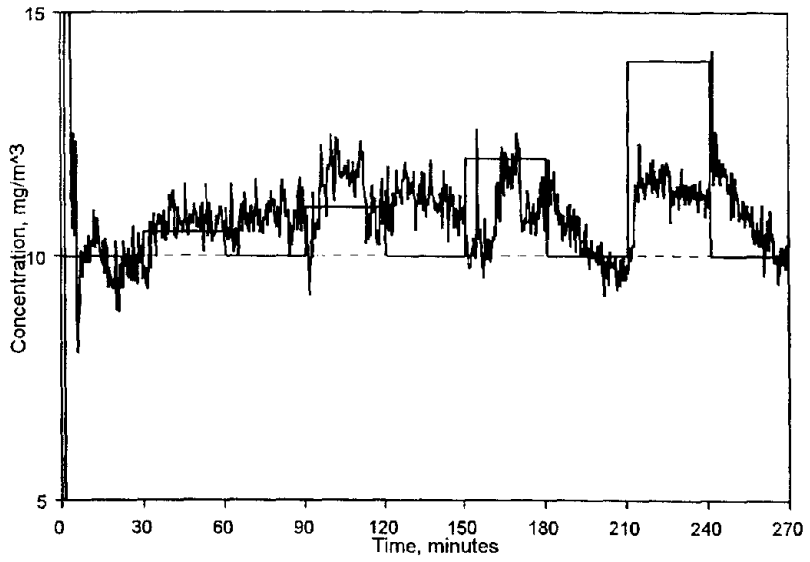

Fig. 22. Step changes in chamber concentration when operating near 10 mg/m^3 using flow control.

PRBS Input Model Estimation. Results obtained when following procedures for estimating model parameters with a PRBS input sequence and manipulating the generator output rate are shown in Figure 23. A portion of the trial shown in Figure 23 is given in Figure 24 (compare time scale) with the response as given by the identified dynamic model. The resulting system model identified with the CAD program when operating with flow rate of 0.3 m^3/min is given in Eq. 27.

$$y_t = \frac{0.0836}{1 - 0.9230q^{-1}} u_{t-4} + \frac{1 - 0.3915q^{-1}}{1 - 0.9176q^{-1}} a_t \qquad \textbf{(27)}$$

The step response results given in the previous section suggested that the average response of the chamber system did not change significantly in relation to changes in operating condition. However, other results showed a considerable amount of variation in response from trial to trial. Therefore, results from the PRBS identification procedure given above, were used as a good indication of the average response of the system over many steps when both increasing and decreasing

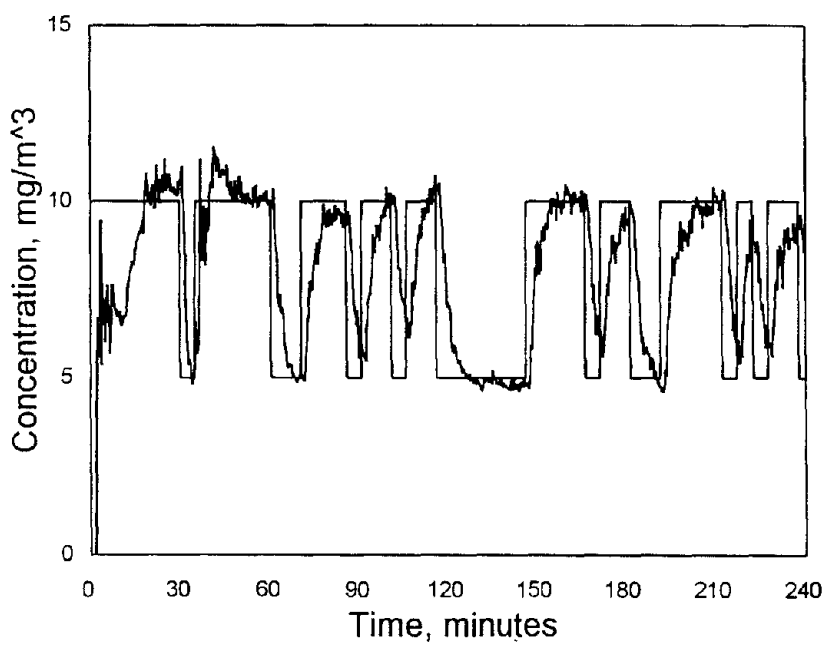

Fig. 23. PRBS input signal and resulting chamber concentrations under generator control.

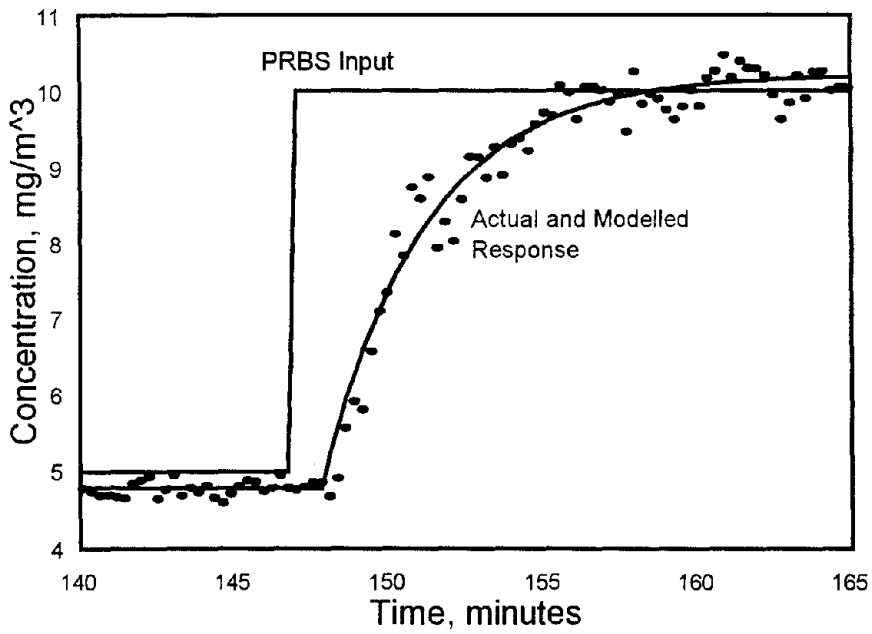

Fig. 24. Actual and modeled response from a system identification routine in MATLAB.

concentration. These results were subsequently used to simulate the chamber system and design control algorithms based on the PID control method as reported in the next section.

In addition to the PRBS trial performed with a chamber flow rate of 0.3 m^3/min, 4 other trials were also performed with flow rates of 0.1, 0.2, 0.4, and 0.5 m^3/min. A comparison of the step response simulated from the resulting dynamic model from each of these trials is given in Figure 25. The responses shown in Figure 25 were normalized to a common steady-state level of 1 and serve to demonstrate the variation in response pattern observed under different chamber flow rates. In general, a higher flow rate resulted in a faster response which is indicative a change in hydraulic detention time, τ. Although not conclusive, these results indicate the need to formulate different dynamic transfer functions when operating with different flow rates.

The PRBS model estimation method was also performed when changing the chamber flow rate to manipulate chamber concentrations. A trial of this type was performed to give concentrations between 5 and 10 mg/m^3 (Fig. 26). As seen in Figure 26, large, sudden increases in concentration

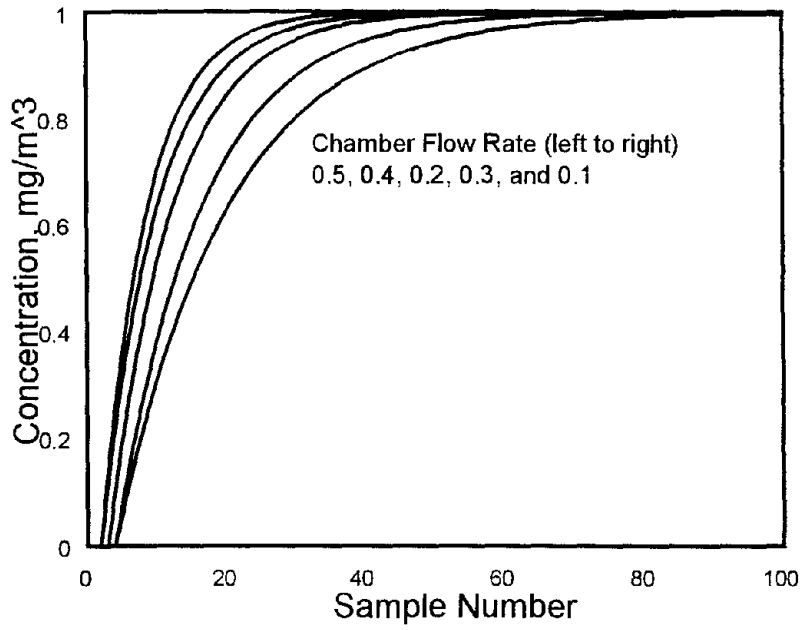

Fig. 25. Modeled unit step response of chamber concentrations at 5 flow rates.

were evident after each attempt to decrease the chamber concentration. These spikes may be attributed to re-entrainment of settled dust after the sudden increase in flow rate required to decrease the concentration. Likewise, a noticeable decrease in concentration occurred after each attempt to increase the concentration. The dynamic transfer function required to model the chamber system under flow control was necessarily more complicated (higher orders) than that under generator control because of the spikes in concentration noted above (Eq. 28).

$$y_t = \frac{-0.0936 + 0.1134q^{-1}}{1 - 1.8073q^{-1} + 0.8943q^{-2} - 0.0655q^{-3}} u_{t-2} + \frac{1 - 0.1437q^{-1}}{1 - 0.8121q^{-1}} a_t \qquad \textbf{(28)}$$

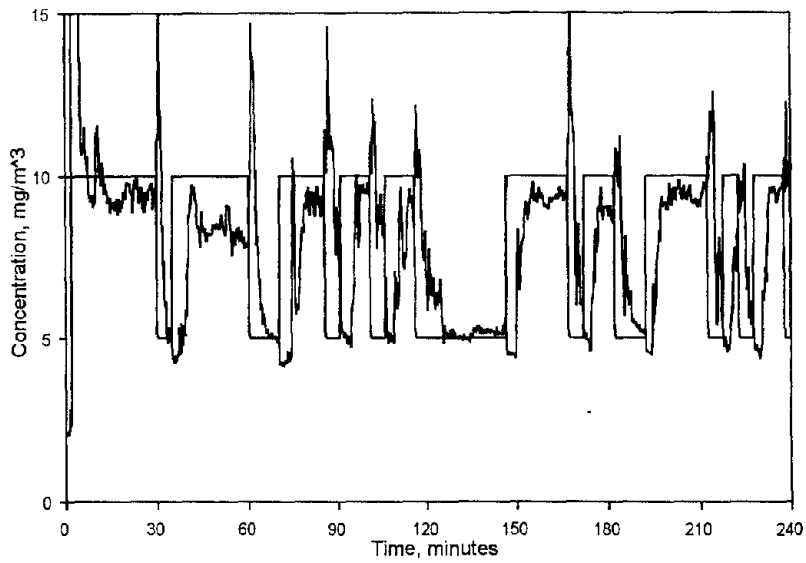

Fig. 26. PRBS input signal and resulting chamber concentrations under flow control.

Generator Controlled Concentrations

PID Control Results. Results from two sets of trials using a PI and PID algorithm are shown in Figs. 27 and 28 respectively. (The tuning constants were chosen from simulation results as shown in Figure 4.) These graphs reveal a marked improvement over those obtained when operating without feedback control (Fig. 18). (The sudden drop seen after a decrease in concentration was later determined to be a consequence of improper computer code rather than an undesirable attribute of the PID control method.) There was little difference between the two controller methods on the output. Linear regressions were performed on plots of the actual versus expected increases that produced slopes of 0.991 and 0.999 for the PI and PID controlled processes respectively.

The mean-squared error (MSE) between actual and expected measurements was also computed for each step made during these trials. Average MSE values for all steps were 0.0121 for PI control and 0.0112 for PID control. This can be compared to the average MSE value of 0.2910 for the data obtained with no control (Fig. 18). Therefore, the feedback control system was capable

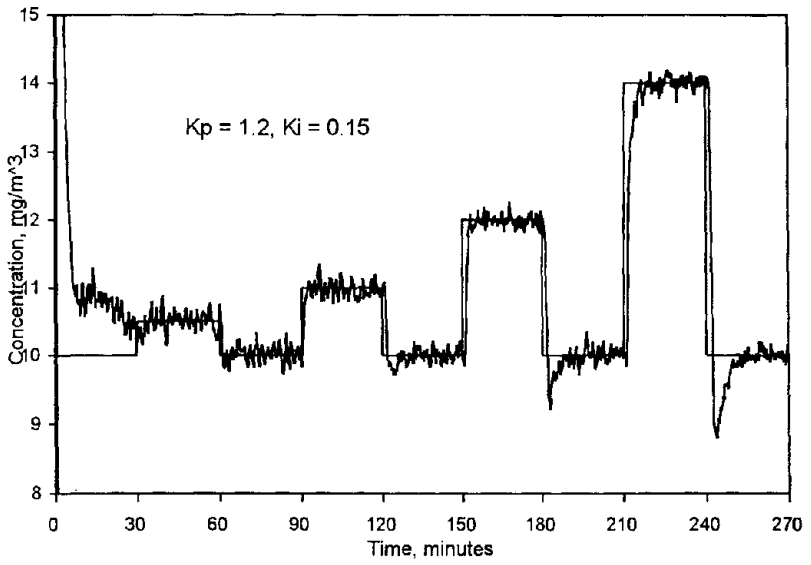

Fig. 27. Step changes in chamber concentration with PI control of the generator.

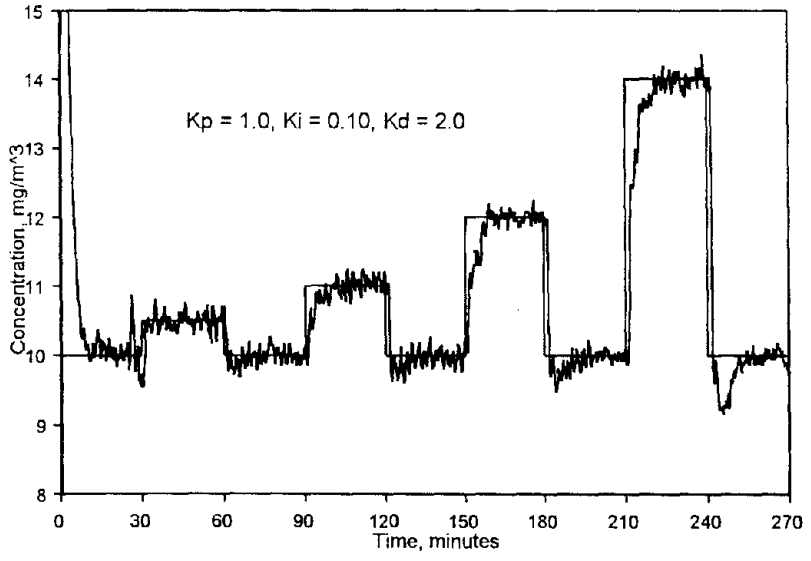

Fig. 28. Step changes in chamber concentration with PID control of the generator.

of significantly improving the ability of the generating system to maintain concentrations near a desired level.

EWMA Control Results. A typical example of the trials performed when using the EWMA control method is given in Figure 29. The relative effectiveness of the control method at various operating conditions was compared by computing the average concentration after the first 30 minutes of operation, the concentration standard deviation over the same time period, and the sum of the adjustments required by the control algorithm during the trial. The average and standard deviation were calculated 30 minutes after the initiation of a trial to allow sufficient time for the concentrations to approach the desired level and therefore offset any effects caused by rising concentrations during start-up. The "sum of adjustments" represents the absolute value of all changes in generator speed made after the initial 30 minutes. This value is an indication of the total magnitude of control actions rather than simply the number of actions.

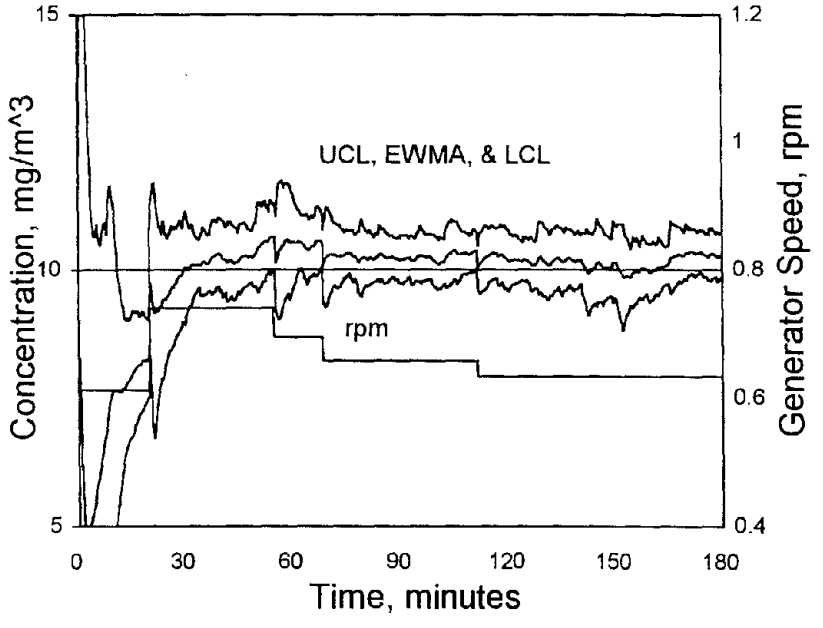

Fig. 29. EWMA control of chamber concentrations (Q_C = 0.3 m^3/min).

As seen in Figure 29, an initial correction was required after 20 minutes in order to increase the concentrations to the desired level. After that correction, only 3 more corrections were required to keep the control limits from crossing the reference line. In this case, the original increase in generator speed was apparently too great and further corrections were required to reduce the speed.

As mentioned, a total of 27 trials were performed when using the EWMA control method at concentration levels of 1, 10, and 25 mg/m^3 and flow rates of 0.1, 0.3, and 0.5 m^3/min. For all trials the average, standard deviation, and "sum of adjustments" was calculated. To normalize the results between trials performed at different concentration levels, the average was divided by the desired concentration level (AC/DC), the standard deviation was converted into the coefficient of variation (CV, standard deviation divided by average), and the sum-of-adjustments was also divided by the average (SA/AC). When compared in this manner, the results indicated a relatively consistent performance of the EWMA method when applied to different operating conditions. Average results for the 3 trials performed at each operating condition are given in Table 1.

Table 1. EWMA Controlled Trial Results.

	Flow, m^3/min			DC, mg/m^3		
	0.1	0.3	0.5	1	10	25
AC/DC	0.970	1.020	1.018	1.013	1.005	0.991
CV	0.083	0.053	0.099	0.121	0.041	0.074
SA/AC	0.016	0.009	0.010	0.014	0.010	0.011

A Two-Way ANOVA was performed to test whether there was a significant difference between these average values in relation to operating flow rate and desired concentration. Results from this analysis showed that flow rate caused a significant difference in the AC/DC ($p = 0.028$). However, as shown above the AC/DC only varied between 0.970 and 1.020. Furthermore, the DC

caused a significant difference in the CV ($p = 0.046$). All other combinations of averages were not significantly different. This analysis indicates that, when using the generator to control chamber concentrations, the EWMA method is relatively effective regardless of the operating condition.

A series of trials similar to those described above were also performed when using the PID control algorithm and when allowing the system to run with no feedback control. These trials were run with a dilution air flow rate of 0.3 m^3/min and desired concentration levels of 1, 10, and 25 mg/m^3. Examples of results taken when operating near 10 mg/m^3 for both a PID controlled and uncontrolled trial are given in Figures 30 and 31 respectively.

Results for the 3 control methods (EWMA, PID, and uncontrolled) are given in Table 2. A Two-Way ANOVA was performed to compare the trial averages between control method and starting level. This analysis revealed a significant difference in the average level obtained ($P = 0.012$) with the uncontrolled trials containing the highest average as shown in Table 2. The CV between control types were not significantly different above a 95% confidence interval.

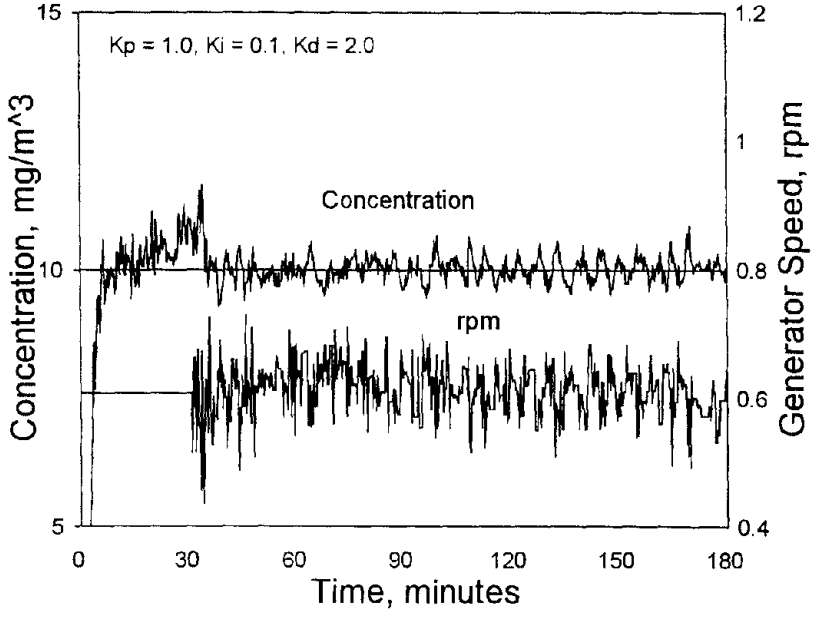

Fig. 30. PID control of chamber concentrations ($Q_C = 0.3$ m^3/min).

Table 2. Generator Feedback Control Method Comparison.

	Control Method			Desired Concentration		
	EWMA	PID	None	1	10	25
AC/DC	1.020	0.997	1.052	1.102	1.008	0.959
CV	0.053	0.139	0.051	0.144	0.043	0.056
SA/AC	0.009	4.253		3.973	1.341	1.080

As expected, there was a significant difference between the sum-of-adjustments (SA) produced by the two control methods. The average SA (divided by the average concentration) value for all 9 trials performed by the EWMA control method was 0.009 compared with an average value of 4.253 when using the PID method. This information suggests that the PID method involved changes in generator speed almost 500 times greater than changes required by the EWMA method. These constant changes produced by the PID method could represent faster wear of an actuating device and/or a significant increase in operating expense if a cost is applied to the control action.

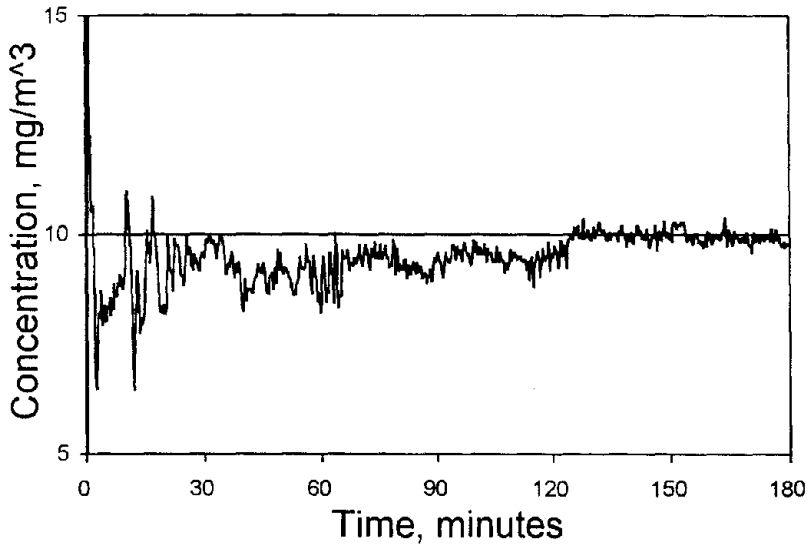

Fig 31. Chamber concentrations resulting from an uncontrolled trial ($Q_C = 0.3$ m³/min).

Step-Induced Trials Results. These trials were performed to test the relative effectiveness of the EWMA and PID control methods to respond to a change in desired concentration (DC) level during a trial. After performing the trials, a comparison of the time required to reach the new concentration level and the sum-of-adjustments required to reach that level were determined. Because of the noise qualities of the measurements, a moving average of 8 samples (2 minutes) was calculated after each step-increase. The time required for the moving average to approach 95% of the new concentration level was chosen to give the best indication of the time needed to reach a new steady-state level. Furthermore, the sum-of-adjustments, as previously described, was also calculated on all adjustments in generator speed made after the step-increase.

Results from the trials described above are given in Table 3. A Two-Way ANOVA relating the time to reach steady state level with both control method and starting level resulted in significant differences in both comparisons ($p = 0.001$ and $p = 0.017$ respectively). As shown in Table 3, the PID method resulted in a faster response of the system to reach a new steady-state level. This result can be explained by examining the nature of the theoretical step responses. Based on the transfer function model for the chamber system, the system should respond faster when operated with PID control than when operated as an open-loop process subject only to a proportional increase in generator speed as when using the EWMA method (Figure 32).

Table 3. Step-Increase Comparison Results.

	Control Method			DC, mg/m^3		
	EWMA	PID	Comb.	1-6	10-15	25-30
Time, min	17.8	7.0	15.3	9.8	13.2	17.0
SA/AC	0.130	4.877	1.476	4.819	0.994	0.670

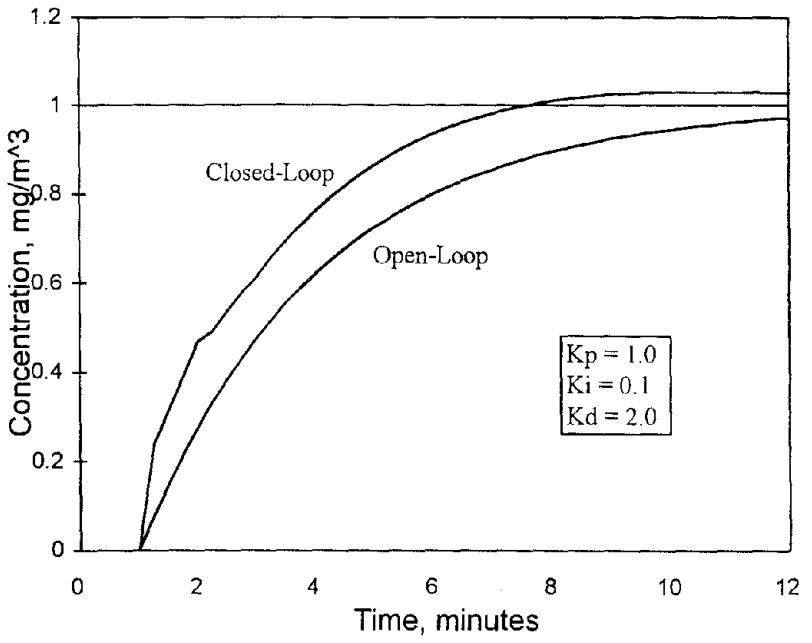

Fig. 32. Simulated response of chamber concentrations when operated with either a closed-loop (feedback control) or open-loop control algorithm.

The combination method, as expected, resulted in settling times between the other two methods. The time required to reach a new steady-state level also varied in relation to the concentration level with more time required with an increase in concentration.

A statistical comparison between the normalized sum-of-adjustments also resulted in significant differences between both control method and starting level ($p < 0.001$ in both cases). The results indicate that the EWMA method required much less adjustments to reach the new level as did either of the other two methods. As when comparing the settling time, the "combination" method gave results between those of the other two control methods. In relation to starting level, these results indicate that far more adjustments, relative to the concentration level, was required when operating at the lowest concentration level. These results are similar to those shown in Table 2 when comparing total adjustments.

Increased Noise Trial Results. A comparison between uncontrolled and EWMA controlled trials when the large cylinder was used to increase the noise qualities of the measured concentrations are given in Figures 33 and 34 respectively. These figures demonstrate the large increase in measurement variation caused when using the large scraper. The average coefficient of variation for uncontrolled trials using the large scraper was 0.659 compared with 0.043 when using the smaller scraper at the same concentration level.

Despite the large measurement variation, the EWMA control method was capable of maintaining the average concentration level relatively close to the desired concentration (DC) level. The overall average for trials conducted with no control was 18.38 mg/m^3 compared with 11.06 mg/m^3 for EWMA controlled trials. These averages compare with a value of 10.22 mg/m^3 when using the small scraper and the EWMA control method for a DC of 10 mg/m^3. The average deviation of over 1 mg/m^3 from the DC when using the large cutter was caused by the much larger span between upper and lower control limits. The large measurement variation likewise caused a large

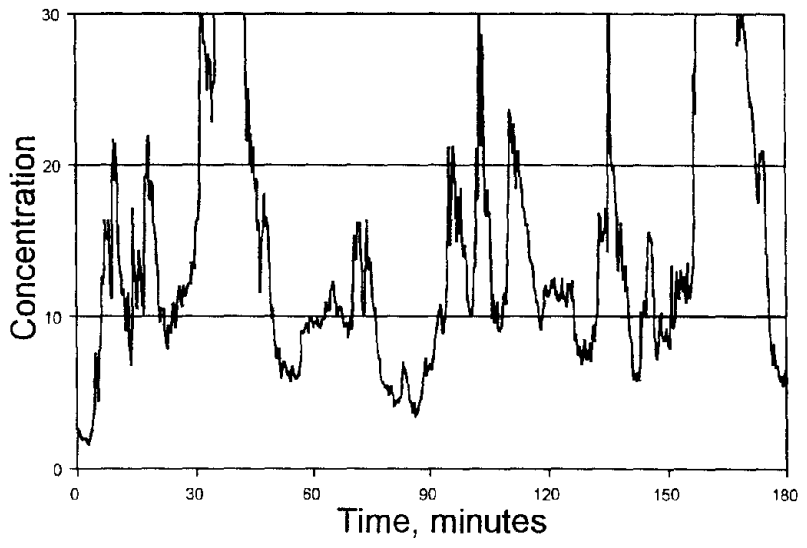

Fig. 33. Chamber concentrations resulting from an uncontrolled trial (Q_C = 0.3 m^3/min).

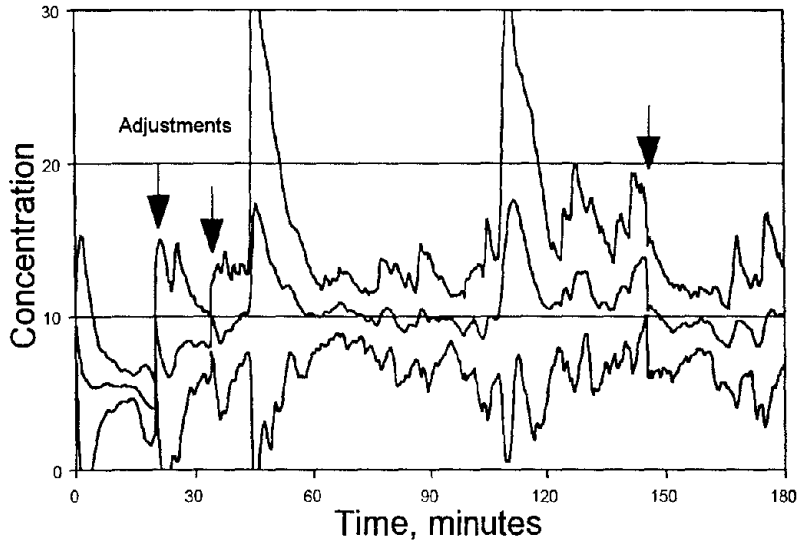

Fig. 34. Chamber concentrations resulting from an EWMA controlled trial (Q_C = 0.3 m^3/min).

measurement standard deviation and extended the distance between UCL and LCL. Therefore, the actual concentrations were "allowed" to vary to a greater extent before a control limit passed the reference line. The EWMA control method, therefore, can be used in systems where there is a wide variety of measurement noise characteristics. However, as the measurement standard deviation increases, the ability of this control method to accurately track a reference level diminishes.

Dilution Air Controlled Concentrations

As when controlling chamber aerosol concentrations with a dust generator, both the PID and EWMA feedback control methods were applied to the control of concentrations with variations in the dilution air flow rate. As discussed in the "Procedures" section, air flow rate was manipulated by sending a milliamp signal to a positioning device attached to the valve controlling air flow into the chamber. With this apparatus, attempts were made to automatically change the flow rate to compensate for deviations in aerosol concentration from a desired level.

PID Control Results. By simulating the response of the chamber system under PID control, a set of constants was chosen ($K_P = 0.9$, $K_I = 0.1$, $K_D = 0.5$) that appeared to give a satisfactory response pattern to a unit step-change in concentration. A trial was then performed in which a series of steps were induced to test the performance of the PID control algorithm when manipulating the chamber flow rate to affect a change in concentration in a step-wise fashion (Fig. 35). As seen in Figure 35, oscillations developed after each change in concentration level that were not apparent from the simulated response (Fig. 36).

A different set of constants were chosen ($K_P = 0.8$, $K_I = 0.08$, $K_D = 0.1$) that appeared to dampen the step-response when simulated (Fig. 36) and, therefore, should minimize oscillations in the actual response. Results from another step-induced trial, using the second set of PID constants, revealed a smaller tendency for oscillations in the response (Fig. 37).

As when analyzing other trials of this nature, the average concentration at each level and the mean squared error (MSE) between actual and desired concentrations was computed. During the

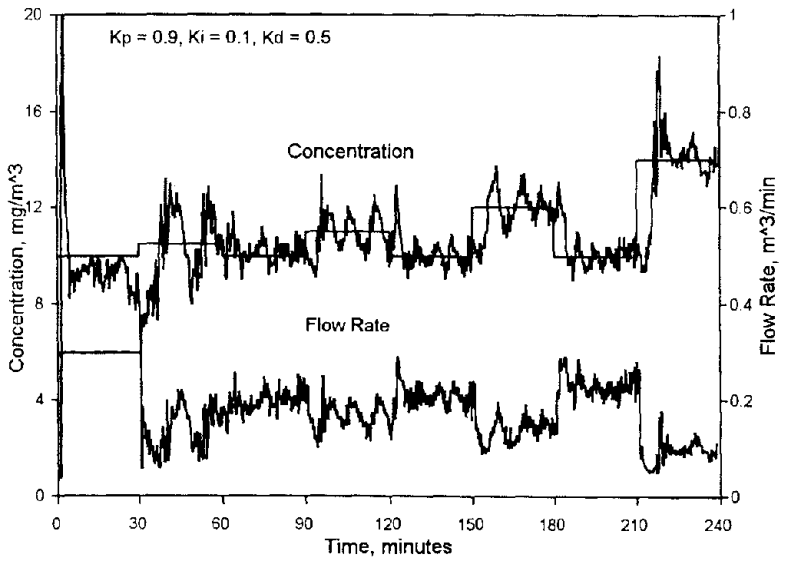

Fig. 35. PID control of concentrations with changes in flow rate.

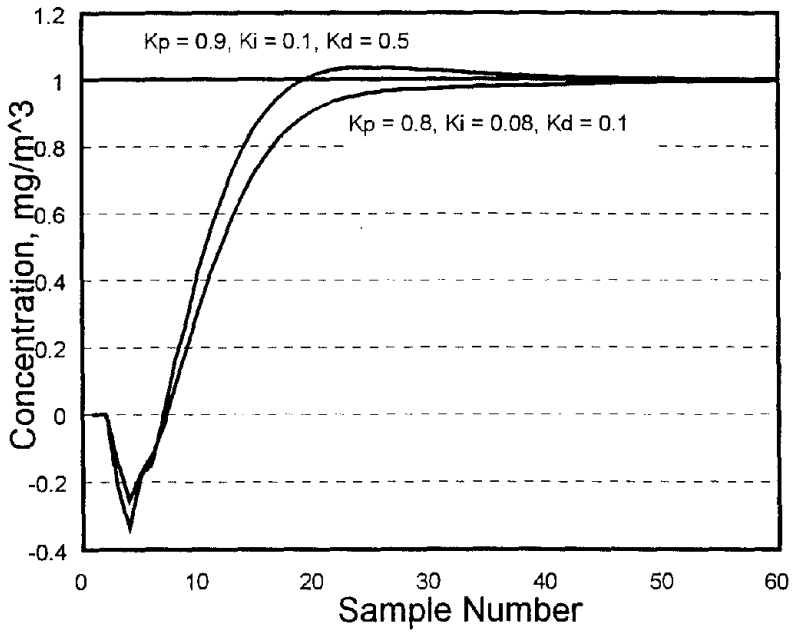

Fig. 36. Simulation of concentration response under PID control of the chamber flow rate.

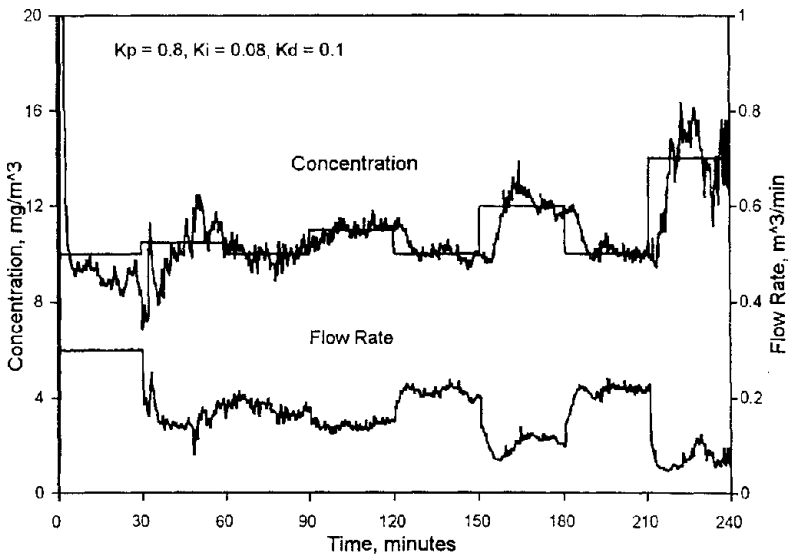

Fig. 37. PID control of concentrations with changes in flow rate and new tuning constants.

trial shown in Figure 37, the slope of actual to desired concentrations was 0.996 and the average MSE for all steps was 1.025. The average MSE value in this case is well above the similar value reported earlier of 0.0112 calculated from a similar trial using PID control of the generator. Therefore, dilution air control of the chamber concentrations was capable of maintaining average concentrations near a desired level but the measurements at each level varied significantly about the mean level.

As can be seen in both Figures 35 and 37, the PID control method resulted in concentration levels that approached a desired level to a greater extent when using large changes in flow rate than when using small changes in flow. These results appear to indicate that the response of the system when controlled by changes in flow rate is not linear in relation to the magnitude of the desired change in concentration. Unlike control with the generator, in which small changes in output rate gave a proportional change in concentration, small changes in flow rate have little affect on chamber concentration levels.

The results mentioned above also point out a problem associated with the accuracy of the identified system model. If this model is accurate, then simulated responses will give an accurate indication of the system's response under feedback control. In such situations, chosen tuning constants can be applied directly to the actual control system with confidence in their ability to affect a desired response. However, as seen above, the actual response resulted in far greater oscillations than was predicted by simulation. Therefore, the identified model was not valid. Unlike when using the generator, a separate system model may be necessary for all of the various operating conditions capable with this system. This situation points out one of the advantages of using the EWMA technique over that of the PID method; its use is not dependant on a knowledge of the step response behavior of the system and, therefore, does not require an accurate system model. As mentioned

previously, the EWMA method only requires an understanding of the general relationship between a desired output level and the necessary change in input required to (eventually) reach that level.

EWMA Control Results. Results from a trial conducted to control concentrations with changes in flow rate with the EWMA control method are given in Figure 38. A set of 9 such trials were performed with the EWMA control method; 3 each at concentration levels of 1, 10, and 25 mg/m^3 and a starting flow rate of 0.3 m^3/min. Measurements from each trial were analyzed in a way similar to that described for trials performed with control of the aerosol generator: the overall average was computed and divided by the desired concentration (AC/DC); the coefficient of variation was computed for each concentration level; and the sum-of-adjustments was computed and divided by the overall average for each trial. The statistics listed above were computed for each trial and an average value for each across the 3 trial runs per level are shown in Table 4. The results in Table 4 also shows similar statistics calculated from 9 trials conducted with PID control of the flow rate for comparison between the two methods and that of the trials conducted with no feedback control.

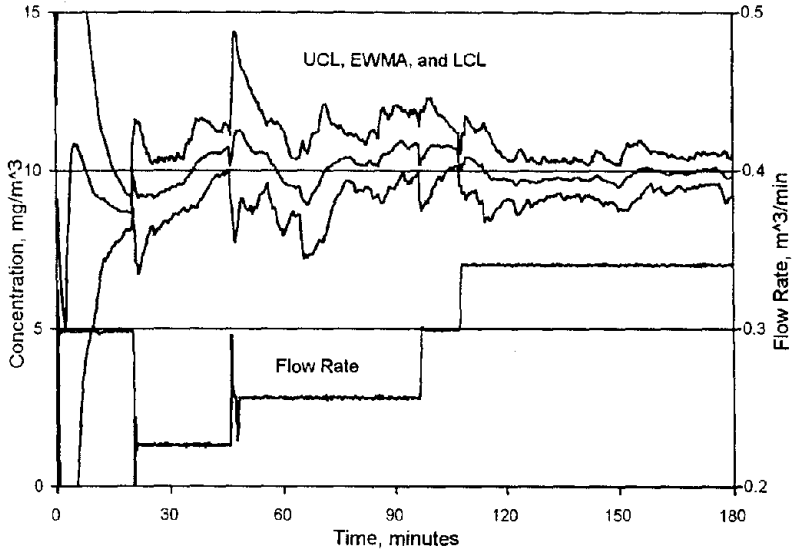

Fig. 38. EWMA control of concentrations with changes in flow rate.

Table 4. Valve Control Method Comparison Results.

	Control Method			Desired Concentration		
	EWMA	PID	None	1	10	25
AC/DC	1.001	1.004	1.052	1.099	1.005	0.952
CV	0.088	0.112	0.051	0.106	0.072	0.073
SA/AC	0.076	3.142		4.120	0.581	0.045

A Two-Way ANOVA was performed to compare the relationship between control method and DC level on the average concentration. Both the EWMA and PID produced average concentrations significantly different from those of the uncontrolled trials ($p = 0.017$). However, the ability of these methods to maintain a desired concentration level decreased significantly when operating at the highest concentration level ($p < 0.001$).

A similar analysis to compare the coefficient of variation computed for each control method also revealed a significant difference among methods ($p = 0.003$). It is interesting to note that, like when using the generator, the trials conducted under feedback control had higher CV's than did the uncontrolled trials. This information suggests that the increased accuracy of the system to track a desired level is compensated for by a corresponding increase in the standard deviation of the measurements. This condition is especially apparent when using the PID control method.

As when using the generator to control concentrations, the EWMA trials conducted when controlling the air flow rate also required significantly less input energy ($p = 0.009$) in terms of the sum-of-adjustments calculated from each trial. As shown in Table 4, significantly more input energy was also required by the control methods when operating at lower concentration levels.

Not apparent from the results given above was the tendency for either control method to occasionaly "demand" a flow rate in excess of the allowable flow rates (0.15 to 0.45 m^3/min) for the chamber system. (To minimize extremely large fluctuations in chamber static pressure, flow rates

were limited to ± 0.15 m^3/min about a starting flow rate of 0.3 m^3/min.) Therefore, a desired change in concentration level was not possible because the valve was already at a minimum or maximum. This condition is prevalent in any controlled system, either manual or automatic, especially in cases such as this where a change in flow rate has a confined ability to change the overall concentration level.

Step-Induced Trials Results. Step-trials were limited to changes of 2 mg/m^3 above starting concentrations of 10 and 25 mg/m^3 when using the EWMA method. Results from these trials were not conclusive, possibly because small decreases in flow rate to affect an increase in concentration were generally not effective as shown in Figure 22. An example of one of these trials is given in Figure 39. Notice in Figure 39, a few corrections were necessary prior to the induced increase in concentration at 60 minutes to first decrease then increase the concentration level. After the step-increase, several more corrections were required to maintain a concentration near 12 mg/m^3. However, in other similar trials, corrections in excess of the allowable flow rate were attempted. In

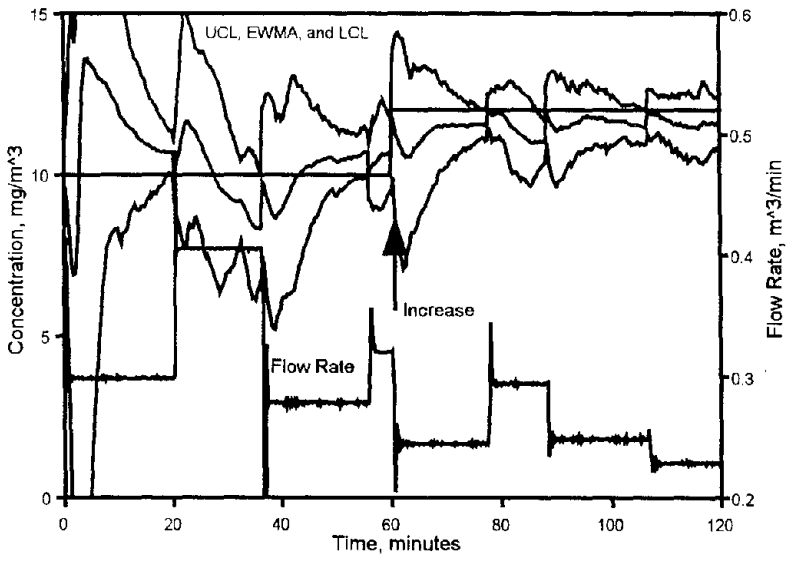

Fig. 39. Step-increase in concentration caused by a corresponding decrease in flow rate.

some cases, the flow rate was already at a minimum prior to expecting a further decrease to increase the concentration.

Similar step trials were also performed when using PID control except, to avoid reaching a limit in flow rate, only a step of 1 mg/m^3 was required. Results from these trials revealed a better response in concentration to changes in flow rate (Fig. 40). However, a conciderable amount of variation in the measured concentrations was still evident in these trials as shown in Figure 40.

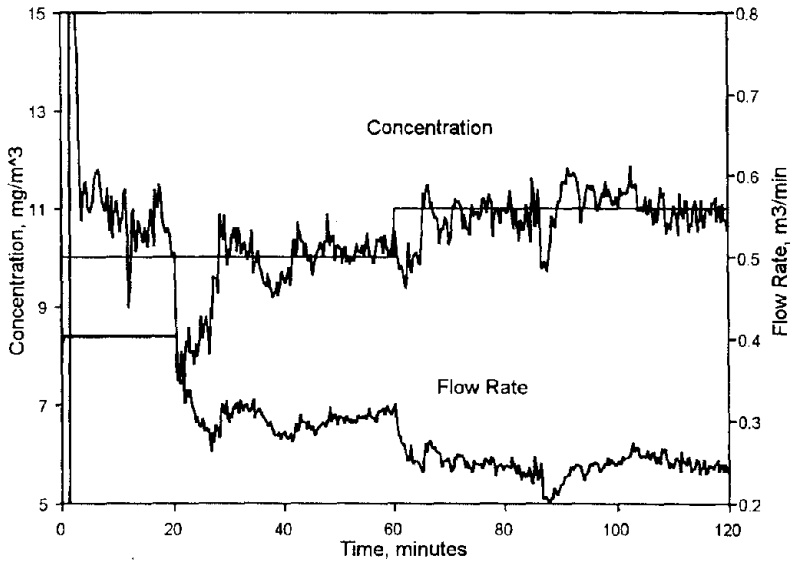

Fig. 40. Step-increase in concentration when using the PID control method and changes in flow rate.

CONCLUSIONS

Application of a conventional feedback control system requires a knowledge of the dynamic behavior of the process after a change in input level. Theory and methods associated with identifying and estimating a dynamic model in the form of a discrete transfer function were provided in this report. However, as emphasized throughout this report, these techniques were only applicable when using the PID control method. Furthermore, results from this research demonstrated that some processes may not respond to a change in input in a manner predicted by a single model under all operating conditions. Therefore, the application of a PID controller may result in an undesirable response if applied over a wide range of operating characteristics.

As a way to alleviate the problem associated with an unpredictable system response, a novel technique based on theory associated with statistical process control was proposed. This method, which utilized a recursive update of the exponentially weighted moving average (EWMA) of the process measurements, made corrections to a change in input level based on the proportional relationship between input and output. Therefore, only the level of the eventual response to a change in input level had to be constant over the range of possible operating conditions. Even in cases where this assumption was not valid, a series of corrections made with this method eventually brought the process to its desired level. This quality of the EWMA method was proven in this research even when using operating conditions that greatly increased the noise qualities of the measured signal.

Results from this study demonstrated that the concerns mentioned above were valid when either controlling chamber concentrations with changes in generator output rate or chamber air flow rate. A statistical comparison of the step response analyzed at various operating conditions revealed a similar response regardless of condition. However, when viewed separately, an extremely wide

range of responses was shown to be possible despite having similar average responses. Although control with dilution air was not tested as exhaustively as control with the generator, that method of concentration control appeared to be less predictable than when controlling with the generator and therefore was more difficult to control accurately.

This research demonstrated that, when attempting to control airborne contaminants with changes in air flow rate, an understanding of the relationship between the monitor response and the actual concentration was necessary. Furthermore, the ability of the moving air to dilute concentrations varied with flow rate. In this case, losses due to impaction of the dust on piping greatly offset a decrease in sedimentation at the higher flow rates. This change in the fraction of dust lost in the system required a greater reduction in flow to increase concentrations than would be expected when calculating a simple proportional change in flow rate.

An added complication when using flow rate to control concentrations appeared when a sudden increase in flow produced a large increase in concentration. This increase, possibly caused by re-entrainment of settled dust, was short-lived prior to a decrease caused by dilution but must be considered if it were to result in concentrations in excess of a permissible exposure limit. Finally, these results demonstrated that control with air flow rate has a limited range of adjustment to the aerosol concentrations.

Results from this research indicated that computer control of airborne particles was possible. Both control methods under investigation improved the ability of the chamber system to maintain concentrations near a desired level. The PID method was more effective at producing small corrections in concentration as indicated by the step-trials. However, this method was shown to require a significant increase in input energy over the EWMA method in terms of the number and total magnitude of adjustments. These constant changes in valve position may induce faster wear

with a resulting increase in capitol and operating costs.

A final point related to the economics of applying a feedback control system should be made. This topic is related to an examination of the need for a feedback control system to control airborne contaminant levels. The research described above centered around controlling concentrations about some desired level. However, another goal for using such a system may be to maximize the reduction of a contaminant rather than maintain it near a given level. Therefore, a design solution may be to install the largest ventilation equipment possible to maximize the dilution effect of the flowing air. Obviously, however, budgetary constraints will limit the size of the equipment with a resulting limit on its ability to remove airborne contaminants.

When controlling concentrations with dilution air as described in this report, a relatively constant source of aerosol was created with the aerosol generator. Only small changes in air flow within the chamber, intermittent changes in losses, the development of eddy currents, and other factors caused the concentrations to wander from a desired level that necessitated adjustments to the flow rate. However, in most situations the source of the contaminant will not be controllable or consistent. This condition lends itself to the application of feedback control, perhaps to a greater extent than was provided in this research, because such a system would minimize the energy required to maintain contaminants below some threshold. Rather than continuously apply the same flow rate to compensate for the largest expected concentrations, a feedback control system could regulate flow according to the concentrations measured at any given moment, therefore, minimizing the energy (and associated cost) applied to the ventilation system.

ACKNOWLEDGMENTS

The investigators wish to thank NIOSH for the support from this R03 grant. The funds from this demonstration grant enabled a doctoral student (Patrick O'Shaughnessy) to successfully complete his Ph.D. as well as publish several papers in the area of Feedback & Control. The research and subsequent data will be invaluable for developing an R01 or a SERCA proposal, which, without this support, would be impossible.

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APPENDIX A
Continuous To Discrete Transfer Function

When a computer is used to control a process, the measured output signal from the process and the input signal are necessarily discrete because of the time delay needed to process the signals into a digital form applicable to computers. The continuous transfer function in the time domain expressed by the Laplace transform must be modified by the z-transform to correctly represent discrete signals. The relationship between the Laplace transform and z-transform is described below (Palm, 1986).

Let $\delta(t)$ be the unit-impulse function, then $\delta(t - kT)$ is a unit impulse occurring at time kT. A sequence of sampled measurements, denoted $y^*(t)$, can be represented as a train of impulses extending back in time as:

$$y^*(t) = y(0)\delta(t) + y(T)\delta(t - T) + y(2T)\delta(t - 2T) + \ldots \qquad \textbf{(A1)}$$

The Laplace transform of $y^*(t)$ is:

$$Y^*(s) = y(0) + y(T)e^{-Ts} + y(2T)e^{-Ts} + \ldots \qquad \textbf{(A2)}$$

Let $z = e^{Ts}$, then $Y^*(s)$ as a function of z is:

$$Y(z) = y(0) + y(T)z^{-1} + y(2T)z^{-1} + \ldots \qquad \textbf{(A3)}$$

Comparing Eq. A1 with Eq. A3 shows that z^{-1} is a delay operator representing a time delay T. Therefore, z^{-1} is analogous to the delay operator q used in ARIMA and ARMAX system identification models as described in the text. The equations given above also indicate the significance of the sample period, T, when developing a model of the system. The reliance on a specific sample period is not readily apparent in equations representing ARIMA models (see Eqs. 4 and 5) but Eq. A3 demonstrates a unique solution of the z-transform for a particular sample period. This implies that an ARMAX model identified with a sample period, T, cannot be used to represent the system when sampled at any other period.

APPENDIX B
Step Response Trial Results

H Trials, Conc 1 to 6					
Trial #	Flow Rate	Max	Max-Min	4 Tau	Delay
H1	0.1	5.556	4.555	10.813	1.330
H2	0.2	6.509	5.494	8.557	1.860
H3	0.3	6.153	5.171	10.402	1.060
H4	0.4	5.319	4.352	8.758	1.060
H5	0.5	5.151	4.160	8.877	1.060
	Average	5.738	4.746	9.481	1.274

G Trials, Conc 10 to 15					
Trial #	Flow Rate	Max	Max-Min	4 Tau	Delay
G2	0.1	13.993	3.974	9.660	1.880
G3	0.2	14.552	4.489	6.119	1.630
G1	0.3	13.823	3.853	9.700	1.600
G4	0.4	15.746	5.692	7.486	1.330
G5	0.5	14.381	4.375	6.462	1.600
	Average	14.499	4.477	8.327	1.608

I Trials, Conc 25 to 30					
Trial #	Flow Rate	Max	Max-Min	4 Tau	Delay
I1	0.1	27.870	3.074	7.443	1.860
I2	0.2	31.569	6.225	3.903	1.370
I3	0.3	30.625	5.676	12.520	1.350
I4	0.4	27.647	2.677	0.853	1.900
I5	0.5	27.949	3.065	11.078	1.900
	Average	29.132	4.143	8.736	1.676

Averages of the 3 trials					
Trial #	Flow Rate		Max-Min	4 Tau	Delay
1	0.1		3.868	9.305	1.690
2	0.2		5.403	6.193	1.620
3	0.3		4.900	10.874	1.337
4	0.4		4.240	5.699	1.430
5	0.5		3.867	8.806	1.520
	Average		4.455	8.795	1.519

LIST OF PUBLICATIONS

Present Publications

O'Shaughnessy PT, Hemenway DR, Absher RG: System Identification and Feedback Control of An Aerosol Production Process. Aerosol Science and Technology. (in press)

O'Shaughnessy PT, Hemenway DR: Computer Automation of a Dry-Dust Generating System. Inhalation Toxicology. 6:95-113, 1994

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O'Shaughnessy PT: Real-Time Process Control Techniques for a System With Unpredictable Disturbances. Advances in Instrumentation and Control. 50(1):11-19. Instrument Society of America Conference, Toronto, Canada. 1995

Conference Poster Session

O'Shaughnessy PT, Hemenway DR, Absher RG: Model Identification and Control of an Aerosol Production Process. American Association of Aerosol Research, Annual Conference. Pittsburgh, Penn. 1995

Future Publications

O'Shaughnessy PT, Haugh LD: Application of an Automated Bounded Adjustment Method For Airborne Contaminant Control. Journal of Quality Technology (or Technometrics). Article to relate the novel EWMA control method to statisticians and other continuous-process control experts.

O'Shaughnessy PT, Hemenway DR: Computer Control of Dilution Air Flow Rates For Airborne Contaminant Control. American Industrial Hygiene Association Journal. Article to relate findings in this report that pertain to flow rate control for airborne contaminant reduction.