Authorized Reprint from Standard Technical Publication 1067 -1990

#4349

Hiroshi Yoshino,[1] *Muneshige Nagatomo,*[1] *Yorifusa Yamamoto,*[1]
Hiroshi Matsumoto,[2] *and Yasuo Utsumi*[3]

Measurement of Airtightness, Air Infiltration, and Indoor Air Quality in Ten Detached Houses in Sendai, Japan

REFERENCE: Yoshino, H., Nagatomo, M., Yamamoto, Y., Matsumoto, H., and Utsumi, Y., **"Measurement of Airtightness, Air Infiltration, and Indoor Air Quality in Ten Detached Houses in Sendai, Japan,"** *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 249–266.

ABSTRACT: Airtightness, indoor air quality, and air infiltration were measured in ten occupied, detached, two-story houses of wooden construction in the winter of 1986–87. The floor area of the houses was 120 to 160 m^2. The houses had various types of heating systems. Seven of the houses had exhaust fan units for ventilating living rooms with air-to-air heat exchangers. Airtightness was measured by the fan pressurization method. Equivalent leakage area per floor area was 1.9 to 5.7 cm^2/m^2. The concentrations of CO_2, NO_2, and suspended particles were measured. CO_2 and NO_2 concentrations in the houses where unvented oil heaters were used were higher than in the other houses. The airtightness and indoor air quality measured during this period were compared with measured results obtained for 13 detached houses during the winter of 1984–5. Air infiltration was measured by the concentration decay method using SF_6 as a tracer gas and was compared with the calculated value on the basis of equivalent leakage area.

KEY WORDS: airtightness, air infiltration, indoor air quality, detached houses, investigation

Nomenclature

- c_k Pressure coefficient for surface element k (−)
- g Acceleration of gravity (m/s^2)
- h_k Height of surface element k (m)
- n Exponent of the pressure difference (−), or air infiltration rate (1/h)
- p_i Inside pressure (Pa)
- Δp Pressure difference (Pa)
- Δp_r Pressure difference at reference condition (Pa)
- Δp_k Pressure difference for surface element k (Pa)
- v Wind velocity (m/s)
- A Effective leakage area (cm^2)
- A_r Effective leakage area at reference condition (cm^2)

[1]Associate professor, professor, and graduate student, respectively, Department of Architecture, Faculty of Engineering, Tohoku University, Sendai, 980, Japan.
[2]Lecturer, Department of Regional Planning, Toyohashi University of Technology, Toyohashi, 440, Japan.
[3]Associate researcher, Department of Architecture, Miyagi National College of Technology, Sendai, 980, Japan.

Ar^* Effective leakage area per floor area at the reference condition for Δp of 9.8 Pa (cm^2/m^2)
Q Air flow rate through a building component (m^3/h)
Q_r Air flow rate at reference conditions (m^3/h)
Q_k Air flow rate through surface element (m^3/h)
ρ_o Density of the outside air (kg/m^3)
ρ_i Density of the inside air (kg/m^3)

Newly constructed, detached houses in Japan, especially in the northern regions, are becoming more and more airtight and highly insulated due to the trend toward energy conservation and the demand for thermal comfort. In such houses, it is expected that the quality of the indoor thermal environment will be better than that of existing houses. On the other hand, there is the possibility of indoor air pollution due to poor air infiltration. Many existing reports reveal indoor air quality in residential houses. For example, Nakai et al. [1] reported the results of nitrogen dioxide (NO_2) concentration measurements in all-electric houses and houses using gas to prepare meals. However, there are few reports which investigate the relationship between the indoor air quality and the airtightness of a building envelope. Therefore, the authors investigated airtightness, indoor air quality, and air infiltration in ten occupied, detached wooden houses of a type common to middle class Japanese in the winter of 1986–87 and analyzed the relationship between these three factors. The authors [2] have already reported the results of indoor quality and airtightness as measured for 13 other detached houses in the winter in 1984–85. So, airtightness and indoor air quality measured during this period in 1986–87 were compared with measured results obtained in the winter of 1984–85. Air infiltration was measured by the concentration decay method, using sulfur hexafluoride (SF_6) as a tracer gas, and was compared with the value calculated on the basis of equivalent leakage area. The houses were situated in Sendai, which is located near the Pacific Coast and the main city in the Tohoku region. The latitude of Sendai is 38° 16′. The mean outdoor temperature in January is 0.9°C.

Description of Houses Studied

Table 1 describes the houses studied. All were constructed between 1985 and 1986. Houses 1 and 9 were built by conventional Japanese construction methods, which used columns and beams as structural materials. The other eight houses were built with wood-frame constructions. All of the houses had thermally insulated walls, ceilings, and floors. The walls had vapor barriers made of polyethylene sheets. The windows had double glazings or double sashes except for House 1, which had single glazings. The grade of thermal insulation used was higher than that in the existing houses, which had less than 5-cm fiberglass insulation in the wall. Houses 9 and 10 were experimentally constructed by a house builder and building material production companies working in cooperation.

The houses studied were heated by different types of heating systems: hot water floor heating, hot water heating with panel radiators or fan convectors, hot air central heating, and vented or unvented oil heaters. Houses 4, 5, 7, and 10 had concrete floors including hot water pipes with thermal insulation furnished under it. House 2 had a vented oil heater as well as an unvented oil heater in the living room. House 9 had a hot-air central heating system as well as an unvented oil heater in the child's room. All houses except for Houses 1, 3, and 9 had exhaust fan units situated in the outer walls, with air-to-air heat exchangers for ventilating the living rooms. House 9 had a central ventilation system with an air-to-air heat exchanger. House 3 had fans in the walls between rooms for circulating indoor air, as well as exhaust fans with air-to-air heat exchangers in the three rooms of the kitchen, the washroom, and the lavatory. But House 1 did not have an air-to-air heat exchanger.

TABLE 1—*Description of measured houses.*

House Number	Date of Completion	Floor area,[b] m^2	Depth of Insulation,[c] (cm)			Window[e]	Heating[f] Equipment	Ventilation in Living Room	Number of Family Members	House Builder
			Wall	Floor	Ceiling					
1	Dec. 1986	119	10	3	10	S.G.	CH. HW. Fan. con	Natural	3	A
2	Nov. 1986	120	10	5	10	D.S.	LH. V.&UV.	Mech.[g]	4	B
3	Dec. 1986	158	10	15	20	D.S.	CH. HW. Panel rad.	Mech.[h]	4	C
4	Dec. 1985	141	10	3F[d]	10	D.S.	CH. HW. Floor H.	Mech.[g]	3	B
5	Dec. 1986	144	10	3F	10	D.S.	CH. HW. Floor H.	Mech.[g]	4	B
6	Dec. 1986	142	10	5	10	D.S.	LH. V.	Mech.[g]	3	B
7	Sep. 1986	120	10	3F	10	D.S.	CH. HW. Floor H.	Mech.[g]	4	B
8	Dec. 1986	140	10	5	10	D.G.	LH. V.	Mech.[g]	4	B
9[a]	May 1986	124	10	7.5	20	D.G.	CH. HA. + LH. V.&UV.	Central[i]	4	B
10[a]	Apr. 1986	121	15	5F	15	D.G.	CH. HW. Floor H.	Mech.[h]	7	B

[a]This house was experimentally constructed by a group of a house builder and building material productions companies.
[b]All houses have two stories.
[c]Glass wool is used for walls and ceilings except for House 1 with rock wool. Floors are insulated with foam polystyrene.
[d]F means that floor is made of concrete.
[e]D.S. = double sashes, D.G. = double glazing.
[f]CH. = central heating, LH. = local heating, HW. = hot water, HA. = hot air, V = vented oil heater, UV. = unvented oil heater, Floor H. = floor heating, Fan con. = fan convector, Panel rad. = panel radiator.
[g]Mech. = mechanical ventilation with an exhaust fan unit, which is situated in an outer wall, with an air-to-air heat exchanger.
[h]This house has fans in inner walls between rooms for circulating indoor air and exhaust fans with air-to-air heat exchanger in the kitchen, in the face washing room, and in the lavatory.
[i]Central mechanical ventilation with an air-to-air heat exchanger.

Airtightness

Method of Measurement

Airtightness measurements were made by the fan pressurization method [*3,4*]. Internal pressure was increased by a fan attached to a duct penetrating a thin board set in an open window. The pressure differences were measured by a capacitance manometer. Flow rate in the duct was measured by a thermistor anemometer. Measurements were carried out under conditions of such low wind speed that the indoor-outdoor pressure difference was stable. The inside and outside temperatures were not measured.

Results of Measurement

Figure 1 shows the relationship between the pressure difference across the building envelope and the volumetric flow rate. The pressure difference ranged from 4 to 30 Pa, where the capacity of the fan used gave the maximum pressure difference. The outside wind speed

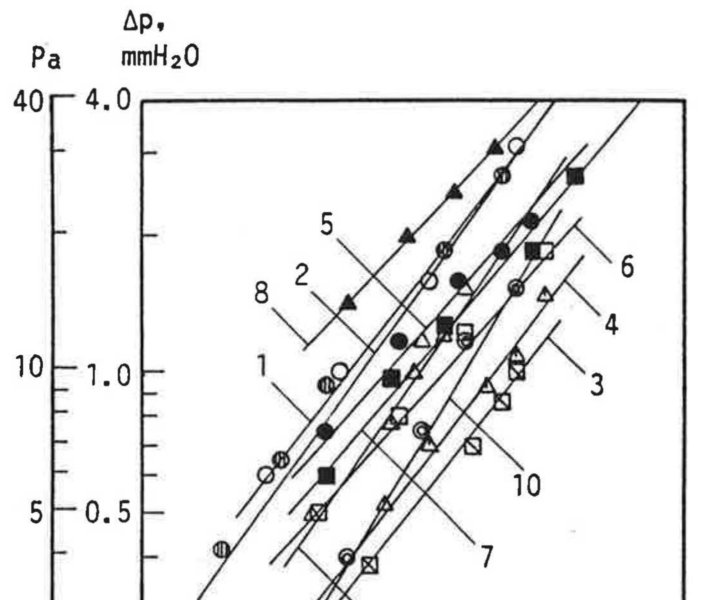


FIG. 1—*Pressure difference and volumetric flow rates.*

restricted the lower limit of the range. The relationship between the two factors is expressed by

$$Q = Q_r\left(\frac{\Delta p}{\Delta p_r}\right)^{1/n} \quad (1)$$

Table 2 shows Q_r and n for each house, which can be calculated by the linear curve fitting with each measurement data set. The Q_r is the value of Q when Δp is equal to the reference pressure, Δp_r. The reference pressure used is different between countries and between researchers. For example, in Norway and Sweden, the value used in the airtightness standard is 50 Pa. The 1985 ASHRAE handbook gives the value as 4 Pa. In Japan, the reference pressure of 1 mm H_2O (9.8 Pa) is usually used because it takes into consideration the pressure range exerted upon the building surface in a natural environment, the easy realization of the indoor-outdoor pressure difference by the pressurization method, and the easy handling of the figure of one in calculating formulas. The reference pressure is also given as 1 mm H_2O (9.8 Pa) in the draft of a Japanese industrial standard on airtightness measurement of buildings. The value of Q_r is distributed from 385 to 1290 m^3/h. The value of n ranges from 1.02 to 1.61. Table 2 also shows the effective leakage area [*5*], A_r, for each house, which can be calculated by the following equation (see Appendix A).

$$A_r = 2.78Q_r\left(\frac{2}{\rho_o}\Delta p_r\right)^{-0.5} \quad (2)$$

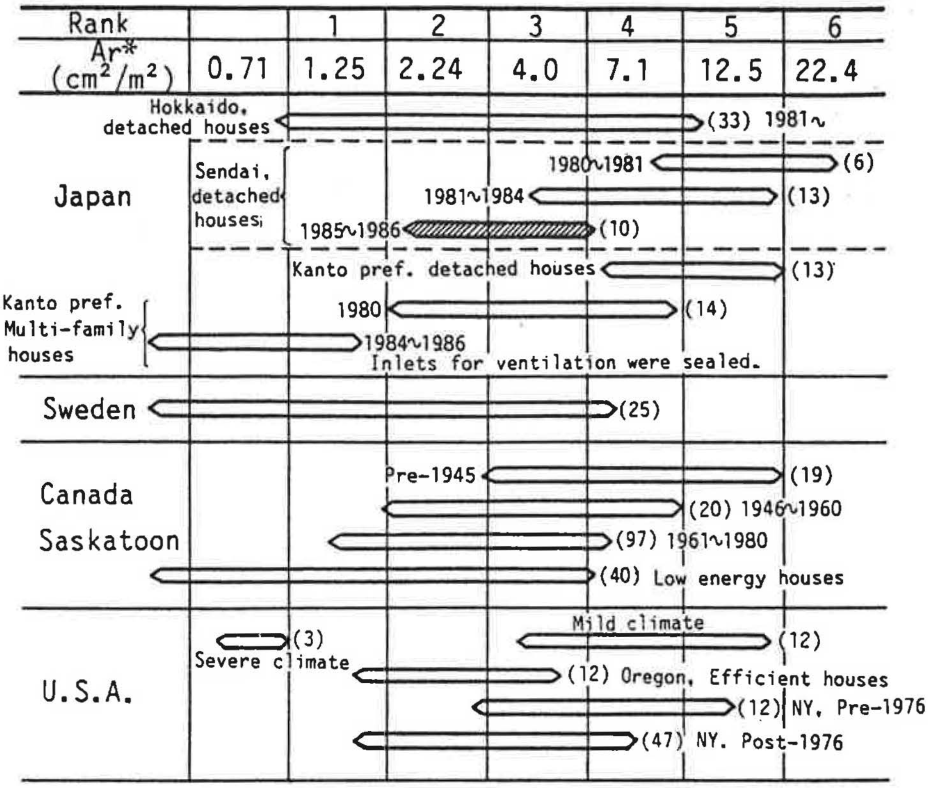
In Eq 2, ΔP_r is given as 9.8 Pa. The effective leakage area per floor area, Ar^*, is also included in Table 2. The value of Ar^* is widely distributed from 1.9 to 5.7 cm^2/m^2. House 8 was found to be the most airtight.

Comparison of Airtightness for Houses Using Effective Leakage Area Per Floor Area

Figure 2 shows the range of Ar^* for various houses in different countries. Where the original airtightness data were not shown as A_r for Δp_r = 9.8 Pa, these data were converted, assuming $1/n$ = 0.6. The original figure is presented in the paper by Murakami and Yoshino [*6*]. The houses measured in this test are located from Rank 2 to 5 and appear tighter than the houses measured in 1985 in Sendai. The description of the houses measured in 1985 is presented in Appendix B.

TABLE 2—*Airtightness of measured houses.*

House No.	Q_r, m^3/h	n	A_r, cm^2	Ar^*, cm^2/m^2
1	528	1.33	369	3.1
2	563	1.37	396	3.3
3	1290	1.25	901	5.7
4	1120	1.28	776	5.5
5	641	1.12	446	3.1
6	857	1.12	596	4.2
7	752	1.17	528	4.4
8	385	1.02	266	1.9
9	760	1.44	521	4.2
10	976	1.61	690	5.7



Note: Figures in parenthesis indicate the number of housing units measured.

FIG. 2—*Airtightness for various houses in different countries using* Ar*.

Indoor Air Quality

Method of Measurement

The concentration of carbon dioxide (CO_2) was measured by an infrared analyzer in the living room of each house. The concentration of NO_2 was measured by bare detector badges exposed for the measurement period in the living rooms and kitchens. This measurement follows the method utilized by Yanagisawa and Nishimura [7]. The concentration of suspended particles was measured by a dust meter of the light diffusion type. The measurement period differed from two to five days due to the occupant's availability to participate in the study.

Results of Measurement

Figure 3 shows variations of CO_2 concentration measured in each house during a single weekday of different measuring periods. In many houses, the CO_2 concentration increased in the morning between 7 a.m. and 9 a.m. and at night after 9 p.m. Figure 4 shows the cumulative frequency distribution of CO_2 concentration throughout the measuring period. The Building Standards Code of Japan prescribes that the limit of CO_2 for indoor air in air-conditioned space of office buildings be less than 1000 ppm. In Houses 2 and 9, the CO_2

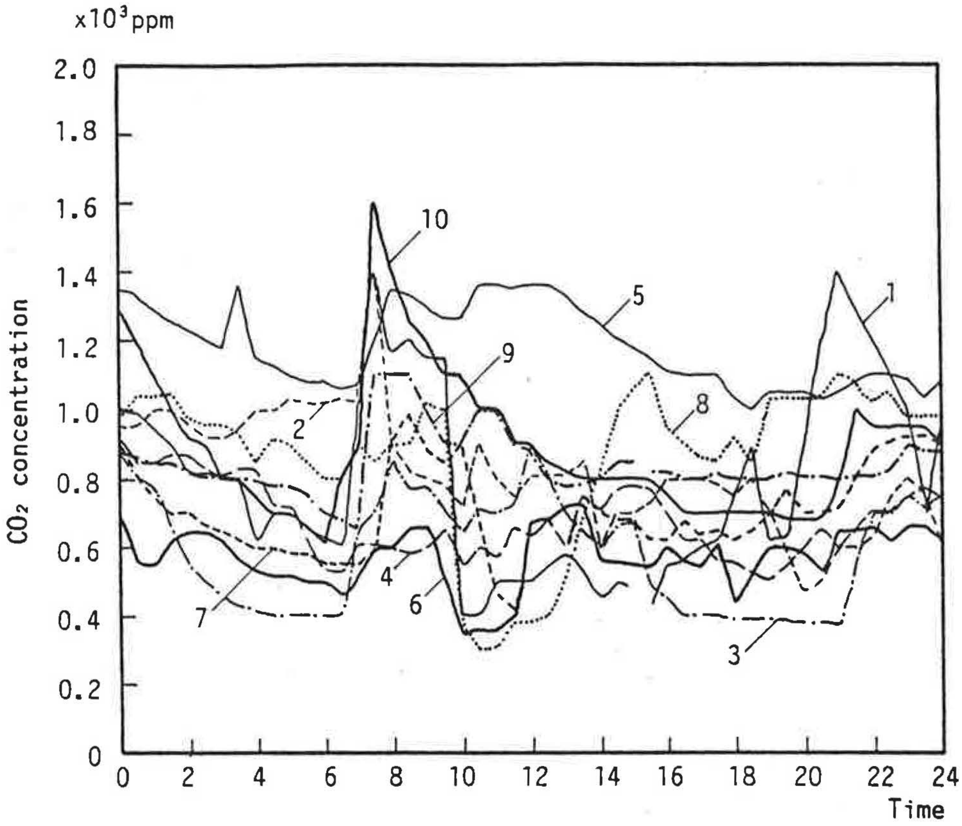


FIG. 3.—*Variations of CO_2 concentration during a single weekday.*

concentration was over 2000 ppm when the cumulative frequency was more than 95% because unvented oil heaters were sometimes used in the child's bedroom in House 9 and in the living room in House 2. In House 5, the CO_2 concentration was over 1000 ppm when the cumulative frequency was more than 27%. The occupant in House 5 reported that the exhaust fan unit with an air-to-air heat exchanger installed in the living room was scarcely used. Table 3 shows the mean concentration of CO_2, the value of which ranged from 560 to 1100 ppm. In Houses 2, 5, and 9, the mean CO_2 concentration was over 1000 ppm. The mean CO_2 concentration was lowest in House 6, where the occupant reported that the exhaust fan unit was always used in the evenings. These results show that the indoor CO_2 concentration was affected by the use of an unvented heater and an air-to-air heat exchanger. In House 1, which had no exhaust fan unit, the mean CO_2 concentration intervened among the mean values of the investigated houses.

Table 3 also shows the mean concentration of NO_2 in living rooms and kitchens. The bare detector badges used to measure the NO_2 concentration gave us only the mean value during the measurement period. The mean NO_2 concentration measured in the living rooms and kitchens was 9 to 74 ppb and 11 to 72 ppb, respectively. There is no standard of the acceptable level of NO_2 in indoor air. But according to The Environmental Recommendation of Outdoor Air Quality in Japan, the limit of the daily mean NO_2 concentration is 20 ppb. The mean NO_2 concentration in Houses 2 and 9 was higher than that in the other houses, because, as mentioned above, these two houses used unvented portable oil heaters. In the other houses,

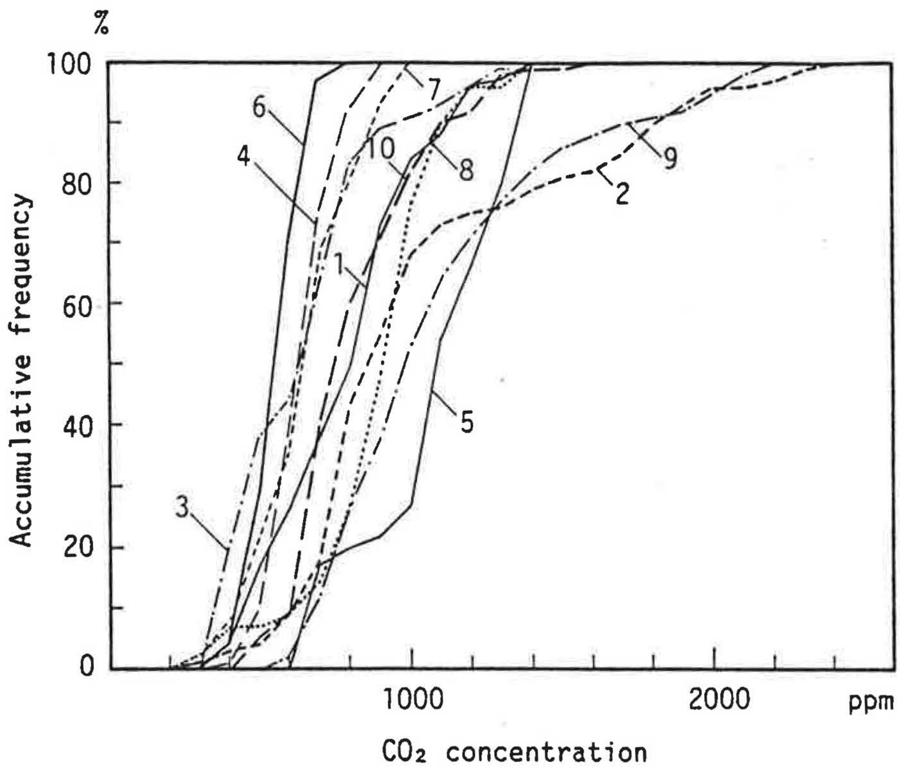


FIG. 4.—*Cumulative frequency distribution of CO_2 concentration for the measuring period.*

TABLE 3—*Mean concentration of CO_2, NO_2, and suspended particles.*

House Number	Measuring Period, 1987	CO_2 Concentration in Living Room, ppm	NO_2 Concentration, ppb: Living Room	NO_2 Concentration, ppb: Kitchen	Suspended Particles, mg/m^3
1	May 12, 13:00 to May 14, 9:30	800	11.5	14.6	0.030
2	May 14, 14:30 to May 17, 10:30	1044	42.9	39.8	0.011
3	May 17, 19:00 to May 19, 15:00	653	12.6	16.5	0.020
4	May 19, 19:00 to May 23, 9:00	642	9.0	10.6	0.017
5	May 23, 17:00 to May 25, 9:30	1078	8.5	13.1	0.012
6	May 25, 12:30 to May 27, 9:00	562	11.7	15.8	0.017
7	May 27, 12:00 to May 28, 17:00	656	9.2	12.0	0.011
8	May 30, 12:30 to Apr. 1, 10:00	892	14.5	16.5	0.029
9	Jan. 26, 12:30 to Jan. 28, 14:00	1111	74.1	72.2	0.035
10	Feb. 4, 14:00 to Feb. 6, 14:00	841	15.6	24.1	0.016

the mean NO_2 concentrations in the kitchens were higher than those in the living rooms due to the emmission of NO_2 from gas cooking stoves.

The relationship between mean CO_2 and NO_2 concentrations in the living room of each house is shown in Fig. 5, including the results measured in 1985. It is recognized again that the mean NO_2 and CO_2 concentrations in houses with unvented oil heaters are comparatively high.

The mean concentrations of suspended particles are also shown in Table 3. The Building Standards Code of Japan prescribes that the limit of suspended particles for indoor air in air-conditioned spaces of office buildings be less than 0.15 mg/m^3. The values are so low in all houses that no pollution problem for suspended particles was evident.

However, it is plain that unvented heaters should be used sparingly, and that exhaust fans with air-to-air heat exchangers should be used regularly in airtight houses such as those investigated in the present study.

The Relationship Between Airtightness and Indoor Air Quality

Figure 6 shows the relationship between the effective leakage area per floor area, Ar^*, and the mean concentrations of CO_2, including the data measured in 1985. The CO_2 concentration was averaged during the same day as shown in Fig. 3, which excluded the period when the unvented oil heater was used. The periods and the averaged values are shown in Table 4. The black marks in Fig. 6 during 1987 indicate a slightly negative correlation between the two factors. That is, the CO_2 concentration was higher in the more airtight houses. Compared

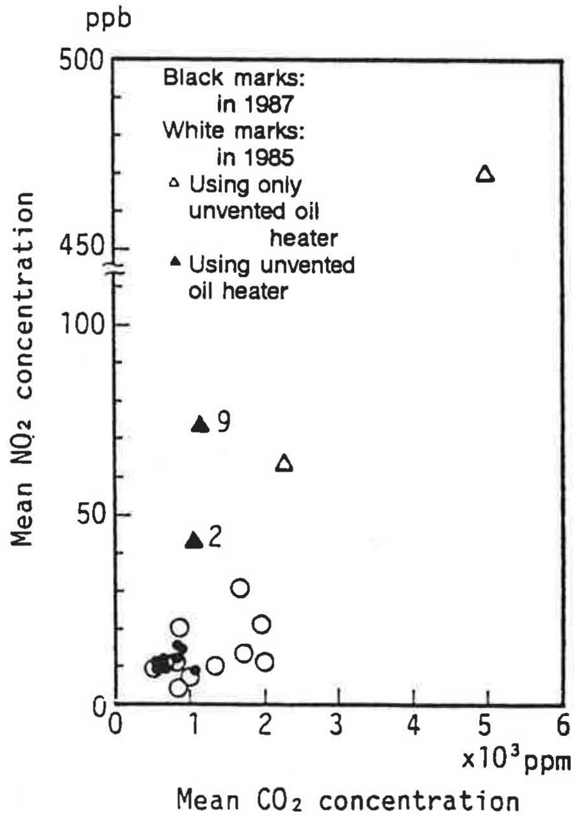


FIG. 5—*Relationship of mean concentration between NO_2 and CO_2 in living room.*

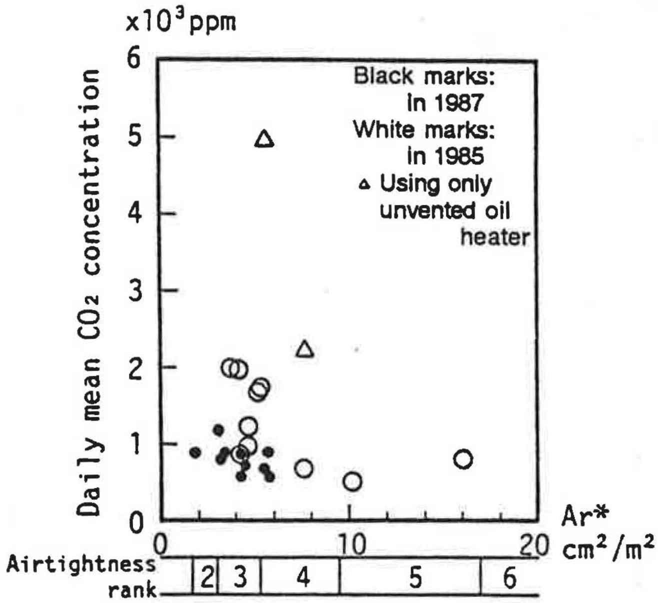


FIG. 6—*Mean CO_2 concentration during a single weekday and* Ar*.

TABLE 4—*Daily mean CO_2 concentration in a weekday.*

	Period, 1987	CO_2 Concentration
1	May 12, 15:30 to May 13, 15:00	789
2	May 16	828
3	May 18	583
4	May 20	678
5	May 24	1183
6	May 24	568
7	May 27, 12:00 to May 28, 11:30	714
8	May 31	873
9	Jan. 29, 15:30 to Jan. 30, 15:00	845
10	Feb. 5	893

to the results measured in 1985, the leakage areas of houses measured in 1987 were smaller and CO_2 concentrations were lower.

Figure 7 shows the relationship between effective leakage area per floor area, *Ar**, and the mean concentration of NO_2 in the living room during the measurement period. The value of NO_2 is the same as shown in Table 3. The results measured in 1985 are included in this figure. It is difficult to find the correlation between the two factors. In both Houses 2 and 9, having unvented oil heaters, NO_2 concentration was relatively high.

Air Infiltration

Method of Measurement

The air infiltration rate was measured by the SF_6 concentration decay technique [*8*]. Under the conditions that all windows and entrance doors were closed, all internal doors were

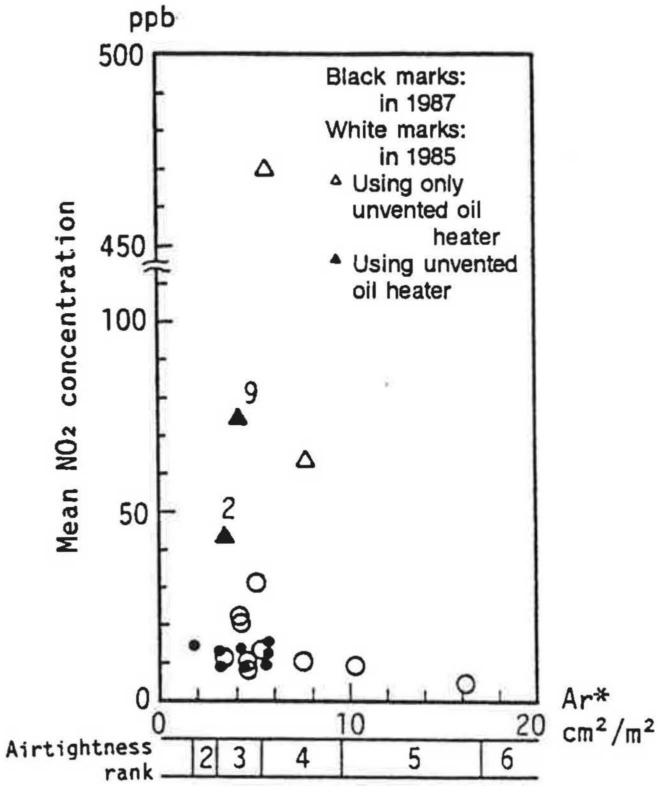


FIG. 7—*Mean NO_2 concentration during the measuring period and* Ar*.

open and exhaust fans were not operated, SF_6 gas, of a volume of about 50 cm^3, was released in the living room. After the indoor air and the SF_6 gas were mixed by electric fans for approximately 10 min, the indoor air in the living room was sucked into sampling bags by a pump to get a 0.5-L sample within 30s. This was repeated several times during the course of 1 h. In the rooms other than the living rooms, indoor air samples were taken a few times in order to check the mixing of SF_6 gas between the rooms. As the measurement was the first experience for the authors and was made when the house was occupied, the sampling interval and the kind of rooms in which SF_6 gas was sampled were different from house to house. The air samples were brought to our laboratory and analyzed a few days later by an electron capture detector. The air in each collected sampling bag was analyzed several times and averaged.

Results of Measurement

Figure 8 shows the decay of SF_6 concentrations plotted on a semilog chart in each house. The SF_6 concentration in the living room decreased in all houses except for House 8, where SF_6 concentration increased a half hour after the beginning of measurement due to incomplete mixing. In House 3, the SF_6 concentration in the second floor increased for 20 min following the beginning of measurement and finally reached the same level of concentration as in the living room. In House 4, the SF_6 concentration in the second floor at the beginning of measurement was higher than that in the living room. These results in Houses 3 and 4

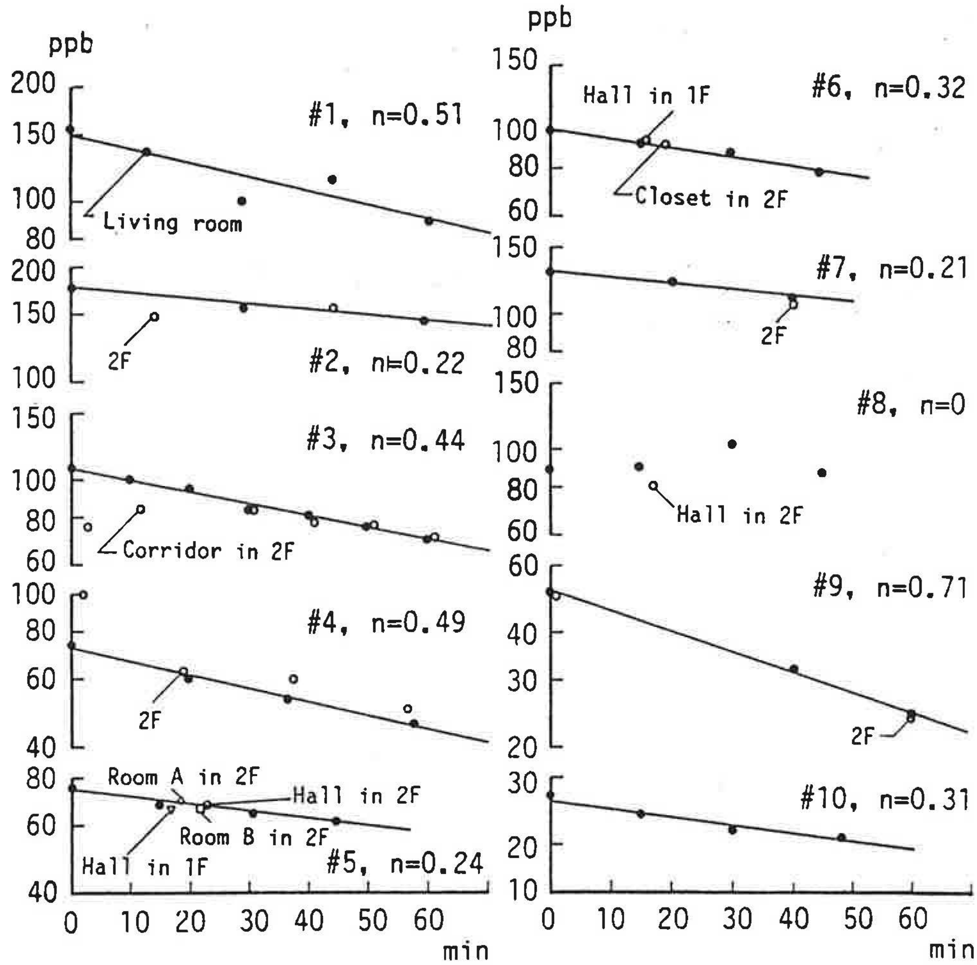


FIG. 8—*Concentration decay of SF_6.*

show that initial mixing between the rooms was incomplete. After about 20 min from the beginning of measurement, the SF_6 concentration in the other spaces was close to that in the living room. Therefore, it can be said that at least 30 min mixing by the fan was necessary for uniform distribution of tracer gas in the detached houses measured in this study.

The air infiltration rate in a whole house was estimated by a regression line on the basis of the SF_6 concentration measured in the living room. The results are shown in the column of "measurement" in Table 5. The air infiltration rate is widely distributed from 0 to 0.71. In the case of House 8, the SF_6 concentration did not decrease for 45 min. It was expected that the air infiltration rate would be significantly lower in spite of the problem of incomplete mixing. Therefore, the infiltration rate was interpreted as being zero for further analysis.

Air Infiltration Rate and Ar*

Figure 9 shows the relationship between the air infiltration rate and the equivalent leakage area per floor area. The air infiltration rate, of course, depends on both outdoor wind speed

TABLE 5—*Measured air infiltration rates using SF_6 and calculated values.*

House Number	Wind[a] Velocity, m/s	Indoor-Outdoor Temperature Difference, °C	Air Infiltration Rates, 1/h	
			Measurement	Calculation
1	1.5	7.7	0.51	0.11
2	3.4	9.0	0.22	0.15
3	3.5	16.1	0.44	0.33
4	0.6	8.5	0.49	0.19
5	12.6	9.5	0.24	0.35
6	13.6	12.1	0.32	0.55
7	3.5	20.0	0.21	0.27
8	4.9	17.1	0.0	0.09
9	6.4	12.0	0.71	0.29
10	7.7	13.0	0.31	0.55

[a]Wind velocity was measured at 52.1 m high at the meteorological station.

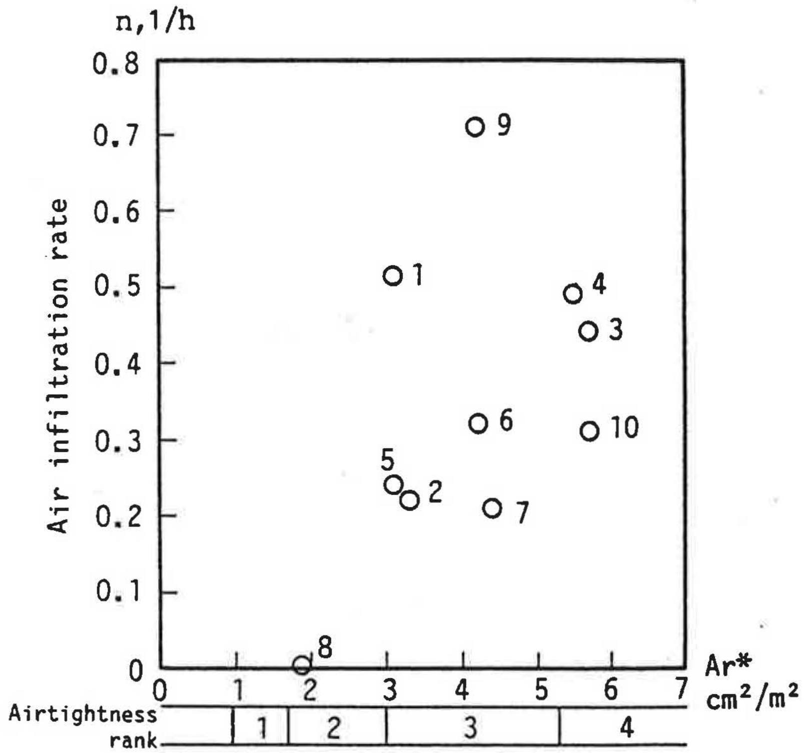


FIG. 9—*Relationship between airtightness and air infiltration.*

and indoor-outdoor temperature difference. Nevertheless, a positive correlation can be found between the two factors.

Comparison of Air Infiltration Rate Between Measurement and Calculation

Yoshino et al. [9] reported that, for estimating air infiltration from the results of an airtightness test, the assumption of uniform distribution of air leakage over the building envelope provided a good estimate, on the basis of a detailed field measurement of airtightness and air infiltration using three small test houses.

Then the authors calculated the air infiltration in the investigated houses utilizing the same method as one used by Yoshino et al. [9], taking into account some assumptions as shown in the following:

1. All the houses are of a simple rectangular shape with dimensions of 8 m in width, 8 m in depth, and 5 m in height. Also, it is assumed that each house was comprised of a single room.
2. Air leakage was uniformly distributed, that it, the effective leakage area of each house was distributed among the four walls, the ceiling and the floor, according to the area of each surface. Each wall was divided laterally into ten parts, and uniformly distributed cracks in each part were concentrated at the center of the surface.
3. The profile of the outdoor wind speed depends on the power law. The exponent is assumed to be 0.28 [10]. The wind speed at 5 m above the ground surface was used for a reference wind speed for calculating the surface pressures on the houses.
4. Wind pressure coefficients are assumed to be 0.12 for two of the walls, −0.08 for the other two walls, −0.06 for the attic, and 0.02 for the crawl space, taking into account that the houses measured were constructed close to one another [2]. The wind pressure coefficient depends on the shape of each house and obstacles surrounding the house; however, these coefficients are assumed to be constant for all houses.

The air infiltration rate was calculated using the network method [11], which is described below.

The pressure difference, Δp_k, across a concentrated crack k at height, h_k, from the floor level due to both wind and buoyancy effects is given as the following equation

$$\Delta p_k = C_k \left(\frac{\rho_o}{2}\right) v^2 - p_i + g h_k(\rho_i - \rho_o) \tag{3}$$

The air flow, Q_k, and the Δp_k for the crack k have the relationship

$$Q_k = Q_{r,k} \left(\frac{\Delta p_k}{\Delta p_{r,k}}\right)^{1/n_k} \tag{4}$$

The total volume of air flow into the interior through the cracks is zero, that is

$$\Sigma Q_k = 0 \tag{5}$$

Substituting Eq 3 into Eq 4, the inside pressure and the volumetric air flow through each crack are found iteratively by use of Eq 5. The air infiltration rate is obtained by dividing the total of volumetric air flow coming into the house by the interior volume of each house.

Indoor and outdoor air temperatures were measured simultaneously with the measurement of air infiltration. Data for outdoor wind speed were obtained from a meteorological station in Sendai, which was measured at a height of 52.1 m. The distance of the station from the houses studied ranged between 4 and 8 km, except for House 2 which was about 18 km from the station.

Table 5 shows the calculated results in the column of "calculation." Figure 10 indicates the comparison between measurements and calculations. This agreement is not good except for some houses. Especially, the calculation results of Houses 1, 4, and 9 are lower than the measurement results. The reasons for disagreement may be included in both the calculation method and the measurement method. That is, for the calculation, data of outdoor wind speed, which were obtained from a meteorological station far from the houses, were utilized, the wind pressure coefficients used were not adequate enough to model for all of the houses, and the uniform distribution of air leakage of a house was assumed. For the measurement, there was the possibility of incomplete mixing of SF_6 in a whole house. For obtaining better agreement in further study, it is necessary to take into account these factors.

Conclusions

Airtightness, indoor air quality, and air infiltration were measured in ten occupied, detached wooden houses in the winter of 1987–88 and the relationship between airtightness and indoor air quality was examined. Also, air infiltration was calculated on the basis of equivalent leakage area and compared with the measured value. The results are as follows:

1. The values of equivalent leakage area per floor area, Ar^*, were widely distributed from 1.9 to 5.7 cm^2/m^2. The houses measured for airtightness were located from Rank 2 to 5 and appeared to be more airtight than the houses measured in 1984–85.

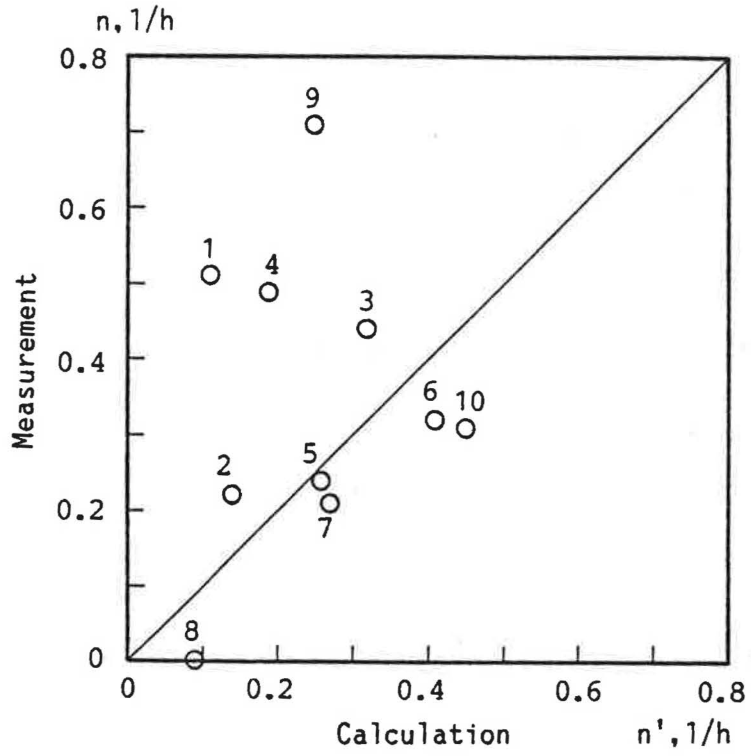


FIG.10—*Comparison of air infiltration rate between measurement and calculation.*

2. The mean concentration of CO_2 during the period of a few days was distributed from 500 to 1100 ppm. The CO_2 concentration was over 1000 ppm in Houses 2 and 9, where unvented oil heaters were used, and in House 5, where an exhaust fan with an air-to-air heat exchanger for ventilating the living room was scarcely used. On the other hand, the CO_2 concentration was lowest in House 6, where an exhaust fan was always used in the evenings. These results show that the indoor CO_2 concentration was affected by use of an unvented heater and an air-to-air heat exchanger. The NO_2 concentration measured in the living room and the kitchen ranged from 9 to 74 ppb and 11 to 72 ppb, respectively. The NO_2 concentration in Houses 2 and 9 was higher than that in the other houses.

3. The air infiltration rates measured using the SF_6 concentration decay technique were widely distributed from 0 to 0.71. The air infiltration rates, of course, depend on both outdoor wind speed and indoor-outdoor temperature differences. Nevertheless, a positive correlation was found between the two factors.

4. Air infiltration rates were calculated on the basis of equivalent leakage area. This agreement was not good except for some houses. The reasons for the disagreement were that data of outdoor wind speed, which was obtained from a meteorological station far from the houses, were utilized for calculation, the wind pressure coefficients used were not adequate enough to model for all of the houses, the uniform distribution of air leakage of a house was assumed, and, for the measurement, there was the possibility of incomplete mixing of SF_6 in a whole house. For obtaining better agreement in further study, it is necessary to take into account these factors.

Appendix A

In the case of orifice plate, the relationship between the pressure difference, Δp (Pa), across an orifice plate and the volumetric air flow, Q (m^3/h) is

$$\Delta p = \frac{\rho_o}{2}\left(\frac{Q}{A} \times \frac{10\ 000}{3600}\right)^2 = \frac{\rho_o}{2}\left(\frac{2.78Q}{A}\right)^2 \tag{A1}$$

where A is the effective orifice area (cm^2).

Therefore, the effective orifice area is obtained by

$$A_r = 2.78Q_r\left(\frac{2}{\rho_o}\Delta p_r\right)^{-0.5} \tag{A2}$$

Substituting Eq 1 into Eq A2, the effective orifice area (effective leakage area) is given by

$$A = 2.78Q_r\left(\frac{\Delta p}{\Delta p_r}\right)^{1/n}\left(\frac{2}{\rho_o}\Delta p_r\right)^{-0.5} \tag{A3}$$

If $\Delta p = \Delta p_r$, Eq A3 is rewritten simply as

$$A = 2.78Q_r\left(\frac{2}{\rho_o}\Delta p\right)^{-0.5} \tag{2}$$

Appendix B

Description of houses measured in 1984–1985.

House Number	Date of Completion	Floor area, m^2	Depth of Insulation, cm			Window	Heating Equipment	Ventilation in Living Room	House Builder
			Wall	Floor	Ceiling				
1	Jan. 1983	109	5	5	7.5	D.S.	Vented oil heater	Natural	A
2	Jan. 1983	105	5	5	7.5	D.S.	Unvented oil heater and "Kotatsu"[b]	Natural	A
3	Jan. 1983	109	5	5	7.5	D.S.	Vented gas heater	Natural	A
4	Mar. 1983	110	5	5	7.5	D.S.	Unvented and vented oil heaters	Natural	A
5	Dec. 1984	109 F	10	2.5	10	D.S.	Floor heating and "Kotatsu"	Mechanical[a]	B
6	Sept. 1984	142 F	10	...	10	D.S.	Vented oil heater and "Kotatsu"	Mechanical	B
7	Sept. 1984	183 F	15	5	15	D.S.	Floor heating	Mechanical	B
8	Jan. 1982	110	5	5	7.5	D.G.	Vented oil heater and "Kotatsu"	Natural	A
9	Oct. 1984	152 F	5	5	10	D.S.	Floor heating	Mechanical	C
10	Mar. 1983	147 F	5	5	10	D.G.	Floor heating and "Kotatsu"	Natural	C
11	Aug. 1983	163 F	5	5	10	D.S.	Floor heating	Natural	C
12	June 1981	120 F	5	5	10	D.G.	Floor heating	Mechanical	C
13	Aug. 1981	109 F	5	5	10	D.G.	Floor heating and "Kotatsu"	Mechanical	C

NOTE: F = concrete floor is constructed. D.S. = double sashes, D.G. = double glazing. All houses have two stories except for House 13 with a flat.

[a]"Mechanical ventilation" means an exhaust fan unit, which is situated in an outer wall, with an air-to-air heat exchanger, except for House 13.

[b]"Kotatsu" means a traditional Japanese electric heater that is mounted under a low table.

References

[1] Nakai, S., Arai, H., and Maeda, K., "A Preliminary Study on the Comparison of Indoor NO_2 Levels in Electric Homes and in Gas Cooking Homes," *Japanese Journal of Public Health,* Vol. 34, No. 3, March 1987, pp. 128–136 (in Japanese).
[2] Yoshino, H., "Airtightness and Ventilation Strategy in Japanese Residences," *Energy and Building,* Vol. 9, 1986, pp. 321–331.
[3] Narasaki, M. and Kusumi, T., "Airtightness Testing of Industrialized Houses," Annual meeting of Architectural Institute of Japan, Tokyo, October 1974 (in Japanese).
[4] Sticker, S., "Measurement of Air-Tightness of Houses," ASHRAE Transaction, Part 1, 1975.
[5] Allen, C., "AIRGLOSS: Air Infiltration Glossary (English edition)," Air Infiltration Center, Coventry, Great Britain, December 1981, pp. 26.
[6] Murakami, S. and Yoshino, H., "Air-Tightness of Residential Buildings in Japan," *Proceedings,* 4th Air Infiltration Conference, Air Infiltration Center, Coventry, Great Britain, 1983, pp. 15.1–15.20.
[7] Yanagisawa, Y. and Nishimura, H., "A Personal Sampler for Measurement of Nitrogen Dioxide in Ambient Air," *Journal of Japan Society of Air Pollution,* Vol. 15, No. 8, August 1980, pp. 316–323 (in Japanese).
[8] Grot, R. A., "Low-Cost Method for Measuring Air Infiltration Rates in a Large Sample of Dwellings," *Building Air Change Rate and Infiltration Measurements, ASTM STP 719,* American Society for Testing and Materials, Philadelphia, 1987, pp. 50–59.
[9] Yoshino, H., Hasegawa, F., and Utsumi, Y., "Verification of Calculation Models of Air Infiltration Using Three Types of Test Houses," *Proceedings,* 5th Air Infiltration Center Conference, Air Infiltration Center, Coventry, Great Britain, October 1984, pp. 20.1–20.21.
[10] Davenport, A. G., "The Relationship of Wind Structure of Wind Loading," *Proceedings,* 1st International Conference on Wind Effects on Buildings and Structures, H. M. Stationery Office, London, 1965, pp. 53–111.
[11] Ishihara, M., *Ventilation Design of Buildings,* Asakura-Shoten, March 1969, pp. 139–168 (in Japanese).

DISCUSSION

W. DeGids[1] *(written discussion)*—Were your Cp values based on measurements or taken from literature.

H. Yoshino (closure)—They were taken from Ref *2* in the literature.

[1]POB 217, 2600 AE Delft, Netherlands.