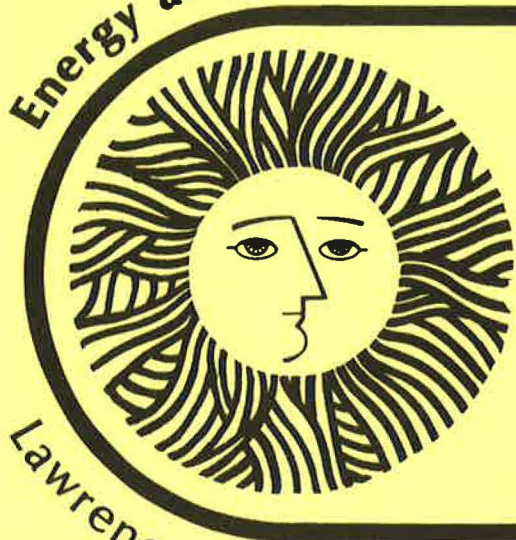#95

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An Automated Controlled-Flow Air Infiltration Measurement System

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AN AUTOMATED CONTROLLED-FLOW AIR INFILTRATION

MEASUREMENT SYSTEM

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ABSTRACT

A description is presented of an automated, controlled-flow air infiltration measurement system. This system measures total air flow, a volume per unit time, due to infiltration in a test space. Data analysis is discussed and the mixing problem is analyzed. Different modes of operating the system are considered: (1) concentration decay, (2) continuous flow in a single chamber and (3) continuous flow in a multichamber enclosure. Problems associated with the use of nitrous oxide as a tracer gas are described.

KEY WORDS

Air infiltration, air flow, ventilation, energy conservation, energy use in buildings.

INTRODUCTION

Air infiltration accounts for a significant fraction of energy lost by buildings. Measurements of air infiltration generally use a tracer gas technique dating back to Dick's measurements in England in the late 1940's [1]. Since then many gases have been used as tracers. Significant improvement in the measurement technique occurred with the introduction of sulfur hexaflouride, (SF_6) as the tracer gas; detectable concentrations of SF_6 are three orders of magnitude smaller than the minimum detectable concentrations of gases previously used. However, SF_6 has a high molecular weight relative to that of air so that it requires thorough mixing within the building volume to prevent biases in infiltration measurements due to stratification. Other gases such as methane, ethane, nitrous oxide and carbon dioxide are, in this regard, more acceptable for use as tracers.

Recently, microprocessor controllers have presented instrument designers with the option of automated measurement. This is particularly appealing since it permits unattended long-term operation which is important in correlating air infiltration rates with external weather parameters. This is an important step in understanding the infiltration process.

Controlled flow systems are one of the four tracer gas measurement techniques described in the review paper of Hitchen and Wilson [2]. A controlled flow technique has been used by Honma in his studies of ventilation rates in high rise apartment buildings [3]. In order to take advantage of the possibilities of automated measurement and to explore fundamental questions in air infiltration research, a controlled flow measurement system has been designed at LLBL and is described below.

DESCRIPTION OF CONTINUOUS FLOW SYSTEM

System Hardware

The system is designed around a microprocessor controller, an Intel 80/20 microprocessor system. In this design the microprocessor is used (1) to control the amount of tracer gas injected into the test space, (2) to control the sampling frequency of the tracer gas concentration and (3) to store the measured concentration data. A block diagram of the system is shown in Figure 1.

The injection system, shown in Figure 2, uses two calibrated dump volumes to deliver a known amount of gas to the test space. Either volume I or volumes I and II form the dump volume depending on the state of solenoid valve B. Gas is delivered to volume I or to volumes I and II when solenoid A is energized. When solenoid A is de-energized the tracer gas is dumped from the calibrated volumes into the test space. The flow rate of tracer gas is controlled by choosing one of the two possible volume options and by varying the repetition rate of solenoid A. Figure 3 shows a chart recording of concentration as a function of time in a test space. Superimposed on the chart record is the time sequence of injection pulses into that same space. In the particular case shown, the gas was injected into the return duct of a forced air heating system of a small house and the concentration measured in the living room of the house. Frequent small injections followed by mixing by the furnace blower duplicates continuous flow injection. We shall discuss this further below.

The sampling system is also shown in Figure 2. Sequential sampling by opening and closing solenoid valves C through J is controlled by the microprocessor. Concentrations are measured using a MIRAN

infrared analyzer. The analog output of the analyzer is converted to a digital signal which is stored by the microprocessor in RAM.

Several control strategies are possible with this system. Flow rates may be stepped through a preprogrammed sequence; initial injection with concentration decay is an example of this strategy and has been used by Harrje and Grot [4]. A desirable alternative to this control strategy would use the measured concentration information to choose the next injection time. This would allow the system to approximate a true continuous flow system where the tracer concentration is held constant; the air flow through the test space is then equal to the injection rate divided by the concentration.

Our present control scheme is designed to adjust the flow rate slowly to cause the concentration to move toward a range of target concentrations. The microprocessor uses the concentration data to update the flow rates at regular intervals. The update interval is determined by the test space; the interval must exceed the mixing time of the space to prevent instabilities in the system.

Data Analysis

Assuming perfect mixing, the volume of the test space times the change in concentration in the space is the difference between the amount of tracer gas injected into the room and the amount lost due to exfiltration. Therefore the differential equation describing the system is

$$V \frac{dC}{dt} = F - VAC \qquad (1)$$

C is the concentration of tracer gas, F is the flow rate of tracer gas injected into the test space (volume/time), V is the volume and A is

the air exchange rate of the test space (1/time). Equation (1) can
be rearranged to give

$$AV = \frac{F}{C} - \frac{V}{C}\frac{dC}{dt} \qquad (2)$$

Equation (2) emphasizes a most attractive feature of the controlled
flow technique. The quantity AV, the product of the air exchange rate
and the volume of the test space, is the total air flow entering (and
exiting) the test space from (to) the outside. We shall call this
quantity the air flow rate and denote it using the symbol R. It is
this quantity, measured as a volume per unit time, that is important
for energy conservation. It is the relationship between this quantity
and driving mechanisms produced by the weather that we hope to under-
stand better.

The form of equation (2) suggests both a control strategy for
operating the system and a method of calculating R. If the second
term on the right hand side of equation (2) is small, i.e. if the
flow rate F is adjusted to produce a nearly constant value of C, then
dC/dt becomes small and the air flow rate, R, is just the quotient
of F and C.

Once the air flow rate is known the volume may be calculated.
Rearranging equation (1) once again gives

$$V = \frac{F - CR}{\dfrac{dC}{dt}} \qquad (3)$$

If we adjust F to cause a rapid change in C, the derivative $\frac{dC}{dt}$ will
have a significant value. In this case the volume is amenable to cal-
culation using equation (3).

Mixing

The flow of tracer gas, represented by F, is not distributed in-
stantaneously through the test space. Instead, it spreads throughout
the space with a finite mixing time. We define an effective flow
rate, $F_{eff}(t)$, in terms of a mixing function, $g(\tau)$, and the actual
flow rate, $F(t)$. These are related by

$$F_{eff}(t) = \int_0^\infty g(\tau) \, F \, (t-\tau) d\tau. \tag{4}$$

The mixing function, g, has the property

$$\int_0^\infty g(\tau) d\tau = 1. \tag{5}$$

We interpret F_{eff} as the flow rate which affects the concentration
in the actual test space. It is F_{eff} which must be used in equa-
tions 1-3 to determine R and V. Only in the ideal case of instan-
taneous mixing would F_{eff} and F be equal. Therefore we must measure
g as a function of τ for the test space in order to find the relation-
ship between F_{eff} and F.

Consider the special case in which the initial concentration is
zero and we quickly inject a large pulse of tracer gas into the test
space. This injection rate is approximated by $F(t) = V_o \, \delta(t)$ where
$\delta(t)$ is the Dirac delta function. Substituting into (4) gives

$$F_{eff}(t) = \int_0^\infty g(\tau) V_o \, \delta(t-\tau) d\tau$$

or $$F_{eff}(t) = V_o \, g(t). \tag{6}$$

The differential equation which describes the concentration of the tracer
is equation (1); substituting $F_{eff}(t)$ from (6) we can write

$$\frac{dC}{dt} + AC = \frac{V_o}{V} g(t) \tag{7}$$

The mixing function g can be computed (cf. Figure 4) by using the following approximation; since the initial concentration is zero, $dC/dt >> AC$ and the differential equation can be written approximately as

$$\frac{dC}{dt} \approx \frac{V_o}{V} g(t) . \tag{8}$$

In the particular test shown, the concentration changes from an initial value of zero to a near steady state value of 30 ppm in approximately 300 seconds, while A is a number of the order of one per hour. Thus the approximation is true initially, is true on average over the five minute interval, and only breaks down as the equilibrium concentration is reached. The mixing function $g(t)$ calculated using this approximation is plotted in Figure 4 for this example. The size of the pulse used to determine g in this case is two orders of magnitude larger than the typical pulse used to inject gas into the test space in the continuous flow mode of operation. Therefore we consider the five minute time interval that is seen before the system has reached a quasi-steady concentration to be an upper limit on the mixing time for the system.

APPLICATIONS OF THE SYSTEM

Concentration Decay

One of the features of the controlled flow system which we find appealing is its versatility. By altering the injection sequence several types of tracer measurement procedures can be implemented. For example, if F goes to zero at $t = t_o$ the solution of equation (1) becomes $C(t) = C_o e^{-A(t-t_o)}$ where C_o is the concentration at t_o, the familiar concentration decay relation. Figure 5 shows the log of the concentration vs time when the system receives a pulse injection every 45 min. This trace was obtained when all windows in the house were open 1 cm to produce a large air exchange rate.

Continuous Flow

The test space used in the measurements described above is an unoccupied one-story three bedroom house having a floor area of 100 m^2 and a volume of 234 m^3. The house is quite loose; the dominant leakage sites in this structure seem to be the sliding single glazed windows. Figure 6 shows a measurement of the air flow rate, R, over a three hour time span. Error bars are shown on three of the calculated air flow rates to indicate the range of uncertainties in the measurements. Also shown on Figure 6 is the concentration as a function of time.

The volume calculated for the trial shown in Figure 6 averages 221 m^3. We interpret this number to be the effective volume coupled to the tracer gas that is injected into the test space. If this volume is considerably smaller than the geometric volume of the test space, the gas is not mixing completely with the entire space; if the calculated volume is larger than the geometric volume there is evidence of leakage of tracer gas out of the test space through the distribution system,

i.e. leakage from the ducts in the case of a forced air heating system. We emphasize that this calculated volume is the volume of interest when considering the effects of infiltration on energy consumption. It is the volume contained in the air flow rate term, AV. An interpretation in the case of many connected chambers is given below.

Multi Chamber Flow

One of the attractive features of the controlled-flow technique is its applicability to the multi-chamber problem. This has been considered by Honma [3] and Sinden [5]. Multi-chamber effects are important if one considers cross flow interaction between, for example, an attic and a living space in a house or between adjacent apartments in a multi-unit dwelling.

Consider as a model, N well mixed chambers each of which is connected to the others and to the outside by exactly two pipes. Air flow is allowed only in one direction in each pipe; one pipe from each pair allows air to enter the chamber while the other allows air to leave. If a tracer gas is used to measure the infiltration the following definitions can be made:

V_i: the volume of chamber i

R_{ij}:   the negative of the air flow from chamber j to chamber i

R_{ii}:   the total air flow out of chamber i

F_i: the flow rate of tracer gas injected into chamber i

C_i: the concentration of tracer gas in chamber i

In a multi-chamber analysis the air exchange rate of an individual chamber is not a well-defined concept. There are three definable exchange rates, each of which can be useful in certain circumstances.

$A_i^{(+)}$: The number of air changes per hour in chamber i which come from the outside. This will be called the external infiltration rate of chamber i.

$A_i^{(-)}$: The number of air changes per hour that go from chamber i to the outside. This will be called the external exfiltration rate.

$A_i^{(o)}$: The total number of air changes into chamber i. This will be called the toal infiltration rate of chamber i.

If the continuity equation for an incompressible fluid is assumed valid, then R_{ii} is also equal to the total air flow into chamber i, and $A_i^{(o)}$ is equal to the total number of air changes out of chamber i. Therefore

$$A_i^{(+)} = \sum_{j=1}^{N} R_{ij}/V_i \tag{9}$$

$$A_i^{(-)} = \sum_{j=1}^{N} R_{ji}/V_i \tag{10}$$

$$A_i^{(o)} = \frac{R_{ii}}{V_i} \tag{11}$$

Consider now the flow of tracer gas and the attendent change in concentration within a given chamber. The amount of tracer gas flow into chamber i is

$$F_i + \sum_{j=1}^{N} (-R_{ij})C_j \quad (i \neq j) \tag{12}$$

The amount of tracer gas flowing our of chamber i is

$$R_{ii} \, C_i$$

therefore by continuity

$$V_i \frac{dC_i}{dt} = F_i - \sum_{j=1}^{N} R_{ij} \, C_j - R_{ii} \, C_i \quad (i \neq j) \tag{13}$$

equivalently

$$V_i \frac{dC_i}{dt} + \sum_{j=1}^{N} R_{ij} C_j = F_i \ . \qquad (i = 1,2,\ldots,N) \qquad (14)$$

Defining a volume matrix V_{ij} :

$$V_{ij} = \delta_{ij} V_i \qquad (15)$$

where δ_{ij} is the Kronecker delta, allows us to write

$$\sum_{j=1}^{N} (V_{ij} \frac{dC_i}{dt} + R_{ij} C_j) = F_i \qquad (16)$$

which can be expressed in matrix notation

$$\underline{\underline{V}} \cdot \frac{d\underline{C}}{dt} + \underline{\underline{R}} \cdot \underline{C} = \underline{F} \ . \qquad (17)$$

This matrix equation consists of $2N^2$ unknowns and contains N equations. Therefore, if $\frac{dC}{dt}$, $\underline{C}$ and $\underline{F}$ are measured at 2 N different times, $\underline{\underline{V}}$ and $\underline{\underline{R}}$ can be determined using standard linear algebra inversion routines.

In the derivation of eq. (17) we assumed perfect mixing in each chamber. This led us to consider a volume matrix which was diagonal. However, in a real situation there will not be perfect mixing and hence we may expect to find off-diagonal elements in the volume matrix. In order to gain some insight into these off-diagonal elements we will now consider some of the mixing problems that occur in real situations.

1) Random inhomogeneous mixing will cause scatter in the concentration readings. This can be estimated by using multipoint sampling in a single chamber, or by a regression calculation of the concentration after $\underline{\underline{V}}$ and $\underline{\underline{R}}$ have been found as functions of time.

2) Short-circuit type inhomogeneous mixing will cause gas injected into room i to cause an increase in concentration in room j which cannot be attributed to the measured concentration in room i. This type of

behavior couples the flow rate in room i with a change in concentration in room j which is exactly what the off diagonal elements of the volume matrix do.

3) Stratification effectively partitions off a single chamber into a number of well mixed subchambers. In general, the behavior of such a stratified chamber will be complicated and depend critically on how the, injector and the other chambers couple to each subchambers. Some comments can be made; if a given subchamber has neither the injector nor the measuring device and the communication to other chambers is small its volume will be subtracted from the actual volume to give the effective volume of the room.

There are two effects that can affect the volume matrix. The short circuiting effect will tend to increase the diagonal elements while decreasing the off diagonal elements. Stratification could either increase or decrease any of the volume elements depending on the placement of the measuring devices. Taking into account these effects a redefinition of the infiltration rates is necessary

$$A_i^{(+)} = \sum_{j=1}^{N} \sum_{k=1}^{N} V_{ik}^{-1} R_{kj} \qquad (18)$$

$$A_i^{(-)} = \sum_{j=1}^{N} \sum_{k=1}^{N} V_{jk}^{-1} R_{ki} \qquad (19)$$

$$A_i^{(o)} = \sum_{k=1}^{N} V_{ik}^{-1} R_{ki} \qquad (20)$$

NITROUS OXIDE AS A TRACER GAS

An ideal tracer gas has the following properties; it is inert, non-toxic, a non-irritant, odorless, non-explosive, is not present as background in the test space, is easily detectable in small concentrations and, to facilitate mixing, has a molecular weight close to that of air.

When this sytem was designed, nitrous oxide, a common anesthetic, was chosen to be the tracer. All the measurements shown above were made using this gas. However, one of the experiments to be performed will monitor the total ventilation rate in occupied classrooms in elementary schools; for this application N_2O fails to satisfy the requirements stated above.

Recently Bruce and Bach [6] have studied response of subjects to various audiovisual tasks when exposed to a mixture of nitrous oxide and halothane for four hours. Exposure at 500 ppm of N_2O indicated performance decrements on six of seven tests administered. Exposure to a mixture of 50 ppm of N_2O and 1 ppm of halothane showed a performance decrement on one of the seven tests administered. Exposure at 25 ppm with 0.5 ppm of halothane showed no performance degradation. More serious than this, however, is the extensive survey of female anaesthesiologists, nurse-anesthetists, operating room nurses and technicians reported in NIOSH 77-140 [7]. The survey showed that this population had a statistically significant higher risk of spontaneous abortion than a similar population of medical personnel not exposed to operating room conditions. No measurements of exposure to anesthetic gases were part of this survey. Other studies have shown that average concentration of nitrous oxide in operating rooms range from mean

concentrations of 15 ppm to 135 ppm with gas scavenging; 130 ppm to 6000 ppm without scavenging.

For these reasons we shall not use nitrous oxide in occupied space. Instead we shall use a non-flammablle mixture of ethane in nitrogen. The detectors must be modified to work at a different wavelength. Otherwise the system designed for nitrous oxide is completely compatible with an ethane tracer.

CONCLUSION

A controlled flow infiltration system capable of long-term unattended measurement of infiltration has been described. Analysis of the flow equations shows that this system determines directly the total air flow rate due to infiltration, R, i.e. the product of the air exchange rate and the volume of the test space.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Figure 1. Block diagram of the controlled-flow system.

Figure 2. Injection and sampling system details.

Figure 3. Strip chart record of concentration and
flow injections as a function of time.

Figure 4. Concentration and mixing function in test house.

Figure 5. Concentration decays following large injection pulses.

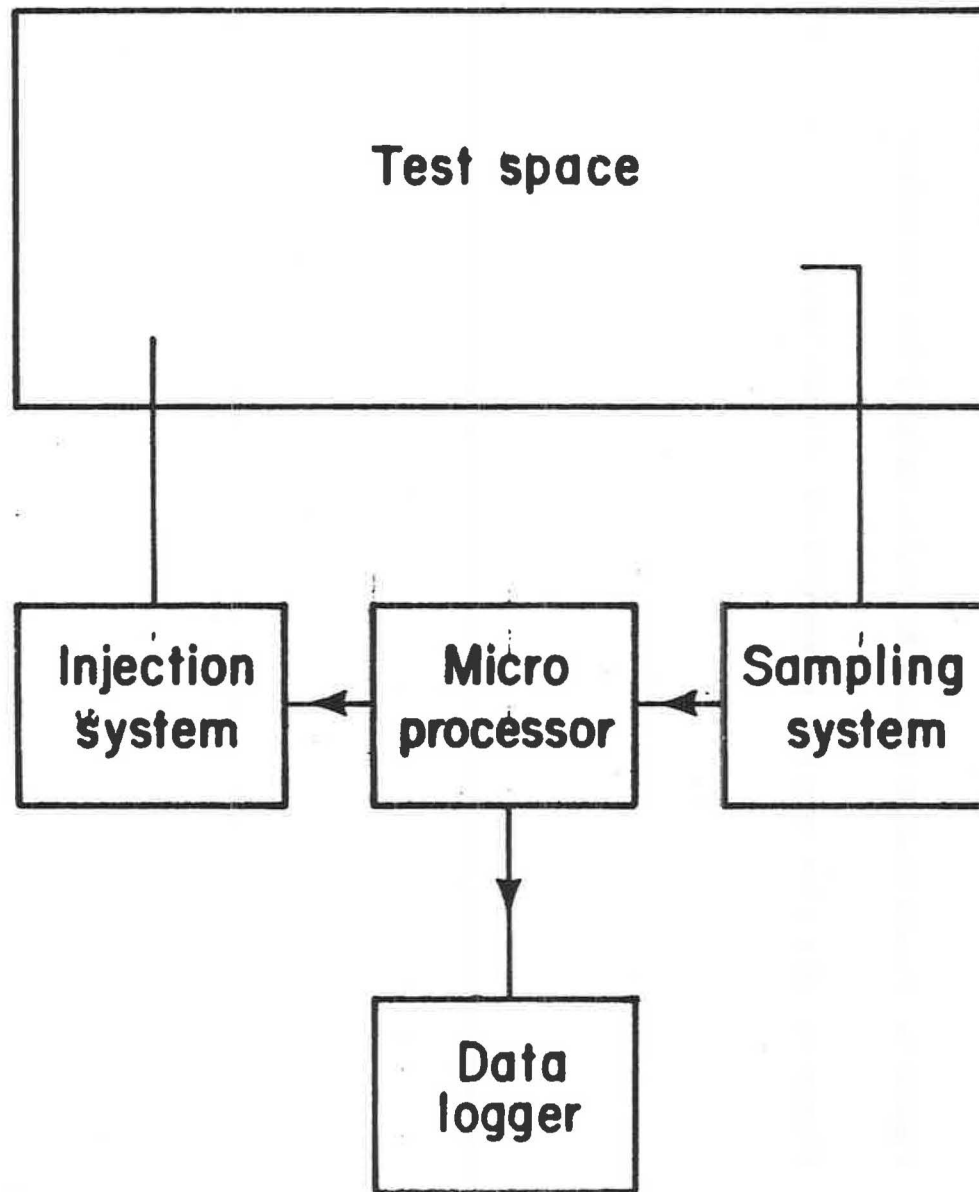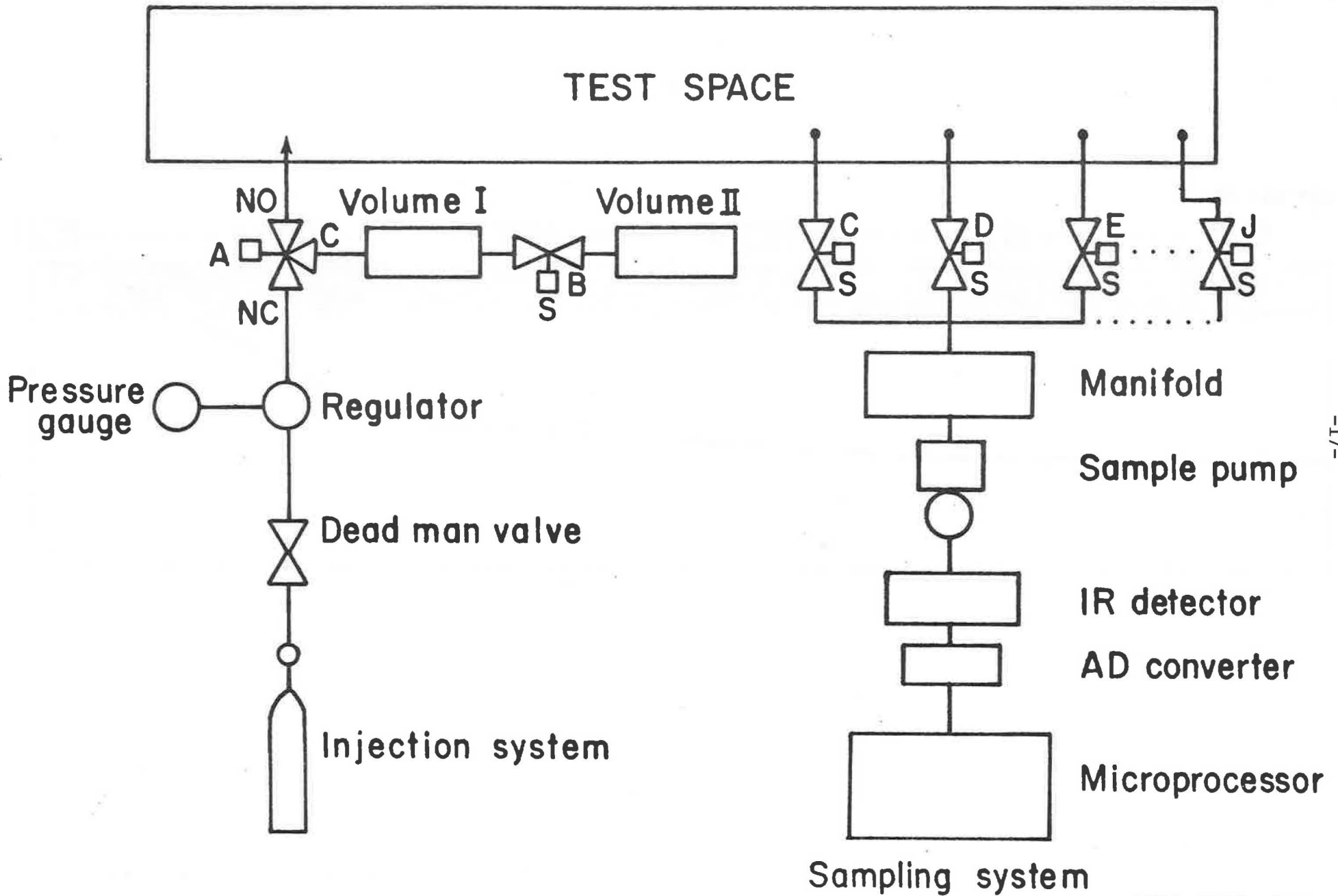Figure 6. Air flow rate and concentration in test house.
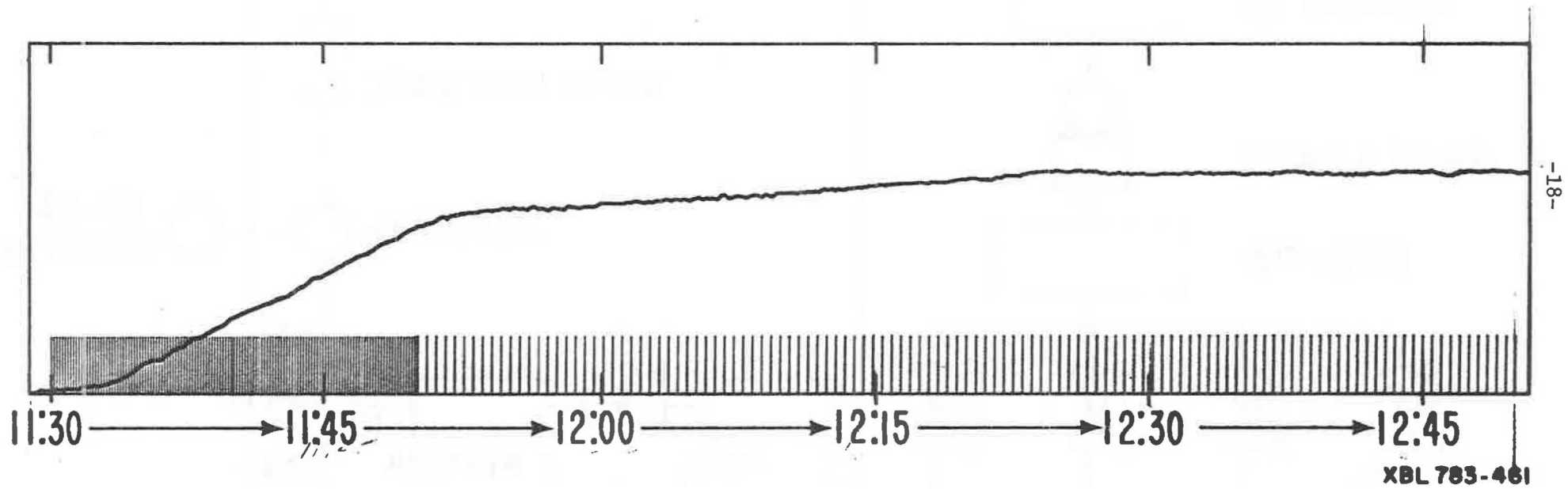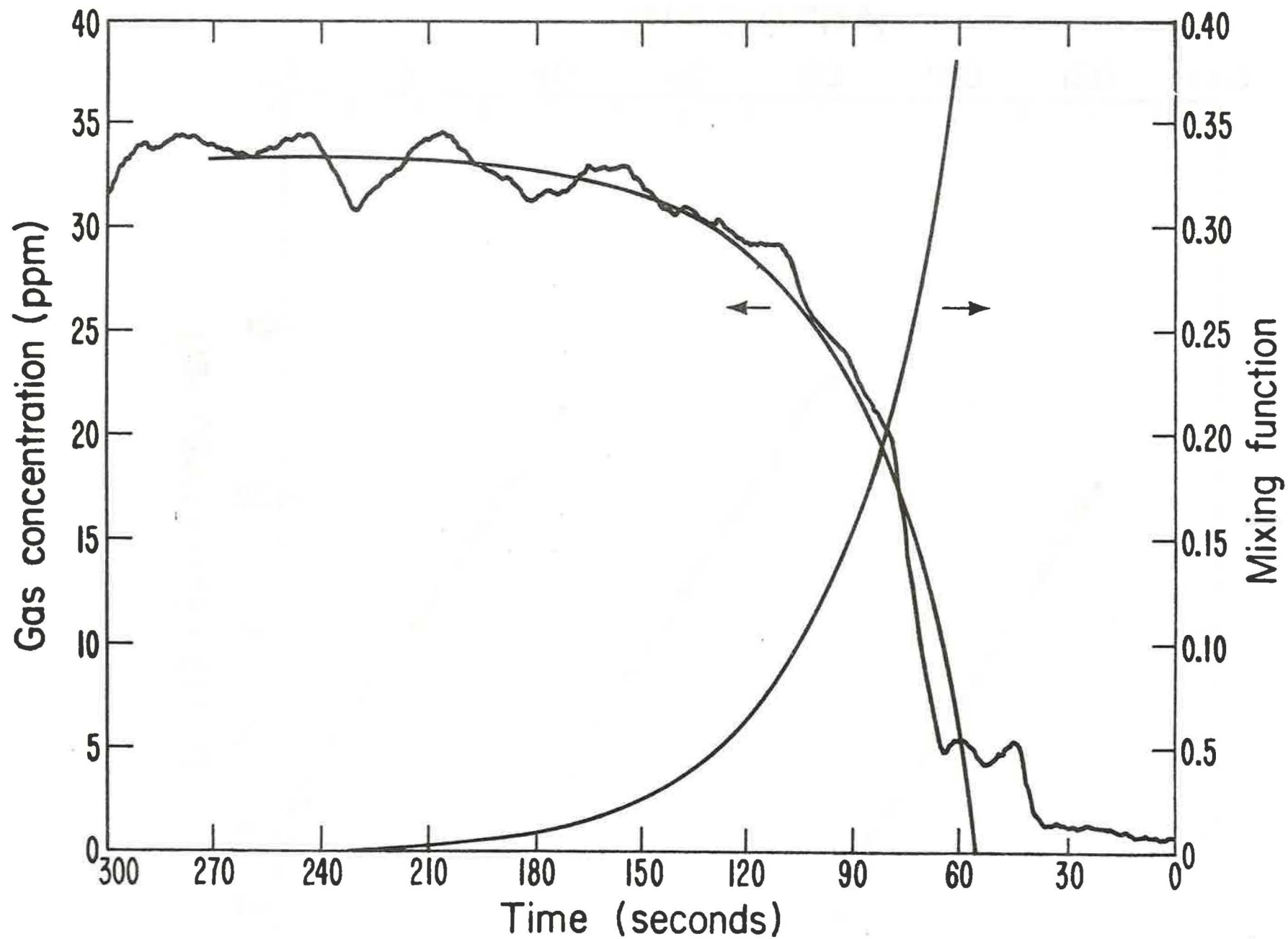
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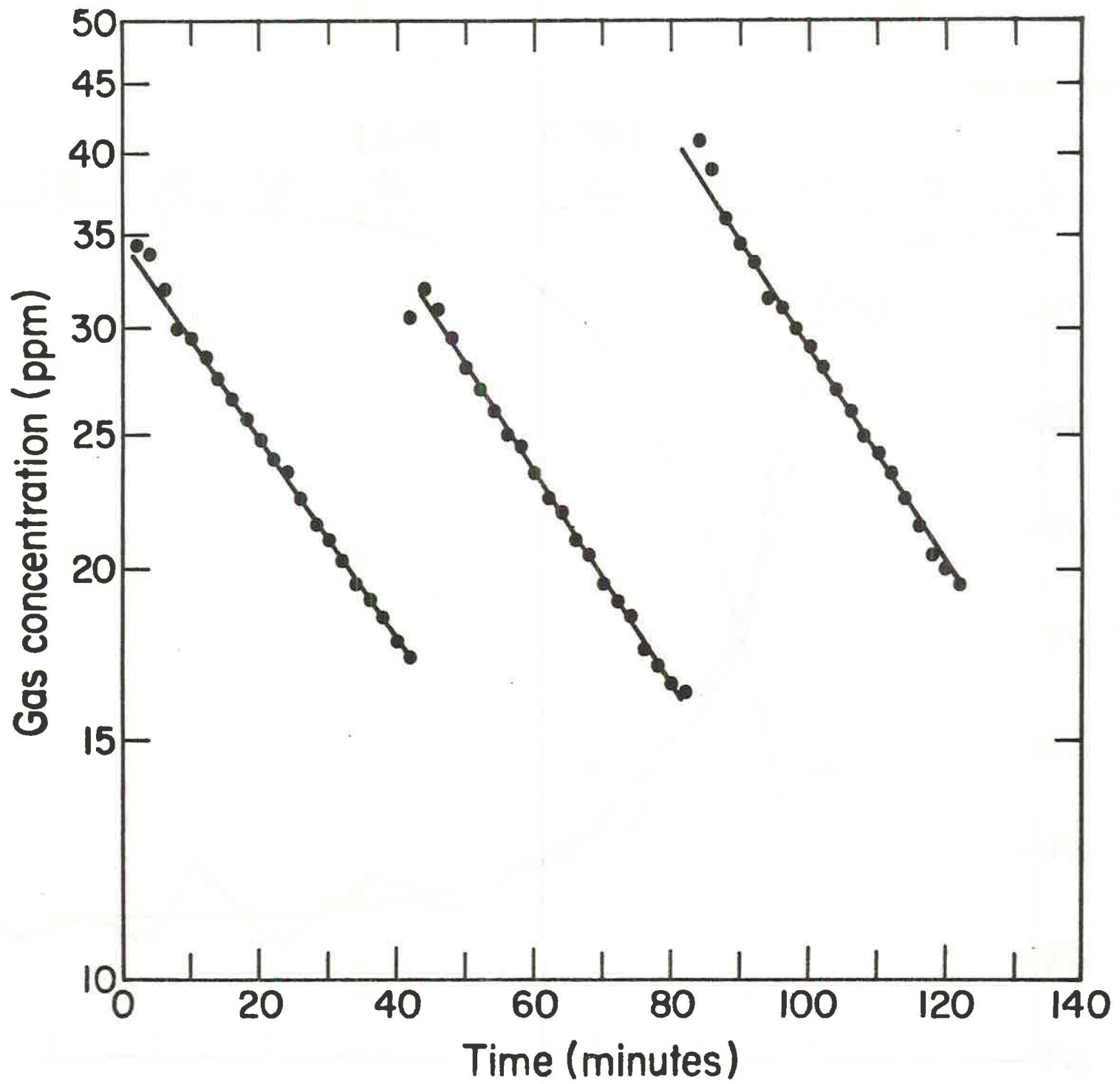
Fig. 2

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Fig. 3

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Fig. 4

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Fig. 5

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Fig. 6

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