COO-2704-2

The Pennsylvania State University

Department of Architectural Engineering

AIR CHANGE MEASUREMENTS USING A TRACER GAS TECHNIQUE

by

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March 1976

MASTER

ACKNOWLEDGMENTS

The author wishes to express his gratitude and appreciation to Professor E.R. McLaughlin for his assistance, expert guidance and encouragement during the course of this study. Acknowledgment is extended to the United States Energy Research and Development Administration for financial support through contract number E(11-1)-2704, "Evaluation of the Solar Building, Albuquerque, New Mexico," Dr. Stanley F. Gilman, professor of architectural engineering, project director.

Appreciation is extended to George Edwards and Edward Hull, staff members of the Department of Architectural Engineering, The Pennsylvania State University, for their technical assistance in the computer programming portion of this research. Thanks are also due Professor Gifford H. Albright for review and suggestions.

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ABBREVIATIONS AND NOTATIONS

c	Concentration, PPB SF_6 in air
cc	Volume in cubic centimeters
cc/min.	Volumetric flow rate in cubic centimeters per minute
cfm	Volumetric flow rate in cubic feet per minute
^oF	Temperature in degrees Fahrenheit
ft	Length in feet
ft^2	Area in square feet
ft^3	Volume in cubic feet
in.	Length in inches
IN DB	Indoor dry bulb temperature
m^2	Area in square meters
m^3	Volume in cubic meters
m^3/s	Volumetric flow rate in cubic meters per second
MDST	Mountain Daylight Savings Time
mm	Length in millimeters
mph	Wind velocity in miles per hour
mv	Millivolts
N	Air change rate in room or building air changes per hour
OD DB	Outdoor dry bulb temperature
o.d.	Outside diameter
PPB	Parts per billion
psi	Pressure in pounds per square inch
Q	Volumetric flow rate in cubic feet per hour
SF_6	Sulfur hexafluoride
t	Time
V	Volume in cubic feet

PH
SC
k — Described in Section 4.1.4 of Text.
λ
A

ABSTRACT

The air change rate in a single story office building was measured using a tracer gas technique. The air change rate was determined by the rate of decay method using sulfur hexafluoride as the tracer gas. A total of eight tests were conducted within a forty-eight hour period under small temperature differences and wind velocities. Two different building conditions were investigated: (1) supply ventilation fan on, producing a positive pressure in the building, and (2) supply ventilation fan off. Two sampling techniques were used: (1) multipoint sampling, (2) single-point return air sampling.

From this research an effective technique was developed for calibrating portable gas chromatographs. For this particular building, tests showed that the single-point return air sampling technique compared favorably with the multi-point sampling technique. With the limited number of tests, no empirical relationship between temperature difference, pressure difference and air change rate could be developed, although certain trends were established.

Key words: air change rate, infiltration, sulfur hexafluoride, tracer gas, ventilation.

1.0 INTRODUCTION

1.1 Statement of Objective

The intent of this research was to devise an accurate and suitable method of measuring the air change rate in a building without disturbing the occupants. This study is one part of a research project conducted by the Department of Architectural Engineering at The Pennsylvania State University on a solar energy building in Albuquerque, New Mexico. The ultimate goal of this work is to measure the air change rate over varying environmental and building conditions for the purpose of determining the buildings energy consumption. The major focus of this thesis is on describing the equipment, calibration of the gas detector, experimental procedure and data analysis used for these measurements. One objective of these tests was to determine if a single-point return air sample would accurately represent the total air change rate for this particular building. For future testing, if the above turned out to be true, this would greatly reduce the amount of equipment and data analysis involved with multi-point sampling.

1.2 Overview of Thesis Content

Chapter 2 deals with background material, sulfur hexafluoride (SF_6) as a tracer gas, and the equations governing the rate of decay method. A description of building dimensions and conditions appear in Chapter 3. An accurate technique for calibrating a portable SF_6 gas chromatograph was developed by the author. Several alterations to the machine were made to accommodate the calibration method and for the purpose of obtaining useful output. The above technique and alterations are discussed in Chapter 4. Equipment was built to automatically sample the gas concentration with respect to time. This equipment is also described in Chapter 4. Chapter 5 describes the tests and testing procedure, while Chapter 6 deals with data analysis and results. Conclusions and recommendations are discussed in Chapter 7.

2.0 BACKGROUND

An appreciable part of most buildings' energy load for heating and cooling is due to infiltration or air change rate. Formulas used to calculate the air change rate (1) can rarely be used with confidence. Techniques have therefore been developed to measure building air change rates. One of the most successful techniques has been to measure the deconcentration of a tracer gas in a building space.

2.1 Former Research

Almost any gas that can be conveniently measured in small quantities can be used as a tracer gas. One of the first and most prevalent gases used is helium (2,3,4,5,6). In more recent years, with the development and refinement of electron capture detectors, SF_6 has played an increasing role as a tracer gas used in building air change rate measurement (7,8,9). Good results have also been obtained using SF_6 as a meterological and stack effluent tracer (10,11,12).

2.2 Sulfur Hexafluoride as a Tracer Gas

Sulfur hexafluoride has the properties of being chemically and thermally stable, inert, nontoxic, colorless, odorless, tasteless, nonflammable, noncorrosive and can be stored easily. The gas has limited uses and is not likely to be found in the atmosphere. The gas is capable of being measured in the parts per billion range (9,10,12) therefore requiring very small amounts. Although SF_6 has a high molecular weight when compared to that of helium, Hunt and Burch (9) while testing simultaneously with helium and sulfur hexafluoride, concluded that molecular diffusion played no more than a secondary role in air change rate measurements. The above properties make SF_6 ideally suited as a tracer gas.

2.3 Equation Governing the Rate of Decay Method

The rate of decay method was used for this experiment where an initial concentration of tracer gas was distributed in the space followed by the measurement of rate of decay. Isenberg and McLaughlin (7) used the sustained rate of injection method while making air change rate measurements in multi-story buildings. For this experiment such a small volume of tracer gas was needed (50 cc), that it made this method impractical.

If an initial concentration of tracer gas is distributed in a space at time t = 0, the deconcentration of the tracer, assuming no tracer reentry and perfect mixing of the tracer with air, may be expressed mathematically as:

$$\frac{dc}{dt} = -Nc \qquad [1]$$

where c = concentration of tracer gas at time t

N = number of air changes per hour

t = time

with $c = c_o$ at $t = t_o = 0$ equation [1] expressed logarithmically becomes

$$\log_e c/c_o = -N(t-t_o) \qquad [2]$$

where $N = Q/V$

and Q = Volumetric flow rate in ft^3/m

V = Volume in ft^3

Inspection of equation [2] shows that if the log of concentration is plotted against time, this relationship calls for a straight line with a negative slope N equal to the air change rate.

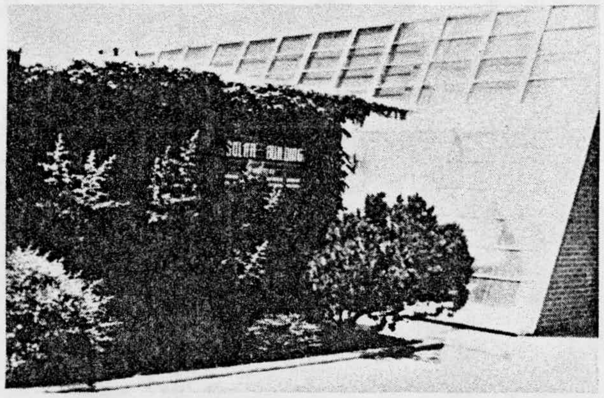
3.0 BUILDING DESCRIPTION

The building tested is a single-story office building housing the consulting engineering firm of Bridgers and Paxton and is located in Albuquerque, New Mexico. The building uses a solar assisted heat pump system for heating and consists of individual office space, a reception area, a computer room, a print room, a conference room, a mechanical equipment room, restrooms and a large drafting room. Pictures of the building exterior appear in Figure 1.

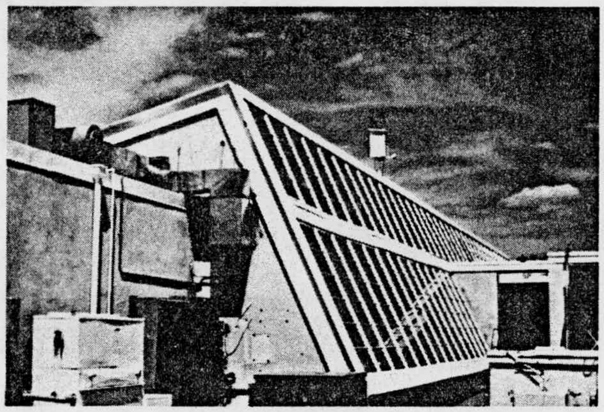
3.1 Dimensions and Construction

The building has a usable floor area of 4,300 ft^2 (400 m^2) and a total volume of 40,100 ft^3 (1136 m^3). Included in the total volume is a small half story attic space located above the eastern half of the building. This space houses mechanical equipment and acts as the return air space for the air handling unit. For purposes of testing the building was divided into thirteen zones. The location of the zones are shown on the building floor plan (Figure 2) and a description and volumes of the zones appear in Table 1.

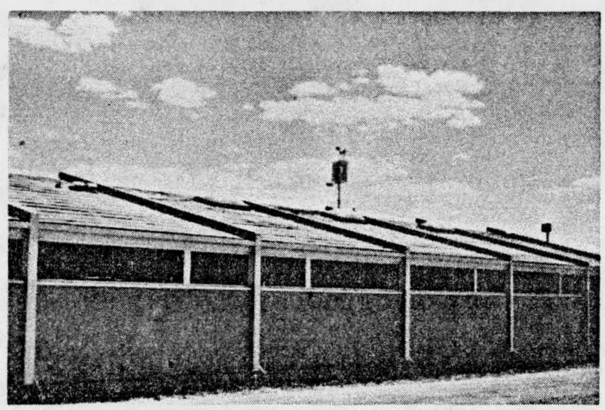
Construction is of structural steel beams framing members on 18 ft. centers. Exterior walls consist of nominal 2 x 4 in. wood framing, full thick batt type insulation, gypsum board interior and fiber board sheathing. The east side of the building has a face brick exterior. The northwest and part of the south facings have a 1 in. stucco exterior. The remainder of the south facing is covered with double glass, flat plate solar collectors with an insulated backing. The roof system consists of an insulated built-up roof with six plastic skylights over interior glass panels.



East Facing



South Facing



North Facing

Figure 1. Test Building--Albuquerque, New Mexico

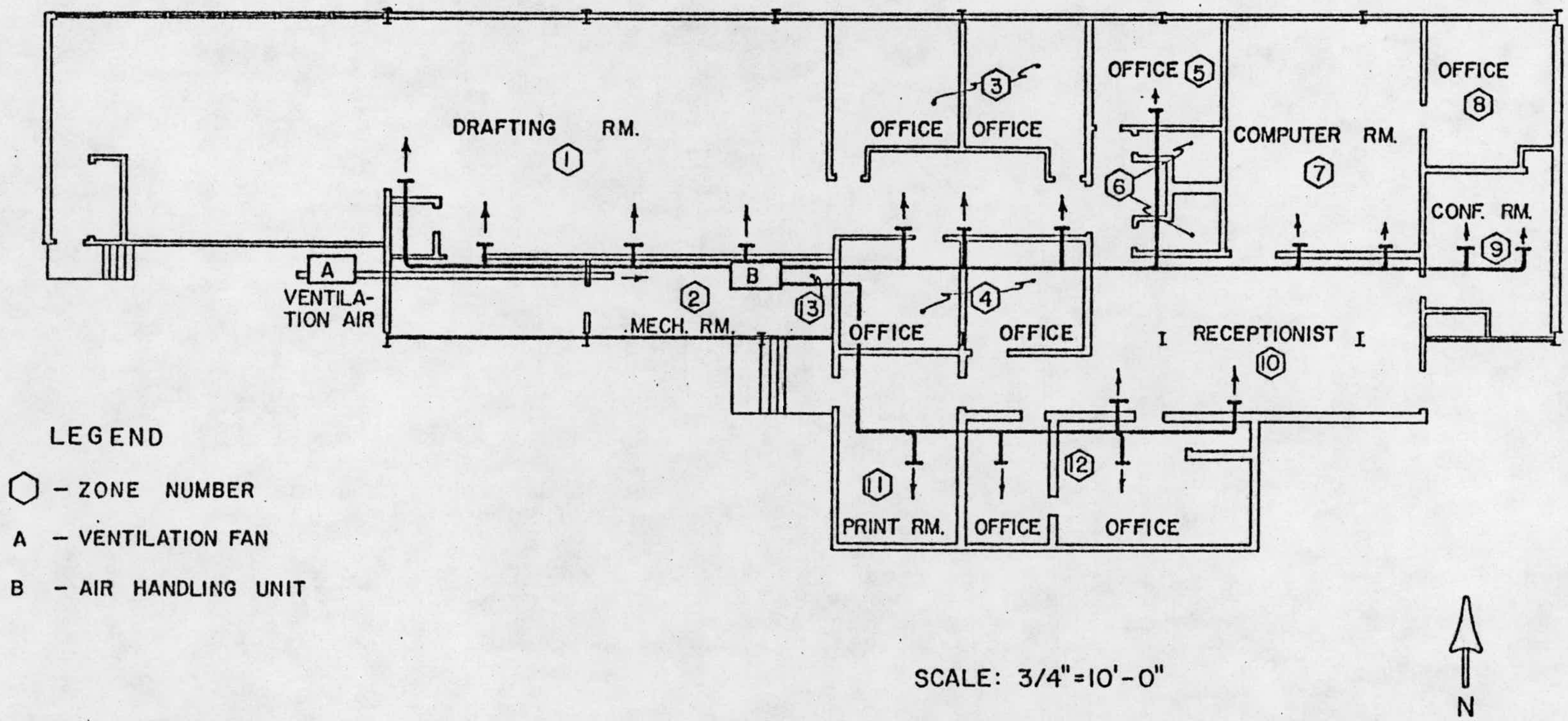


Figure 2. Building Floor Plan — Showing Zone Locations and Air Distribution System

Table 1. Description and Volumes of Zones

Zone Number	Description	Volume ft^3	Fraction of Total Volume
1	Drafting Room and Hall	16,699	0.416
2	Mechanical Equipment Room	1,218	0.030
3	Two North Offices	2,167	0.054
4	Two Central Offices	1,836	0.046
5	North Office	1,035	0.026
6	Restrooms and Hall	1,058	0.026
7	Computer Room	4,105	0.102
8	North East Office	969	0.024
9	Conference Room	1,232	0.031
10	Reception Area	3,425	0.085
11	Print Room	1,616	0.040
12	Two South Offices	2,685	0.067
13	Return Air Space (Attic)	2,075	0.052
	Total Volume	40,120 ft^3	

All windows are of the single-glazed, fixed type and are well fitted. All windows are located on the north facing with a combined area of 264 ft^2 (24.5 m^2). The two exceptions to this are the six overhead skylights with a combined total area of 50 ft^2 (4.6 m^2) and 41 ft^2 (3.8 m^2) of window area on the east facing. Two of the three exterior doors are well fitted. The front door leading to the reception area is poorly fitted and does not close properly.

3.2 Ventilation and Air Distribution

The ventilation air for the building is provided by an exterior squirrel cage fan supplying approximately 1700 cfm (0.802 m^3/s) through a duct to the mechanical equipment room housing the air-handling unit.

The air-handling unit runs continuously and draws its supply air from both the ventilation fan and the attic return air space (Zone 13). The air is distributed by an overhead duct system running throughout the building (see Figure 2). There are three unit exhaust fans, each exhausting approximately 50 cfm (0.024 m^3/s). Two of the fans are located in Zone 6, one in each of the bathrooms. The remaining exhaust fan is located in the print room (Zone 11).

3.3 Building Conditions

Two unique building conditions were deemed appropriate in test: (1) the day condition, and (2) the night condition. During the daytime from 7:00 a.m. to 5:30 p.m., the ventilation fan runs continuously, two restroom exhaust fans run continuously and the print room fan runs when needed to vent noxious fumes. During the nighttime only the exhaust fan in the women's restroom operates. As mentioned before, the fan in the air-handling unit runs continuously, day and night.

4.0 INSTRUMENTATION AND EQUIPMENT

4.1 Sulfur Hexafluoride Detector

Concentrations of SF_6 were measured with an Ultra-Sensor Leak Detector (Model 6000B) manufactured by Analytical Instruments, Ltd., Cambridge, England, and distributed by Scientific Systems Corporation of Arcadia, California.

4.1.1 Principle of Operation

The instrument used was a portable gas chromatograph which is sensitive to gases that have an affinity for thermal electrons. The major components of the machine are a detector cell containing a 300 milli-Currie radioactive trituim source, a one-foot stainless steel tube separation column packed with 100-200 mesh aluminum oxide, a small reciprocating diaphragm pump, a plunger type sample valve and an amplifying circuit.

The detector requires two gases for operation. One gas, called the carrier gas, flows constantly through the system and serves as both the transport mechanism for the sample and as an ionization mechanism in the detector. The carrier gas flowing through the detector produces a measurable standing current. When a tracer gas enters the detector, electrons are captured thus reducing the standing current. This decrease in standing current is a measure of concentration of the tracer gas. For this experiement 99.998 percent pure nitrogen was used as the carrier gas. Argon with 5 percent to 10 percent methane may be used as the carrier gas and will produce a slighly higher standing current.

With the tracer gas flowing through the detector and the diaphragm pump operating, sample air is continuously vented out the pump. If the sample valve is depressed a 0.5cc quantity of sample air is injected into the carrier gas stream. The sample is carried through the column where a separation of gases occurs. The separated gases which are detected are first oxygen and second the tracer gas, oxygen also having a high affinity for electrons. A schematic diagram of the detector circuit is shown in Figure 3.

4.1.2 Alterations to Detector

Three alterations were made to the detector to facilitate the calibration and testing procedure and to obtain a usable output. In order to use the calibration system, it was necessary to measure the nitrogen and sample air flow rate. The diaphragm pump on the detector vented all gases to the inside of the detector cabinet. A small length of copper tubing was attached to the pump vent and run through the detector housing where a flow meter was attached. The sample injection valve was fitted with a solenoid device in order to automatically control the sampling sequence. Usable output from the detector was obtained by connecting a Honeywell ElectroniK 19 strip chart voltage recorder in parallel with the taut-band meter equipped on the detector.

4.1.3 Detector Flow Rates

Nitrogen was supplied to the detector from a high pressure cylinder through a double-stage regulator and a short length of 1/8 in. o.d. copper tubing. With the diaphragm pump off the regulator was adjusted to produce a nitrogen flow rate of 150 cc/min. through the detector. At this flow rate the regulator registered a gage pressure of approximately 20 psi. With the diaphragm pump on the combined flow rate for both nitrogen

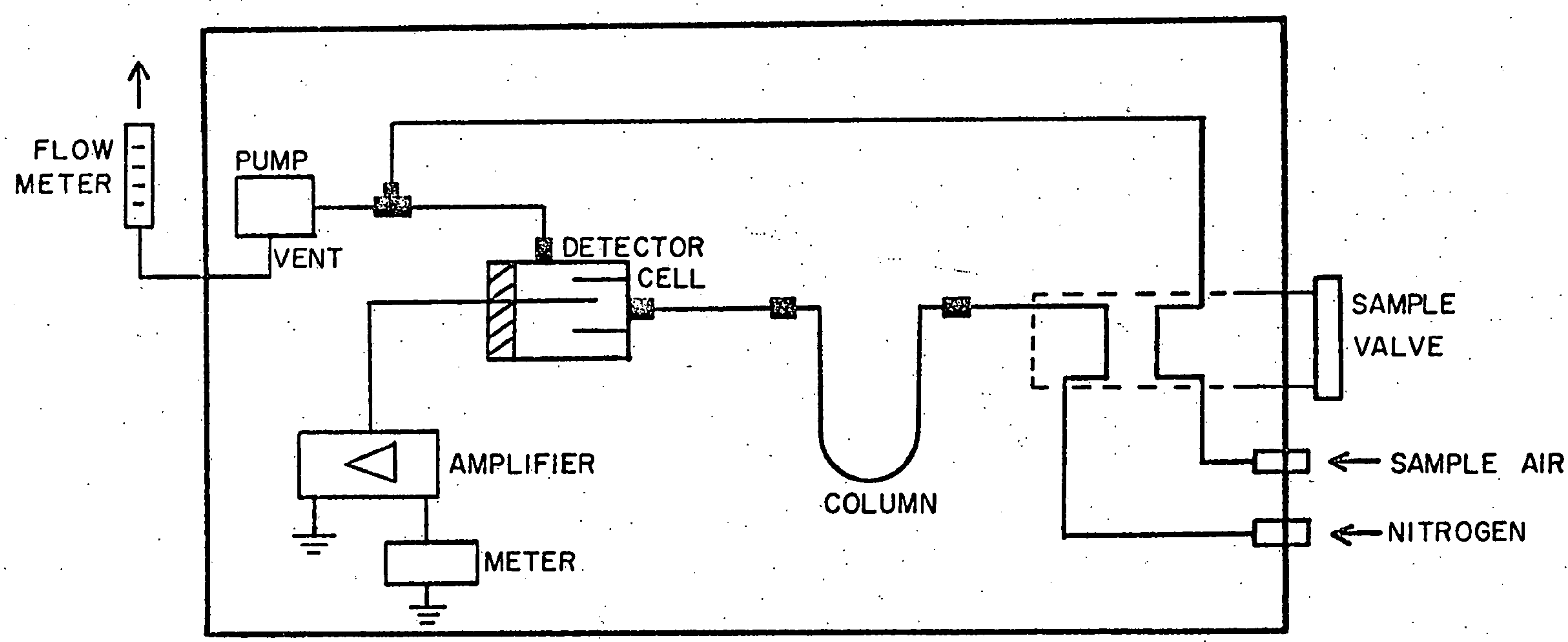


Figure 3. Schematic Diagram of Detector

and sample air was 375 cc/min. Of this quantity 50 cc/min. entered the sample air port.

4.1.4 Calibration of Detector

The response of the detector when encountering a concentration of SF_6 in air is a decrease in standing current, first as the separated oxygen enters the detector cell followed by a second decrease in standing current as the SF_6 passes through the detector cell. A representation of the detector output as measured with the strip chart recorder is shown in Figure 4. Hunt and Burch (9) using a similar detector found the response to SF_6 followed a form of Beer's law. That is

$$\log_e \frac{PH}{SC} = -kc$$

where: c is the concentration of tracer

k is an empirical constant

SC is standing current

PH is the low point of a chromatograph deflection

Figure 4 shows the relationship between standing current and peak height. The term standing current is somewhat of a misnomer in that the standing current in this experiment was measured as a millivolt output rather than measured as a current. Both standing current and peak height were measured in millivolts.

By calibrating the instrument periodically with a known concentration of SF_6 in air a calibration equation can then be developed. Hunt and Burch (9) note that a possible source of error in concentration measurements is failure to consider the small intercept when PH/SC = 1. A more exact equation would then take the form:

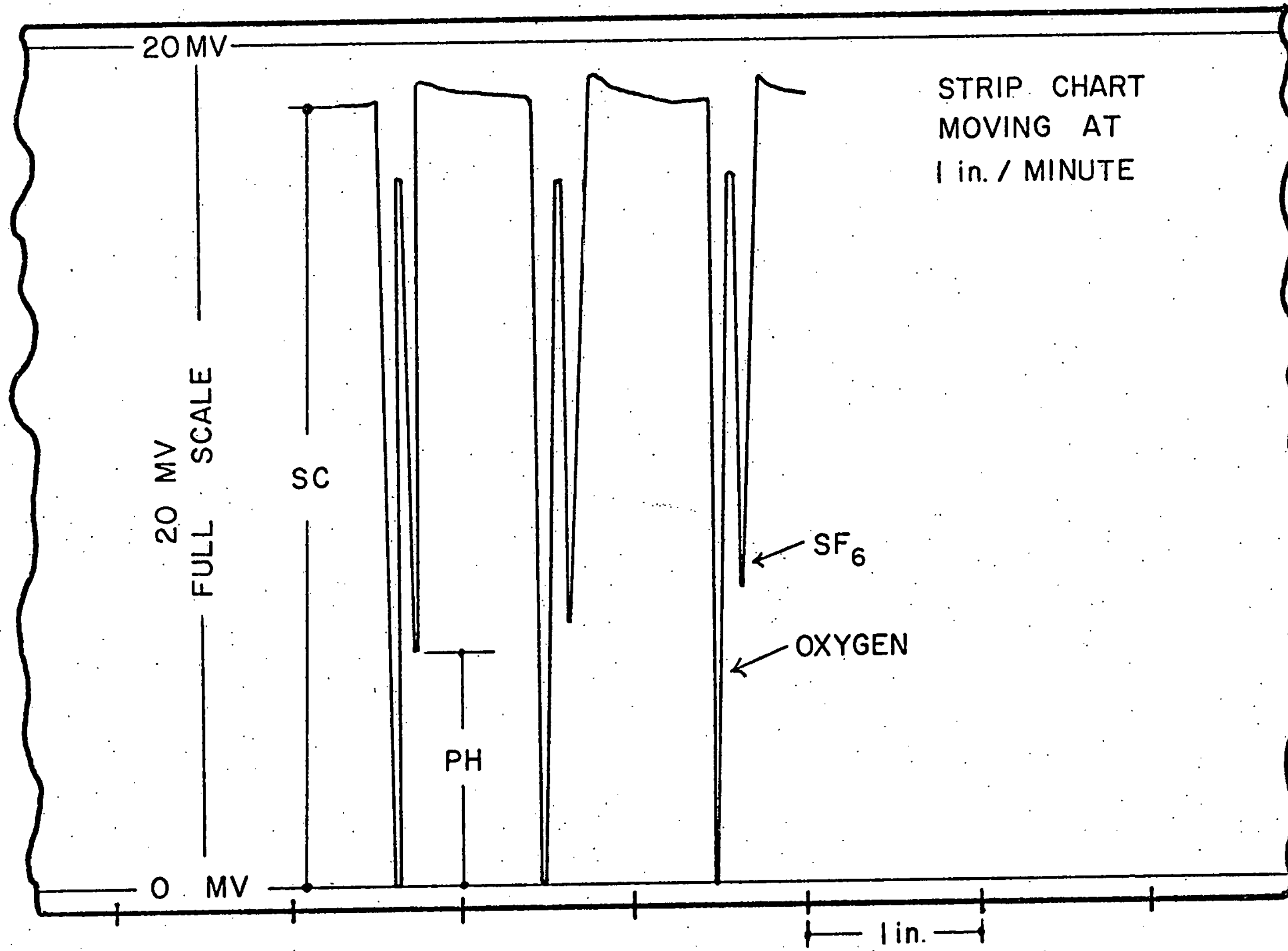


Figure 4. Detector Output — As Measured by a Strip Chart Recorder

$$\log_e \frac{PH}{SC} = -k\,(c-\lambda)$$

where λ represents the intercept at PH/SC = 1. For these tests, two known concentrations of SF_6 in air (4.1 PPB and 12.4 PPB) were used to calibrate the instrument. Machine drift with time made it necessary to calibrate the instrument approximately once every eight minutes. By alternating the calibration gases a calibration equation accounting for the intercept λ could be developed. Concentration measurements were taken in fifteen minute segments with readings being taken once each minute. The first calibration gas was read at minute one with the second calibration gas being read at minute eight followed by the first calibration gas being read at minute one of the second fifteen minute segment. A calibration equation was then developed using the readings of minute one and eight to determine the SF_6 concentration for the readings between minute one and eight. A calibration equation was then calculated using the readings from minute eight of the first fifteen minute segment and minute one of the second fifteen minute segment for use in determining the concentrations of SF_6 between these two points. A sample calculation taken from test Single 1 follows.

Minute	PH (mv)	SC (mv)	(PH/SC)	PPB SF_6 Calibration	PPB SF_6 Calculated
1	21.50	9.45	0.4395	12.4	
2	21.55	7.70	0.3573		15.5
3	21.60	8.00	0.3704		14.9
4	21.65	8.25	0.3811		14.5
5	21.70	8.65	0.3986		13.8

Minute	PH (mv)	SC (mv)	(PH/SC)	PPB SF_6 Calibrated	PPB SF_6 Calculated
6	21.75	8.90	0.4092		13.5
7	21.89	9.35	0.4271		12.8
8	21.80	16.80	0.7706	4.1	
9	21.90	10.05	0.4580		12.3
10	21.95	10.40	0.4738		11.8
11	22.00	10.70	0.4864		11.4
12	22.00	11.00	0.5000		10.9
13	22.00	11.30	0.5136		10.5
14	22.00	11.60	0.5273		10.1
15	22.10	11.95	0.5407		9.7
1	22.20	10.10	0.4550	12.4	
2	22.20	12.40	0.5586		

$$\log_e PH/SC = -k\ (c + \lambda)$$

or

$$\log PH/SC = -kc - A$$

where $A = k\lambda$

$\log_e 0.4395 = -k\ 12.4 - A$ for $c = 12.4$ PPB @ minute 1

$\log_e 0.7706 = -k\ 4.1 - a$ for $c = 4.1$ PPB @ minute 8

solving for k and A

$k = -0.06770$

$A = -0.0168$

The calibration equation is

$$\log_e PH/SC = -0.06770c + 0.0168$$

This equation is used to determine the SF_6 concentrations for observation at minute 2 through 7. Next

$\log_e 0.7706 = -k4.1 - A$ for $c = 4.1$ PPC @ minute 8

$\log_e 0.4550 = -k12.4 - A$ for $c = 12.4$ PPC @ minute 1

solving for k and A

$k = 0.06350$

$A = 0.0003$

the calibration equation is

$$\log_e PH/SC = -0.0635c - 0.0003$$

this equation is used to determine the SF_6 concentrations for minutes 9 through 15.

To determine if the detector output conformed to Beer's law and to find its operating range, a 33.99 ft^3 (962,408 cc) cubic test chamber was constructed of galvanized sheet metal. The chamber was fitted with a septum and small internal mixing fan. By injecting pure SF_6 into the chamber with a microliter syringe, known concentrations of SF_6 in air could be obtained. From this technique, it was determined that the detector's response followed Beer's law in the range from 25 PPB to 3 PPB. It was decided to operate the machine between 20 PPB and 3 PPB in the field if at all possible.

Two calibration gases of different concentrations were prepared by MG Scientific, Kearny, New Jersey. Concentrations of 12.4 PPB in air and 4.1 PPB in air were stored in #7 high pressure cylinders (approximately 4 in. in diameter and 16 in. in height). Great care was taken in preparing the cylinders for filling (13). The cylinders were polished internally with glass beads to reduce the effects of surface absorption and were baked in a vacuum to remove all moisture. Initially, each cylinder contained approximately 20 liters (if expanded to standard conditions) of calibration gas under a gage pressure of approximately 1500 psi.

Each cylinder was fitted with a single stage regulator. A small needle valve with a one-foot section of 1/8 in. o.d. copper tubing was connected to the regulator outlet port. When calibrating the detector the regulator gauge pressure was set at 1 to 2 psi. With the needle valve closed, the copper tubing was connected to the sample air port of the detector. The flow reading measured at the pump vent would decrease from 375 cc/min. to approximately 325 cc/min. as the sample air port was blocked. Thirty seconds before the calibration reading was to be taken, the needle valve was opened and adjusted to provide a flow rate of 375 cc/min. This amount of time allowed the copper tubing and internal detector flow circuitry to be flushed of all preceding sample air. Immediately after the calibration sample was taken, the calibration gas was disconnected from the sample air port and the room air sampling system was reconnected to the port. This procedure used only about 30 cc of calibration gas per calibration reading. Each cylinder provides enough gas for approximately 650 calibration readings.

This calibration technique proved satisfactory in all respects. The cylinders are easily handled and provide enough capacity for a large number of tests.

4.2 Air Sampling and Control Equipment

Two different sampling methods were used. In the first method, zone by zone samples were taken through a network sampling system. In the second method, samples were taken from the return air space only (Zone 13). One of the objectives of this experiment was to determine if the single-point sample method was representative of this particular building's total air change rate, thus reducing the amount of equipment and data analysis necessary in future testing.

It was necessary to measure the SF_6 decay rate in all thirteen zones during a particular test run. To accomplish this an automatic sample air collection system was constructed along with an automatic system to monitor and record data. The air sample collection system consisted of lengths of 1/2 in. (12.7 mm) polyethylene pipe connected to an automatic multi-valve device. This system is basically the same collection system used by Isenberg and McLaughlin in 1968 (7). The pipe is readily available and easy to work with and proved satisfactory in every respect.

A length of pipe was run from each zone to the test station. The pipe inlets were located three to four feet above floor level and their approximate locations correspond to the zone number designations on Figure 2. At the test station, the pipes were connected to the multi-valve device. This device contains fifteen electrically controlled three-way valves arranged in line on two chambers. Each valve is open normally to the upper chamber, allowing air from the connected zones to be drawn off continuously. This maintains a fresh sample of air from each zone at the test station location. An industrial shop vacuum cleaner, connected to the upper chamber, was used to draw sample air through the network system. The vacuum cleaner discharged the sample air into the women's restroom which contained an exhaust fan. Although the pipes were of varying length (varying from 20 ft. to 60 ft.) the flow rates through the pipes varied from only 22,000 cc/min to 27,000 cc/min. This provided for an air change rate in the 60 ft. length of five per minute and an air change rate of 17 per minute in the 20 ft. length. Therefore, it took a quantity of sample air 3.4 second to travel the 20 ft. length of pipe and 12.6 second to travel the 60 ft.

length of pipe. A time lag difference of 9.2 seconds was considered negligible since each zone was sampled once every 15 minutes and normal variation in the decay rate would mask this small error.

When a particular value was activated, sample air from one zone would be delivered to the lower chamber. A 10 liter per minute diaphragm pump drew air from the lower chamber and discharged the sample at approximately atmospheric pressure. The sample air entered the detector from the pump discharge through a 1 ft. length of 1/8 in. o.d. teflon tubing. Figure 5 is a schematic layout of the valving arrangement showing sample air movement through the system.

Concentration readings were taken automatically once a minute with each zone being sampled once every 15 minutes. A control device automatically sequenced the activation of the 15 valves and also activated the sample valve pushing mechanism. The control device had the capability of either automatically or manually activating the valves. Valve positions one and eight were not used. Calibration of the detector took place during the time periods when these valves were to sequence. Sample air from a particular zone would flow through the bottom header for 58 seconds. At this time, the control device would activate the sample valve pushing mechanism, thus taking a concentration measurement for that particular zone. At time sixty seconds the next valve would activate thus diverting sample air from the next zone into the bottom header. A concentration measurement for that zone would then be taken fifty-eight seconds later. The time of fifty-eight seconds allowed a sufficient period to flush sample air of the previous zone from the bottom chamber. For the single point

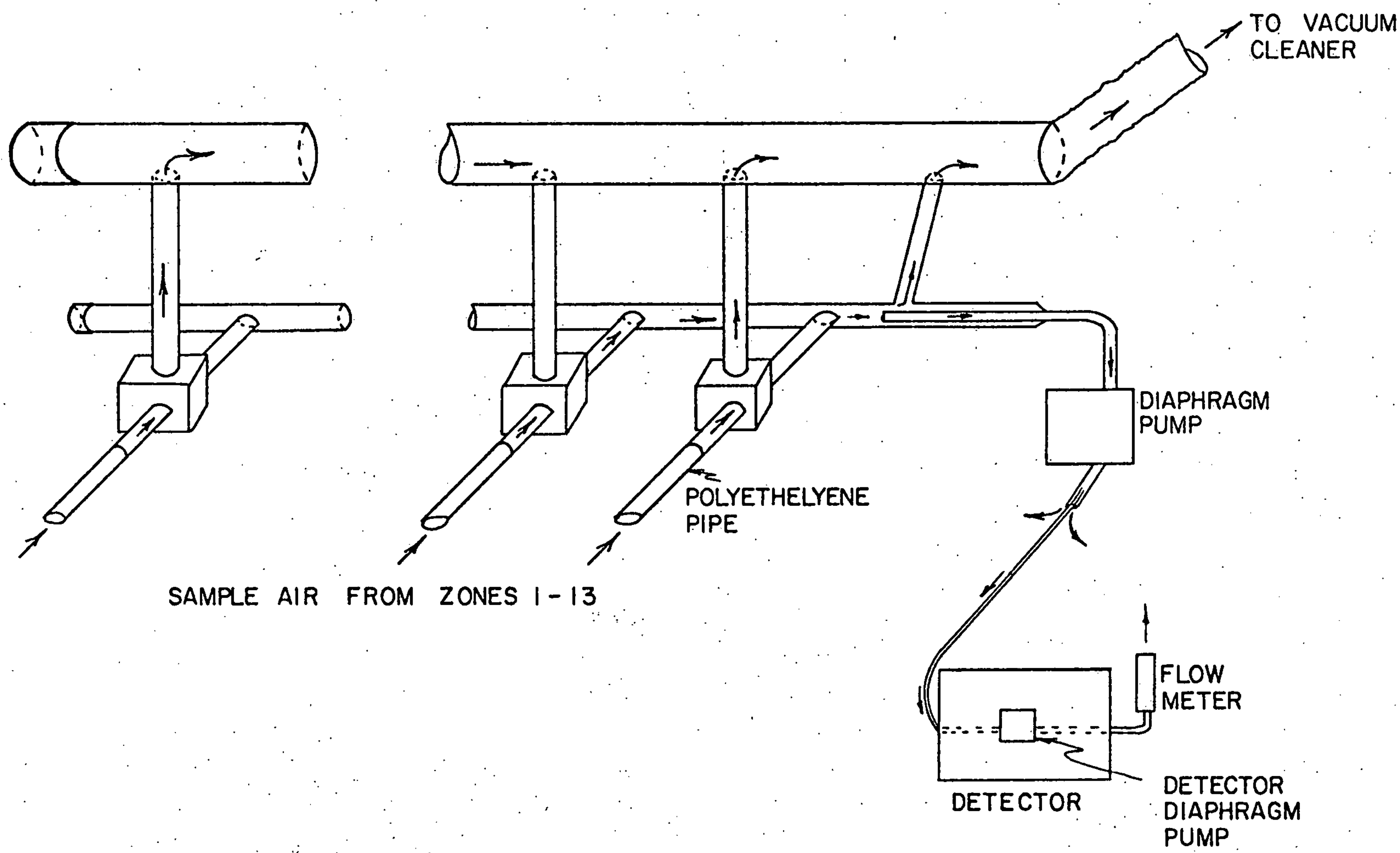


Figure 5. Schematic Diagram of Automatic Multi-Valve Sampling System

return air sample tests, samples were taken once every minute from Zone 13 only.

Electrical noise created by the control system and existing in the building made it necessary to supply power to the detector and strip charge recorder through an isolation transformer. A schematic diagram of the test station appears in Figure 6. Figure 7 is composed of three photographs; showing the test station, the polyetheylene pipe, and the instrument used for reading and recording environmental data.

4.3 Measurement of Environmental Conditions

Wind velocity and direction, and temperatures were recorded by a Kaye Instrument System (Model 8001). A weather station located on top of the building (Figure 1, bottom) housed the wind velocity and direction instrument and a thermistor used for measuring the outdoor dry bulb temperature. Five thermistors located in Zones 1, 6, 7, 10 and 11 were used to measure the indoor dry bulb temperatures. Temperature readings were recorded once every 10 minutes while wind velocity and direction were recorded every 10 seconds. A Decker Differential Pressure Meter (Model 306-2) was connected to an outdoor pressure tap located five feet above the ground immediately outside the print room door and to an inside pressure tap located four feet above the floor in the reception area. This was the only static pressure difference monitored. The output was recorded continuously on a Honewell ElectroniK 19 strip chart recorder. Environmental data for further testing will be recorded on an IBM System 7 (Figure 7, bottom). The IBM data acquisition system was out of service for programming while this experiment was being conducted.

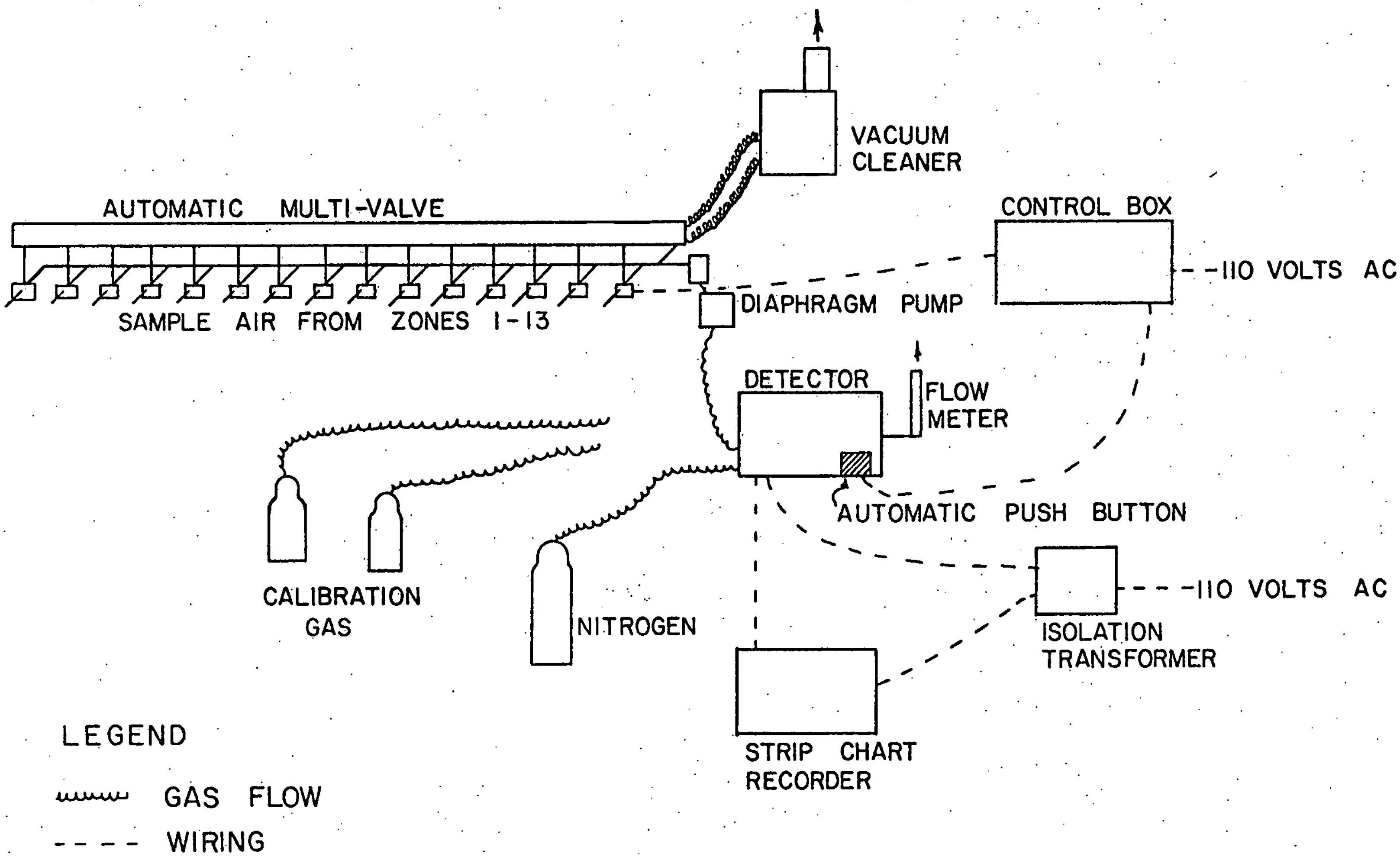
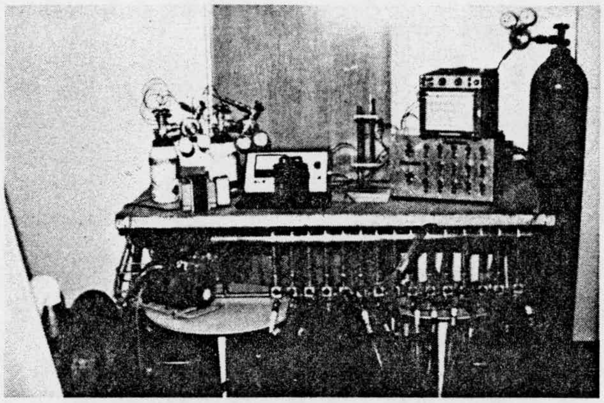
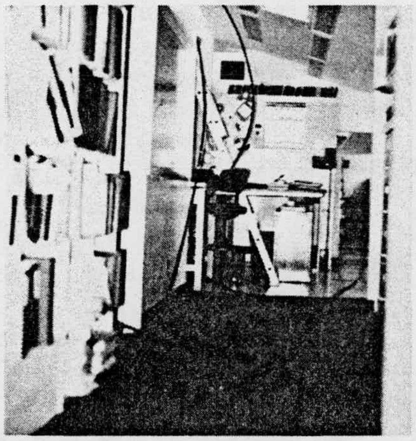


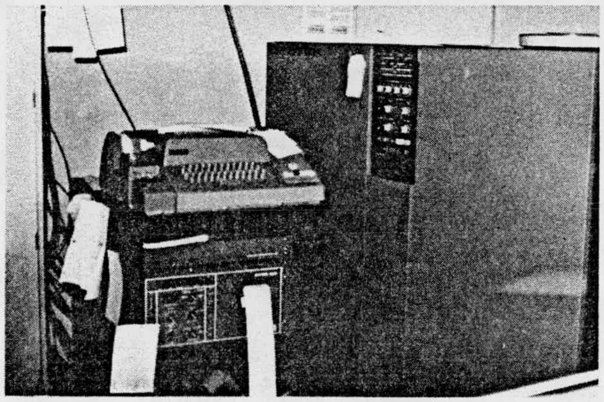
Figure 6. Schematic Diagram of Test Station



Test Station



Polyethylene Pipe



Environmental Data Recording Instruments

Figure 7. Test Equipment

5.0 TEST DESCRIPTIONS AND PROCEDURE

5.1 Description of Tests

A total of eight tests, two groups of four tests each, were conducted on June 12 and June 13, 1975. The first four tests were taken in the time period from 21:00 MDST June 12 through 5:00 MDST June 13, and the second group of tests were taken from 17:00 MDST June 13 through 24:00 MDST June 13.

Two types of tests were conducted: (1) multi-point sample or zone sample hereafter referred to as a room test, and (2) a single-point return air sample hereafter referred to as a single test. Two types of building conditions were investigated: (1) the day condition, and (2) the night condition, descriptions of these conditions appear in Section 33. Test name, time period, and building conditions appear in Table 2.

Table 2. Test Descriptions

Test Name	Date	Start Time (MDST)	Stop Time (MDST)	Total Time (Minutes)	Building Condition
Room 1	6/12/75	21:08	22:08	60	Day
Single 1	6/12/75	23:11	23:56	45	Day
Room 2	6/13/75	1:37	2:52	75	Night
Single 2	6/13/75	3:31	4:53	82	Night
Room 3	6/13/75	17:17	18:17	60	Day
Single 3	6/13/75	19:07	19:52	45	Day
Room 4	6/13/75	20:25	21:25	60	Night
Single 4	6/13/75	22:59	23:50	51	Night

By inspection of test groups in Table 2 it is evident of the comparison to be made. By comparing test Room 1 with test Single 1 and by comparing test Room 2 with test Single 2 a determination can be made whether or not a single-point return air sample is indicative of the total building air change rate. The second group of tests follows the same pattern. Also, the air change rates for both building conditions can be determined.

5.2 Test Procedure

The cylinder of SF_6 was stored approximately fifty yards downwind from the building to reduce any chance of contamination while the tests were in progress. A 50 cc container was filled with pure SF_6. The container was then opened in front of the supply fan of the air handling unit. The air distribution system carried the tracer gas throughout the building. Preliminary tests showed that good mixing took place throughout the building negating the need for portable fans to mix the air. This building is ideally suited for distributing and mixing the tracer gas and made this part of the test a single process. When it was determined that a suitable concentration of well-mixed tracer gas was contained within the space, the sampling process was started. This took from between five to ten minutes depending on the residual concentrations remaining from previous tests. Tests were run as long as seemed appropriate by inspecting the decay rate on the strip chart recorder. Testing during the night condition took somewhat longer since the air change rate was greatly reduced. For future testing the day condition tests can be held to forty-five minutes and the night condition tests to one hour.

6.0 DATA ANLAYSIS AND RESULTS

6.1 Data Analysis

The computer was used to organize the raw concentration data and to make the necessary calculations. The concentrations were calculated from the raw data using the procedure described in Section 4.1.4. The Appendix contains the raw data and concentration values for all eight tests in the order they were taken. The air change rate for each test was determined using the slope of a best fit least square straight line approximation of the concentration versus time data points. In the case of the Zone tests an air change rate for each zone was determined and weighted according to its volume. By summing the weighted values of all zones, the total building air change rate was determined. Figure 8 through Figure 11 are plots of decay rate observations for tests Single 1 through Single 4 respectively. Minute zero values on the figures correspond to minute two value in the Appendix. Table 3 through Table 6 shows individual zone air change rates and the total weighted air change rate for tests Room 1 through Room 4 respectively.

The average indoor temperature for a given test is a weighted average using the temperature data from the five indoor zone locations. The outdoor dry bulb temperature is the average of the ten-minute readings for a given test period. Wind velocity and direction were read every ten seconds and compiled in five-minute averages. Although the anemometer used had questionable accuracy when reading in the lower range (0-5 mph), the wind velocity was extremely low for all tests. This was confirmed by the non-fluctuating output of the differential

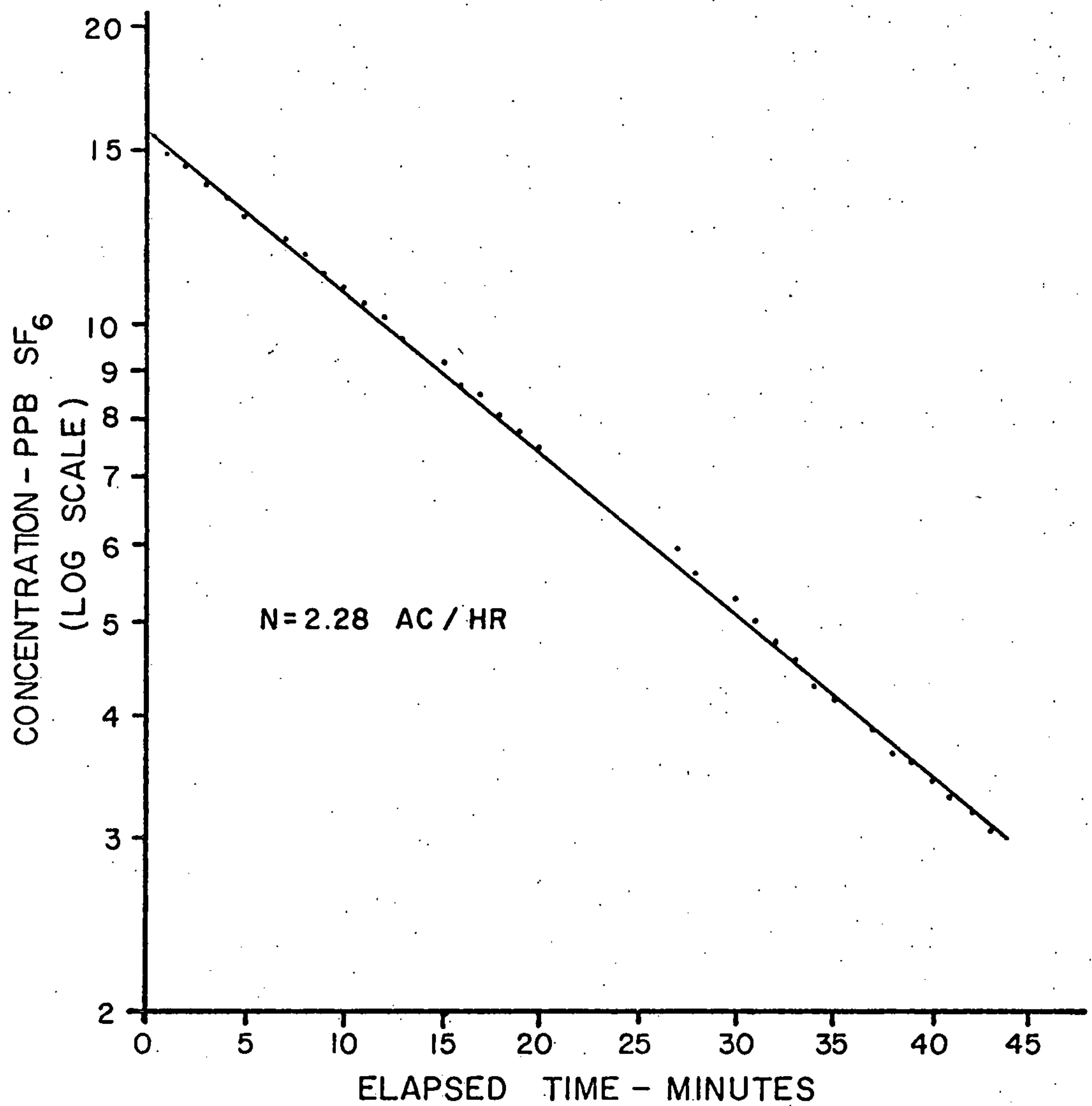


Figure 8. Decay Rate Observation — Test Single 1

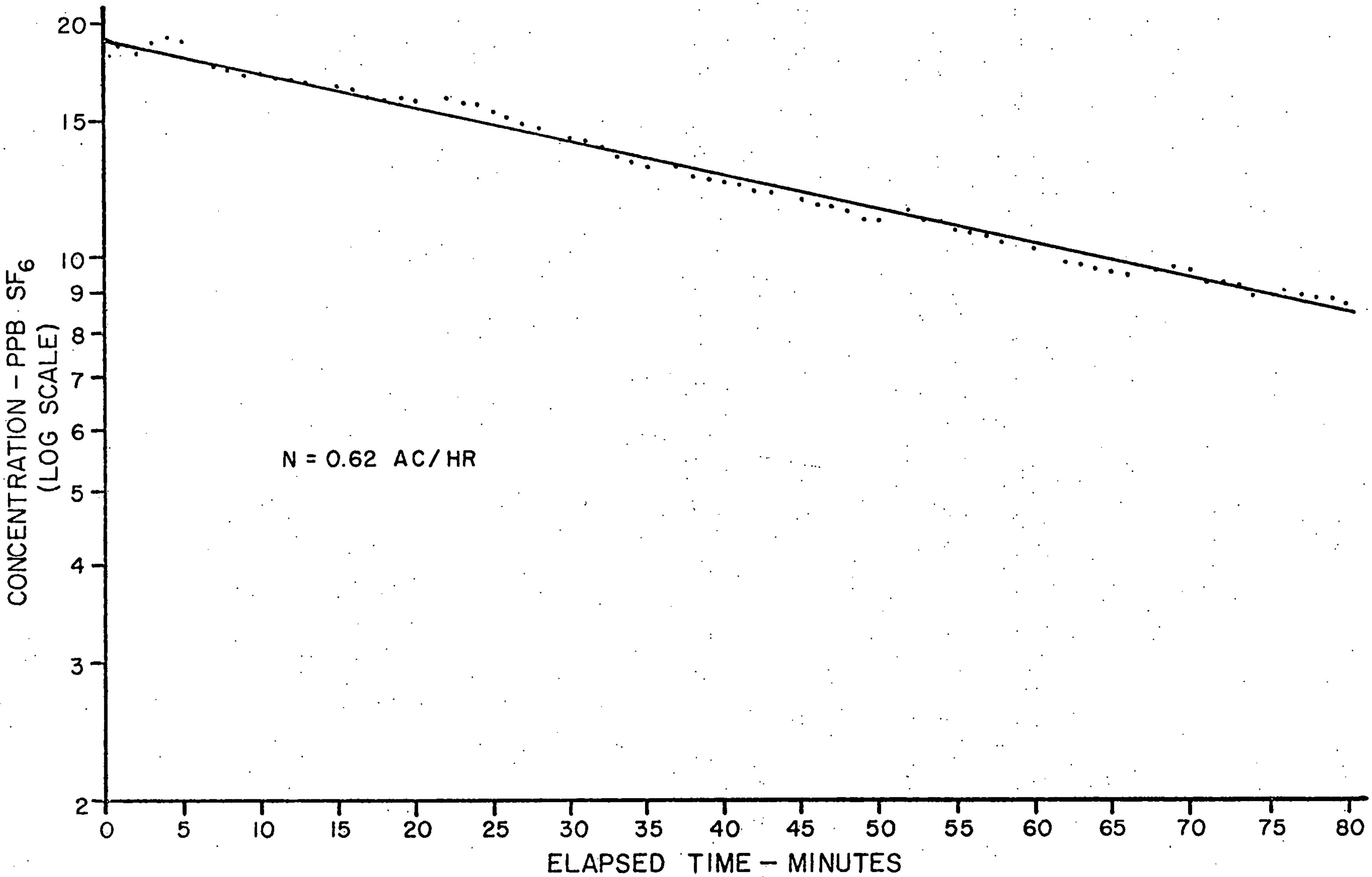


Figure 9. Decay Rate Observation — Test Single 2

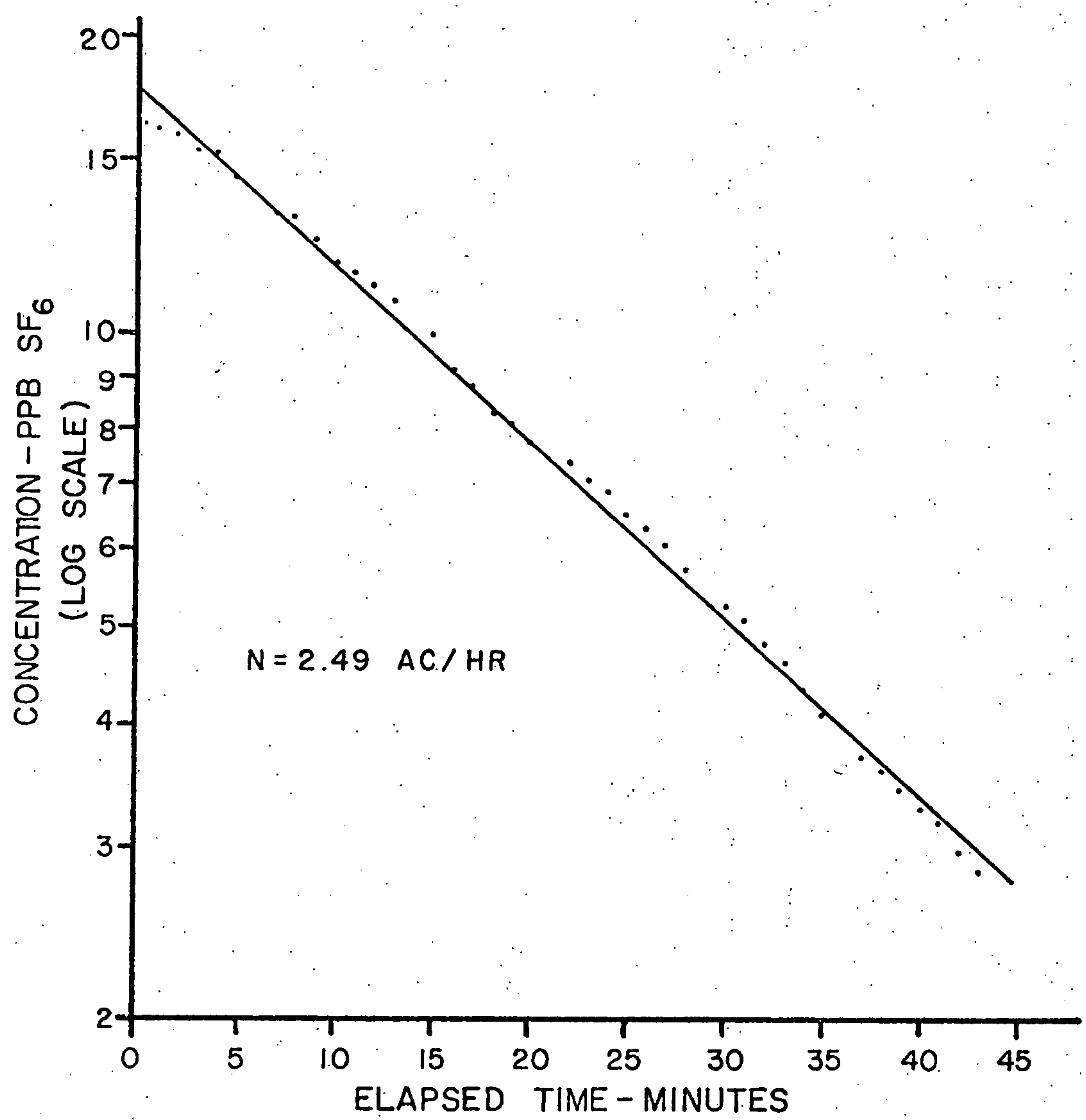


Figure 10. Decay Rate Observation — Test Single 3

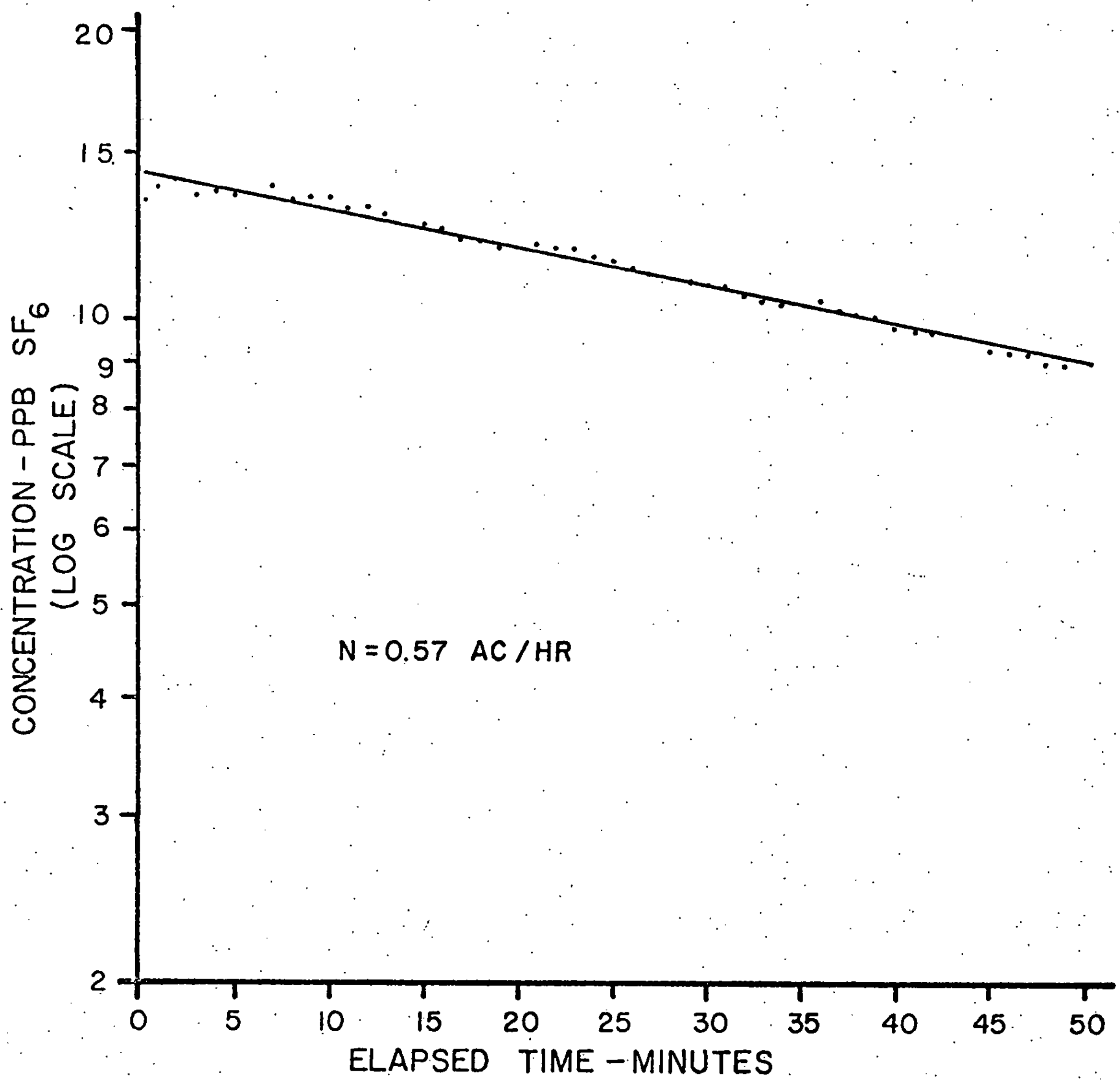


Figure 11. Decoy Rate Observation — Test Single 4

Table 3. Weighted Air Change Rate - Test Room 1

Zone	N AC/HR	% TOTAL Volume	Nx%
1	2.160	0.416	0.899
2	1.960	0.030	0.059
3	1.930	0.054	0.104
4	2.028	0.046	0.093
5	1.532	0.026	0.040
6	2.222	0.026	0.058
7	2.500	0.102	0.255
8	2.515	0.024	0.060
9	2.469	0.031	0.077
10	2.404	0.085	0.204
11	1.924	0.040	0.077
12	2.546	0.067	0.171
13	2.552	0.052	0.133

Weighted Air Change Rate = 2.23/hour

Table 4. Weighted Air Change Rate - Test Room 2

Zone	N AC/HR	% TOTAL Volume	Nx%
1	0.631	0.416	0.262
2	0.510	0.030	0.015
3	0.581	0.054	0.031
4	0.530	0.046	0.024
5	0.539	0.026	0.014
6	0.556	0.026	0.014
7	0.609	0.102	0.062
8	0.614	0.024	0.015
9	0.622	0.031	0.019
10	0.599	0.085	0.051
11	0.991	0.040	0.040
12	0.614	0.067	0.041
13	0.656	0.052	0.034

Weighted Air Change Rate = 0.62/hour

Table 5. Weighted Air Change Rate - Test Room 3

Zone	N AC/HR	% TOTAL Volume	Nx%
1	2.798	0.416	1.164
2	2.803	0.030	0.084
3	2.067	0.054	0.112
4	2.141	0.046	0.098
5	2.462	0.026	0.064
6	1.917	0.026	0.050
7	2.690	0.102	0.274
8	2.831	0.024	0.068
9	2.746	0.031	0.085
10	2.765	0.085	0.235
11	2.518	0.040	0.101
12	2.493	0.067	0.167
13	2.672	0.052	0.139

Weighted Air Change Rate = 2.64/hour

Table 6. Weighted Air Change Rate - Test Room 4

Zone	N AC/HR	% TOTAL Volume	Nx%
1	0.684	0.416	0.285
2	0.738	0.030	0.022
3	0.521	0.054	0.028
4	0.489	0.046	0.022
5	0.679	0.026	0.018
6	0.612	0.026	0.016
7	0.685	0.102	0.070
8	0.712	0.024	0.017
9	0.711	0.031	0.022
10	0.706	0.085	0.060
11	0.566	0.040	0.023
12	0.662	0.067	0.044
13	0.656	0.052	0.034

Weighted Air Change Rate = 0.66/hour

pressure monitor. The wind velocity taken from the anemometer readings averaged less than one mph for all tests. The building static pressure, as read from the one location in the reception area, averaged +0.027 inches of water with the ventilation fan on and +0.005 with the ventilation fan off. Table 7 contains a summary of all data taken.

6.2 Results

Due to the limited number of tests taken no empirical relationships between temperature difference, pressure difference and air change rate could be made. Using the crack method (1), air change rates were calculated for the single tests where an average pressure difference of 0.027 inches of water existed. The values predicted by the crack method equaled approximately 10 percent of the values measured.

Certain trends were established in the eight tests. With an increasing temperature difference, either positive or negative, the air change rate increased. The day condition tests of the second group of tests (tests Room 3 and Single 3) had air change rates greater than similar tests of the first group (tests Room 1 and Single 1). This was to be expected since there was moderate occupancy traffic in and out of the building during test Room 3 and light traffic during test Single 3, while there was little or no traffic during tests Room 1 and Single 1. The air change rate was of course greatly increased while the ventilation fan was operating. The air change rate measured by the tracer gas technique while the ventilation fan were running approximated the air change rate calculated from pressure measurements obtained from an air flow device in the ventilation duct. On the average, the

Table 7. Summary of Data

Test	Air Change Rate		Temperature °F		ΔT	Wind			Static Pressure Inches of Water
	N	cfm	ID DB	OD DB		VEL mph	DIR °	DIR	
Room 1	2.23	1490	77.9	70.0	7.9	<1.0	52	NE	0.028
Single 1	2.28	1520	77.7	67.0	10.7	<1.0	57	ENE	0.029
Room 2	0.62	417	77.5	64.0	13.5	<1.0	348	NNW	0.006
Single 2	0.62	412	76.9	61.3	15.6	<1.0	352	N	0.002
Room 3	2.64	1765	78.6	91.8	-13.2	<1.0	255	WSW	0.024
Single 3	2.49	1661	79.0	84.0	- 5.0	<1.0	254	WSW	0.026
Room 4	0.66	442	78.6	78.8	- 0.2	<1.0	273	W	0.008
Single 4	0.57	378	78.1	74.5	3.6	<1.0	302	WNW	0.004

tracer gas technique gave values 10 percent less than the 1780 CFM obtained from the ventilation duct measurement. The 1780 CFM value is questionable due to an insufficient straight duct length for measuring purposes.

There is close agreement between values obtained by the single point sample method and values obtained by the weighted zone values. By comparing Room 1 with Single 1, Room 2 with Single 2, etc., it is seen that the largest difference in air change rates is only 0.15. This difference is between tests Room 3 and Single 3 can be explained by more occupant activity and a larger temperature difference for test Room 3. Inspection of Table 3 through Table 6 shows that the air change rate for Zone 13 varies from the weighted value by an average of less than 0.1 air change per hour, and for three of the four tests the average varies less than 0.02 air change per hour.

6.3 Sources of Error

The straight line deconcentration relationship used assumes perfect mixing within the space and no reentry of tracer gas. If poor mixing is a problem a curved plot of the log of concentration versus time will be obtained, which was not the case for these tests.

Errors in concentration measurement could also occur due to inadequate flushing of the air sampling equipment. Sufficiently high flow rates reduce this source of error although leaks in the valving networks will cause mixing of zone samples leading to erroneous readings. Inspection of the room tests shows this to be at most a secondary source of error.

Drift in instrument response with time proved to be a problem. That is the reason for numerous calibration readings and the calibration technique explained in Section 4.1.4. This problem was not totally alleviated as illustrated by the pronounced sinusoidal (but of low amplitude) decay rate plot for test Single 2 (Figure 9). This sinusoidal effect was produced by using a different calibration equation for each seven and eight minute segments. By using the two-point calibration system described and calibrating the instrument with sufficient frequency, the error caused by machine drift can be minimized.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Air change measurements were made on a one-story office building using SF_6 as a tracer gas. Testing was conducted within a forty-eight hour period and the experimental equipment and procedures proved satisfactory. Testing was carried out with only limited inconvenience to the building occupants.

For this particular building, close agreement was demonstrated between air change rates determined by the single-point return air sampling and the multi-point zone sampling techniques.

Due to an insufficient number of tests, no correlation between temperature difference, pressure difference and the air change rate could be made. However, expected trends were confirmed.

The problem of machine drift on the portable gas chromatograph was overcome by a calibration technique devised by the author. This technique proved quite suitable, giving confidence to measurements taken.

7.2 Recommendations

The major emphasis of this thesis was on refining a technique used to measure the air change rate in buildings. The present energy situation makes air change rate studies not only timely but necessary. Air change rate measurements are needed for all building types. With this knowledge, accurate evaluations can be made to determine suitable ventilation rates with respect to energy use and comfort.

Although the automatic air sampling network proved quite versitile, it necessitated an intermediate diaphragm pump to draw sample air out of the lower header due to the reduced pressure within the header. A redesign of the venting system on the sample header would alleviate the need for this pump. For single-point sampling a small diaphragm pump and length of pipe is all that is necessary to draw sample air to the test station.

The technique described in this thesis performed quite satisfactorily and is highly recommended for making air change measurements.

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APPENDIX

LEGEND FOR APPENDIX

CAL(PPB)	–	calibration gas concentration, parts per billion SF_6 in air
TIME	–	elapsed time in hours and minutes (MDST)
MIN	–	elapsed time in minutes
CNT	–	count, referring to the 15-minute data blocks
SC(MV)	–	standing current in milli-volts
PH(MV)	–	peak height in milli-volts
RATIO PH/SC	–	peaks height divided by standing current
ZONE	–	refers to building zone numbers
CONC (PPB)	–	concentration, parts per billion SF_6 in air

Concentration data for each of the eight tests follows in the order tests were taken. Other pertinent data for the tests appear in Table 2 and Table 7.

ROOM1

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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	ZONE	CONC (PPB)
12.4	2108	1	1	18.05	7.10	0.3934		
	2109	2	2	18.10	2.00	0.1105	1	28.73
	2110	3	3	18.10	5.40	0.2983	2	15.96
	2111	4	4	18.10	3.05	0.1685	3	23.31
	2112	5	5	18.05	3.30	0.1828	4	22.26
	2113	6	6	18.05	6.70	0.3712	5	13.15
	2114	7	7	18.05	2.80	0.1551	6	24.37
4.1	2115	8	8	18.00	13.50	0.7500		
	2116	9	9	18.00	3.80	0.2111	7	20.34
	2117	10	10	18.00	3.30	0.1833	8	22.15
	2118	11	11	18.00	4.10	0.2278	9	19.36
	2119	12	12	18.05	4.10	0.2271	10	19.40
	2120	13	13	18.10	5.55	0.3066	11	15.56
	2121	14	14	18.15	5.10	0.2810	12	16.67
	2122	15	15	18.15	4.50	0.2479	13	18.28
12.4	2123	16	1	18.10	7.10	0.3923		
	2124	17	2	18.20	4.80	0.2637	1	17.31
	2125	18	3	18.25	8.85	0.4849	2	9.78
	2126	19	4	18.30	5.80	0.3169	3	15.04
	2127	20	5	18.40	5.60	0.3043	4	15.54
	2128	21	6	18.40	5.80	0.3152	5	15.11
	2129	22	7	18.45	6.70	0.3631	6	13.36
4.1	2130	23	8	18.50	14.20	0.7676		
	2131	24	9	18.55	8.55	0.4609	7	10.88
	2132	25	10	18.65	8.30	0.4450	8	11.34
	2133	26	11	18.75	9.25	0.4933	9	9.97
	2134	27	12	18.80	9.30	0.4947	10	9.94
	2135	28	13	18.90	9.30	0.4921	11	10.01
	2136	29	14	18.90	8.00	0.4233	12	12.01
	2137	30	15	18.95	7.75	0.4090	13	12.46
12.4	2138	31	1	19.10	7.85	0.4110		
	2139	32	2	19.20	9.90	0.5156	1	9.34
	2140	33	3	19.25	13.20	0.6857	2	5.49
	2141	34	4	19.40	10.35	0.5335	3	8.88
	2142	35	5	19.40	10.40	0.5361	4	8.81
	2143	36	6	19.50	9.55	0.4897	5	10.04
	2144	37	7	19.60	11.40	0.5816	6	7.71

(CONTINUED)

ROOM1

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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	ZONE	CONC (PPB)
4.1	2145	38	8	19.60	14.90	0.7602		
	2146	39	9	19.75	12.90	0.6532	7	6.38
	2147	40	10	19.80	12.90	0.6515	8	6.42
	2148	41	11	19.90	13.45	0.6759	9	5.87
	2149	42	12	19.95	13.30	0.6667	10	6.08
	2150	43	13	20.00	13.15	0.6575	11	6.29
	2151	44	14	20.00	13.80	0.6900	12	5.56
	2152	45	0					
12.4	2153	46	1	20.20	8.85	0.4381		
	2154	47	2	20.30	14.30	0.7044	1	5.33
	2155	48	3	20.40	15.95	0.7819	2	3.78
	2156	49	0					
	2157	50	5	20.50	14.80	0.7220	4	4.96
	2158	51	6	20.60	15.65	0.7597	5	4.21
	2159	52	7	20.60	15.25	0.7403	6	4.59
4.1	2200	53	8	20.65	15.80	0.7651		
	2201	54	9	20.75	17.00	0.8193	7	3.02
	2202	55	10	20.80	16.75	0.8053	8	3.29
	2203	56	11	20.90	17.20	0.8230	9	2.95
	2204	57	12	20.95	17.10	0.8162	10	3.08
	2205	58	13	20.95	16.50	0.7876	11	3.64
	2206	59	14	20.95	17.65	0.8425	12	2.58
	2207	60	15	21.05	17.45	0.8290	13	2.84
12.4	2208	61	1	21.15	9.55	0.4515		

SINGLE1

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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	CONC (PPB)
12.4	2311	1	1	21.50	9.45	0.4395	
	2312	2	2	21.55	7.70	0.3573	15.46
	2313	3	3	21.60	8.00	0.3704	14.93
	2314	4	4	21.65	8.25	0.3811	14.51
	2315	5	5	21.70	8.65	0.3986	13.84
	2316	6	6	21.75	8.90	0.4092	13.46
	2317	7	7	21.89	9.35	0.4271	12.82
4.1	2318	8	8	21.80	16.80	0.7706	
	2319	9	9	21.90	10.05	0.4589	12.27
	2320	10	10	21.95	10.40	0.4738	11.76
	2321	11	11	22.00	10.70	0.4864	11.35
	2322	12	12	22.00	11.00	0.5000	10.91
	2323	13	13	22.00	11.30	0.5136	10.49
	2324	14	14	22.00	11.60	0.5273	10.08
	2325	15	15	22.10	11.95	0.5407	9.68
12.4	2326	16	1	22.20	10.10	0.4550	
	2327	17	2	22.20	12.40	0.5586	9.20
	2328	18	3	22.20	12.80	0.5766	8.71
	2329	19	4	22.25	13.00	0.5843	8.50
	2330	20	5	22.35	13.40	0.5996	8.09
	2331	21	6	22.40	13.65	0.6094	7.84
	2332	22	7	22.40	13.90	0.6205	7.56
4.1	2333	23	8	22.40	17.35	0.7746	
	2334	24	0				
	2335	25	0				
	2336	26	0				
	2337	27	0				
	2338	28	0				
	2339	29	14	22.55	15.65	0.6940	5.95
	2340	30	15	22.60	16.00	0.7080	5.62
12.4	2341	31	1	22.60	10.70	0.4735	
	2342	32	2	22.65	16.30	0.7196	5.29
	2343	33	3	22.75	16.65	0.7319	5.00
	2344	34	4	22.75	16.90	0.7429	4.75
	2345	35	5	22.75	17.10	0.7516	4.55
	2346	36	6	22.80	17.40	0.7632	4.29
	2347	37	7	22.80	17.60	0.7719	4.10

(CONTINUED)

SINGLE1

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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	CONC (PPB)
4.1	2348	38	8	22.80	17.60	0.7719	
	2349	39	9	22.80	17.85	0.7829	3.85
	2350	40	10	22.90	18.10	0.7904	3.69
	2351	41	11	22.90	18.20	0.7948	3.59
	2352	42	12	22.95	18.40	0.8017	3.44
	2353	43	13	22.90	18.50	0.8079	3.31
	2354	44	14	22.90	18.65	0.8144	3.17
	2355	45	15	23.00	18.90	0.8217	3.02
12.4	2356	46	1	23.00	11.00	0.4783	

ROOM2
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****

CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	ZONE	CONC (PPB)
12.4	137	1	1	18.75	6.40	0.3413		
	138	2	2	18.85	3.25	0.1724	1	19.86
	139	3	3	19.00	4.35	0.2289	2	16.77
	140	4	4	19.10	3.35	0.1754	3	19.68
	141	5	5	19.20	3.65	0.1901	4	18.80
	142	6	6	19.30	4.15	0.2150	5	17.45
	143	7	7	19.40	3.95	0.2036	6	18.05
4.1	144	8	8	19.40	14.15	0.7294		
	145	9	9	19.55	4.95	0.2532	7	17.55
	146	10	10	19.60	4.85	0.2474	8	17.85
	147	11	11	19.70	5.10	0.2589	9	17.27
	148	12	12	19.80	5.40	0.2727	10	16.61
	149	13	13	19.95	8.80	0.4411	11	10.49
	150	14	14	19.95	5.85	0.2932	12	15.69
	151	15	0					
12.4	152	16	1	20.15	7.65	0.3797		
	153	17	2	20.20	5.60	0.2772	1	16.26
	154	18	3	20.30	6.10	0.3005	2	15.27
	155	19	4	20.40	5.70	0.2794	3	16.17
	156	20	5	20.50	5.80	0.2829	4	16.01
	157	21	6	20.60	6.35	0.3083	5	14.96
	158	22	7	20.60	6.20	0.3010	6	15.25
4.1	159	23	8	20.70	15.45	0.7464		
	200	24	0					
	201	25	10	20.90	7.15	0.3421	8	15.39
	202	26	11	21.00	7.35	0.3500	9	15.06
	203	27	12	21.05	7.50	0.3563	10	14.80
	204	28	13	21.20	11.00	0.5189	11	9.36
	205	29	14	21.20	8.20	0.3868	12	13.61
	206	30	0					
12.4	207	31	1	21.40	9.00	0.4206		
	208	32	2	21.45	8.20	0.3823	1	13.74
	209	33	3	21.50	8.50	0.3953	2	13.27
	210	34	4	21.60	8.00	0.3704	3	14.18
	211	35	5	21.70	8.00	0.3687	4	14.25
	212	36	6	21.80	8.60	0.3945	5	13.30
	213	37	7	21.80	8.60	0.3945	6	13.30

(CONTINUED)

ROOM2

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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	ZONE	CONC (PPB)
4.1	214	38	8	21.85	16.60	0.7597		
	215	39	9	21.70	9.25	0.4263	7	12.89
	216	40	10	21.80	9.25	0.4243	8	12.96
	217	41	11	21.90	9.50	0.4338	9	12.62
	218	42	12	21.95	9.60	0.4374	10	12.50
	219	43	13	21.95	13.60	0.6196	11	7.20
	220	44	14	21.90	9.85	0.4498	12	12.07
	221	45	0					
12.4	222	46	1	22.15	9.75	0.4402		
	223	47	2	22.20	10.00	0.4505	1	12.05
	224	48	3	22.20	10.35	0.4662	2	11.54
	225	49	4	22.25	9.80	0.4404	3	12.39
	226	50	5	22.40	9.80	0.4375	4	12.49
	227	51	6	22.40	10.60	0.4732	5	11.32
	228	52	7	22.40	10.40	0.4643	6	11.60
4.1	229	53	8	22.50	17.25	0.7667		
	230	54	9	22.60	11.20	0.4956	7	11.01
	231	55	10	22.60	11.15	0.4934	8	11.08
	232	56	11	22.65	11.40	0.5033	9	10.77
	233	57	12	22.70	11.45	0.5044	10	10.74
	234	58	13	22.75	15.45	0.6791	11	6.02
	235	59	14	22.70	12.00	0.5286	12	9.99
	236	60	15	22.85	11.80	0.5164	13	10.36
12.4	237	61	1	22.90	10.40	0.4541		
	238	62	2	22.95	11.75	0.5120	1	10.49
	239	63	3	23.00	12.00	0.5217	2	10.19
	240	64	4	23.00	11.50	0.5000	3	10.87
	241	65	5	23.05	11.45	0.4967	4	10.97
	242	66	6	23.15	12.05	0.5205	5	10.23
	243	67	7	23.20	12.00	0.5172	6	10.33
4.1	244	68	8	23.20	17.75	0.7651		
	245	69	9	23.20	12.80	0.5517	7	9.57
	246	70	10	23.30	12.70	0.5451	8	9.77
	247	71	11	23.30	13.00	0.5579	9	9.38
	248	72	12	23.35	13.15	0.5632	10	9.22
	249	73	13	23.35	18.20	0.7794	11	3.79
	250	74	14	23.30	13.70	0.5880	12	8.50
	251	75	0					
12.4	252	76	1	23.40	10.90	0.4658		

SINGLE2
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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	CONC (PPB)
12.4	331	1	1	20.05	8.10	0.4040	
	332	2	2	20.20	5.30	0.2624	18.18
	333	3	3	20.20	5.15	0.2550	18.57
	334	4	4	20.10	5.20	0.2587	18.37
	335	5	5	20.05	5.05	0.2519	18.73
	336	6	6	20.00	4.90	0.2450	19.10
	337	7	7	20.00	5.00	0.2500	18.83
4.1	338	8	8	19.85	14.90	0.7506	
	339	9	9	19.90	5.00	0.2513	17.54
	340	10	10	19.90	5.05	0.2538	17.42
	341	11	11	19.90	5.15	0.2588	17.18
	342	12	12	19.90	5.15	0.2588	17.18
	343	13	13	19.90	5.20	0.2613	17.06
	344	14	14	19.95	5.30	0.2657	16.86
	345	15	15	19.90	5.30	0.2663	16.83
12.4	346	16	1	19.90	7.60	0.3819	
	347	17	2	19.95	5.40	0.2707	16.65
	348	18	3	20.00	5.45	0.2725	16.57
	349	19	4	20.00	5.70	0.2850	16.02
	350	20	5	20.10	5.80	0.2886	15.86
	351	21	6	20.15	5.75	0.2854	16.00
	352	22	7	20.20	5.80	0.2871	15.93
4.1	353	23	8	20.20	15.10	0.7475	
	354	24	9	20.30	6.25	0.3079	16.08
	355	25	10	20.40	6.40	0.3137	15.83
	356	26	11	20.40	6.45	0.3162	15.72
	357	27	12	20.50	6.60	0.3220	15.48
	358	28	13	20.50	6.80	0.3317	15.08
	359	29	14	20.60	6.85	0.3325	15.04
	400	30	15	20.60	7.05	0.3422	14.66
12.4	401	31	1	20.65	8.35	0.4044	
	402	32	2	20.80	7.25	0.3486	14.37
	403	33	3	20.85	7.40	0.3549	14.13
	404	34	4	20.95	7.60	0.3628	13.84
	405	35	5	21.00	7.80	0.3714	13.53
	406	36	6	21.00	7.95	0.3786	13.27
	407	37	7	21.05	8.10	0.3848	13.06

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SINGLE2

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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	CONC (PPB)
4.1	408	38	8	21.15	16.00	0.7565	
	409	39	9	21.20	8.30	0.3915	13.13
	410	40	10	21.35	8.60	0.4028	12.74
	411	41	11	21.40	8.70	0.4065	12.61
	412	42	12	21.40	8.80	0.4112	12.45
	413	43	13	21.55	8.90	0.4130	12.39
	414	44	14	21.55	9.05	0.4200	12.16
	415	45	15	21.60	9.10	0.4213	12.12
12.4	416	46	1	21.80	9.00	0.4128	
	417	47	2	21.80	9.35	0.4289	11.87
	418	48	3	21.90	9.60	0.4384	11.57
	419	49	4	21.95	9.55	0.4351	11.68
	420	50	5	22.00	9.70	0.4409	11.49
	421	51	6	22.05	9.95	0.4512	11.18
	422	52	7	22.15	10.05	0.4537	11.10
4.1	423	53	8	22.20	16.75	0.7545	
	424	54	9	22.25	10.25	0.4607	11.78
	425	55	10	22.40	10.60	0.4732	11.36
	426	56	11	22.40	10.80	0.4821	11.07
	427	57	12	22.45	10.90	0.4855	10.96
	428	58	13	22.55	11.00	0.4878	10.89
	429	59	14	22.55	11.20	0.4967	10.61
	430	60	15	22.60	11.35	0.5022	10.44
12.4	431	61	1	22.70	10.05	0.4427	
	432	62	2	22.80	11.75	0.5154	10.04
	433	63	3	22.85	12.00	0.5252	9.75
	434	64	4	22.90	12.00	0.5240	9.78
	435	65	5	22.95	12.10	0.5272	9.69
	436	66	6	23.00	12.15	0.5283	9.66
	437	67	7	23.00	12.25	0.5326	9.53
4.1	438	68	8	23.15	17.50	0.7559	
	439	69	9	23.15	12.55	0.5421	9.85
	440	70	10	23.20	12.50	0.5388	9.96
	441	71	11	23.25	12.65	0.5441	9.79
	442	72	12	23.30	13.00	0.5579	9.36
	443	73	13	23.35	13.05	0.5589	9.32
	444	74	14	23.30	13.20	0.5665	9.09
	445	75	15	23.40	13.40	0.5726	8.91

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SINGLE2

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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	CONC (PPB)
12.4	446	76	1	23.40	10.95	0.4679	
	447	77	2	23.50	13.30	0.5660	9.23
	448	78	3	23.50	13.55	0.5766	8.92
	449	79	4	23.60	13.55	0.5742	8.99
	450	80	5	23.60	13.65	0.5784	8.86
	451	81	6	23.65	13.85	0.5856	8.66
	452	82	7	23.70	14.00	0.5907	8.51
4.1	453	83	8	23.65	18.20	0.7696	

ROOM3

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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	ZONE	CONC (PPB)
12.4	1717	1	1	17.75	7.20	0.4056		
	1718	2	2	17.85	2.20	0.1232	1	33.05
	1719	3	3	17.95	7.80	0.4345	2	11.21
	1720	4	4	18.00	4.80	0.2667	3	19.67
	1721	5	5	18.05	5.00	0.2770	4	19.01
	1722	6	6	18.20	4.90	0.2692	5	19.50
	1723	7	7	18.20	4.80	0.2637	6	19.86
4.1	1724	8	8	18.25	11.95	0.6548		
	1725	9	9	18.25	5.85	0.3205	7	16.74
	1726	10	10	18.40	4.90	0.2663	8	20.02
	1727	11	11	18.45	6.20	0.3360	9	15.90
	1728	12	12	18.55	6.00	0.3235	10	16.57
	1729	13	13	18.60	6.40	0.3441	11	15.48
	1730	14	14	18.60	7.70	0.4140	12	12.21
	1731	15	0					
12.4	1732	16	1	18.80	7.70	0.4096		
	1733	17	2	18.80	6.60	0.3511	1	14.75
	1734	18	3	18.85	14.60	0.7745	2	2.68
	1735	19	4	19.00	7.60	0.4000	3	12.76
	1736	20	5	19.00	7.15	0.3763	4	13.69
	1737	21	6	19.15	7.90	0.4125	5	12.29
	1738	22	7	19.20	8.20	0.4271	6	11.76
4.1	1739	23	8	19.20	13.55	0.7057		
	1740	24	9	19.25	11.05	0.5740	7	7.47
	1741	25	10	19.40	10.60	0.5464	8	8.27
	1742	26	11	19.40	11.50	0.5928	9	6.94
	1743	27	12	19.50	11.30	0.5795	10	7.31
	1744	28	13	19.60	10.30	0.5255	11	8.91
	1745	29	14	19.60	12.30	0.6276	12	6.01
	1746	30	0					
12.4	1747	31	1	19.80	8.40	0.4242		
	1748	32	2	19.90	11.45	0.5754	1	7.81
	1749	33	3	20.00	17.10	0.8550	2	1.84
	1750	34	4	20.00	11.65	0.5825	3	7.62
	1751	35	5	20.50	11.75	0.5732	4	7.86
	1752	36	6	20.20	12.90	0.6386	5	6.24
	1753	37	7	20.20	12.60	0.6238	6	6.59

(CONTINUED)

ROOM3

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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	ZONE	CONC (PPB)
4.1	1754	38	8	20.25	14.90	0.7358		
	1755	39	9	20.40	15.20	0.7451	7	3.91
	1756	40	10	20.40	14.95	0.7328	8	4.16
	1757	41	11	20.50	15.45	0.7537	9	3.73
	1758	42	12	20.60	15.45	0.7500	10	3.80
	1759	43	13	20.60	14.85	0.7209	11	4.42
	1800	44	14	20.60	15.80	0.7670	12	3.46
	1801	45	15	20.60	15.50	0.7524	13	3.75
12.4	1802	46	1	20.80	8.95	0.4303		
	1803	47	2	20.85	15.75	0.7554	1	3.97
	1804	48	3	20.95	19.00	0.9069	2	1.23
	1805	49	4	21.00	15.65	0.7452	3	4.17
	1806	50	5	21.00	16.00	0.7619	4	3.84
	1807	51	6	21.05	16.80	0.7981	5	3.14
	1808	52	7	21.10	15.00	0.7109	6	4.88
4.1	1809	53	8	21.10	15.80	0.7488		
	1810	54	9	21.20	17.90	0.8443	7	2.21
	1811	55	10	21.25	17.75	0.8353	8	2.38
	1812	56	11	21.25	18.20	0.8565	9	1.99
	1813	57	12	21.35	18.20	0.8525	10	2.06
	1814	58	13	21.40	17.85	0.8341	11	2.40
	1815	59	14	21.40	18.50	0.8645	12	1.84
	1816	60	15	21.40	18.40	0.8598	13	1.92
12.4	1817	61	1	21.50	9.50	0.4419		

SINGLE3
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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	CONC (PPB)
12.4	1907	1	1	18.05	5.90	0.3269	
	1908	2	2	18.15	4.20	0.2314	16.09
	1909	3	3	18.15	4.20	0.2314	16.09
	1910	4	4	18.20	4.30	0.2363	15.87
	1911	5	5	18.20	4.55	0.2500	15.27
	1912	6	6	18.20	4.65	0.2555	15.03
	1913	7	7	18.20	5.05	0.2775	14.15
4.1	1914	8	8	18.15	12.90	0.7107	
	1915	9	9	18.25	5.70	0.3123	13.21
	1916	10	10	18.30	5.70	0.3115	13.24
	1917	11	11	18.40	6.15	0.3342	12.46
	1918	12	12	18.40	6.55	0.3560	11.76
	1919	13	13	18.50	6.75	0.3649	11.49
	1920	14	14	18.50	6.90	0.3730	11.24
	1921	15	15	18.60	7.30	0.3925	10.68
12.4	1922	16	1	18.60	6.25	0.3360	
	1923	17	2	18.65	7.90	0.4236	9.85
	1924	18	3	18.80	8.45	0.4495	9.19
	1925	19	4	18.85	8.80	0.4668	8.78
	1926	20	5	18.90	9.20	0.4868	8.32
	1927	21	6	19.00	9.50	0.5000	8.02
	1928	22	7	19.00	9.90	0.5211	7.57
4.1	1929	23	8	19.05	13.60	0.7139	
	1930	24	9	19.20	10.45	0.5443	7.49
	1931	25	10	19.20	10.80	0.5625	7.08
	1932	26	11	19.25	11.00	0.5714	6.88
	1933	27	12	19.40	11.40	0.5876	6.53
	1934	28	13	19.40	11.60	0.5979	6.31
	1935	29	14	19.50	11.90	0.6103	6.06
	1936	30	15	19.40	12.15	0.6263	5.74
12.4	1937	31	1	19.60	7.20	0.3673	
	1938	32	2	19.75	12.85	0.6506	5.28
	1939	33	3	19.80	13.10	0.6616	5.07
	1940	34	4	19.80	13.35	0.6742	4.83
	1941	35	5	19.90	13.60	0.6834	4.66
	1942	36	6	19.95	14.00	0.7018	4.33
	1943	37	7	20.00	14.30	0.7150	4.10

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SINGLE3
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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	CONC (PPB)
4.1	1944	38	8	20.00	14.30	0.7150	
	1945	39	9	20.05	14.80	0.7382	3.67
	1946	40	10	20.20	15.00	0.7426	3.59
	1947	41	11	20.20	15.15	0.7500	3.45
	1948	42	12	20.35	15.45	0.7592	3.28
	1949	43	13	20.40	15.60	0.7647	3.19
	1950	44	14	20.40	15.85	0.7770	2.97
	1951	45	15	20.40	16.05	0.7868	2.80
12.4	1952	46	1	20.60	8.00	0.3883	

ROOM4
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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	ZONE	CONC (PPB)
12.4	2025	1	1	20.05	7.15	0.3566		
	2026	2	2	20.05	7.15	0.3566	1	12.40
	2027	3	3	20.00	8.10	0.4050	2	10.83
	2028	4	4	20.00	8.00	0.4000	3	10.98
	2029	5	5	20.00	8.00	0.4000	4	10.98
	2030	6	6	20.00	7.65	0.3825	5	11.53
	2031	7	7	20.05	7.95	0.3965	6	11.09
4.1	2032	8	8	20.05	14.00	0.6983		
	2033	9	9	20.05	7.95	0.3965	7	11.01
	2034	10	10	20.10	7.65	0.3806	8	11.51
	2035	11	11	20.20	8.20	0.4059	9	10.72
	2036	12	12	20.20	8.30	0.4109	10	10.57
	2037	13	13	20.20	13.60	0.6733	11	4.55
	2038	14	14	20.20	8.80	0.4356	12	9.86
	2039	15	15	20.20	8.55	0.4233	13	10.21
12.4	2040	16	1	20.35	7.20	0.3538		
	2041	17	2	20.40	8.75	0.4289	1	10.08
	2042	18	3	20.40	10.00	0.4902	2	8.47
	2043	19	4	20.50	8.85	0.4317	3	10.00
	2044	20	5	20.60	8.90	0.4320	4	9.99
	2045	21	6	20.60	9.50	0.4612	5	9.20
	2046	22	7	20.70	9.15	0.4420	6	9.72
4.1	2047	23	8	20.80	14.65	0.7043		
	2048	24	9	20.95	10.00	0.4773	7	9.41
	2049	25	10	21.00	9.90	0.4714	8	9.58
	2050	26	11	21.00	10.30	0.4905	9	9.03
	2051	27	12	21.20	10.60	0.5000	10	8.77
	2052	28	13	21.20	15.50	0.7311	11	3.59
	2053	29	14	21.20	10.80	0.5094	12	8.52
	2054	30	0					
12.4	2055	31	1	21.40	8.20	0.3832		
	2056	32	2	21.40	11.20	0.5234	1	8.28
	2057	33	3	21.45	12.35	0.5758	2	7.02
	2058	34	4	21.60	11.10	0.5139	3	8.53
	2059	35	5	21.60	11.00	0.5093	4	8.64
	2100	36	6	21.75	11.55	0.5310	5	8.09
	2101	37	7	21.80	11.40	0.5229	6	8.30

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ROOM4

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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	ZONE	CONC (PPB)
4.1	2102	38	8	21.85	15.70	0.7185		
	2103	39	9	21.95	12.00	0.5467	7	8.08
	2104	40	10	22.00	11.90	0.5409	8	8.23
	2105	41	11	22.05	12.50	0.5669	9	7.55
	2106	42	12	22.20	12.75	0.5743	10	7.36
	2107	43	13	22.20	14.00	0.6306	11	6.00
	2108	44	14	22.20	12.85	0.5788	12	7.25
	2109	45	15	22.20	12.80	0.5766	13	7.30
12.4	2110	46	1	22.40	9.10	0.4063		
	2111	47	2	22.40	12.85	0.5737	1	7.48
	2112	48	3	22.50	14.10	0.6267	2	6.23
	2113	49	4	22.60	12.95	0.5730	3	7.50
	2114	50	5	22.60	12.80	0.5664	4	7.67
	2115	51	6	22.65	13.60	0.6004	5	6.84
	2116	52	7	22.70	13.45	0.5925	6	7.02
4.1	2117	53	8	22.75	16.55	0.7275		
	2118	54	9	22.80	14.10	0.6184	7	6.54
	2119	55	10	22.85	14.00	0.6127	8	6.68
	2120	56	11	22.90	14.40	0.6288	9	6.29
	2121	57	12	22.95	14.50	0.6318	10	6.22
	2122	58	13	23.00	15.40	0.6696	11	5.35
	2123	59	14	23.00	14.75	0.6413	12	6.00
	2124	60	15	23.00	14.50	0.6304	13	6.26
12.4	2125	61	1	23.15	9.70	0.4190		

SINGLE4
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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	CONC (PPB)
12.4	2259	1	1	20.20	6.75	0.3342	
	2300	2	2	20.20	6.20	0.3069	13.40
	2301	3	3	20.15	6.00	0.2978	13.75
	2302	4	4	20.10	5.85	0.2910	14.02
	2303	5	5	20.05	6.10	0.3042	13.50
	2304	6	6	20.00	6.00	0.3000	13.66
	2305	7	7	20.00	6.00	0.3000	13.66
4.1	2306	8	8	20.00	13.60	0.6800	
	2307	9	9	20.00	6.00	0.3000	13.87
	2308	10	10	20.00	6.20	0.3100	13.47
	2309	11	11	20.00	6.15	0.3075	13.57
	2310	12	12	20.00	6.20	0.3100	13.47
	2311	13	13	20.05	6.40	0.3192	13.13
	2312	14	14	20.10	6.40	0.3184	13.16
	2313	15	15	20.10	6.50	0.3234	12.97
12.4	2314	16	1	20.05	6.80	0.3392	
			99				
	2315	17	3	20.20	6.70	0.3317	12.66
	2316	18	4	20.30	6.85	0.3374	12.46
	2317	19	5	20.35	7.10	0.3489	12.07
	2318	20	6	20.40	7.00	0.3431	12.27
	2319	21	7	20.40	7.20	0.3529	11.94
4.1	2320	22	8	20.45	14.20	0.6944	
	2321	23	9	20.50	7.60	0.3707	12.01
	2322	24	10	20.60	7.70	0.3738	11.91
	2323	25	11	20.65	7.75	0.3753	11.86
	2324	26	12	20.80	8.00	0.3846	11.55
	2325	27	13	20.80	8.05	0.3870	11.47
	2326	28	14	20.80	8.20	0.3942	11.24
	2327	29	15	20.80	8.25	0.3966	11.16
12.4	2328	30	1	21.00	7.55	0.3595	
	2329	31	2	21.00	8.55	0.4071	10.87
	2330	32	3	21.05	8.60	0.4086	10.82
	2331	33	4	21.20	8.60	0.4057	10.91
	2332	34	5	21.20	8.95	0.4222	10.42
	2333	35	6	21.30	9.10	0.4272	10.28
	2334	36	7	21.40	9.10	0.4252	10.33

(CONTINUED)

SINGLE4

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CAL (PPB)	TIME	MIN	CNT	SC (MV)	PH (MV)	RATIO PH/SC	CONC (PPB)
4.1	2335	37	8	21.40	15.10	0.7056	
	2336	38	9	21.40	9.30	0.4346	10.62
	2337	39	10	21.50	9.60	0.4465	10.26
	2338	40	11	21.60	9.70	0.4491	10.18
	2339	41	12	21.60	9.80	0.4537	10.04
	2340	42	13	21.70	10.15	0.4677	9.63
	2341	43	14	21.80	10.15	0.4656	9.69
	2342	44	15	21.80	10.10	0.4633	9.76
12.4	2343	45	1	21.80	8.30	0.3807	
	2344	46	0				
	2345	47	3	22.00	10.60	0.4818	9.25
	2346	48	4	22.05	10.60	0.4807	9.28
	2347	49	5	22.20	10.65	0.4797	9.31
	2348	50	6	22.20	10.95	0.4932	8.94
	2349	51	7	22.25	11.10	0.4989	8.79
4.1	2350	52	8	22.30	15.80	0.7085	