AUTOMATED FEEDBACK CONTROL OF AN INHALATION EXPOSURE SYSTEM WITH DISCRETE SAMPLING INTERVALS: TESTING, PERFORMANCE, AND MODELING

Brian A. Wong
CIIT Centers for Health Research, Research Triangle Park, North Carolina, USA

The application of a proportional-integral-derivative (PID) control algorithm to an inhalation exposure system using a building automation system is described. Previous studies had utilized a control system in which concentration was monitored continuously and adjustments to the generator were made on a continuous basis. In this system, benzene vapor was generated into a chamber, and a gas chromatograph was used to measure the concentration in a chamber at discrete 30-min intervals. Thus only limited opportunities were available to sample and adjust the vapor generator flow rate. A series of tests were conducted in which the generator was operated without control, with control, with an additional load, and with nonoptimal settings. The results showed that the PID control loop could function effectively to restore a system back to the target set point, even with an additional load on the system. With nonoptimal control settings, the system showed oscillatory behavior. A model to simulate operation of the chamber was developed on a spreadsheet program. The model was accurate at simulating the various testing scenarios and useful for selecting the proper control settings. A PID feedback control system operating with a concentration monitoring system that sampled on a 30-min cycle was shown to produce exposures that were accurate in matching the target set point and maintaining a constant concentration.

An inhalation exposure study typically involves maintaining an experimental subject in a known and constant environment while exposing the subject to a defined concentration of a test material. Environmental parameters should be monitored over the course of the exposure to verify the conditions and to maintain the parameters at the proper settings. The test material is administered under defined conditions such as a steady concentration for a set period of time or in some predetermined pattern. In either case, the concentration of the test material must be monitored and the generation system adjusted to maintain the test material at the target levels.

The development of the computer, especially the personal computer, has led to the automation of inhalation exposures. Computer systems are applied to monitor environmental conditions such as temperature, humidity, air flow, and concentration of the substance being studied (Hinners, 1978;...
Van Stee & Moorman, 1978; Snellings & Dodd, 1990). Instruments that monitor for specific compounds such as ozone, oxides of sulfur, and oxides of nitrogen may also be connected to a computer network to synchronize the collection of data (Mokler et al., 1984; Schreck et al., 1981; Crider et al., 1980). Currently, various data acquisition systems and data logging systems are being used to periodically record information from various sensors and analytical instruments including systems validated for Good Laboratory Practices (Decker et al., 2001; Gilkison et al., 2001). We previously reported on the use of a building automation system to monitor and control an inhalation system (Wong & Moss, 1996).

In addition to monitoring and data logging, most of these systems also used the computer to actuate devices such as valves or flow controllers to control exposure systems. Many systems incorporated some kind of feedback control loop to maintain target concentrations in the chamber (Van Stee & Moorman, 1978; McFarlane & Pfleeger, 1987; Cloutier & Malo, 1992; Crider et al., 1980; Karanian et al., 1986). A feedback control loop based on a proportional-integral-derivative (PID) algorithm linked a continuous particle concentration monitor to a dust generator for controlling aerosol concentration in a chamber (O'Shaughnessy & Hemenway, 1994; O'Shaughnessy et al., 1996). A system was described (Johnson et al., 1995; Johnson & Fechter, 1996) to produce a vapor atmosphere of constant concentration. Johnson and colleagues used a systolic metering pump to carry liquid toluene into a heated flask where it was vaporized and carried into an exposure chamber. An infrared spectrophotometer continuously sampled the chamber atmosphere and transmitted the information to a commercially available controller that used a PID algorithm to control metering pump flow. The system had excellent control, maintaining the average concentration within tenths of a percent of the target set point, with a root-mean-square variability of around 3 to 5% about the set point. Larger deviations from target at lower concentrations (100 ppm) and some cyclical variation in chamber concentration were also observed. Many reasons for those observations were given, including pulsations from the systolic pump and lag times for mixing and concentration buildup in the chamber (chamber equilibrium time). The pulsatile nature of the flow coupled with the system dead time (time between a control adjustment and the time when a change is detected) may have increased variability in control of the system or induced some oscillations in chamber concentration.

In systems that use a continuously monitoring instrument such as an infrared spectrophotometer, the control system adjusts the generator on a continuous basis. In such a system, changes in atmospheric concentration can be detected as rapidly as the sample can be drawn and analyzed. Hence, feedback to the control device is nearly immediate, and adjustments can be made as a change is detected. However, there are experimental systems in which an instrument may sample the chamber infrequently (Van Stee & Moorman, 1984). For example, a single instrument may be used to measure the atmospheric concentration of a compound sequentially
from several chambers. A sample is drawn and analyzed from one chamber. An automated valve system then switches to draw a sample from the next chamber. With several chambers in the system, a significant amount of time may elapse between analyses of samples from the same chamber. Opportunities to measure concentration and adjust the generation system to bring chamber concentration to the target level are limited. Another situation in which concentration in a chamber is measured infrequently exists when the analytical process requires a length of time for completion. In a gas chromatograph, the sample must proceed through a long chromatography column before analysis is completed and results determined. There may be a significant time period before the control system can adjust the generator. In the meantime, concentration in the chamber may continue to change.

This report describes the implementation of a PID feedback control system used in an inhalation exposure system in which the test material concentration was measured on a discrete 30-min time schedule. To use such a time schedule, we demonstrate that the generation system was relatively stable in the absence of any adjustments during the course of an exposure. The reaction of the system under ideal and under stress conditions is demonstrated. We also show how a mathematical simulation of the system was used to determine the proper control-loop parameters and show that the simulation can predict the behavior of the exposure system.

MATERIALS AND METHODS

An automated feedback control loop was implemented in an exposure system that had an interval of time between readings of the chamber concentration. A typical inhalation exposure system consisting of a vapor generation system, an exposure chamber, and an analytical instrument to measure concentration of vapor in the chamber (Figure 1) was used. The system was monitored and controlled automatically (Wong & Moss, 1996) by a building automation system (Infinity, Andover Controls, Andover, MA). This study was conducted to demonstrate the effectiveness of the control system in preparation for an inhalation study of benzene (CAS No. 71-43-2, 99.9+%, Sigma Aldrich Chemical Co.). The benzene study protocol was designed for three doses (1, 10, and 100 ppm) and a control group. This preliminary study utilized only one of the exposure chambers, but the system was operated as if all chambers were on line.

Exposure System

A 1-m³ glass and stainless steel inhalation chamber (H1000, Lab Products, Inc., Seafor, DE) was used in the study. Airflow through the chamber was maintained around 225 L min⁻¹ or 13.5 air changes per hour. Temperature and humidity of the incoming air were maintained at approximately 22.2°C (72°F) and 50% relative humidity, respectively. These parameters were also controlled by feedback control loops, but the performance of
these control systems is not discussed here. The exposure chamber was operated under typical conditions with caging and waste catch pans in place, although no animals were used in the preliminary study.

**Vapor Generation System**

A simple vapor generation system was used (Wong, 1995), consisting of a 37.8-L (10-gal) stainless-steel pressure vessel that contained a small amount of liquid benzene (100–300 ml). The pressure vessel was pressurized to approximately 34–69 kPa (5–10 psi) with house nitrogen. A check valve prevented the backflow of nitrogen and vapors. The vessel usually sat for several hours to allow the liquid to reach equilibrium with its vapor prior to a run. The mixture of benzene vapor and nitrogen gas was metered through a mass flow controller into the chamber inlet air stream. The flow through the mass flow controller was adjusted by setting an input voltage either manually or by the building automation system.

**Determination of Vapor Concentration in the Chamber**

A gas chromatograph (GC) (HP5890 Series II, Hewlett-Packard Co., Avondale, PA) equipped with a multiport gas sampling valve and integrator
was used to measure vapor concentration in the chamber. The GC was cali-
ibrated by sampling atmospheres of known benzene concentration through
the gas valve system. A continuous flow of the chamber atmosphere was
pulled from the center of the chamber through a sample line. A sample
from the chamber was drawn and analyzed by the GC when the multiport
valve selector rotated to the appropriate port position. In this multiple cham-
ber study, the GC valve system cycled and sampled sequentially from each
chamber once every 30 min.

An integrator (HP 3396 Series II, Hewlett-Packard Co., Avondale, PA)
connected to the GC analyzed the chromatogram and calculated the con-
centration of vapor in the atmosphere. The integrator was programmed (in
HP 3396 Series II BASIC) to coordinate the multiport sampling valve and
GC sample valve.

**Control System**

After analyzing the chromatogram, the GC integrator was programmed
to transmit the concentration as alphanumeric information via an RS232
connection to the building automation system (BAS) (Infinity, Andover
Controls Corp., Andover MA). The BAS was programmed to parse this infor-
mation and distribute it to the appropriate controller linked to a specific
chamber. The controller used a PID algorithm to compare measured con-
centration with target concentration. The program then altered the voltage
to the mass flow controller to change the vapor-nitrogen flow to bring the
measured concentration toward the target.

An infrared spectrophotometer (MIRAN 1B, Foxboro, MA) was calibrated
for benzene (wavelength = 3.33 µm, response time = 4 s) using a standard
closed-loop injection technique. The infrared spectrophotometer (IR) was
used in this study to provide a continuous reading of the concentration with-
in the exposure chamber. It was used to illustrate chamber concentration
during the test runs but was not used in the feedback control loop. The output
of the IR was captured by a stripchart recorder. For publication, the chart
paper was digitally scanned. The image was reversed to read from left to
right and digitally manipulated to enhance readability of the recorded line.
Axes were added to the image to show the approximate scales.

**Chamber Concentration Simulation Model**

To understand how the PID control loop and discrete sampling time inter-
vals might interact with the chamber equilibrium time, a simple model of the
concentration in the exposure chamber was generated using a spreadsheet
program. The chamber was assumed to behave as a well-mixed system for
which the following equation describes the rate of change of concentration in
a chamber where material is being introduced (Hill, 1977):

\[
\frac{dC}{dt} = \left(C_{in} - C\right) \frac{Q}{V} - kC
\]  (1)
where $C$ is the current chamber concentration, $C_{\text{in}}$ the concentration of vapor entering chamber, $Q$ the flow rate through chamber, $V$ the chamber volume, and $k$ the first-order rate constant.

If no reaction of the chemical inside the chamber is occurring ($k = 0$) and the inlet concentration is constant, the analytical solution to Eq. (1) is:

$$C = C_{\text{in}} + (C^* - C_{\text{in}}) \exp \left( -\frac{Q}{V} t \right)$$

(2)

where $C^*$ is the initial concentration in chamber and $t$ the time.

In this equation, it can be observed that when $C^* = 0$ (at the start of the exposure, for instance), the concentration starts at 0 and increases until the concentration is equal to the inlet concentration, $C_{\text{in}}$. Conversely, if the inlet concentration drops to zero (generator is turned off), the chamber concentration will drop from $C^*$ to 0. The time required to achieve 90% of the final concentration is $t_{0.9} = 2.303 \times V/Q$. These equations are widely used to describe the idealized operation of an inhalation exposure chamber (Silver, 1946; MacFarland, 1983; Cheng & Moss, 1995; Wong, 1999).

The concentration of vapor in the inlet stream entering the chamber was calculated as $C_{\text{in}} = \alpha_{\text{gen}} C_{\text{vap}} Q_{\text{gen}} / Q$, where $C_{\text{vap}}$ is the theoretical vapor concentration in the generator and $Q_{\text{gen}}$ is the flow through the generator vessel. The factor $\alpha_{\text{gen}}$ was used to correlate simulation results with the experimental data. This factor may be necessary because the experimental equilibrium concentration within the generator vessel may differ from the theoretical value, $C_{\text{vap}} = P_{\text{vap}} / P_{\text{gen}}$. The primary reason for the difference may be an inaccurate measurement of the total pressure in the pressure vessel, $P_{\text{gen}}$, or inaccurate knowledge of the vapor pressure of benzene, $P_{\text{vap}}$. Cooling of pressure vessel contents due to evaporation of benzene would decrease the vapor pressure of benzene, which would contribute uncertainty in the benzene vapor concentration. Finally, the flow of a mixture of nitrogen and benzene through a mass flow controller calibrated for nitrogen could lead to a systematic bias in determining the equilibrium concentration. The generator factor that provided the best results in this study for comparing the experimental data collected by the GC to the simulation model was $\alpha_{\text{gen}} = 0.7$.

**PID Feedback Loop**

A feedback loop was used to adjust the generation system to maintain the measured concentration near the target set point. For this study, a standard proportional-integral-derivative (PID) control algorithm was used to calculate the corrected signal based on the deviation from the target set point or error (Johnson, 1988). The term deviation is used instead of error to avoid confusion with other terms such as standard error. In this algorithm, the corrective signal to the control device is a combination of a proportional
factor of the deviation, the integral of the deviation over time, and the
derivative (rate of change) of the deviation:

\[ S = k_{\text{Prop}}E_p + k_{\text{Prop}}\int E_p \, dt + k_{\text{Prop}}k_{\text{Der}} \left( \frac{dE_p}{dt} \right) + S(0) \]  

(3)

where \( S \) is the signal to control device, \( S(0) \) the initial control device set-
ing, \( E_p \) the percent deviation, \( k_{\text{Prop}} \) the proportional constant, \( k_{\text{Int}} \) the inte-
ral gain constant, and \( k_{\text{Der}} \) the derivative gain constant.

The integral factor in Eq. (3) requires knowledge of the history of the
deviation from the start of the procedure. Since the history may be inconve-
nient to maintain, the algorithm may be simplified (Johnson, 1988) by re-
placing the derivative and integral terms with approximations based on pre-
vious deviation terms and the time interval between samples:

\[ S(i) = S(i - 1) + k_{\text{Prop}} \times \left[ E(i) - E(i - 1) \right] + k_{\text{Prop}}k_{\text{Int}}(\Delta t) \times E(i) \]

\[ + k_{\text{Prop}}k_{\text{Der}} \times \frac{E(i) - 2E(i - 1) + E(i - 2)}{\Delta t} \]  

(4)

where \( S(i) \) is the current signal to control device, \( S(i - 1) \) the previous signal
to control device, \( E(i) \) the current deviation, \( E(i - 1) \) the deviation at previ-
ous time step, \( E(i - 2) \) the deviation two time steps prior, and \( \Delta t \) the time
interval between time steps.

Equation (4) is readily used when concentration in the chamber is de-
termined on a regular basis with a set time interval between readings. This
algorithm also has the advantage that knowledge of the deviations from
time zero is not required. Only the current deviation and previous two de-
viation terms need be retained in memory.

The spreadsheet model was constructed by dividing the calculations
into discrete time periods. The length of a time period (\( \Delta t \)) was defined by
the interval between GC readings. Within a time period, \( i \), the concentra-
tion was calculated according to equation 5 [based on Eq. (2)], where \( t' \) ranged
from 0 to \( \Delta t \):

\[ C(t) = C_{\text{in}}(i) + \left[ C(i - 1) - C_{\text{in}}(i) \right] \exp \left( -\frac{Q}{V} t' \right) \]  

(5)

At the end of the time period, the PID calculation [Eq. (4)] was applied,
which, based on the previous generator setting and deviation from the con-
centration set point, calculated a new generator setting. A new time period
was started, with a new \( C_{\text{in}} \) and time \( t' \) reset to zero. The value \( C^* \) in Eq. (2)
becomes \( C(i - 1) \), which is the ending concentration from the previous time
period.
The spreadsheet calculations reproduced the classical behavior (Johnson, 1988) of the proportional, integral, and derivative controller modes, and combinations of the three modes (results not shown). The most important factor that governs the behavior of the PID control loop is the selection of the proportional, integral, and derivative gain constants, $k_{\text{Prop}}$, $k_{\text{Int}}$, and $k_{\text{Der}}$. Various methods may be used to determine the PID constants, including simple trial and error, and experimental procedures (Johnson et al., 1995; Johnson, 1988) that depend on empirical observation of the system under defined conditions. Also, stand-alone PID controllers may incorporate logic that automatically selects the gain constants. The spreadsheet model provided a way to determine the PID constants by trial and error on computer, yielding information quickly. Once optimum constants were determined on the computer, an experimental trial run could be performed to verify the appropriateness of the PID constants.

**Startup Overshoot**

The PID control algorithm has a well-known characteristic during the initial startup phase in which the controlled variable overshoots the target set point with a subsequent (and sometimes oscillatory) return to the target set point. The cause of the overshoot is the action of the PID during the startup, when the initial measured concentration is far from the target. The PID controller response when the deviation is large is to maximize generator output until the concentration approaches the target set point. Overshoot of the target concentration may cause an overcorrection back to the target set point. This overresponse can be moderated by reducing the $k_{\text{Int}}$, but with the risk of a slower response to concentration drift from the set point once past the startup phase. One solution to this problem (Johnson et al., 1995) was to program a slow increase in the set point from 0 to the ultimate target value over the first 30 min of the exposure. This minimized the error and overresponse during the initial ramp up. This problem was also noted in an aerosol system (O’Shaughnessy & Hemenway, 1994) at the beginning of exposure runs, but no special instructions were programmed to reduce the overshoot.

The solution to slowly increase the set point is feasible in the situation where a concentration reading is taken continuously and the PID feedback loop is constantly adjusting the generator output. In this exposure system, however, a concentration reading was taken only every 30 min. Therefore an adjustment to the generator output could only be made every 30 min, and continuously changing the set point could not be applied. Our solution to the initial overshoot problem was to apply the PID control only after the first concentration reading, as opposed to the start of the exposure when the concentration is zero. At the start of the exposure, the generator output was set to a value that was predicted to produce a concentration close to the target concentration. The first concentration reading was taken 25 min after the start of the exposure, well after the $t_{90}$ time for the chamber conditions (10.2 min in this study), to ensure that the concentration had neared...
equilibrium. With an accurate initial setting, the concentration was close to the target. A small error from target would cause the response of the PID loop to make only a small change to the output generator and minimize large swings in concentration.

RESULTS

Operation of the exposure system was subjected to various test runs to confirm and stress the PID control loop. Four of the tests are described here.

Run 1: Generation System with No Control

In the first test, the generation system was operated without any feedback control. A normal 6-h run was conducted with the generator set to a flow to achieve a concentration of approximately 100 ppm. No attempt was made to adjust the flow. The IR chart recording (Figure 2) shows that the concentration rose to above 100 ppm during the initial part of the exposure and then slowly decreased for the remaining period of the exposure. Sample times during the exposure and the corresponding concentration values determined by the GC are shown in Table 1. The concentration decreased to less than 90 ppm at the end of the exposure.

Run 2: Generation System with Control

A normal 6-h run was conducted with the generator subject to PID control with the control parameters as determined by the spreadsheet model. The target concentration was 100 ppm. The IR chart recording (Figure 3) shows changes in chamber concentration resulting from adjustments to the vapor generator. The first GC reading was taken 25 min after the start of the exposure and every 30 min thereafter. Individual concentration readings stayed within 2% of the target set point over the 6-h exposure period (Table 1). The overall average concentration was within 0.2% of the target concentration. Standard deviation was 1.5 ppm (standard error = 1.5%).

FIGURE 2. Chart recording of benzene concentration measured by IR with no adjustments to the vapor generation system (Run 1).
Run 3: Stress Testing

A normal 6-h run with a target concentration of 100 ppm was conducted. A second vapor generator similar to the main generator was set up to produce 25 ppm in the chamber. Initially, the main generator was set to produce a low concentration of about 85 ppm. After 2 h into the test run, the second generator was turned on; 4 h into the run, the second generator was turned off. This test simulated a sudden, unexpected change in the generation and exposure conditions. The IR chart recording (Figure 4a) shows the initially low concentration and the correction toward the target concentration. The recording then shows the sudden increase in benzene concentration at 2 h (120 min). When the GC system detected the concentration, the chart recording shows the

![Graph showing benzene concentration over time](image.png)

**FIGURE 3.** Chart recording of benzene concentration measured by IR as adjusted by a PID feedback control loop (Run 2).

<table>
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<th>Time (min)</th>
<th>Run 1 (ppm)</th>
<th>Run 2 (ppm)</th>
<th>Run 3 (ppm)</th>
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adjustment of the main generation system and the gradual return of the concentration to target. About 4 h into the exposure, the extra generation system was turned off, and the results show the drop in concentration to about 75 ppm and the subsequent rise back to the target concentration.

Results of the simulation model of the exposure system incorporating the additional vapor addition are shown in Figure 4b. The concentration of benzene in this model clearly shows a very similar pattern to the IR chart recording. Additionally, the values of concentration as measured by the GC (Table 1) are superimposed on the model and match quite well.

**Run 4: Nonoptimal Control Constants**

A normal 6-h run with a target concentration of 100 ppm was conducted. The vapor generator was initially set to produce about 80 ppm to force the PID algorithm to make corrections. A nonoptimal proportional constant was selected that was predicted to produce an oscillatory behavior in the
PID response. The experimental response of the PID feedback control system to this nonoptimal constant is shown in Figure 5a. The oscillatory response predicted by the model is clearly shown in the IR chart recording. The decreasing oscillatory response predicted for the selected value of $k_{\text{Prop}}$ is shown in Figure 5b. The solid lines are predicted by the program, while the points are the measured concentrations from the GC (Table 1).

**DISCUSSION**

The results of the generation system operated without feedback control showed that the output of the generation system was not perfectly stable but drifted downward over time. This drift was most likely due to the decrease in benzene vapor pressure as the temperature of the benzene reservoir decreased. The temperature decrease occurred as the benzene vapors were carried from the pressure vessel, the benzene liquid evaporated, and the latent heat of vaporization was extracted from the surrounding vessel. However, the output of the generator was stable over short time periods and was also observed to be reasonably linear in response to changes in the mass flow controller set point.

![Figure 5](image-url)
When the feedback control loop was implemented, the adjustments could be observed (Figure 3). The results showed that the controlled generator could maintain the concentration very close to the target set point. The initial startup of the generation system could be set without PID control, approach the target concentration with reasonable consistency, and avoid the classical startup overshoot. The elapsed time between samples (30 min) was intentionally longer than the $t_{90}$ time of the chamber. Stability of control was enhanced by allowing the chamber concentration to equilibrate after adjustments to the generator flow had been made. The accuracy of the control system was excellent, with an overall average within 0.2% of the target set point and a standard error of 1.5%.

When the system was stress tested by adding and then removing an unaccounted source of benzene (Figure 4, a and b), the control loop responded appropriately by first decreasing the controllable flow of benzene into the chamber, and then increasing the flow. In both cases, the PID control loop brought the measured concentration back to within 5% of the target concentration in 2 or 3 cycles without overresponding. This type of testing indicates how the system would perform in the event of an unforeseen problem such as a decrease in the airflow through the chamber or a leak in the system. It also indicates the problem with sampling on a periodic interval: The concentration will remain off target until the next sample is taken. If maintaining a tight tolerance to the target concentration is important, then samples need to be taken more frequently. The comparison of the simulation model with the experimental measurements is very close. The spreadsheet model did an excellent job in simulating the concentration changes in the chamber.

The operation of the system with a nonoptimal $k_{prop}$ shows (Figure 5, a and b) that the system can be made to oscillate. The overall average of 98.9 ppm is an acceptable value for an exposure day, and a standard error of 7.6% is not unreasonable (Table 1). However, the higher standard error as compared with 1.5% for Run 2 shows that Run 4 was not quite as stable with the nonoptimal control constant. In this particular case, the oscillations eventually die out; however, constants can be selected that will cause the system to oscillate unstably. In an actual experimental system, the oscillations would eventually be limited by the capacity of the generation system to respond to the demand for higher or lower output. Again, the simulation model was able to accurately demonstrate the behavior of the system, as the comparison between the model and the GC measurements showed.

This report and others have shown the PID control loop to be effective for monitoring and controlling an inhalation exposure. To help maintain control in the event of unforeseen circumstances, other safeguards and control measures were also incorporated into the inhalation exposure control. The control system was programmed so that the generation system was not started or would be turned off if the airflow dropped below 80% of the set point. Additionally, the program controlling the generator could not increase the generator production rate greater than 120% of the flow rate.
expected to produce the target concentration. In other words, if the concentra-
tion was low, the feedback control program could not call for an adjust-
ment of the generation system that would exceed 120% of the normal
flow rate. This prevented the PID control loop from overresponding and
producing a concentration significantly higher than target. If the concentra-
tion was low, there was a limit to how rapidly the system would try to
increase the concentration; if the concentration was too high, there was no
limit to how quickly the system would try to decrease the concentration (to
the point of shutting off the generator completely).

Finally, there was also a system of alarms to alert personnel if the con-
centration was too high or too low for an extended period of time. Per-
sonnel were also alerted if other environmental parameters such as tem-
perature, humidity, and airflow were out of range.

As indicated in most of the references, the primary advantage to automa-
tion is the ability to record data more accurately and consistently than by
hand. Also, adjustments may be made on a more precise and consistent
basis than by hand. The PID control loop with constants evaluated by the
chamber concentration simulation model operated effectively. However, this
report has shown how the system could potentially perform erratically with
incorrectly selected gain constants. An automated system requires an experi-
enced technician to periodically observe and judge its operation.

**CONCLUSIONS**

A feedback loop control system of the atmosphere in an inhalation
chamber was tested and validated. The system used a standard propor-
tional-integral-derivative feedback loop. The system differed from some of those
previously described in that the concentration readings were not continu-
ous but taken once per 30 min. Any resultant correction to the generation
system occurred only periodically. Hence, the generation system must be
reasonably stable in the periods between adjustments, and the control pro-
gram must be robust so as not to throw the system into extreme swings of
concentration. Examples showed that the PID control loop could function
effectively to restore a system back to the target set point, even with an
additional load on the system. On the other hand, with nonoptimal con-
stants, the system could respond with oscillations. A model was developed
as a spreadsheet program to simulate the behavior of the system and was
very effective in testing the various parameters of the feedback loop. The
resultant exposures were very accurate in the matching the target concen-
tration and maintaining a constant concentration.

**REFERENCES**


