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METHOD FOR ASCERTAINING SMOKE LEAKAGE THROUGH SMALL OPENINGS USING TRACER GAS

T. Yamada, Dr.Eng.

ABSTRACT

Smoke leakage through openings concealed behind ceilings and/or walls can create confusion and therefore a hazard that can threaten occupants in case of a building fire. This kind of small opening, which is the result of defective construction work and/or aging, cannot be found easily after the completion of a building. This paper presents a method for estimating the effective areas of these openings, as well as the smoke leakage rates, by measuring air infiltration rates of buildings with SF_6 tracer gas.

Two test series, consisting of a total of 11 full-scale experiments, were conducted to determine the degree of accuracy of this prediction method. Smoke leakage rates estimated from tracer gas concentrations and ventilation rates agree well with experimental data measured by an orifice flowmeter. The maximum error is about 20%. However, rapid concentration change and its non-homogeneity in the fire room immediately after purging tracer gas increase the degree of error.

INTRODUCTION

In Japan, a little less than half the deaths in fires are reported to be the result of smoke inhalation (FDA 1988). However, many victims seem to be trapped by thinner smoke in the early stage of a fire and spend much time struggling to escape before dying. As pointed out by Jin and Yamada (1988), evacuees lost visibility and mobility in relatively thin smoke (an extinction coefficient of $Cs \leq 1.0$ m^{-1}) before carbon monoxide (CO) concentration reached a dangerous level.

Many smoke problems in Japan are the result of smoke infiltration through unexpected openings, such as unused air ducts, unplugged piping shaft, etc., as well as staircases. Small openings, which are consequences of defective construction work and/or aging, cannot be found easily after completion of a building. Unanticipated smoke leakage through these openings creates confusion among evacuees. In addition, these openings constitute an even greater danger when they permit the spread of fire into other parts of a building.

Many efforts to predict smoke movement in fires have been made in the past and continue now. However, no mathematical model can predict smoke spread without knowing the size and locations of such openings. Mathematical models–zone models, for example–are powerful prediction tools for designers and engineers involved in the planning of new buildings, but they do not always adequately address the problem of smoke propagation in existing buildings. For this reason, we need some other experimental method to get the boundary conditions for predicting smoke propagation in more practical situations.

One study concerned with this problem was conducted by Fung and Zile (1975). They tried to predict the possibility of smoke propagation in an existing building using SF_6 tracer gas. However, the results are limited to the character of the building they studied and are not expandable to a general method of prediction. This paper presents a method for estimating such smoke leakage rates and the openings, which applies a method for measuring the rate of air infiltration in a building using SF_6 tracer gas and provides a basis for the practical inspection of existing and future buildings.

ESTIMATION METHOD OF SMOKE LEAKAGE AND AREA OF OPENING

Estimation of infiltration through openings has been investigated in the field of building physics (Kamata et al. 1983; Yoshino et al. 1983; Sherman et al. 1979). The principal interest of those studies was the ventilation rate between the inside and outside of the building from the viewpoint of energy saving. However, almost the same method is applicable to smoke leakage between rooms inside a building.

When effective areas of openings between rooms are known, the smoke leakage rate can be obtained by the following simple equation. For simplification, locations of openings, especially their heights, are not considered.

$$\dot{Q} = \alpha A \left[\frac{2\Delta P}{\rho} \right]^{1/n} \tag{1}$$

where

$\dot{Q}$ = volumetric leak rate (m^3/s)
n = nondimensional value that varies from 1.6 to 2.0 depending upon the opening character and passing flow rate; 2.0 is commonly used when the pressure difference is relatively large (≥ 45 Pa [= 0.18 in. Aq.]) and/or the opening area is large
α = opening coefficient
A = area of opening (m^2)
ΔP = pressure difference across the opening between rooms (Pa)
ρ = density of fluid (kg/m^3)

The difference between normal ventilation and smoke leakage is the magnitude of the pressure difference. Compared with normal ventilation, the pressure difference in the

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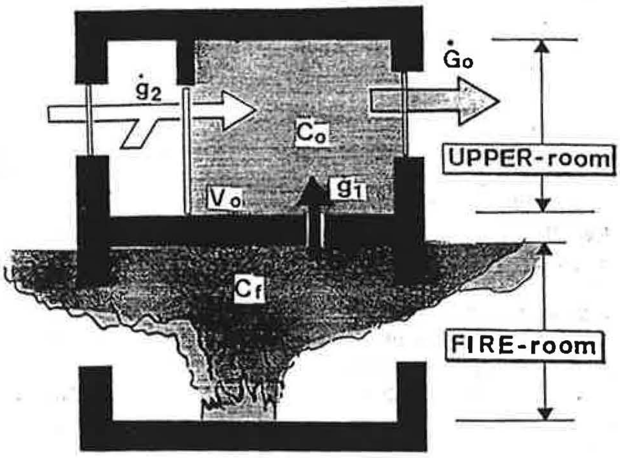
Tokiyoshi Yamada is a Research Member in the Fire Research Institute of the Fire Defense Agency, Ministry of Home Affairs, Tokyo, Japan.

case of fire is larger, so even a small opening cannot be neglected.

To obtain the αA value, the values of both Q and P are required. Once αA is known, the smoke leakage rate through the opening under certain fire conditions can be predicted with mathematical models. To get the smaller αA, we had to produce more pressure difference or take much time to measure Q under a lower pressure difference. However, the latter is not practical, since the surrounding conditions vary, especially wind, and lengthy exclusive possession for testing is inconvenient for the tenants of the building.

To simplify the situation, we consider the case shown in Figure 1. Smoke leaks through openings from the lower fire room to the room directly above and gradually contaminates the air in the upper room. (Here we express these rooms as FIRE-room and UPPER-room.) The smoke leakage can be estimated easily with the mass conservation equation (Equation 2) given the concentration of smoke and ventilation rate, provided the following quasi-steady-state conditions are satisfied: (1) smoke concentration distribution in the upper room is uniform, (2) change of density due to temperature rise is negligible, (3) smoke leaks only from assumed FIRE-room to the UPPER-room and does not turn back and/or come from other routes, i.e., corridor, stairwell, etc., and, as a preferable condition for assessing the experimental prediction method, (4) leak and ventilation rate are quasi-steady.



$$\overline{\dot{g}_1(t)} \fallingdotseq \frac{\{C_o(t) - C_o(t_o)\} V_o + \int_{t_o}^{t} C_o(t)\, \dot{G}_o(t) dt}{\int_{t_o}^{t} C_f(t)\, dt}$$

Nomenclature

C—smoke concentration
$\dot{G}_o$—ventilation outflow
$\dot{g}_1$—smoke leakage
$\dot{g}_2$—fresh air inflow $(=G - g_1)$
V_o—room volume

suffix
o ···· UPPER room
f ···· FIRE room
$\overline{}$ ···· $t - t_o$ time average

Figure 1 *Schema of smoke leakage model: Buoyant fire smoke leaks out from a FIRE-room to an UPPER-room through small openings, and air in the UPPER-room is gradually contaminated by smoke with fresh air ventilation*

The conditions mentioned above are not the same as those that occur in a real fire, even in the early stage. However, it is not necessary to duplicate the fire condition to determine αA for the opening.

The mass conservation equation in the UPPER-room is:

$$\overline{\dot{g}_1}(t) = \frac{\{ Co(t) - Co(t_0) \} V_o + \int_{t_0}^{t} Co(t)\, \dot{G}o(t)\, dt}{\int_{t_0}^{t} Co(t)\, dt} \tag{2}$$

where

$\dot{g}_1(t)$ = mean leak rate during time t_0 to t (m^3/min)
$C(t)$ = smoke or tracer gas concentration at time t (volume %)
$\dot{G}(t)$ = ventilation rate at time t (m^3/min)
V = room volume (m^3) (note: weight unit is also available for $\dot{g}_1$, C, and $\dot{G}$ instead of volumetric unit)
o = observation UPPER-room (2 FL)
f = FIRE-room (1 FL)
0 = basic time point.

In practical estimation methods for leakage, certain tracer gases (SF_6 in this study) can be used instead of smoke, and the αA can be obtained from Equations 1 and 2 when the pressure difference between rooms is measured. In this paper, the first priority is to assess the degree of accuracy of the smoke leakage rate estimated with Equation 2. However, αA is also estimated in one series of experiments.

There are two methods for producing the required pressure difference between rooms. One utilizes the buoyant effect (i.e., warm the FIRE-room to an adequate temperature level) and the other uses mechanical venting (i.e., pressurize the FIRE-room and/or exhaust from the UPPER-room. The latter is a useful and powerful method when a VHA system and other ventilation fan are available.

EXPERIMENTS

Installation

Two series of experiments were conducted to assess the degree of accuracy of the estimation method for the leak rate from a small opening and its effective area.

Each experiment had one FIRE-room and one upper observation room directly above, as shown in Figures 2 and 3. An orifice flowmeter (I.D. 50-40 mmϕ [1.97-1.57 in.ϕ]) was installed at a slab between two rooms and served as an "unknown" small opening. The leakage through this opening was measured directly with the orifice flowmeter and also estimated by tracer gas concentration and ventilation rate as indicated by Equation 2. Thus comparisons between estimations and experiments are possible.

The difference between the two series of experiments was the method used to produce the pressure difference. Natural ventilation force due to the buoyancy effect was adopted in the six runs in the first series of experiments, and mechanical exhausting with a ventilation fan was used to produce the pressure difference in the five runs in the second series of experiments.

Producing Pressure Difference

Series I In this experimental series, the electrical fan heater was used to warm the FIRE-room. Two operating conditions of the fan were examined: In Runs 1 through 3,

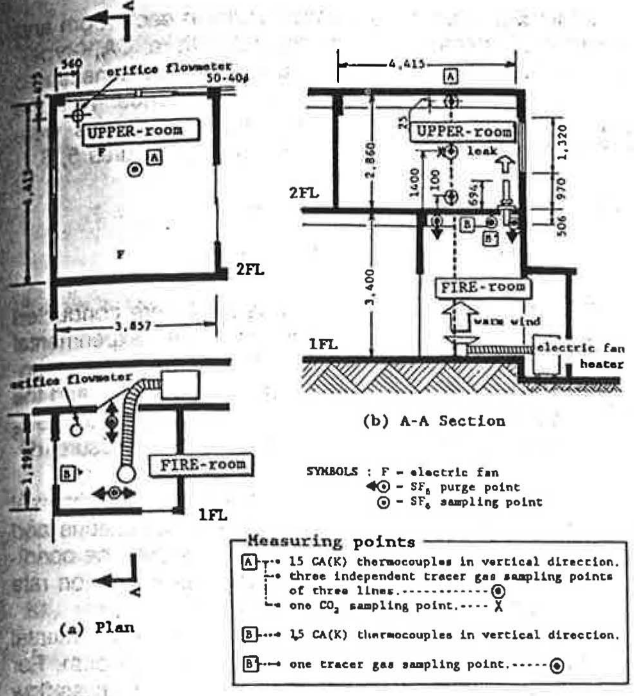


Figure 2 *Installation of full-scale test (series I): A room on the first floor and another room directly above are supposed to be the FIRE-room and the UPPER-room, respectively. Tracer gas is used instead of fire smoke to estimate leakage from the FIRE-room to the UPPER-room, while the leakage is measured by an orifice flowmeter installed at a slab. A pressure difference is produced by stack effect.*

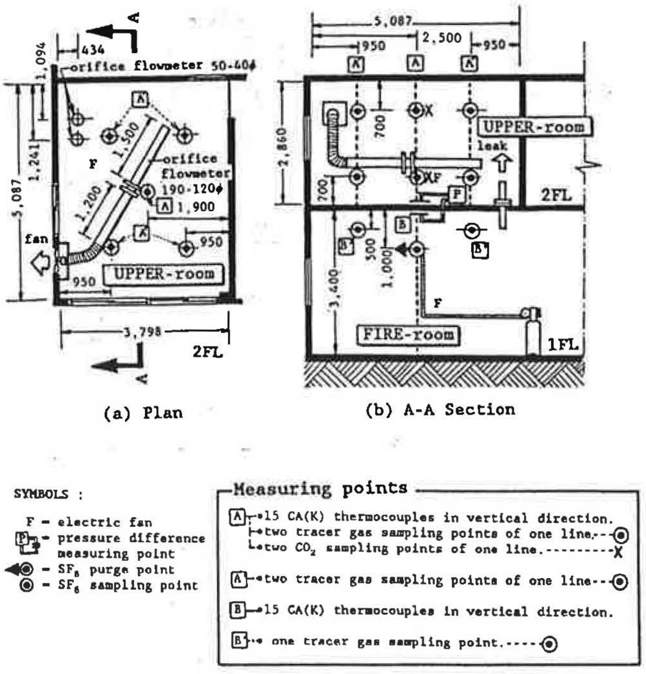


Figure 3 *Installation of full-scale test (series II): Mechanical ventilation is used to produce the pressure difference between rooms. Ventilation rate is measured by an orifice flowmeter and the CO_2 decay method.*

the temperature was higher and wind volume greater (12 kW, 7.3 m^3/min [258 cfm]). The other condition was lower temperature and less wind volume (8 kW, 10.2 m^3/min. [360 cfm]). About 10 minutes prior to releasing the SF_6 tracer gas, warm wind was blown into the FIRE-room. The FIRE-room temperature rose from 8°C to 20°C (14.4°F to 36°F) above ambient temperature, and a steady-state temperature was achieved and maintained in each run. Under these conditions, the estimated maximum pressure difference due to buoyant effects was about 2.8 Pa (0.011 in. Aq.). Some difference in temperature rise between runs was caused by changes in the opening condition of the FIRE-room.

Series II Two levels of pressure difference were produced by mechanical exhausting with the ventilation fan in the UPPER-room with all windows and a door of the room closed; values of about 3 Pa (0.012 in. Aq.) and 2.3 Pa (0.92×10^{-2} in. Aq.) pressure differences were obtained. In this series of experiments, the ventilation rate was directly measured with an orifice flowmeter connected to the fan.

Description of Measurements

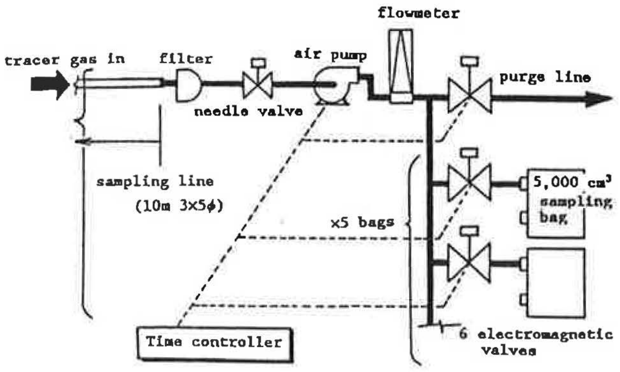
Tracer Gas To estimate the leak rate, the gas concentration in each room and the ventilation rate of the UPPER-room are required. SF_6, which is ordinarily used for measuring building ventilation or investigating atmospheric dispersion, was selected as the tracer gas for these experiments.

Charging Gas 99.9 vol.% pure SF_6 gas was charged into the FIRE-room at a constant rate of 400 cm^3/min (0.014 cfm) in series I and about 80 cm^3/min (2.8×10^{-3} cfm) in series II to reach some 10 ppm after 20 minutes. In these experiments, time = 0 occurs at the initiation of charging.

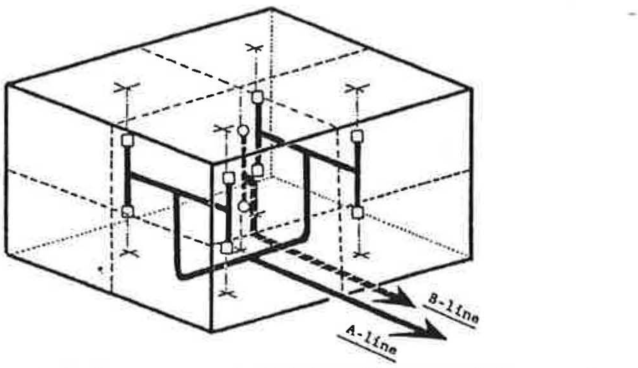
Sampling and Analysis In each series of experiments, air was sampled with automated gas-sampling equipment, as shown in Figure 4, on the time schedules indicated in Figures 5 and 6. In both series, the sampling rate was one sample/4 minutes. Differences between the series were the time interval during which the sample was accumulated (sampling time), sample volume, and sampling location. In series I, the sampling time was two minutes and samples were taken at three different levels at the center of the UPPER-room using three independent sampling lines. In series II, the sampling time was one minute and samples were drawn through two independent lines: one line connected to eight sampling ports and the other to two sampling ports, as shown in Figure 4.

The air in the FIRE-room was sampled from a line having four sampling ports located 50 cm (1.6 ft) below the ceiling. These test specimens were accumulated in a 5000 cm^3 (0.176 ft^3) sampling bag at a rate of 1000 cm^3/min (0.035 cfm) in series I and 4000 cm^3/min (0.14 cfm) in series II. The specimens were quantitatively analyzed by a gas chromatograph with a flame photometric detector within 24 hours after each experiment. Details of the gas chromatograph and its operating conditions are shown in Table 1. With this method, the error in analysis was found empirically to be within 5%.

Ventilation Rate The ventilation rate was measured with the CO_2 decay method. Prior to each run, CO_2 gas was released to attain some thousands ppm level in the UPPER-room. The depletion of the CO_2 concentration was then measured during the experiment. Since the ventilation rate seems to be quasi-steady, an average ventilation rate



(a) Auto gas sampling equipment



A-line : The Upper-room was devided into eight parts of the same volume, and sampling points were set at the center of the parts.
B-line : The Upper-room was devided into two parts (upper and lower), and sampling points were set at the center of the parts. Sampling was made with these two lines at the same time.

(b) Sampling points and lines in the UPPER-room

Figure 4 Schema of tracer gas sampling equipment

(number of exchanges) was obtained from a tangent of the regression line of -ln{$Cco_2(t_i)/Cco_2(t_0)$} against time lapse $t_i - t_0$, where t_i is the ith time increment. In these experiments, data obtained every one minute with the infrared analyzer are used to get a mean average between t_i and t_0. In series II, the ventilation rate was measured directly by an orifice flowmeter, as mentioned previously, as well as by the decay method.

Leak Rate and Pressure Difference The leak rate through an orifice (αA = 11.3 cm^2 [1.75 in^2]) was measured with a pressure transducer. In series II, the pressure difference between the rooms–i.e., between the ceiling level of the FIRE-room and floor level of the UPPER-floor–was measured at the center of the room, as shown in Figure 3, with a high-resolution pressure transducer. These data were recorded with a pen recorder in series I and II and digital recorder of one-second interval in series II.

TABLE 1
Condition of Chromatographic Analysis

Column	porapack Q, SUS.col. , I.D. 3ϕ × 2 m
Temperature	Col.230 °C, Inj.240 °C, Det.230 °C
Detector	FPD (Flame Photometric Detector)
	H_2 flow rate 0.4 cm³/min, applied Voltage 800 V O_2 flow rate 0.2 cm³/min N_2 flow rate 0.2 cm³/min
Carrier gas	N_2 flow rate 70 cm³/min
Working Curve	concentration ∝ Ln(peak height)

Other Equipment Gas temperatures in each room and ambient temperature were measured with a CA(K-type)-thermocouple. The room temperature profiles were measured at 15 points in a vertical line every 15 seconds. With the above-mentioned equipment, the experimental runs were conducted on the time schedules shown in Figures 5, 6.

RESULTS AND CONSIDERATIONS

Experimental Conditions and Results

Six runs in series I and five in series II were conducted under quasi-steady-state conditions. The experimental conditions (ventilation rate in the UPPER-room, SF_6 concentration level in the FIRE-room, and temperature) and the results (consisting of the leakage rate from the orifice, SF_6 concentration in the UPPER-room, and the pressure difference) are indicated in Tables 2 and 3.

In spite of efforts to establish the same experimental conditions in some runs, the experimental conditions and leakage rates are slightly different. For example, the condition of the outer wind appears to affect the ventilation rate and leak rate.

In series I, a principal parameter of the experimental condition was the temperature rise in the FIRE-room. For example, runs 1 through 3 show more heat and mass flow to the FIRE-room than the other three runs, as explained above. The SF_6 concentrations in the FIRE room were intentionally changed slightly to determine the effect on estimation accuracy.

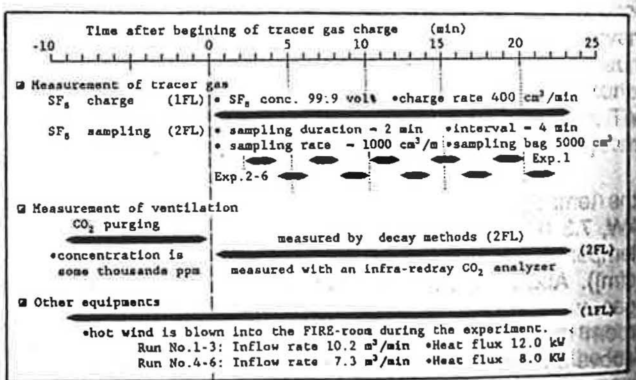


Figure 5 Time schedule of experiment (series I)

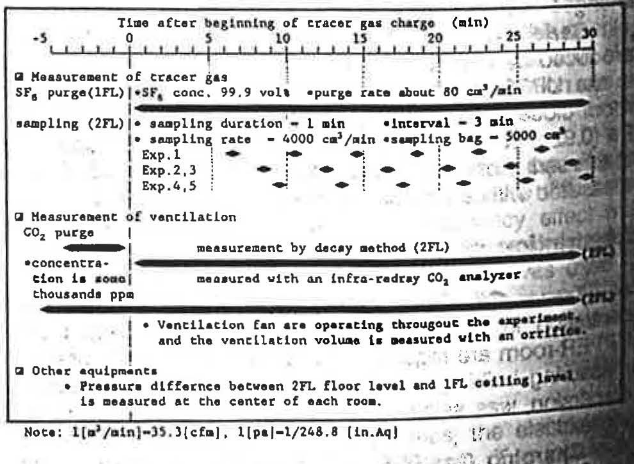


Figure 6 Time schedule of experiment (series II)

TABLE 2
Conditions, Leak Rate, and SF_6 Concentration (Series I)

Exp. Run No.	Temperature [°C] Rm. temp. rise 2FL	Temperature [°C] Rm. temp. rise 1FL	Temperature [°C] Ambient temp.	Vent. rate [turn /hour]	Leak rate [×10⁻³ m³/m.]	SF_6 Concentration [ppm] 2FL. (UPPER)	SF_6 Concentration [ppm] 1FL (FIRE)	SF_6 Concentration [ppm] dilution [%]
1	+5.9	18.9	19.8°C	1.9	100.1	0.931	38.3	2.4
2	0.9	18.2	17.8	2.7	79.0	0.477	20.7	2.3
3	0.1	14.4	26.6	2.1	82.3	0.485	17.0	2.9
4	2.4	11.1	20.4	1.9	80.1	0.597	27.5	2.2
5	2.3	9.2	21.5	3.1	87.9	0.781	47.7	1.6
6	0.6	7.9	25.3	2.4	61.9	0.471	24.5	1.9

Notes: 1. Room temperature rises in the 1FL and 2FL are average temperature rises of 15 vertical measuring points from ambient temperature.
2. Ventilation rate is expressed by the number of room air exchanges in 5 to 20 minutes.
3. SF_6 concentration is the average of three vertical sample points at 20 to 22 minutes (exp.5, 18 to 20). "Dilution" is the diluted concentration of 2FL. against 1FL concentration.
4. 1[m³/min] = 35.3[cfm], 1[pa]=1/248.8[in.Aq], F[°F]=1.8·C[°C]+32

In series II, runs 1 through 3 were conducted under almost the same conditions; however, run 4 was conducted with two orifice openings and run 5 was done under smaller pressure difference. Other conditions were the same.

The dilution listed in Tables 2 and 3 is the ratio of the SF_6 concentration in the UPPER-room to that in the FIRE-room. These results indicate how easily the air in the UPPER-room is contaminated through relatively small openings, even under lesser pressure difference conditions than occur in a real fire.

Comparisons between Estimation and Experiment

Estimation of Leak Rate The leak rate is estimated with a numerical approximation of Equation 2, that is,

$$\bar{\dot{g}}_{1\,i_0 \to i} = \frac{(Co_i - Co_{i_0})\,Vo + \bar{\dot{G}}_{i_0 \to i} \sum_{i=i_0}^{i-1} (Co_i + Co_{i+1})/2\ \Delta T}{\sum_{i=i_0}^{i-1} (C_{f\,i} + C_{f\,i+1})/2\ \Delta T} \tag{2'}$$

where

$\bar{\dot{g}}_1\ i_0 \to i$ = mean estimation of leak rate during Ti_0 and Ti time duration (m³/min)
$\bar{\dot{G}}\ i_0 \to i$ = mean ventilation rate during Ti_0 and Ti time duration (m³/min)
Ci = mean SF_6 concentration of the ith sampling duration (volume %)
Ti = mid-time of the ith sampling duration
ΔT = $T_{i+1} - Ti$ (min)
i_0 = basic time point
o = observation UPPER-room (2 FL)
f = FIRE-room (1 FL)
0 = basic time point.

Thus, the mean leak rate through a small opening (orifice in these experiments) is obtained by the above simple procedure. In this analysis, a base point Ti_0 and accumulated time duration ($i_0 \to i$) are varied to determine their effects on the accuracy of this prediction method.

Comparisons between Estimation and Experiment Tables 4 and 5 show the ratio of estimation against the experiment.

Basic Time and Sampling Interval As shown in Table 4, the error is larger when the starting time of the SF_6 charge is chosen as the basic time (Ti_0) and an averaging time duration ($Ti_0 \to i$) is shorter. These results show that the rapid concentration change immediately after starting the SF_6 charge is not desirable for this prediction method.

TABLE 3
Conditions, Leak Rate, and SF_6 Concentration (Series II)

Exp. Run No.	Vent.rate [T/H] by orifice (SD/M)	Vent.rate [T/H] by CO_2 decay	Leak rate [m³/m.] (SD/M)	Pressure differ. ΔP [pa] (SD/M)	SF_6 Conc. [ppm] 2FL. UPPER	SF_6 Conc. [ppm] 1FL. FIRE	SF_6 Conc. [ppm] dilution [%]
1	4.58 (.01)	4.6	0.173 (.04)	2.99 (.08)	1.07	35.5	3.0
2	4.57 (.05)	4.7	0.181 (.05)	2.84 (.11)	1.22	38.2	3.2
3	4.45 (.11)	4.6	0.175 (.11)	3.21 (.29)	0.59	26.2	2.2
4	4.43 (.07)	4.6	0.340 (.07)	2.89 (.17)	1.87	39.0	4.8
5	3.22 (.16)	3.6	0.158 (.16)	2.32 (.47)	0.82	28.2	2.9

Notes: 1. Ventilation rate is expressed by the number of room air exchanges in 29 minutes after start of SF_6 injection.
2. Ventilation rate, leak rate, and pressure are mean values during 29 minutes. The value in parenthesis is a standard deviation/mean.
3. SF_6 concentration is the average of 8 sample points at the 23 to 24 one-minute period (exp.1, 24 to 25; exp.2, 20 to 21). "Dilution" is the diluted concentration of 2FL against the 1FL concentration.
4. Exp.1 to 3 are almost the same experimant condition except SF_6 purge rate.
5. 1[m³/min] = 35.3[cfm], 1[pa]=1/248.8 [in.Aq].

TABLE 4
Comparison of Experimental and Estimated Leak Rates under Different Basic Time (Ti_0) and Duration ($Ti_0 \to i$) (Series I)

[unit:ratio = estimation/experiment]

Exp. Run No.	Basic Time (Ti_0) = beginning of SF_6 inj. to 5 min	9.	13.	17.	21.	Ti_0 = 9 min to 13 min	17.	21.
1	1.57	1.21	1.10	1.17	1.17	0.85	1.08	1.07
2	1.89	1.32	1.22	1.25	1.31	1.05	1.16	1.27
3	1.51	1.30	1.25	1.23	1.22	1.16	1.16	1.19
4	1.65	1.21	1.16	1.22	1.18	0.92	1.04	1.02
5	0.76	0.61	0.65	0.77	0.84	0.69	0.87	0.91
6	1.16	1.02	1.07	1.09	1.23	1.17	1.15	1.30

Notes: 1. The values in the table are estimation/experiment of leak rate calculated through each duration from basic time Ti_0 to a certain time.
2. Estimated values are calculated with Equation 3. Steady state of ventilation rate is assumed as shown in Table 1.
3. The SF_6 concentration of two minutes' sampling time is assumed to be the concentratin of mid-time in each sampling period, and linear approximation between data is assumed.
4. The time shown is a mid-time of each two-minute sampling period (in Run No.5, deduct two minutes from each time including basic time = 9 in right side).

TABLE 5
Comparison of Experimental and Estimated Leak Rates under Different Basic Time (Ti_0) and Duration ($Ti_0 \to i$) (Series II)

[unit: ratio = estimation/experiment]

Exp. Run No.	Basic Time (Ti_0)=8.5 min after SF_6 inj. to 12.5	16.5	20.5	24.5	28.5	Ti_0 = 16.5 min. to 20.5	24.5	28.5
1	0.90	0.90	0.90	0.98	1.09	0.88	1.01	1.13
2	0.95	0.98	0.97	1.00	1.05	0.94	1.00	1.03
3	0.98	0.91	0.92	0.94	0.98	0.91	0.95	1.00
4	0.82	0.84	0.85	0.89	0.96	0.87	0.92	1.01
5	0.70	0.91	0.95	0.97	1.07	0.99	0.99	1.15

Notes: 1. Values in the table are estimation/experiment of leak rate calculated through each duration from basic time Ti_0 to a certain time.
2. Estimated values are calculated with Equation 3. Steady state of ventilation rate is assumed as shown in Table 1.
3. The SF_6 concentration of one-minute sampling time is assumed to be the concentration of mid-time in each sampling period, and linear approximation between each data is assumed.
4. The time shown is a mid-time of each one-minute sampling period (in Run No.1, deduct two minutes from each time point and add one minute for Runs No.4 and 5)

When the basic time is set at seven or nine minutes and the averaging time duration is longer than eight minutes, the prediction agrees with the experimental results fairly well (see Tables 4 and 5). The averaging procedure required for this method and shorter time interval for sampling can be used when the basic time is set to be later than the beginning of SF_6 purging.

In these experiments, the errors were found to be within 20%. For example, an average value of error is about 8% when Ti_0 = 9 minutes and Ti = 17 minutes are chosen in series I. More accurate estimations are obtained in series II (within a few percent) when a later basic time is adopted.

Ventilation Term Compared with the series II experimental results, a tendency of lesser accuracy at the longer durations is found in series I. This difference appears to be caused by the ventilation term in Equation 2'. In series II, the mechanically ventilated rate was stable and the measurement error was less than that for the natural vent in series I. In this estimation method, the effect of the ventilation term becomes larger when the SF_6 concentration level is higher as time goes by. So although the averaging effect improves the estimation, the error in the ventilation measurements seems to offset this improvement.

Estimation of Effective Opening Area (αA) The effective area of the opening can be estimated from Equation 1. Table 6 shows the estimated effective area for each run in series II. The estimation error is about 20% and is sufficiently accurate for estimating these areas for practical use. The measured pressure difference is underestimated in the experiments, and more improvement is needed for the measurement of pressure difference between rooms of different floors.

CONCLUSIONS AND FUTURE DIRECTIONS

A simple experimental method for estimating the smoke leakage through small openings and the effective areas of the openings is presented. Two series of experiments were conducted to determine the degree of accuracy of the method by measuring tracer gas density, ventilation rate, and pressure difference. Comparisons of estimated and experimental leak rates show agreement within 20%. When the exhaust system is used to produce the pressure difference between rooms, the accuracy is within a few percent. These results indicate that this estimation method is a practical estimation method.

However, this experimental study was limited to only one type of opening between rooms of relatively small volume. Uniformity inside the room and a quasi-steady state are very important for this method. Further experimental studies are desirable for verifying its appropriateness to rooms of larger volume. The size of opening that can be distinguished with this method is determined by room volume, charged tracer gas concentration, and pressure difference produced and mostly depends on the resolution of the tracer gas analyzer. Future work will formulate relationships between distinguishable opening sizes and other parameters for practical building configurations.

TABLE 6
Comparison of Estimated Effective Area with Orifice Opening
(Series II)

Exp. Run No.	Leak rate estimation [m^3/min]	Pressure difference [pa]	Estimated effective area [cm^2]	Description of orifice opening.
1	0.174	2.97	12.9 (1.14)	effective area of 40-50 mmϕ orifice is 11.3cm^2 (α-0.89, A-12.6 cm^2)
2	0.173	2.83	13.2 (1.17)	
3	0.167	3.22	11.9 (1.05)	
4	0.312	2.82	23.6 (1.04)	
5	0.167	2.74	12.9 (1.14)	

Notes: 1. The value inside the parenthesis indicates the ratio against the effective area of orifice. In run No.4, two orifices of the same area were used.

2. The values were obtained from measured data of Ti_0-16.5 to Ti-24.5.

3. 1[m^3/min] - 35.3[cfm], 1[pa]-1/248.8[in.Aq], 1[cm^2]-0.155[in^2]

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DISCUSSION

Herb Becker, Engineer, New York, NY: Did you attempt to correlate your leakage measurements with those you might get if it were real smoke instead of tracer gas?