Paper B.4.

Determination of Combined Air Exfiltration and Ventilation Rates in a Nine-Story Office Building

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Introduction

In the course of retrofitting a building for energy conservation, it is usually necessary to establish the conditions prior to beginning the alterations. The extent of this determination depends upon the detail to which one wants to analyze the results. For instance, records of energy bills before and after the retrofit can be used to identify the magnitude of the energy savings but are not likely to indicate the magnitude of savings as a result of any particular conservation step. At the other extreme, complete submetering of each energy system and an establishment of the existing comfort conditions in the building are required. This latter determination is necessary so that if the energy savings are due in part to making the space less comfortable (which requires virtually no engineering innovation), this may be duly noted.

The intent of the project discussed in this paper was to establish this complete energy and comfort record for a typical multistory office building prior to the start of a retrofit program. Establishing these conditions required that measurements be made of the air infiltration that occurred in the building. Measurements had to be made in the air handling system as well as at other places inside the building. The measurements in the air handling system included the total, velocity, and static head pressure which could be used to compute air flow rates through the use of traditional techniques. In addition, the tracer gas technique was utilized simultaneously (during the same day) so that it was possible to make a comparison between the two methods. The specific tracer gas used was sulfur hexafluoride (SF_6) and the apparatus included a small gas chromatograph with an electron capture detector plus other accessories[1/] Similar apparatuses have been used to determine air leakage rates in several houses and smaller structures with considerable success[2,3,4,5/]. However they have not, to our knowledge, been used to measure air leakage rates of an occupied high rise office building.

This study cannot be cited as conclusive proof that either of the techniques are absolutely correct; however, it will be shown that there is excellent agreement between them. Considering that the two methods are based on completely different physical principles, it does give some confidence that either the direct method or the tracer gas method can be used to estimate a building's air exchange with its surroundings.

Description of Test Building

The nine story, square cross-sectional Union Plaza building, which was occupied by the Federal Power Commission in July, 1973, is located in downtown Washington, D.C. Exterior dimensions of the building are 57.6m (189 ft) x 57.6m (189 ft) x 28.3m (93 ft). The exterior walls of floors three through nine consist of precast concrete panels with exposed aggregate backed by batt insulation with 1.3 cm (1/2 in.) gypsum board on the inside. The windows are single pane of grey plate-glass, mounted in aluminum frames and sealed. Floors one and two have a mixture of store-front glass and face brick.

The first floor is below street level, but there is adequate space around the base of the building to provide entranceways on all sides including a service entrance and loading dock. The only other openings in the building are located on the roof, as shown in Figure 1. These include the elevator shaft vents, record lift shaft vent, toilet exhausts, door from west stairwell to penthouse, and first floor kitchen exhaust hood vent.

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The core and perimeter zones of floors two through nine, which have approximately 27% glass relative to the exterior facing, are serviced by the main variable air volume system. Two air handling units, each rated at 49.1 m^3/s (104,100 cfm), are located in the first-floor air handling room. One supplies air to the north riser and the other to the south riser. On each floor, the supply ducts from each of the two risers join together at the end of their runs. The air-handler room acts as a plenum.

Air which is drawn through the ceiling of each floor returns to the air handler room via the masonry duct shafts in the space not occupied by supply air risers. A maximum of 21.2 m^3/s (45,000 cfm) of outside air may be introduced into the air handler room through first-floor level air louvers connecting to the mechanical room, which has air inlet dampers to the outside. The first floor, which has a lobby, snack bar, kitchen, cafeteria, liquor store, bank and information center is supplied with air from a separate air handling unit independent of the main system.

Infiltration Rates by Tracer Gas Technique

In the measurement of air infiltration by the tracer dilution method, a tracer gas is distributed throughout a building, and the decay in concentration is measured as a function of time. The theory of the method can be briefly outlined by considering the governing equation for the uniform concentration of a tracer gas in air as a function of time:

$$\frac{dC_i}{dt} = (C_o - C_i)\frac{v}{V} \qquad (1)$$

where C_o and C_i are respectively the outside and inside concentrations of tracer at time t. v is the rate at which air enters the building. It is also the rate at which air leaves the building unless there is a buildup or loss of pressure. V is the ventilated volume of the building, and v/V is the air-infiltration rate per unit time. By proper selection of units, v/V has the units of air changes per hour.

If the outside concentration of tracer is small enough nto be neglected, equation (1) can be reduced to:

$$\frac{dC_i}{dt} = -C_i\frac{v}{V} \qquad (2)$$

Equation (2) can be integrated to give:

$$v/V = -\frac{1}{t}\ln\,(C_i/C_io) \qquad (3)$$

where C_{io} is the initial indoor concentration of tracer. Equuations (2) and (3) have the form of the radioactive decay law or the equation of the well mixed tank. Equation (3) can be solved directly using specific values of the variables on the right hand side; however, when manual calculation is performed it is common practice to plot $\ln\frac{C_i}{C_{io}}$ against t and calculate the infiltration rate from the slope of the line. It should also be noted that it is not necessary to know absolute tracer concentrations to calculate infiltration rates since relative concentrations, C_i/C_{io}, are all that are needed.

Concentrations of SF_6 in air were measured with a small gas chromatrograph equipped with a pulse-mode electron capture detector. Sampling points are shown by number in Figure 2 which is an abridged diagram of the air handling units in the building and their associated space. Sulfur hexafluoride was metered into one of the fans at point A indicated in the Figure, and concentrations of the gas were monitored downstream at point 1 in the supply duct. Spot checks were also made at the other sampling points to determine tracer uniformity. In one series of tests, samples were taken from the corridors on floors two through nine as a further check on uniformity.

To determine infiltration rates, the SF_6 level was built up to a suitable level (usually about 20 ppb) allowing 15 minutes or longer to reach steady state conditions. Samples were then taken at timed intervals from point 1 and analyzed.

Figure 3 shows typical plots of relative concentration vs. time from which the total air exchange rates were calculated. These exchange rates were measured on two different days with the outside air vents closed, and with the outside air vents open, respectively. The calculated infiltration rates are indicated beside the respective plots.

Air Exchange Rates by Direct Measurement and Calculation Technique

The second, independent technique for determining the total air exchange rates involved a combination of measuring and calculating exhaust rates for the building. It was assumed that quasi-steady state conditions existed and that total air leaving the building equaled that incoming.

The building was well suited for determining exhaust rates. As described above, entrances to the building are located only on the first floor, the windows cannot be opened, and all vents associated with the main air handling system serving floors two through nine as well as the exhaust openings are located directly on the roof or in the penthouse.

There are the vents for the elevator shafts, the record lift vent, exhausts from the mens' and womens' toilets, and the door opening to the penthouse from the west stairwell. The exhaust from the first floor kitchen was not considered associated with the main air handling system. Further, direct measurement of pressure difference across exterior walls of the building indicated that floors two through nine were always slightly pressurized by the main air handling units. Thus, exfiltration could occur through the external walls and down from the second floor to the first floor. This is indicted conceptually in Figure 1.

To determine the exfiltration rates through outside air vents, air flow rates through the roof vents and exhaust units were determined from velocity measurements made with a vane anemometer. The flow rates through the walls of floors two through nine, and from the second to the first floor were calculated. The values of the two components were added to obtain the total exfiltration rates. The results are presented in Table 1 for two different conditions, outside air vents closed and open.

All of the exhaust system velocities were measured with a vane anemometer at the roof vent location. Each vent has a grill similar to that on the record lift vent located on the north side of the penthouse. The flow rate through any grill is:

$Q = A\bar{V}\eta\beta\,[m^3/s]$

A = vent area (grill off) $[m^2]$

$\bar{V}$ = average velocity across the face of the vent within the grill $[m/s]$

η = ratio of $\bar{V}$ with grill on to $\bar{V}$ with grill off

β = ratio of $\bar{V}$ based on long periods of operation to $\bar{V}$ based on short tests.

The procedure for the elevator vents only was to measure $\bar{V}$ for each vent with the grill off; because the grill slats made the exit flow patterns quite distorted. While the main elevators and record lift were operating, $\bar{V}$ was determined as the average of five readings taken with a vane anemometer over the face of each vent for one minute periods. The air flow through the record lift vent could be read from inside or outside the grill, i.e., inside or outside the penthouse. Thus, after finding $\bar{V}$ for the record lift without its grill by measuring from the outside, the grill was put in place and the readings repeated from inside the penthouse. The ratio of the two average readings was 0.528, which was considered the same for all vents since all grills were of the same configuration. It was found that $\bar{V}$ determined over long periods was slightly less than that for one minute periods. This was because of the unsteady flow conditions due to the somewhat random operating cycle of the elevators. Several longer tests were made and it was determined that $\bar{V}$ based on one minute test periods could be corrected satisfactorily by the factor $\beta = 0.80$. The procedure for the toilet exhausts was to measure the flow with the grill in place because it was a simple screen and the flow pattern was regular. The η value was therefore 1.

The leakage rate through the exterior walls of a building, Q in m^3/s, was calculated from:

$$Q = q\,A$$

where

q = leakage rate per unit area $m^3/(s \cdot m^2)$, depends on the wall construction (porosity) and the pressure difference, ΔP across the wall.

A = total exterior wall area m^2

In general little is known about determining q theoretically for conventional or contemporary building construction. Usually q must be determined experimentally. Fortunately, some tests were carried out in Canada on buildings similar in construction to the FPC building, and the results were reported by Shaw, et al[6] It was found that the leakage rates for the walls of these type buildings are approximately the same as those tabulated in the ASHRAE Handbook of Fundamentals[7] for 13-inch plain brick wall. To use this data, ΔP across the wall must be known. Therefore, measurements were made across the four walls of the FPC building using a sensitive pressure transducer. The measurements were made at the second floor level and at the ninth floor level, for the two cases, outside air vents closed and outside air vents open. The pressure inside the building was always higher than outside the building.

To determine q from the ASHRAE data, average values of ΔP from the second and ninth floor data were used. Thus,

With outside air vents closed:

$$\Delta P = 6.97 \text{ Pa } (0.028 \text{ inch } H_2O)$$

$$q = 2.8 \times 10^{-4} \text{ m}^3/(\text{s} \cdot \text{m}^2)(3.3 \text{ ft}^3/(\text{h} \cdot \text{ft}^2))$$

With outside air vents open:

$$\Delta P = 27.4 \text{ Pa } (0.11 \text{ inch } H_2O)$$

$$q = 7.3 \times 10^{-4} \text{ m}^3/(\text{s} \cdot \text{m}^2)(8.6 \text{ ft}^3/(\text{h} \cdot \text{ft}^2))$$

During the days these tests were run the wind velocity averaged <5 MPH and the temperature differences between the interior and exterior was <5°F. It would be reasonable to expect higher air exchange rates than determined here under more severe weather conditions.

The second story floor construction was such that a porosity value one-half that of the exterior wall was assumed. The roof was assumed airtight.

Final Results and Conclusions

The summary results of using both the tracer gas and direct measurement technique are listed in Table 2. The tracer gas results were directly in terms of air changes per hour; however, the direct measurement results were not and it was necessary to estimate the total unoccupied volume (net air space) of the building. This net volume determination was made by taking the difference between the total volume indicated from the architectural drawings and the volume occupied by the furniture, etc., which was approximately 15%. The occupied volume was estimated from physical measurements in a typical office. The net volume was then divided into the total air flow leaving the building to obtain the figures listed in Table 2.

Since the direct measurements employed a vane anemometer, it can be assumed that the absolute accuracy of these measurements may be in error by 10%. The tracer gas technique is estimated to have a standard deviation of .07 but a standard error of mean of only .03 air changes per hour, based on experience in other applications.

It is regarded as somewhat fortuitous that the differences between the two measurement methods was only about 3% with the fresh air vents at minimum and 6% with the fresh air vents at maximum considering the typical error of many of the measurement techniques used the necessity for estimating some components of the air exchange. However, there were a number of factors in this particular experiment which tended to reduce the errors in determining total air exchange.

The fundamental criteria for the tracer gas technique to be accurate is good mixing and good sampling. This building was ventilated by two fans within supply and return ducts which were interconnected on every floor. This in effect, made the entire building a single zone ventilation system. This effect was verified by noting that upon injection of the tracer in the supply fan at point A of Figure 2, detection of almost equal amounts was indicated at positions 4 and 3 at the same time. Also once the gas supply was shut off, the decay rates at any of the measurement stations were the same. A second factor which made this test environment ideal was the weather. With low wind speeds, small interior/exterior temperature differences, and a continuously positive pressurized building, the variations due to stack effect, etc., within the building were minimal. It was thus possible to obtain good sampling from the equipment room alone with only spot checks on the second and ninth floors to assure uniformity. Applications where building and weather conditions deviate from those found here may require considerably more effort and/or may result in considerably less accuracy.

Two observations concerning this specific building were that (1) the overall air system was not balanced (positive pressure condition) and (2) a significant portion of conditioned air was being pumped out the elevator vents. This latter condition indicates that there would be good potential for energy conservation through either using thermal recovery from the exhaust or by recycling of the air itself.

References

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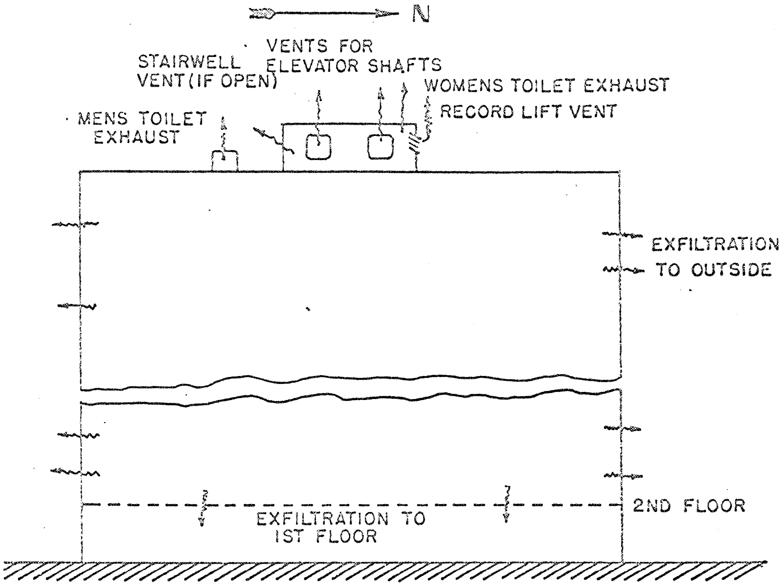

FIGURE 1

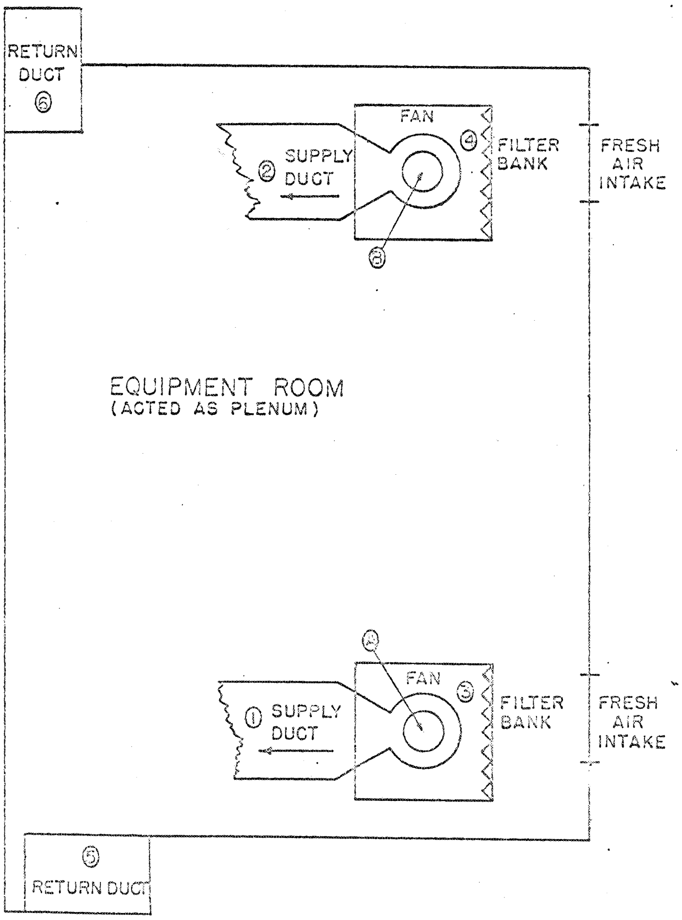

FIGURE 2

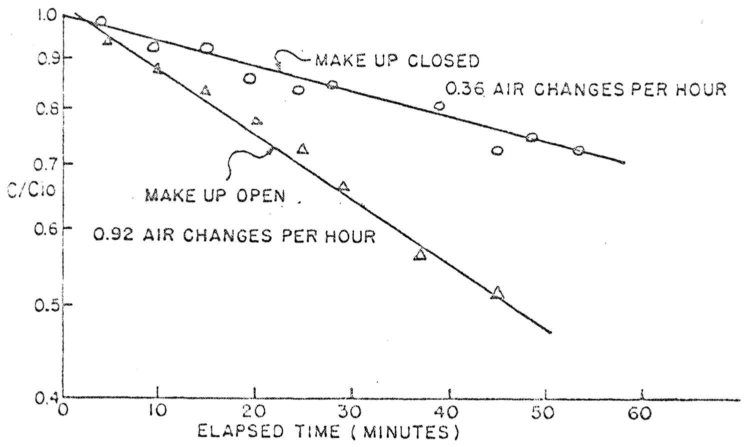

FIGURE 3

Table 1

RESULTS OF DIRECT METHOD DETERMINATION OF AIR EXCHANGE

	Air Flow Rate					
	Outside Air Vents Closed			Outside Air Vents Open		
	m^3/s	cfm	% Total	m^3/s	cfm	% Total
4 Elevator Vents	1.5	3100	22	4.7	10000	29
Toilet Exhausts	3.1	6500	46^+	3.8	8000	24
Stairwell to Penthouse	0	0		2.5	5200	14^+
1st/2nd Floor Exch.	0.47	1000	7	1.2	2600	7^+
Exterior Wall Leakage*	1.7	3500	24^+	4.2	9000	25^+
	6.7	14100	99^+	16.4	34800	99^+
*Pressure Difference Between Interior and Exterior	6.97 Pa (.028"H_2O)			27.4 Pa(.11"H_2O)		

+Implies a fraction of 1% greater than.

Table 2

RESULTS OF AIR EXCHANGE MEASUREMENTS

AIR EXCHANGE RATES, hr^{-1}

	TRADITIONAL METHOD	TRACER GAS METHOD
OUTSIDE AIR VENTS CLOSED	.35	.36
OUTSIDE AIR VENTS OPEN	.87	.92

DISCUSSION

Paper B.4. Kelnhofer, Hunt and Didion, "Determination of Combined Air Exfiltration and Ventilation Rates in a Nine-Story Office Building"

Ralph Torborg

Please comment on other tracer gases (such as methane). How do they (methane) compare to SF_6?

David Didion - Response

The only simultaneous comparison we have made of different tracer gases was between SF_6 with molecular weight of 136 and He with a molecular weight of 4 (C. M. Hunt and D. M. Burch, ASHRAE Transactions 81, Part I, 186-201, 1975). This comparison was performed in a 4-bedroom townhouse. The He results averaged slightly lower than those obtained with SF_6. The purpose of the comparison was to determine if He disappeared faster than SF_6 because of its faster diffusion rate. This effect was not observed.

Other gases have been used as tracers such as: ethane (R. H. Elkins and C. W. Wensman, paper presented at Institute of Gas Technology Conference on Natural Gas Research and Technology, Chicago, Illinois, March 3, 1971); nitrous oxide (O. M. Lidwell, *J. Hygiene* 58, pp. 297-305, 1960); carbon dioxide (J. E. Hill and T. Kusuda, ASHRAE Transactions 81, Part I, pp. 168-185, 1975); and carbon monoxide (R. Prado, R. G. Leonard, and V. W. Goldschmidt, Purdue University Report). There are also additional gases which might be used as tracers, but we are unaware of any simultaneous comparison of different gases other than the one cited.

Charles Erlandson

Was the positive pressure of .028" constant on all floors? Did you take readings at higher wind velocities?

David Didion - Response

Pressure differences across the outer walls were measured on the second and ninth floors only, and for practical purposes they did not vary from each other. Readings at higher wind velocities were not taken.

Preston McNall

Could the OA be measured directly? If so, OA-exhaust air equals infiltration (or exfiltration) and could be a check on the calculated exfiltration.

David Didion - Response

A pitot-static tube traverse in the outside air ducts could have been used to determine outside air rate with the outside air vents open. This was not done because of time limitations. However, your suggestion is well taken and appreciated.

In response to this question the authors' curiosity was sufficiently aroused to cause them to return to the building to obtain an outside air quantity measurement. Considering that it was almost two years since the other measurements and that institutional constraints disallowed a proper pitot traverse, the measurement could only be very approximate. The only convenient place to use a vaned anemometer was at the exit planes of the outside air ducts as they entered the fan room. Unfortunately the dampers are also at this plane and the airflow correction factors for such dampers is unknown. However, assuming a correction factor of .8 the total air flow was determined to be about 37000 cfm for the dampers in the fully open position.

John Palmer

Was any attempt made to evaluate change in elevator shaft openings in relation to outside air vents being opened and closed?

David Didion - Response

The elevator shaft vents for the building are of fixed geometry and always open. If the exfiltration from these vents could be reduced or eliminated, a substantial savings would result.