RESEARCH REPORT

Establishing the Protocol for Measuring Air Leakage and Air Flow Patterns in High-rise Apartment Buildings

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ESTABLISHING THE PROTOCOL FOR MEASURING AIR LEAKAGE AND AIR FLOW PATTERNS IN HIGH-RISE APARTMENT BUILDINGS

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CLIENT REPORT

for

Canada Mortgage and Housing Corporation
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Establishing the Protocols for Measuring Air Leakage and Air Flow Patterns in High-Rise Apartment Buildings

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ESTABLISHING THE PROTOCOLS FOR MEASURING AIR LEAKAGE AND AIR FLOW PATTERNS IN HIGH-RISE APARTMENT BUILDINGS

INTRODUCTION

This study was undertaken jointly by the Canada Mortgage and Housing Corporation (CMHC) and the Institute for Research in Construction. The objective was to establish the protocols for measuring air leakage and air flow patterns in high-rise apartment buildings. The developed protocols will be used by CMHC contractors later for conducting similar measurements on several apartment buildings. The results will then be used as the basis for establishing air tightness and air quality standards for apartment buildings.

SCOPE

The scope included the development of test procedures based on previously developed test methods for measuring air leakage characteristics and air flow patterns for apartment buildings (Shaw et al. 1973, Tamura and Shaw 1976, Shaw 1980, Shaw et al. 1990). The developed procedures were tested on a 5-storey apartment building (170 Booth Street, Ottawa, see Figure 1) to identify potential problems in applying them on occupied buildings. The results were used to modify the detailed test procedures included as Appendix A.

The proposed test plan, as listed in the contract proposal (IRC NP-295), included:

Test 1: Fan pressurization and balanced fan pressurization tests to measure the air tightness values of:

a. the whole building,
b. the exterior walls of 12 apartment units on one floor (3rd floor),
c. the common walls between the test units and their adjacent units,
d. the interior partitions between the test units and the corridor,
e. the floor/ceiling separations of the test units,
f. the elevator shafts (if accessible to the fan),
g. the stair shafts,
h. the floor/ceiling separations of individual storeys;

Test 2: Measurements of pressure differences across the exterior wall of an apartment unit under various weather conditions.

Test 3: Tracer gas method to determine qualitatively the air flow patterns in the building.

The above test plan was made on the assumption that a unanimous consent to participate in the tests would be given by the tenants. As such a consent was not obtained, the following modifications were made:

1. Ten apartment units instead of 12 (Test 1b) were tested because two tenants refused to offer their units for testing. As a result, the air leakage rates through exterior and partition walls of these two units and their adjacent units could not be measured. Also, the corridor partitions were not tested because their leakage characteristics were changed when the apartment entrance door was replaced by a tightly sealed plywood sheet for the installation of the pressurization fan,

2. The elevator shaft (Test 1f) was not tested because it would upset too many tenants (the procedure for conducting elevator shaft tests is included in this report),

3. Test 2 was not conducted because no suitable apartment unit on the 2nd or 3rd floor was available (below the neutral pressure level to ensure the occurrence of air infiltration).

Even though the planned tests could not all be conducted, the results obtained are more than sufficient to provide the data needed to achieve the objectives. In addition, the following two new tests were added:

1. Measurement of the air tightness of the building envelope using the building's heating and ventilating system.

This test was requested by CMHC in lieu of Test 2 (Measurements of pressure differences across the exterior wall of an apartment unit under various weather conditions). The purpose of the new test was to study the feasibility of measuring the overall air tightness of the building envelope using the building's air handling system.

2. Measurements of outdoor air distribution.

The purposes of this test were (1) to study the feasibility of applying the tracer gas decay method for measuring air infiltration rates of the whole building, and

(2) to determine how the outdoor air is distributed within the building through the heating and ventilating system.

3. Measurements of the of the exterior wall air tightness of individual storeys.

The air tightness of the second, third and fourth storey exterior walls was tested.

TEST BUILDING

The five-storey masonry building, located at 170 Booth Street, Ottawa, was constructed in 1981 and was made available to CMHC and IRC by the Centretown Citizens Ottawa Corporation for the tests (Figure 1). The building has a basement, a ground floor and 4 typical storeys. The basement houses a party room, a laundry room, storage areas, a transformer vault and a mechanical room. Approximately half of the ground floor is occupied by commercial tenants (Figure 2). The garbage room is also located on this floor. Each typical storey (2nd to 5th floor) has 12 apartment units, 6 on each side of a corridor (Figure 3). The elevator shaft, enclosed garbage chute and electrical/service room are located at the centre of the building. There are two stairways, one on each end of the building. The South stairshaft has an access door to the roof.

The building has a central heating and ventilating system which supplies air to the corridor of each storey through two supply air registers. There is no return duct. Return air is drawn into the heating and ventilating system through a dampered opening in the outdoor air supply duct inside the basement mechanical room.

Each individual apartment unit is heated by a fan coil unit equipped with a hot water heating coil. There is no outdoor air supply to the fan coil unit or to individual apartment units. Ventilation air is drawn into the apartment unit from the corridor by discharging the indoor air to the outdoors through the kitchen and bath exhaust fans when they are turned on by the occupants.

TEST METHODS

The test methods were modified from those developed previously (Shaw et al. 1973, Tamura and Shaw 1976, Shaw 1980, Shaw et al. 1990). A brief description of these methods is given below:

Test 1a: Air tightness value of the whole building

As shown in Figure 1, a large vane-axial fan was used to depressurize the test building (Shaw et al. 1990). The fan airflow could be adjusted between 0 and 23 m^3/s. The fan inlet was connected by 12 m of 0.9 m diameter ducting to a plywood panel temporarily replacing a rear entrance door which connected to both stairwells. All interior doors to the stairshafts were kept open to provide a free flow path for the air drawn by the fan from the floor spaces, through the stairshaft, to the outdoors. For the test, the building's ventilation system was shut down (with fresh air intake dampers closed) and the dampers in all window air conditioners were closed. Also, the garbage room exhaust fan was shut off and the vent sealed, as was the vent to the transformer vault.

The air flow rate was measured upstream of the fan intake using a pair of total pressure averaging tubes. Flow rate measurements are accurate to within 5% of the measured values. The pressure differences across the building envelope at both the ground and roof levels were measured using an electronic manometer with a strip chart recorder (accurate to within 5% of the measured values). The average of the two measured values was used to represent the mean pressure difference across the building envelope. Prior to and immediately after test, the fan was sealed with a plastic sheet and the pressure differences across the envelope at the ground and top levels were measured. These "base readings" were then averaged and subtracted from the test results to minimize weather effects (wind and stack action).

As an alternative to using a vane-axial fan, the supply fan of the building's heating and ventilating system may in some cases be used for the test (Shaw et al. 1973). To obtain meaningful results, the capacity of the supply fan should be high enough to produce a minimum pressure difference across the building envelope of about 30 Pa. For conducting such a test, the heating and ventilating system is operated under 100% outdoor air conditions by closing the main return and exhaust dampers. Different air flow rates which are needed to produce four or five different pressure differences across the building envelope can be obtained by adjusting the outdoor or supply air damper.

This method was also attempted to measure the air tightness value of the building envelope. Air flow rates were measured with a set of total pressure averaging tubes installed in the outdoor air supply duct. Procedures for measuring the pressure difference across the building envelope and for conducting the air tightness test were identical to that using a vane-axial fan. At the maximum flow rate of 1,280 L/s, the pressure difference was about 3 Pa which was inadequate to produce meaningful results.

Test 1b: Air tightness values of exterior wall of individual apartment units

As shown in Figure 4a, a portable fan was used to depressurize the selected test apartment unit (Shaw 1980). The fan airflow could be adjusted between 0 and 320 L/s. The fan inlet was connected by 3 m of 0.2 m diameter ducting to a plywood panel temporarily replacing the entrance door of the test unit. All interior door in the apartment unit were kept open and all exhaust fans (e.g., kitchen and bath room exhaust fans) were turned off with the grilles sealed.

The air flow rate was adjusted with a manual damper and measured upstream of the fan intake with a pair of total pressure averaging tubes. Flow rate measurements are accurate to within 5% of the measured values. The pressure difference across the exterior wall was measured using an electronic manometer with a strip chart recorder. The pressure difference between the test unit and each of its adjacent units (Figure 4b) was reduced to approximately zero by depressurizing the adjusting units with fans equipped with manual dampers. This would minimize the flow of air through the partition walls and floor/ceiling separations into the test unit. A temporary partition in the corridor outside the test apartment unit could be installed so that the pressure difference across the corridor wall could also be reduced to approximately zero to minimize the air leakage through the corridor wall. This was not done in this building because it would block the corridor completely for a period of at least six hours. Such an installation is rarely acceptable for any fully occupied building. Consequently, the measured exterior wall airtightness value included that of the corridor wall. As shown in Figure 4b, a minimum of four balancing fans were required for this test.

Tests 1c and 1d: Air tightness values of common walls and floor/ceiling separations between a test unit and its adjacent units

Four tests were required to obtain the complete set of results. These four tests were conducted immediately after Test 1b using the same equipment. The test procedures were similar to that of Test 1b except that during each of these tests, one balancing fan was shut down and its flow damper closed (i.e., no pressure balancing was made for that component). The pressure differences across the component in question were measured simultaneously with those across the exterior wall. The leakage rates for each building component as a function of the pressure difference across that component could thus be determined once the exterior wall leakage of the test apartment unit (determined from the Test 1b relationship) had been subtracted from the measured flow.

Test 1e: Airtightness of stair shafts

The method for stairshaft leakage determinations has been reported by Tamura and Shaw (1976). Similar to Test 1a, the fan inlet was ducted to a plywood panel temporarily replacing a stair door. All other doors to the stairshaft were kept closed.

The air flow rate was measured upstream of the fan intake using a pair of total pressure averaging tubes. The pressure differences across the shaft wall were measured at least every second floor by inserting the probe into the shaft through the crack around the door. Again, an electronic manometer with a strip chart recorder was used. The measured values were averaged to represent the mean pressure difference across the shaft. Base readings to correct for weather effects (wind and stack action) were conducted as described for Test 1a.

Test 1f: Air tightness of elevator shafts

The method for elevator shaft leakage determinations has also been reported by Tamura and Shaw (1976). While in the test building, the elevator shaft test was not performed for the reasons given earlier, the test set-up and procedures would be similar to that for the stairshaft. For elevator shaft tests, an elevator service person should be hired to park the elevator car at the bottom of the shaft and open the ground floor elevator door. A plywood door panel would then be installed in the open door, and, similar to Test 1a, a fan connected to the plywood panel. All other elevator doors should be closed during the test.

Test 1g: Air tightness values of exterior walls and floor/ceiling separations of individual storeys

As shown in Figure 5, a portable variable speed fan was used to depressurize the test storey (Shaw 1980). The fan airflow could be adjusted between 0 and 1300 L/s. The fan inlet was connected by 7.3 m of 0.46 m diameter ducting to a plywood panel temporarily replacing a stair door of the test storey. The outside stair door at the ground floor was kept open during the test. The air flow rate was measured upstream of the fan intake with a pair of total pressure averaging tubes. The pressure difference across the exterior wall was measured using an electronic manometer with a strip chart recorder.

For measuring the air tightness value of the exterior wall, the pressures in the test storey and the storeys above and below (Figure 5) were balanced with separate fans (similarly installed in stairwell doors) to minimize the flow of leakage air through the floor/ceiling separations into the test storey. The air flow rates through the balancing fans were also controlled by individual manual dampers.

For measuring the air tightness of floor/ceiling separations, two additional tests were conducted immediately after the above test. During each test, only one balancing fan was used, therefore, the pressures across only one floor/ceiling separation was balanced. The pressure difference across the other floor/ceiling separation was measured simultaneously with the pressure difference across the exterior wall. The measured leakage rates during the floor and ceiling separation tests included the exterior wall leakage of the test floor. By knowing the pressure difference across the exterior wall during the test (this component could be calculated from the results of the first test), the air tightness values of the floor and ceiling separations could be determined.

Test 2: Pressure difference measurements for predicting air infiltration rates (not conducted)

The simplest method for estimating the air infiltration rate to an individual apartment unit would involve the measurement the pressure differences across the exterior wall under various weather conditions (Shaw et al. 1990). These values and the measured air tightness value of the exterior wall (determined in Test 1b) expressed in terms of C and n may then be used to calculate the air infiltration rate from the equation

$$q = C\ (\Delta P)^n$$

where,

- q = air infiltration rate, L/s
- C = exterior wall flow coefficient of test apartment unit, $L/(s.Pa^n)$
- Δp = pressure difference across the exterior wall, Pa
- n = flow exponent

This method has been validated previously using two high-rise apartment building (Shaw et al. 1990).

Test 3: Air flow patterns measurements

To determine qualitatively the air (contaminant) flow patterns within the building, a small amount of tracer gas was injected into a point in a selected location (e.g., a room, corridor on the lower floors, or a vertical shaft in the basement) at the begining of a test to create a local source. Immediately after the injection, tracer gas concentrations were measured at approximately 15 minute intervals at locations throughout the building (Figure 3). The measured tracer gas concentrations at each sampling location were then plotted against time. Based on the results, the air flow directions within the building could be determined.

Test 4: Air infiltration and outdoor air distribution

The method for measuring air infiltration rates and for determining the outdoor air distribution through the building's heating and ventilating system was identical to that for air flow pattern tests except that the tracer gas was injected into the supply air duct. As discussed below, the air infiltration rates for this building could not be measured because adequate mixing between the tracer gas and the interior air could not be achieved. This is because there are no supply air registers and return air grilles in individual apartment units.

RESULTS AND DISCUSSION

Following the developed test procedures, measurements of air tightness values were conducted on the building envelope, ten individual apartment units, three individual storeys and two stairshafts. The air flow patterns within the building were also measured for various contamination source locations.

Air Tightness Values

1. Whole building

The overall air tightness values per unit area of exterior wall for the test building are shown in Figure 6. Figure 6 also shows the overall air tightness values obtained using the building's heating and ventilating system. The results indicate that the building's heating and ventilating system was inadequate to produce a pressure difference across the exterior wall large enough for this purpose.

For comparison, the measured overall air tightness values of three other apartment buildings are shown in Figure 6. Buildings A, D, V are 5, 14 and 17 storeys high respectively. The results indicate that the overall air tightness value of the test building is almost the same as that of Building V and is about 60% and 100% greater than that of Buildings A and D at 50 Pa and 10 Pa respectively.

2. Individual apartment units

Figure 7 shows the overall air tightness values of each of ten apartment units on the third storey. The overall air tightness value included that of the exterior wall, the corridor wall, left and right interior partitions and floor/ceiling separations. As shown, based on a sample of ten, overall air tightness values may vary by as much as 100% of the smallest value.

Subject to the restrictions described above, six of these apartment units were fully tested to determine the air tightness values of the interior partitions, floor/ceiling separations and the exterior wall (which includes the corridor wall leakage). Figures 8 and 9 show typical results from two of the apartment units. In both cases the sum of the individual component air leakage rates is approximately equal to the independently measured overall value (from Figure 7).

The normalized exterior wall air tightness values reported for individual apartments on the third floor (Figure 10a) includes leakage through the corridor wall. The individual values thus exceed that determined for the third floor exterior wall as a whole (from Test 1g, also shown in Figure 10a). An attempt was made to remove the air tightness value of the corridor wall from the individual results by subtracting the averaged values of the left and right partitions (since the construction of the corridor wall is similar to that of the left and right partitions). Figure 10b indicates that these "corrected" values of exterior wall air tightness showed better agreement with the Test 1g observations. The lower value for the whole floor reflects the fact that no results from the corner apartment units could be obtained. Because patio doors and windows are expected to be much leakier than opaque walls (Shaw 1980) and corner units have greater opaque wall area than non-corner units, the normalized exterior wall air tightness value for corner units is likely to be smaller than that for non-corner units. Based on the sample of six apartment units tested, the highest exterior wall leakage value (Apt.301) was approximately double that of the lowest (Apt.306).

The contribution of walls and floor/ceiling separations to the overall air leakage rate was studied in ten apartment units. Figure 11 shows the air tightness values of the individual apartment partitions expressed as a percentage of the overall air tightness. As apartment units 303 and 310 were not tested, the exterior wall leakages of the adjacent units (302, 304, 309, and 311) could not be determined. Note that the exterior wall values reported have been corrected as described above for corridor leakage. At a pressure difference of 50 Pa, exterior walls are the main leakage component, and may account for as much as 60% of the overall value. Next are right partition walls, left partition walls, floors and ceilings which may account for up to 25%, 21%, 19% and 10% of the overall air leakage respectively.

3. Individual storeys

Figure 12 shows the air tightness values of the exterior walls of the 2nd, 3rd and 4th floors. Again, the plotted results have been normalized by exterior wall area. The results indicate that the value of exterior wall air tightness varies from storey to storey. For comparison, the overall air tightness value of the whole building is also included. As shown, the overall air tightness value is about the same of that of the 2nd floor and is much smaller than that of the other two storeys. One reason for the discrepancy was that a significant part of the ground floor where commercial tenants were occupied was separated from the building (i.e., no doors connecting the commercial units to the building). As a result, the air leakage rate through the exterior wall of the ground floor would be smaller than that of the upper floors. This, in turn, would result in a smaller overall air tightness value when it is normalized by the exterior wall area of the whole building including the area of the wall separating the commercial units and the building.

Figure 13 shows the air tightness values of floor/ceiling separations for the ground (ceiling only), 2nd, 3rd and 4th floors. Two tests were conducted on the 2nd-to-3rd and 3rd-to-4th floor separations (depressurizing both above and below). The values indicated for these floors are the means from the two tests. All results were normalized by the floor area of the individual storeys. The data for the 2nd-to-3rd and 3rd-to-4th floor separations shows a relatively high degree of variability when compared to the results for the exterior wall air tightness determinations. This was because the exterior wall air tightness values were approximately nine times greater than those of the floor/ceiling separations. As the air tightness values of floor/ceiling separations were obtained indirectly by subtracting the exterior wall leakage from the overall value, a small error in these measurements would result in a large error in the air tightness values of floor/ceiling separations.

4. Stairshafts

The air tightness of two stairshafts are shown in Figure 14. The South stairshaft, which contains the roof access hatch, is approximately 40% leakier than the North stairshaft.

Air Flow Patterns

1. Contaminant dispersion

Figures 15 through 20 show how a contaminant disperses from its source to other areas within the building. For this example, the tracer gas was injected into the garbage room on the ground floor. The wind was about 17 km/h from the South and the outdoor air temperature was about 11^{o}C during the test. The results indicate that immediately after tracer gas injection, the tracer gas concentrations in the corridor of every floor increased rapidly. The concentration in individual apartment units also increased, but at a slower rate. This suggests that stack action caused the contaminant (tracer gas) to disperse into the corridor on every floor through the garbage chute, stair and elevator shafts. The contaminant then migrated into individual apartment units from the corridors. Due to the influence of the South wind, more contaminant got into the apartment units on the North-East side than on the South-West side. The tracer gas concentrations at most sampling locations reached their peak about 40 minutes after injection.

The test was also conducted in June to minimize the influence of stack action. During the test, the wind was about 6 km/h from the South and the outdoor air temperature was about 22^{o}C. Figure 21 shows the concentration profiles for the 3rd floor. Similar to the winter results, the contaminant dispersed rapidly into the corridor and then into individual apartment units, however values are generally lower than the winter results. High tracer gas concentrations were observed in Apartment 311. This indicates that the exhaust fan in Apartment 311 was probably in use at the beginning of the test. Tracer gas migrating from the garbage shute (adjacent to Apt.311) into the corridor would thus be drawn into the apartment. As shown, the concentration rapidly approached that of other apartment units 20 minutes after tracer gas injection. These results suggest that any contaminant generated in the garbage room will migrate into individual apartment units via the garbage chute and the corridors. The extent and rate of this migration depends on wind speed and direction, stack action and the use of exhaust fans in the apartment units.

This test was repeated three times in winter, each time with a different location as the contaminant source (i.e., party room, mechanical room and front lobby), and each time with similar results.

2. Air infiltration rates and outdoor air distribution by ventilation system

Three tests were conducted, each under different weather conditions. Figures 22 through 27, one for each storey including the basement, show an example of the test results. The tracer gas was injected into the supply air duct of the heating and ventilating system. During the test the wind was about 24 km/h from the West and the outdoor air temperature was about -16^{o}C. The results (for example, Apt. 302 and 308, Figure 25) indicate that the tracer gas was not evenly distributed even on the same floor, nor did the concentrations at different locations decay at the same rate. This suggested that it was not possible to obtain a meaningful air infiltration rate for the whole building from the measured concentrations.

The measured tracer gas concentrations, howerver, give a good inidcation of how the outdoor air is distributed through the heating and ventilating system. As shown, the tracer gas migrated rapidly into the corridors first and then into individual apartment units. The results also show that there was a large difference in tracer gas concentration between Apartment 202 (2nd floor) and Apartment 502 (5th floor, directly above Apt.202), both units are located on the south-west side of the building. At the 2nd floor, however, the West wind and stack effects would both act to increase the air infiltration through the exterior wall which would be strong enough to prevent the corridor air from entering into Apartment unit 202. At the 5th floor, because the wind and stack effect would work against each other, air infiltration was too small to have any effect on the pressure inside the apartment unit, and the corridor air entered into the apartment causing a rapid increase in tracer gas concentration.

A comparison between this test and the test for contaminant dispersion indicates that when the tracer gas was distributed primarily through the building's heating and ventilating system, the concentrations in almost all the sampling locations reached their peak value about 20 minutes after injection. This was about twice as fast as that when the primary tracer gas flow paths were various vertical shafts, such as the garbage chute and stairshafts.

The results suggest that the building's heating and ventilating system is effective in distributing the outdoor air into the corridor of every floor, but the capacity may not be adequate to force the corridor air into all apartment units. Therefore, under certain weather conditions, cooking odours or other contaminants generated in the apartment units on the lower floors may migrate to other apartment units via stairshafts or other vertical shafts. On windy days, especially with North-East or South-West winds, contaminants may be driven across the corridor to the leeward apartments.

CONCLUSION

A set of test procedures have been developed for conducting a systematic study of air leakage and air flow patterns in multi-storey apartment buildings. The test methods were applied successfully to measure the air tightness values for the building enclosure, the exterior walls of individual storeys, and interior partitions of a 5-storey building. The air flow patterns of the building were also examined to determine how a contaminant would migrate from its source to other locations and how the outdoor air would be distributed through the heating and ventilating system.

By checking the test procedures at the five-storey building, it became apparent that the success of the procedures depends heavily on the cooperation of the building occupants. Without complete cooperation some of the proposed tests can not be conducted. As an example, the air tightness value of the corridor walls could not be measured directly because it was not possible to install a temporary partition in the corridor outside the test apartment unit. Without such a partition, the pressures between the test apartment unit and the corridor could not be balanced to minimize the air flow through the corridor wall into the test unit. Consequently, the exterior wall air tightness value for individual apartment units reported here includes the air leakage through the corridor wall.

The application of the tracer gas decay method for measuring the air infiltration rate of the whole building was unsuccessful. The heating and ventilating system could not be used successfully for measuring the air tightness value of the building envelope. These findings would likely be true for other apartment buildings with similar heating and ventilating systems.

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APPENDIX

DETAILED TEST PROCEDURES FOR MEASURING AIR LEAKAGE AND AIR FLOW PATTERNS IN HIGH-RISE APARTMENT BUILDINGS

Test 1: Fan pressurization and balanced fan pressurization tests to measure air tightness values

Test 1a: Air tightness value of the whole building

a) Test Planning:

- conduct initial site inspection and note following:

building details:

- age
- construction type
- number of storeys
- perimeter (m)
- height (m)
- typical floor plan
- apartment details:
  - kitchen exhaust
  - bathroom exhaust
  - window air conditioners
- ventilation system: location of:
  - exhaust fans and controls
  - supply fans and controls
  - fresh air intakes
  - exhaust air ducts
  - supply air ducts and grilles
  - return air ducts and grilles
- location of roof access(es)

- location of all vertical shafts (elevator, garbage, etc)

- space (cm) below doors to apartments from corridor

- space (cm) below internal doors connecting to building periphery

- presence of walls, ceilings, or floors common with adjacent rooms which are not to be included in the test

- underground garage access locations

<u>suitability for testing</u>:

- exterior door access to stairshaft (and elevator shaft if desired) for connection of pressurizing fan:

- door size suitable for fan connection

- outside area adjacent to door suitable for fan installation (including ducting, generator if necessary)

- if multiple stairshafts, connection at ground floor between stairwells

- disruption of traffic flow during testing

- openness of building

- access to outside for pressure tap installation

- cooperation of tenants and requirement for notification prior to testing

- availability of building superintendent to assist with test preparations and management

- space for equipment storage between tests

b) <u>Test Set-Up</u>:

- refer to Figure A1

- turn off all exhaust fans and air conditioners

- consult gas company re operation of any pilot lights on vented gas-fired appliances

- close and lock all apartment exterior doors and windows

- remove or seal all window air conditioners

- close dampers and seal, if possible, all exhaust grilles in the building envelope

- open all interior doors to stairshaft(s)

- for all rooms to be included in the test: inspect opening below doors connecting the rooms to the corridor, remove any obstructions

- if space under door is less than 2 cm, open doors slightly (2 cm is required for unrestricted air flow from apartment into corridor)

- install fan and flow measuring apparatus following instructions recommended in ASHRAE Fundamentals or CGSB Standard CAN/CGSB-149.10-M86 (depending on capacity, more than one fan may have to be installed). Ensure that the installation and operation of the fan(s) is/are consistent with calibration

- install pressure taps (48 mm ID tygon tubing; flattened copper tubing under doors/windows where necessary) at mid-points of four principal exterior walls at least 2m above grade if possible. All the square cut ends must point upwards or downwards (see CAN/CGSB-149.10-M86)

- install pressure taps in centre of top and ground floors

- install pressure tap near the centre of the roof

- protect all interior and exterior pressure taps from the influence of the fan

- install pressure monitoring equipment to measure pressure differences between:

  i) manifolded ground floor exterior and ground floor corridor

  ii) roof and top floor corridor

- seal door panel and all fan connections

- if the test building has doors common with adjacent rooms, buildings or tunnels which are not included in the test, then close the doors and seal the openings with tapes or plastic sheets

c) Inspection of Installed Test Equipment:

- visually inspect for any physical defects
- visually inspect for proper installation according to manufacturer's specifications
- inspect door panel and fan seals
- level any devices where required
- set all indicators to zero positions

d) Suitability of Weather Conditions (On-site or nearest weather station):

- temperature differential: $(t_{in} - t_{out}) < 10^{o}K$
- wind speed: < 20 km/h

e) Test Procedure:

- turn off ventilation system for building and close fresh air intake dampers
- record test date and start time
- measure and record:
  - outdoor air temperature, $t_{out,i}$ (°C)
  - indoor air temperature, $t_{in,i}$ (°C)
  - wind speed, $V_{w,i}$ (km/h)
  - wind direction, $D_{W,i}$
  - initial ambient atmospheric pressure, $P_{a,i}$ (kPa)
- inspect building exterior: make sure all windows and exterior doors are tightly closed
- zero pressure instruments
- seal the pressurization fan opening(s) and record the pressure differences across the envelope at ground and roof levels, $\Delta P_{1,i}$ and $\Delta P_{2,i}$, respectively
- remove fan seal(s) and switch fan(s) on

- adjust air flow to produce a pressure difference of approximately 50 Pa across the envelope (at ground level only)

- allow conditions to stabilize

- measure and record:

  - air flow rate, Q (L/s) at fan

  - pressure differences, ΔP_1 and ΔP_2 (Pa) across building envelope at ground and roof levels, respectively

  - air temperature at fan intake, t_{fan} (°C)

- adjust envelope pressure difference to approximately 40 Pa and repeat measurements

- repeat for envelope pressure differences of approximately 30, 20, 15 and/or 10 Pa (in that order)

- switch fan(s) off, seal the fan(s) and record the final pressure differences across the envelope, $\Delta P_{1,f}$ and $\Delta P_{2,f}$ (Pa)

- note time of test completion

- measure and record:

  - outdoor air temperature, $t_{out,f}$ (°C)

  - indoor air temperature, $t_{in,f}$ (°C)

  - wind speed, $V_{w,f}$ (km/h)

  - wind direction, $D_{W,f}$

  - ambient atmospheric pressure, $P_{a,f}$ (kPa)

- re-inspect building exterior: make sure all windows and exterior doors are still tightly closed (note any exceptions; repeat test if necessary; ideally, windows and doors should be continuously monitored while the test is in progress)

f) Data Analysis:

- correction of pressure readings:

1. Base ground level envelope pressure difference

$$\Delta P_{1,b} = \frac{(\Delta P_{1,i} + \Delta P_{1,f})}{2}$$

2. Base roof level envelope pressure difference

$$\Delta P_{2,b} = \frac{(\Delta P_{2,i} + \Delta P_{2,f})}{2}$$

3. Corrected ground level envelope pressure difference

$$\Delta P^*_1 = (\Delta P_1 - \Delta P_{1,b})$$

4. Corrected roof level envelope pressure difference

$$\Delta P^*_2 = (\Delta P_2 - \Delta P_{2,b})$$

5. Mean corrected envelope pressure difference

$$\Delta P^* = \frac{(\Delta P^*_1 + \Delta P^*_2)}{2}$$

- correction of measured fan flow:

- correct Q values (gives Q^*) according to procedures in CAN/CGSB-149.10-M86

- plot: Q^* vs ΔP^*

- optionally, normalize leakage by exterior wall surface area, S:

- plot: (Q^*/S) vs ΔP^*

Test 1b: Air tightness values of exterior wall of individual apartment units

a) Test Set-Up:

- refer to Figure 4

- tightly shut all windows and exterior doors and turn off all kitchen and bathroom exhaust fans in test apartment and apartments on either side, above and below (the "balancing" apartments)

- remove or seal all window air conditioners in test and balancing apartments

- install pressure tap to exterior surface of living room window of test apartment (tap must point upwards or downwards; see CAN/CGSB-149.10-M86), identify tap as Exterior Wall

- install pressure tap in the centre of the test apartment; identify as Reference Pressure

- install pressure taps in the centre of each balancing apartments and in the corridor outside the test apartment, and identify as follows:

  i) Apartment Left

  ii) Apartment Right

  iii) Apartment Above

  iv) Apartment Below

  v) Corridor

- install plywood panels in entrance doors of each of the five apartments

- connect the pressure taps for the Exterior Wall, Corridor and Balancing Apartments to separate pressure measuring devices (see Figure 4)

- connect the Reference Pressure tap (from the interior of the test apartment) to the reference side of each of the six pressure measuring devices

- install fans and flow controllers in each test panel

- install flow measuring equipment for test apartment fan

- locate pressure measuring devices i-iv immediately adjacent to corresponding flow controllers

- install data acquisition system to record pressure differentials and test apartment flow rates

- seal all door panels and fan connections

- if possible, position two members of test team at the balancing fans located at the apartments above and below the test unit. During the test, communicate balancing instructions and data reporting with these members via two-way radios (check that two-way radio operation does not interfere with instrument operation)

b) Test Procedure:

- record test date and start time

- measure and record:

  - outdoor air temperature, $t_{out,i}$ (°C)

  - indoor air temperature, $t_{in,i}$ (°C)

  - wind speed, $V_{w,i}$ (km/h)

  - wind direction, $D_{W,i}$

  - initial ambient atmospheric pressure, $P_{a,i}$ (kPa)

(Note: weather information can be obtained from local weather station; P_a must not be corrected to sea level)

- zero pressure measuring devices

- with all fans turned off, seal all the fan openings and record intial base pressure differences (Outside $\Delta P_{ew,i}$, Apt left $\Delta P_{l,i}$, Apt right $\Delta P_{r,i}$, Apt below $\Delta P_{f,i}$, Apt above $\Delta P_{c,i}$, and Corridor $\Delta P_{corr,i}$)

- remove seals and turn all fans on

- adjust flow rate of fan for test apartment until pressure difference across exterior wall, ΔP_{ew}, is approximately 50 Pa.

- adjust balancing fans until all balanced partitions show 0 $\pm$ 1 Pa pressure difference (Note: continuous adjustments may be required to maintain ΔP_{ew} at desired level while balancing is in process)

- allow pressures and flows to stabilize

- record all pressures (ΔP_{ew}, ΔP_l, ΔP_r, ΔP_f, ΔP_c, $DP_{corr,i}$)

- record exterior wall flow rate, Q_{ew}, as measured through the fan installed in the test apartment

- record air temperature at fan intake, t_{fan} (°C)

- adjust ΔP_{ew} to approximately 40 Pa

- re-balance and repeat measurements

- repeat for ΔP_{ew} of approximately 30, 20, 15 and/or 10 Pa (in that order)

- turn all fans off and seal their openings

- record final pressure differences ($\Delta P_{ew,f}$, $\Delta P_{l,f}$, $\Delta P_{r,f}$, $\Delta P_{f,f}$, $\Delta P_{c,f}$, $DP_{corr,i}$)

c) Data Analysis:

- correct measured pressure difference values across exterior wall according to procedure given for Test 1a (gives: ΔP^{*}_{ew})

- correct Q_{ew} according to procedures in CAN/CGSB-149.10-M86 if required

- plot: Q^{*}_{ew} vs ΔP^{*}_{ew}

Tests 1c and 1d: Air tightness values of common walls and floor/ceiling separations between a test unit and its adjacent units

a) Test Set-up and Procedure:

- four tests are to be conducted: one for each of the partitions between the test unit and the adjacent "balancing" apartments. One additional test is required if the air tightness value of the corridor partition is to be measured

- for each of the tests, follow instructions for Test 1b, except:

    - turn off the fan (and seal the fan opening) of the balancing apartment for the component under test

    - proceed as for Test 1b and balance the other three apartments

    - record the pressure differences generated across all partitions (ΔP_x)

    - record the flow measured at the test unit fan (Q_{mx}; where x = l, r, f, or c depending on which component is unbalanced)

(Note: Q_{mx} is the combined leakage of the test apartment exterior wall and the unbalanced partition)

b) Data Analysis:

- refer to Figure A2; for each partition:

- plot: Q_{ew} vs ΔP^*_{ew} (from results of Test 1b)

- on same graph plot: Q_{mx} vs $(\Delta P^*_{ew})_{mx}$

(where $(\Delta P^*_{ew})_{mx}$ is the corrected pressure recorded across the exterior wall while Q_{mx} was measured)

- for each $(\Delta P^*_{ew})_{mx}$, determine from the graph, the difference, Q_x (where x = l, r, f, c, or corr depending on which component is unbalanced), between the exterior wall leakage and the combined exterior wall/unbalanced partition leakage (see Figure A2)

- plot: | Q_x vs ΔP_{xm} |

Note ΔP_{xm} and $(\Delta P^{*}ew)_{mx}$ were measured simultaneously.

Tests 1e and 1f: Airtightness of elevator shafts and stair shafts

a) Test Set-Up:

- install plywood panel in doorway of test shaft:
  - for stairshaft: install panel in outside entrance to stairshaft or in a stairshaft doorway which has corridor access to an outside door
  - for elevator shaft: have elevator serviceman move car to lowest position, open ground floor doors, and install panel in door opening. Check for openings in roof or floor of elevator shaft that require sealing (or sizing to estimate leakage contribution)
- install fan in door panel
- install flow measuring equipment
- seal door panel and fan connections
- install pressure tap pairs on either side of shaft doorways:
  - for buildings with 5 or less storeys: one pair on each floor
  - for buildings with more than 5 storeys: 5 evenly spaced pairs

  (protect all pressure taps from the influence of the fan)
- connect pressure tap pairs to pressure measuring devices
- inspect shaft for any roof access doors or hatches and close tightly
- shut all shaft doors tightly
- post warning signs indicating test in progress on all shaft accesses
- open corridor door to exterior if required

- shafts with exterior wall(s)

b) Test Procedure:

- record test date and start time
- measure and record:
  - outdoor air temperature, $t_{out,i}$ (°C)
  - indoor air temperature, $t_{in,i}$ (°C)
  - wind speed, $V_{w,i}$ (km/h)
  - wind direction, $D_{W,i}$
  - initial ambient atmospheric pressure, $P_{a,i}$ (kPa)

  (Note: weather information can be obtained from local weather station; P_a must not be corrected to sea level)

- zero pressure instruments

  (Note: for all pressure measurements, allow sufficient time for pressure recorded to be within 1 Pa of its stable value)

- seal the fan exhaust opening and record the pressure differences across the shaft, $\Delta P_{x,i}$ (where x = 1 to 5)
- remove fan seal and switch fan on
- adjust air flow to produce a pressure difference (at ground level) of approximately 50 Pa across the shaft
- allow conditions to stabilize
- measure and record:
  - air flow rate, Q_s (L/s) at fan
  - pressure differences, ΔP_x (Pa) across shaft
  - air temperature at fan intake, t_{fan} (°C)
- adjust Q_s (L/s) to achieve a mean pressure difference of approximately 40 Pa and repeat measurements
- repeat for mean pressure differences of approximately 30, 20, 15 and/or 10 Pa (in that order)
- switch fan off and seal

- record the final pressure differences across shaft, $\Delta P_{x,f}$ (Pa)
- measure and record:
  - outdoor air temperature, $t_{out,f}$ (°C)
  - indoor air temperature, $t_{in.f}$ (°C)
  - wind speed, $V_{w,f}$ (km/h)
  - wind direction, $D_{W,f}$
  - ambient atmospheric pressure, $P_{a,f}$ (kPa)

c) <u>Data Analysis</u>:

correct Q_s according to procedures in CAN/CGSB-149.10-M86 if required (gives Q^*_s)

- correct measured pressure differences according to procedure given for Test 1a (gives: ΔP^*_x)
- calculate mean corrected pressure difference across shaft, ΔP^*_s for each flow condition
- plot: Q^*_s vs ΔP^*_s

Test 1g: Air tightness values of exterior walls and floor/ceiling separations of individual storeys

a) <u>Test Set-Up</u>:

- tightly shut all windows and exterior doors and turn off all kitchen and bathroom exhaust fans on test floor and floors above and below (the "balancing" floors)

- remove or seal all window air conditioners on test and balancing floors

- install pressure taps to exterior surfaces of windows at mid-points of four principal exterior walls on test floor and manifold the taps (taps must point upwards or downwards; see CAN/CGSB-149.10-M86)

- install pressure taps at centre of corridor on test and balancing floors

- install pressure measuring devices to monitor the pressure differences between the centre of the test floor and:

  i) the manifolded exterior wall taps of the test floor (reads ΔP_{ew})

  ii) the centre of the floor above the test floor (reads ΔP_a)

  iii) the centre of the floor below the test floor (reads ΔP_b)

- install plywood panels in a stairshaft door on the test floor and on each balancing floor

- install fans and flow controllers in each plywood panel (flow direction from corridor to stairshaft)

- seal all door panels and fan connections

- locate pressure measuring devices (ii) and (iii) immediately adjacent to corresponding flow controllers

- install flow measuring equipment for fan on test floor

- if possible, position two members of test team at the balancing fans located on the floors above and below the test floor. During the test, communicate balancing instructions and data reporting with these members via two-way radios.

b) Test Procedure:

- record test date and start time
- measure and record:
  - outdoor air temperature, $t_{out,i}$ (°C)
  - indoor air temperature, $t_{in,i}$ (°C)
  - wind speed, $V_{w,i}$ (km/h)
  - wind direction, $D_{W,i}$
  - initial ambient atmospheric pressure, $P_{a,i}$ (kPa)

  (Note: weather information can be obtained from local weather station; P_a must not be corrected to sea level)
- open door to outside from stairshaft to which fans have been connected
- zero pressure measuring devices
- with all fans turned off and sealed, record pressure differences ($\Delta P_{ew,i}$, $\Delta P_{a,i}$, $\Delta P_{b,i}$)
- remove seals and turn all fans on
- adjust flow rate of fan for test floor until pressure difference across exterior wall, ΔP_{ew}, is approximately 50 Pa.
- adjust balancing fans to give 0 ± 1 Pa pressure difference across floor separations (Note: continuous adjustments may be required to maintain ΔP_{ew} at desired level while balancing is in process)
- allow pressures and flows to stabilize
- record all pressures (ΔP_{ew}, ΔP_a, ΔP_b)
- record exterior wall flow rate, Q_{ew}
- record air temperature at fan intake, t_{fan} (°C)
- adjust ΔP_{ew} to approximately 40 Pa
- re-balance and repeat measurements
- repeat for ΔP_{ew} of approximately 30, 20, 15 and/or 10 Pa (in that order)
- turn all fans off and seal fan openings

- record final pressure differences ($\Delta P_{ew,f}$, $\Delta P_{a,f}$, $\Delta P_{b,f}$)
- repeat test with one balancing fan on floor above turned off and sealed (similar to Test 1d)
- repeat for balancing fan on floor below

c) Data Analysis:

Exterior wall leakage:

- correct measured pressure difference across exterior wall according to procedure given for Test 1a (gives: ΔP^*_{ew})
- correct Q_{ew} according to procedures in CAN/CGSB-149.10-M86 if required
- plot: Q^*_{ew} vs ΔP^*_{ew}

Floor/ceiling separation leakage:

- follow directions given for Tests 1c and 1d to determine Q^*_a and Q^*_b

Test 2: Measurements of pressure differences across the exterior wall of an apartment unit under various weather conditions.

a) Test Set-Up:

- set up pressure taps and pressure measuring device to record pressure difference across apartment exterior wall as specified in Test 1b

b) Test Procedure:

- continuously record ΔP across exterior wall caused by wind and stack action for a preset monitoring period

c) Data Analysis:

- refer to CGSB Standard: CAN/CGSB-149.10-M86, from results of Test 1b, calculate flow coefficient and flow exponent (C and n, respectively) for the exterior wall
- calculate air infiltration rate from the following equation using the pressure differences obtained in b)

$$q = C\,(\Delta P_{ew})^n$$

where,

- q = air infiltration rate, L/s
- C = exterior wall flow coefficient of test apartment unit, $L/(s.Pa^n)$
- ΔP_{ew} = pressure difference across the exterior wall, Pa
- n = flow exponent

Test 3: Tracer gas methods to determine qualitatively the air flow patterns in the building.

a) Test Preparation:

- calculate internal volume of test building, V_b (m^3)

- using the following equation, calculate the volume of SF_6 tracer gas required to achieve a set concentration of SF_6 in the building (50 ppb is recommended):

$$m = V_b * C_t * 10^{-6}$$

where:

m = amount of SF_6 tracer gas, L;
V_b = building volume, m^3;
C_t = maximum concentration, ppb (50 ppb)

- prepare required volume of pure SF_6 and store in tightly sealed syringe(s) or pressurized cylinder

- determine locations within building at which to conduct air sampling

- prepare 20 ml draw Vacutainers (e.g. Fisher 02-683-54) for sampling by taping septums securely in place

  Note: each test will require approximately 10 Vacutainers/sampling location

- prepare one sampling tube for each member of sampling team for insertion under doors (use approximately 1m lengths of approximately 2mm ID stainless steel tubing bent in L-shape). Cap one end of each sampling tube with rubber septum

- assemble following equipment for each member of sampling team:

  - stopwatch
  - marking pen capable of writing on Vacutainers
  - Vacutainers
  - 2 - 60 cc hypodermic syringes with Luer-Lok tips
  - 2 - 21G1 hypodermic needles
  - sampling tube
  - 5 spare septums for sampling tube

b) Test Procedure:

- make sure all exterior windows and doors are closed for the duration of the test
- record test date and start time
- measure and record:
    - outdoor air temperature, $t_{out,i}$ (°C)
    - indoor air temperature, $t_{in,i}$ (°C)
    - wind speed, $V_{w,i}$ (km/h)
    - wind direction, $D_{W,i}$
    - initial ambient atmospheric pressure, $P_{a,i}$ (kPa)

(Note: weather information can be obtained from local weather station; P_a must not be corrected to sea level)

Tracer Gas Release:

- at pre-determined location within the building, assemble sampling team and zero all stopwatches
- release tracer gas (Note: make sure tracer gas container is tightly sealed and do not bring it into the building until ready to release)
- disperse sampling team to their selected sampling locations
- wait 10 minutes after tracer gas injection before taking first sample
- continue sampling every 15 minutes for approximately 2 h

Tracer Gas Sampling Procedure:

a. Insert sampling tube under door. Mount hypodermic needle on syringe and remove needle cover. Purge the syringe by completely depressing the plunger. Insert needle through septum into sampling tube.

b. Just prior to the scheduled sampling time, purge 60 ml syringe twice with room air from first location (removing filled syringe and needle from tube, expelling air and re-inserting)

c. Draw a 60 ml sample of air into the syringe.

d. After pausing several seconds to allow the syringe to reach atmospheric pressure, remove syringe and needle from tube, push the plunger forward to the 50 ml mark.

e. Insert the syringe needle into the rubber septum-type stopper of Vacutainer.

f. **WHILE NOT EXERTING ANY PRESSURE ON THE PLUNGER,** observe the syringe plunger to be drawn forward to approximately the 30-35 ml mark of the syringe. **If the plunger fails to draw near the 30 ml MARK, discard the tube and repeat steps b through f.**

g. Push the plunger forward to the end of the syringe to inject the remaining sample into the sampling tube.

h. While maintaining pressure on the syringe plunger, remove the needle from the tube, and record the sampling time and location on the tube.

i. Move to the next assigned sampling location and repeat steps a to h until all locations have been sampled.

- repeat steps a-i at approximately 15 minute intervals for 2 hours following release of the tracer gas. Replace sampling tube septum every 10-20 samples

- measure and record:

  - outdoor air temperature, $t_{out,f}$ (°C)

  - indoor air temperature, $t_{in.f}$ (°C)

  - wind speed, $V_{w,f}$, (km/h)

  - wind direction, $D_{W,f}$

  - ambient atmospheric pressure, $P_{a,f}$ (kPa)

c) <u>Data Analysis</u>:

- analyse SF_6 concentrations using gas chromatograph equipped with electron capture detector

- for each sampling location, plot SF_6 concentration vs. elapsed time from SF_6 release

GLOSSARY OF TERMS:

C	exterior wall flow coefficient of test apartment unit, $L/(s.Pa^n)$
C_t	maximum concentration, ppb (50 ppb)
ΔP^*	corrected mean envelope pressure difference, Pa
ΔP^*_1	corrected envelope pressure difference at ground level, Pa
ΔP^*_2	corrected envelope pressure difference at roof level, Pa
ΔP^*_3	internal building pressure difference, Pa
ΔP^*_a	corrected pressure difference across floor separation above test floor, Pa
ΔP^*_b	corrected pressure difference across floor separation below test floor, Pa
ΔP^*_c	corrected pressure difference across ceiling, Pa
ΔP^*_{corr}	corrected pressure difference across corridor, Pa
ΔP^*_{ew}	corrected pressure difference across exterior wall, Pa
ΔP^*_f	corrected pressure difference across floor, Pa
ΔP^*_l	corrected pressure difference across left partition, Pa
ΔP^*_r	corrected pressure difference across right partition, Pa
ΔP_1	envelope pressure difference at ground level, Pa
$\Delta P_{1,f}$	final base ground level envelope pressure difference, Pa
$\Delta P_{1,i}$	initial base ground level envelope pressure difference, Pa
ΔP_2	envelope pressure difference at roof level, Pa
$\Delta P_{2,f}$	final base roof level envelope pressure difference, Pa
$\Delta P_{2,i}$	initial base roof level envelope pressure difference, Pa

ΔP_a	pressure difference across floor separation above test floor, Pa
$\Delta P_{a,f}$	final pressure difference across floor separation above test floor, Pa
$\Delta P_{a,i}$	initial pressure difference across floor separation above test floor, Pa
ΔP_b	pressure difference across floor separation below test floor, Pa
$\Delta P_{b,f}$	final pressure difference across floor separation below test floor, Pa
$\Delta P_{b,i}$	initial pressure difference across floor separation below test floor, Pa
ΔP_c	pressure difference across ceiling, Pa
ΔP_{corr}	pressure difference across corridor, Pa
$\Delta P_{c,f}$	final pressure difference across ceiling, Pa
$\Delta P_{c,i}$	initial pressure difference across ceiling, Pa
ΔP_{ew}	pressure difference across exterior wall, Pa
$\Delta P_{ew,f}$	final pressure difference across exterior wall, Pa
$\Delta P_{ew,i}$	initial pressure difference across exterior wall, Pa
ΔP_f	pressure difference across floor, Pa
$\Delta P_{f,f}$	final pressure difference across floor, Pa
$\Delta P_{f,i}$	initial pressure difference across floor, Pa
ΔP_l	pressure difference across left partition, Pa
$\Delta P_{l,f}$	final pressure difference across left partition, Pa
$\Delta P_{l,i}$	initial pressure difference across left partition, Pa
ΔP_r	pressure difference across right partition, Pa
$\Delta P_{r,f}$	final pressure difference across right partition, Pa
$\Delta P_{r,i}$	initial pressure difference across right partition, Pa

$D_{W,f}$	final wind direction
$D_{W,i}$	initial wind direction,
m	amount of SF_6 tracer gas, L
n	flow exponent
$P_{a,f}$	final ambient atmospheric pressure, kPa
$P_{a,i}$	initial ambient atmospheric pressure, kPa
Q	air flow rate, L/s
q	air infiltration rate, L/s
Q^*	corrected air flow rate, L/s
Q^*_a	corrected air flow rate through floor separation above test floor, L/s
Q^*_b	corrected air flow rate through floor separation below test floor, L/s
Q^*_c	corrected air flow rate across ceiling, L/s
Q^*_{ew}	corrected air flow rate across exterior wall, L/s
Q^*_f	corrected air flow rate across floor, L/s
Q^*_l	corrected air flow rate across left partition, L/s
Q^*_r	corrected air flow rate across right partition, L/s
Q^*_s	corrected shaft air flow rate, L/s
Q_a	air flow rate through floor separation above test floor, L/s
Q_b	air flow rate through floor separation below test floor, L/s
Q_c	air flow rate across ceiling, L/s
Q_{ew}	air flow rate across exterior wall, L/s
Q_f	air flow rate across floor, L/s
Q_l	air flow rate across left partition, L/s
Q_m	measured air flow rate, L/s
Q_r	air flow rate across right partition, L/s

Q_s	shaft air flow rate, L/s
S	exterior wall surface area, m^2
t_{fan}	air temperature at fan intake, ^oC
$t_{in,f}$	final indoor air temperature, ^oC
$t_{in,i}$	initial indoor air temperature, ^oC
$t_{out,f}$	final outdoor air temperature, ^oC
$t_{out,i}$	initial outdoor air temperature, ^oC
V_b	building volume, m^3
$V_{w,f}$	final wind speed, km/h
$V_{w,i}$	initial wind speed, km/h

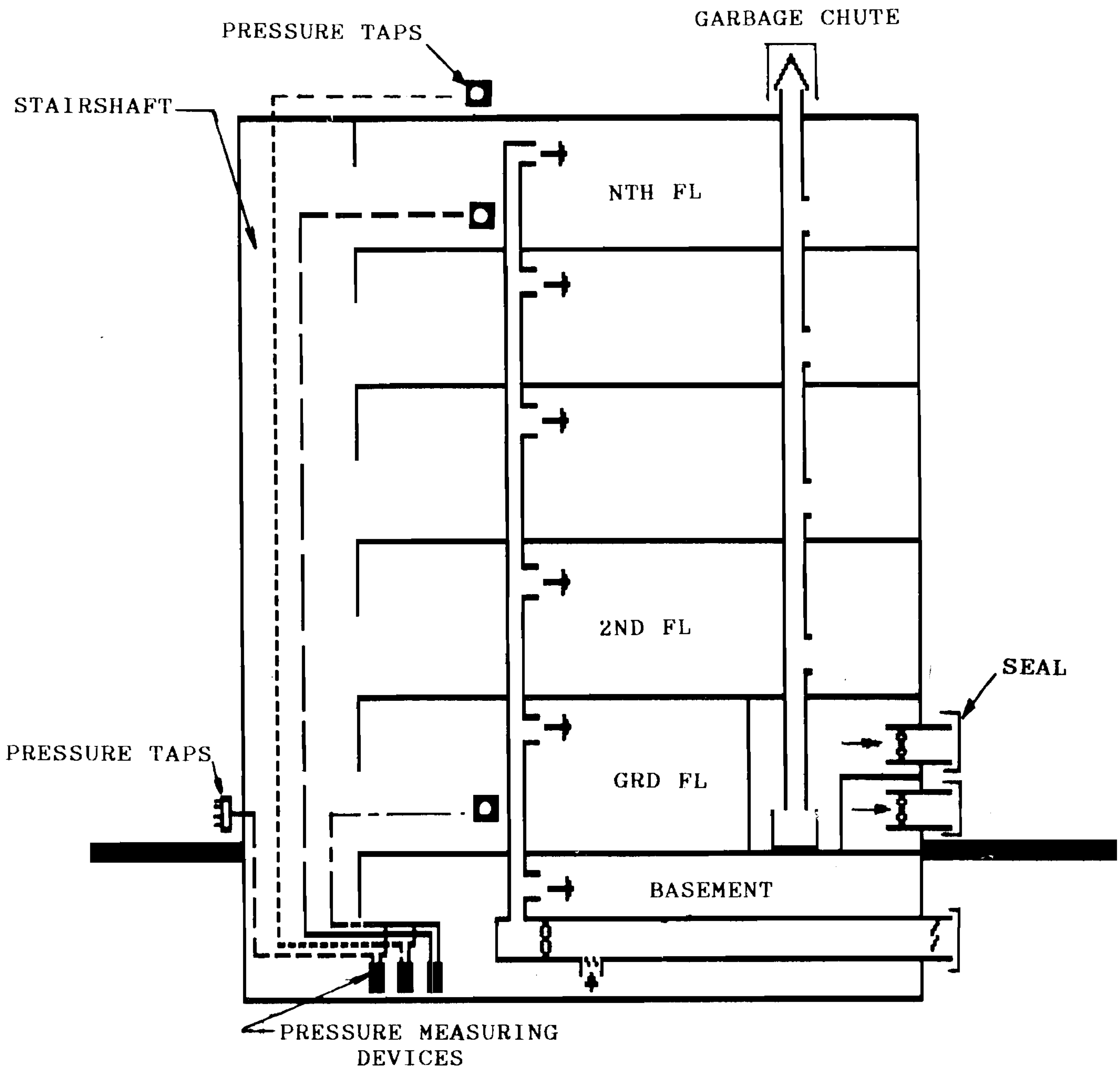


Figure A1 Test set-up showing locations of pressure taps

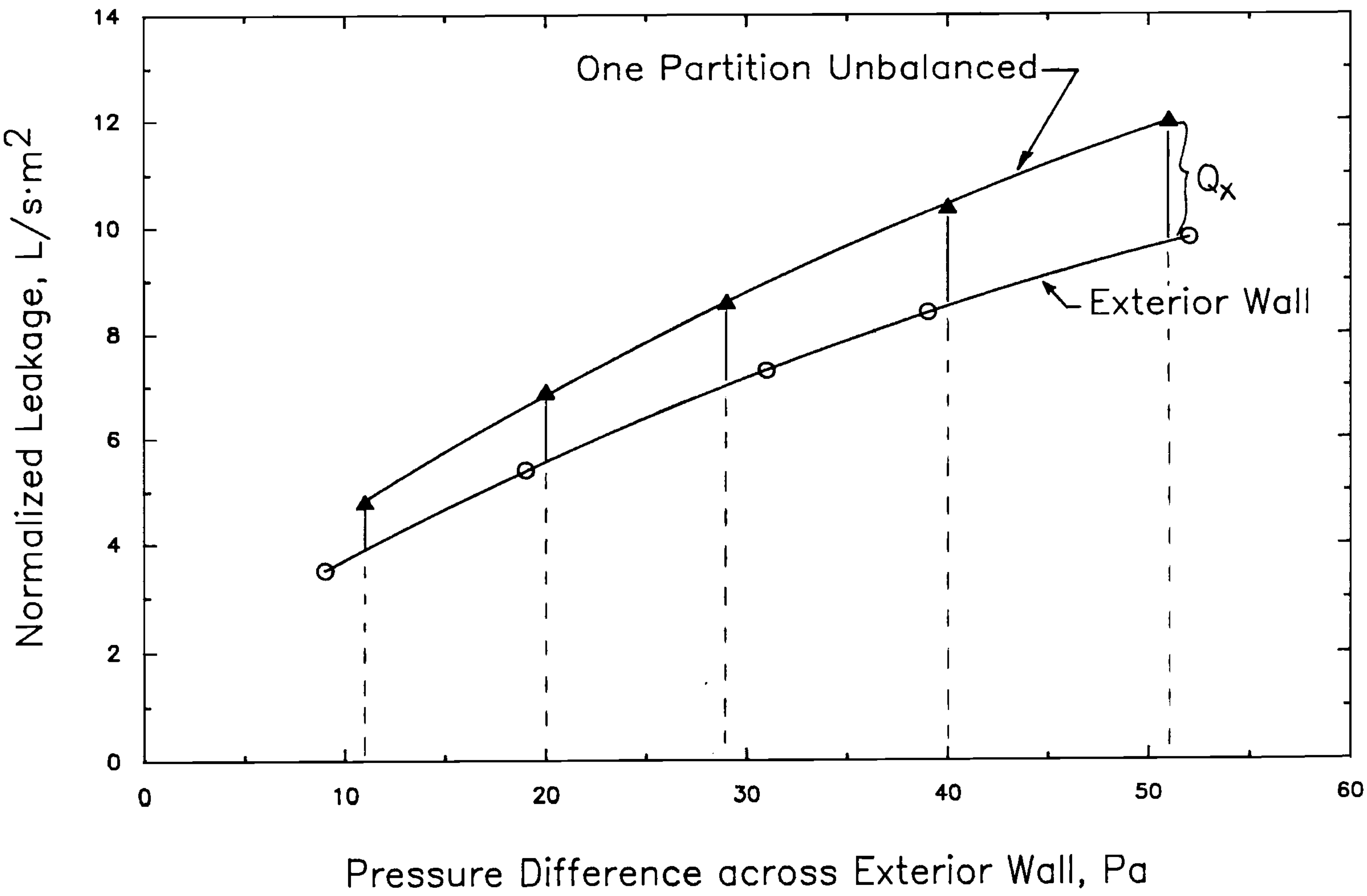


Figure A2 Measured flows vs. exterior wall pressure difference

Figure 1 Test building showing test set-up for measuring air tightness value of the building envelope

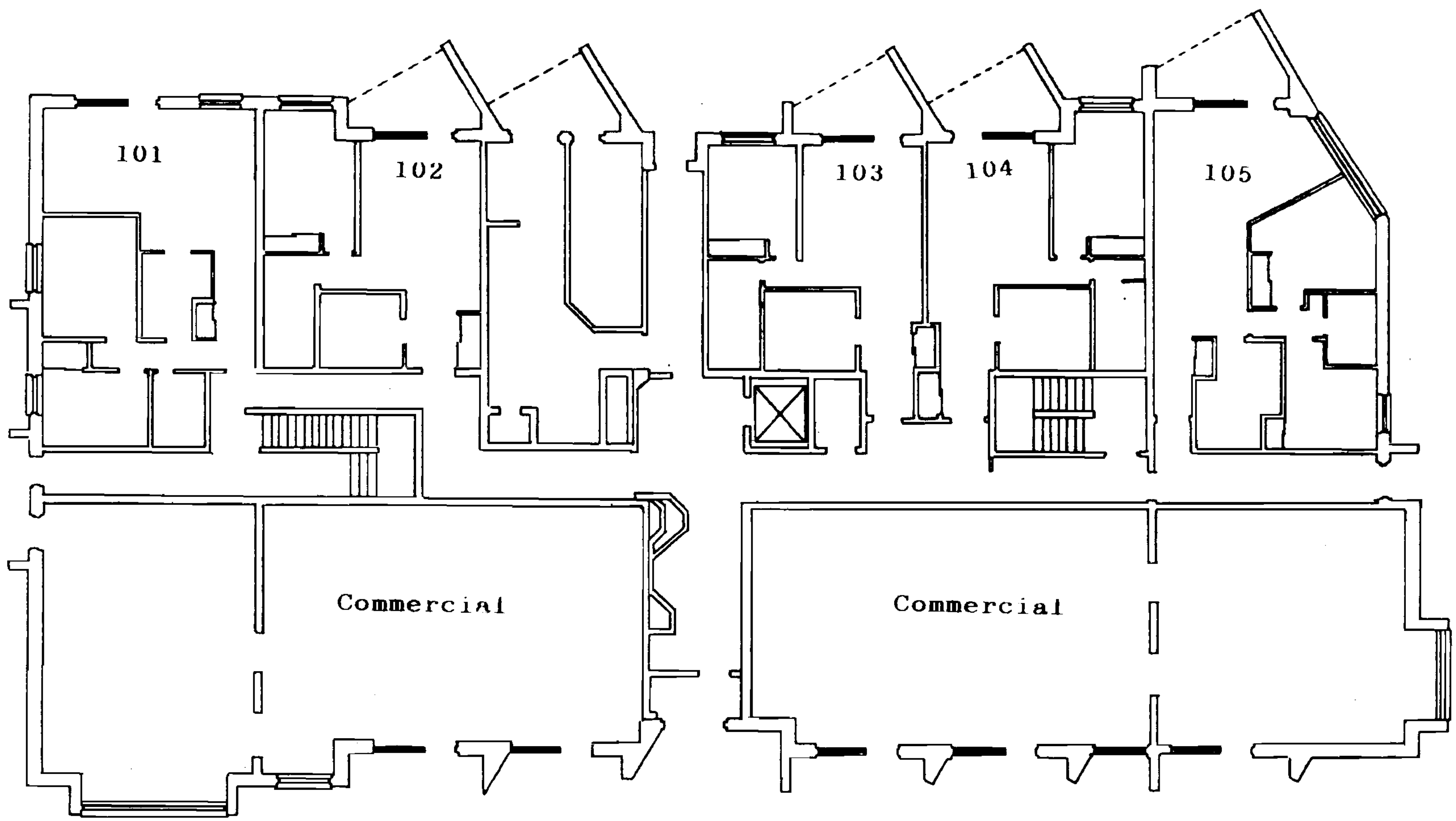


Figure 2 Ground floor plan

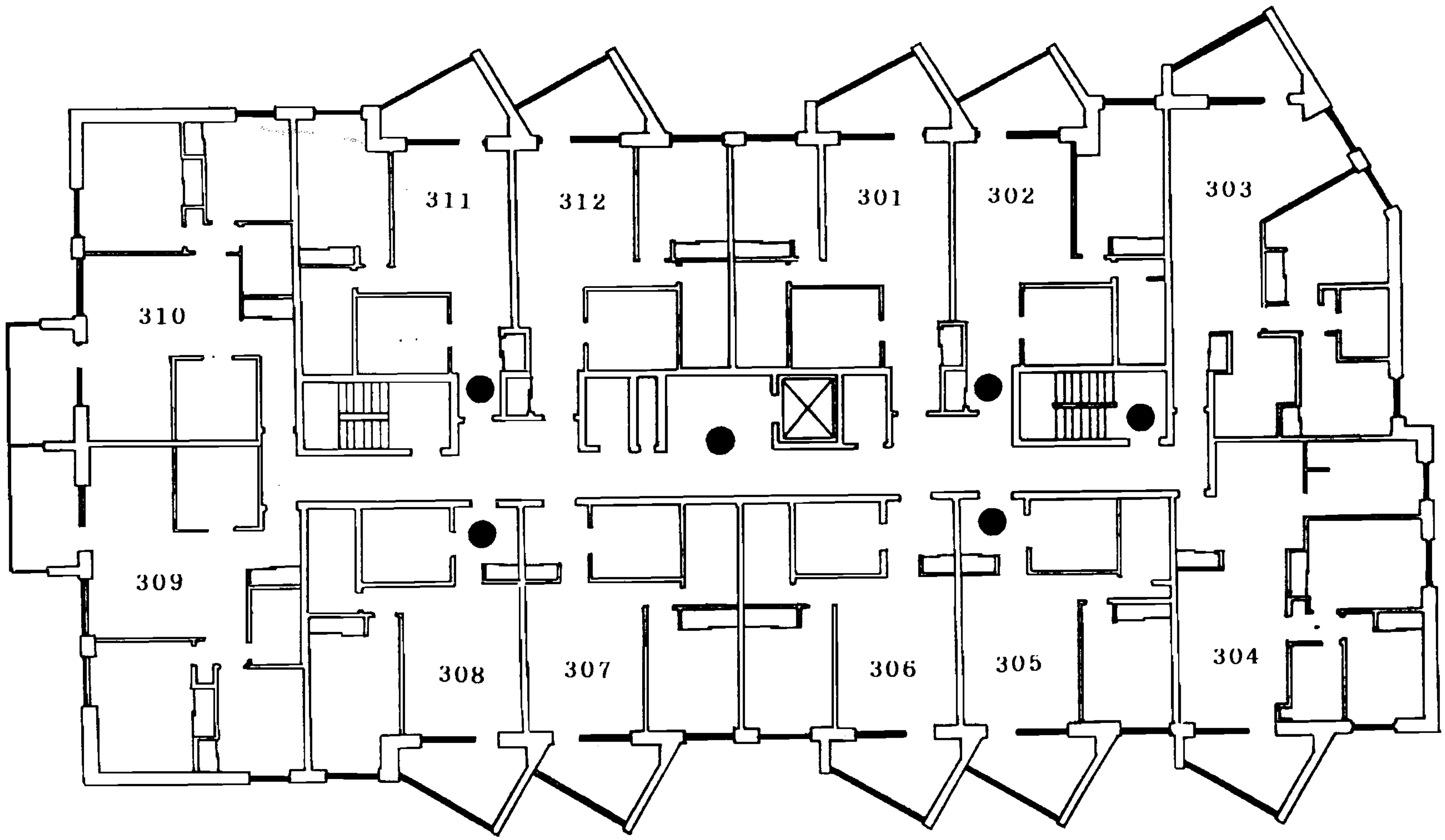
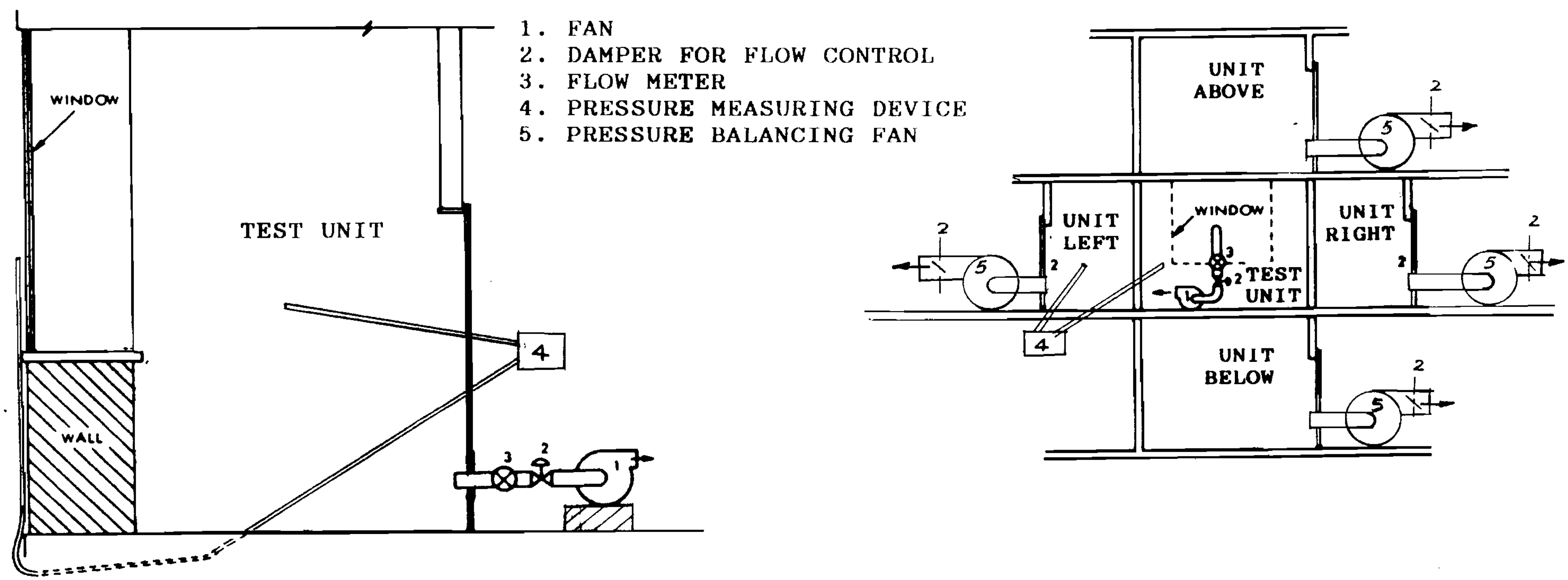


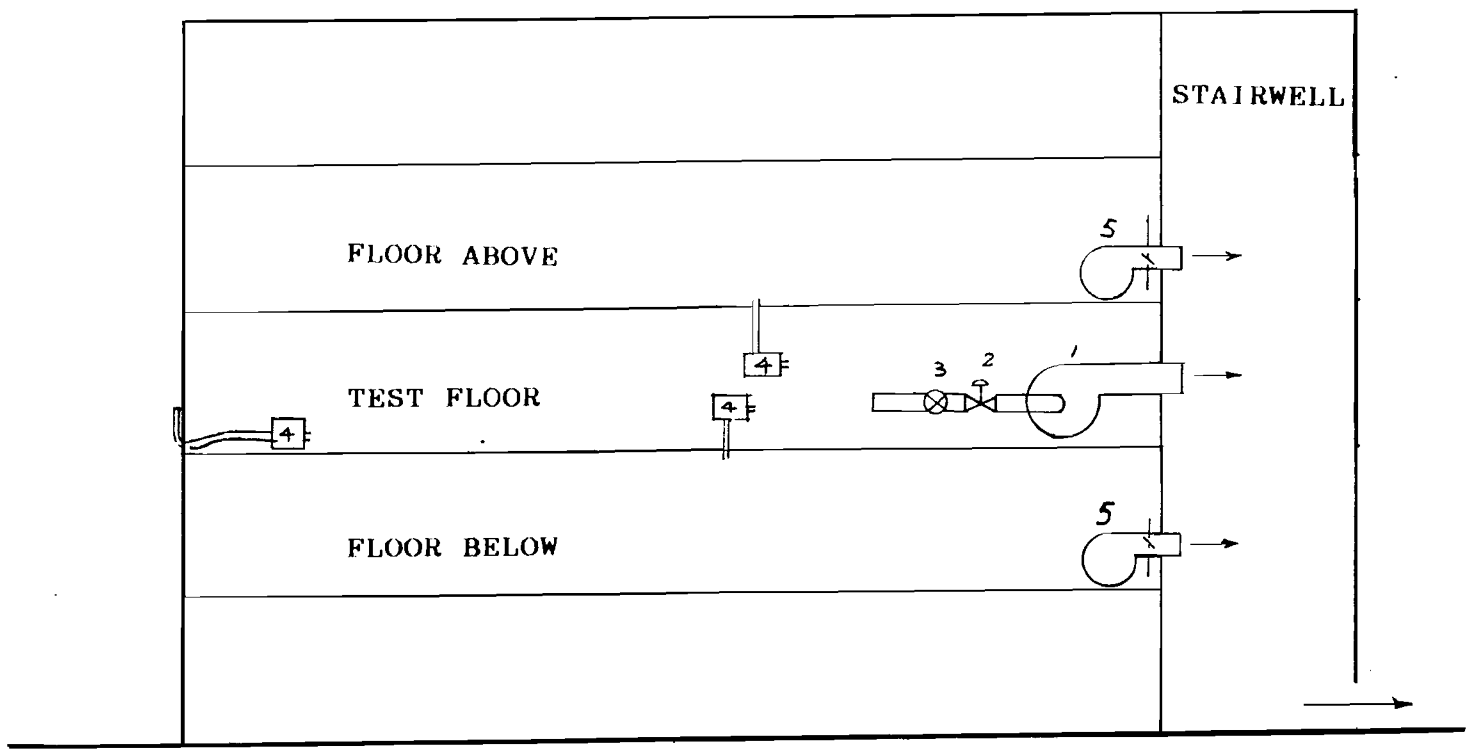
Figure 3 Typical floor plan showing tracer gas sampling locations ●



(a) MEASURING AIR LEAKAGE RATE

(b) BALANCING PRESSURES BETWEEN TEST CHAMBER AND ADJACENT ROOMS

Figure 4 Test set-up for measuring air tightness values of exterior walls, interior partitions separations of individual apartment units and floor/ceiling



1. FAN
2. DAMPER FOR FLOW CONTROL
3. FLOW METER
4. PRESSURE MEASURING DEVICE
5. PRESSURE BALANCING FAN

Figure 5 Test set-up for measuring air tightness values of exterior walls and floor/ceiling separations of individual storeys

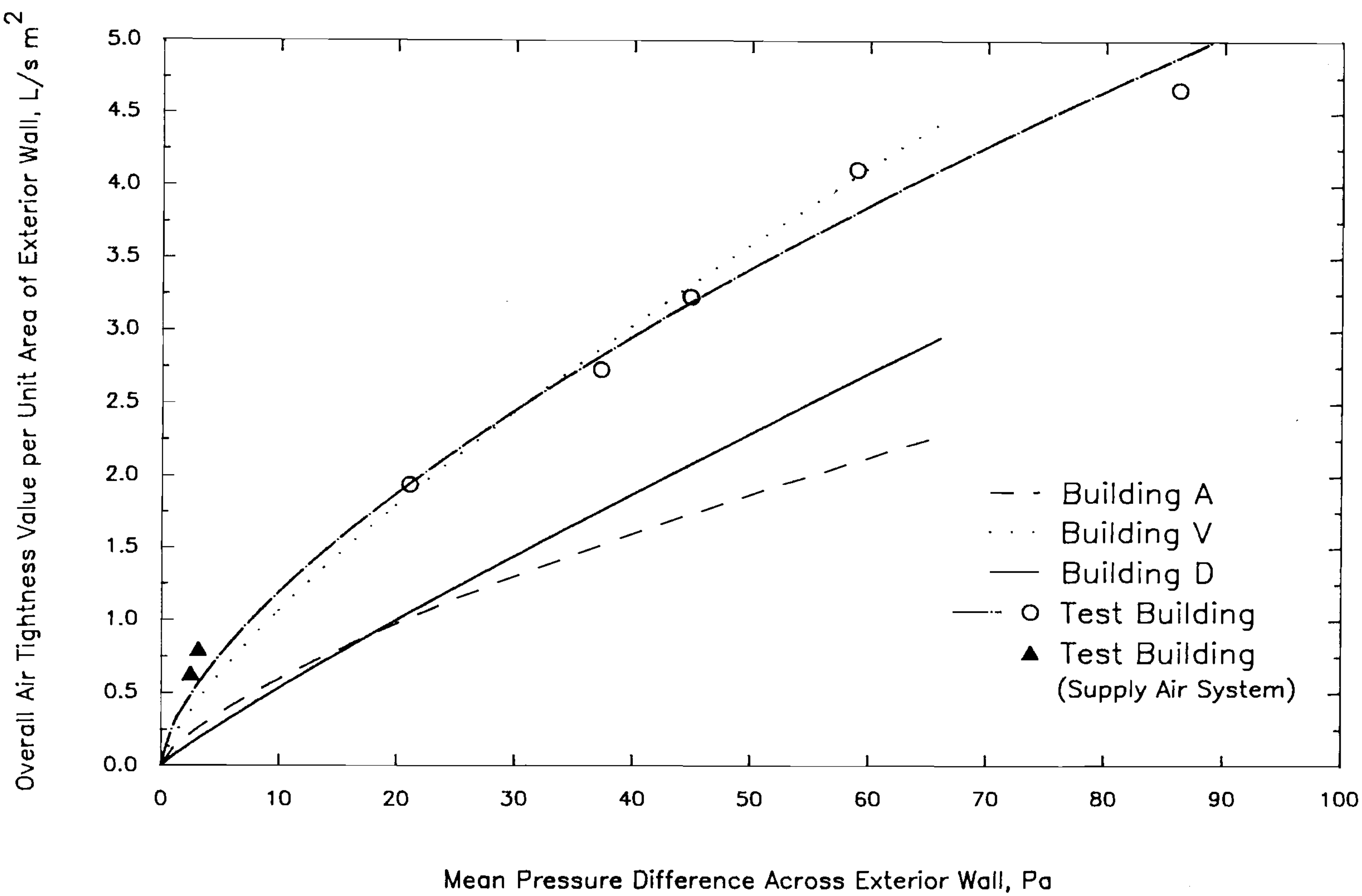


Figure 6 Overall air tightness value

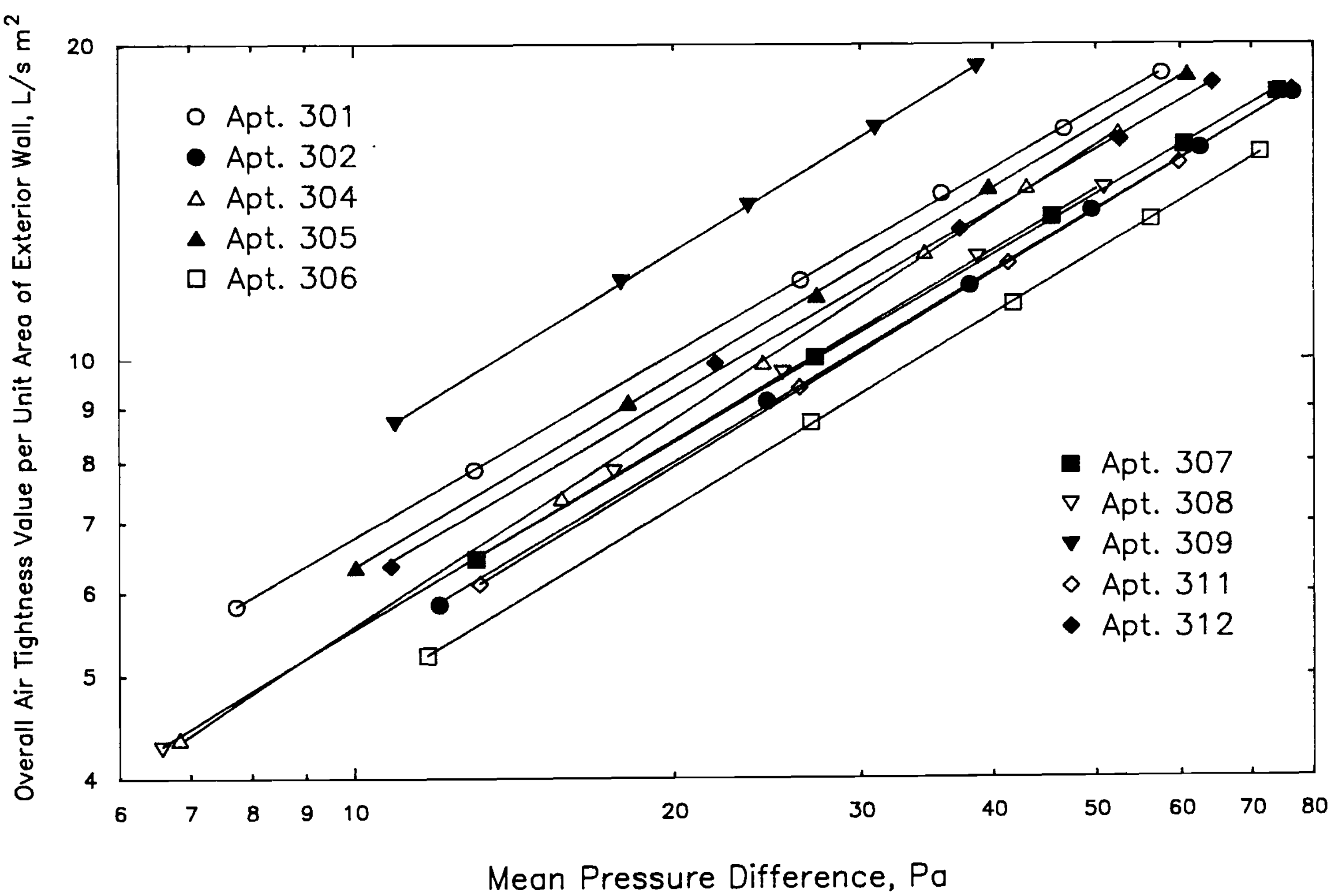


Figure 7 Overall air tightness values of individual apartment units

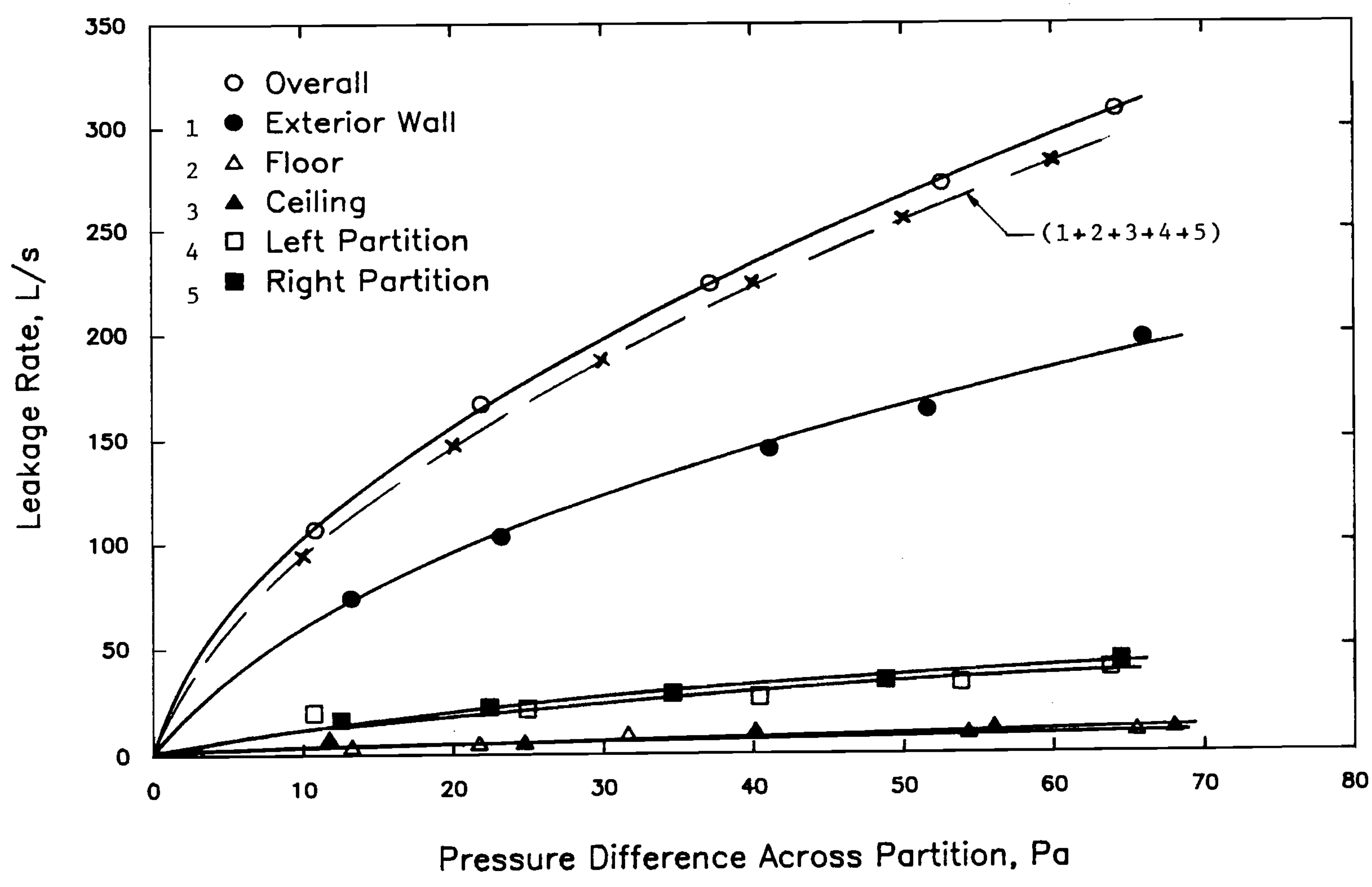


Figure 8 Overall and partition air leakages for Apartment 312

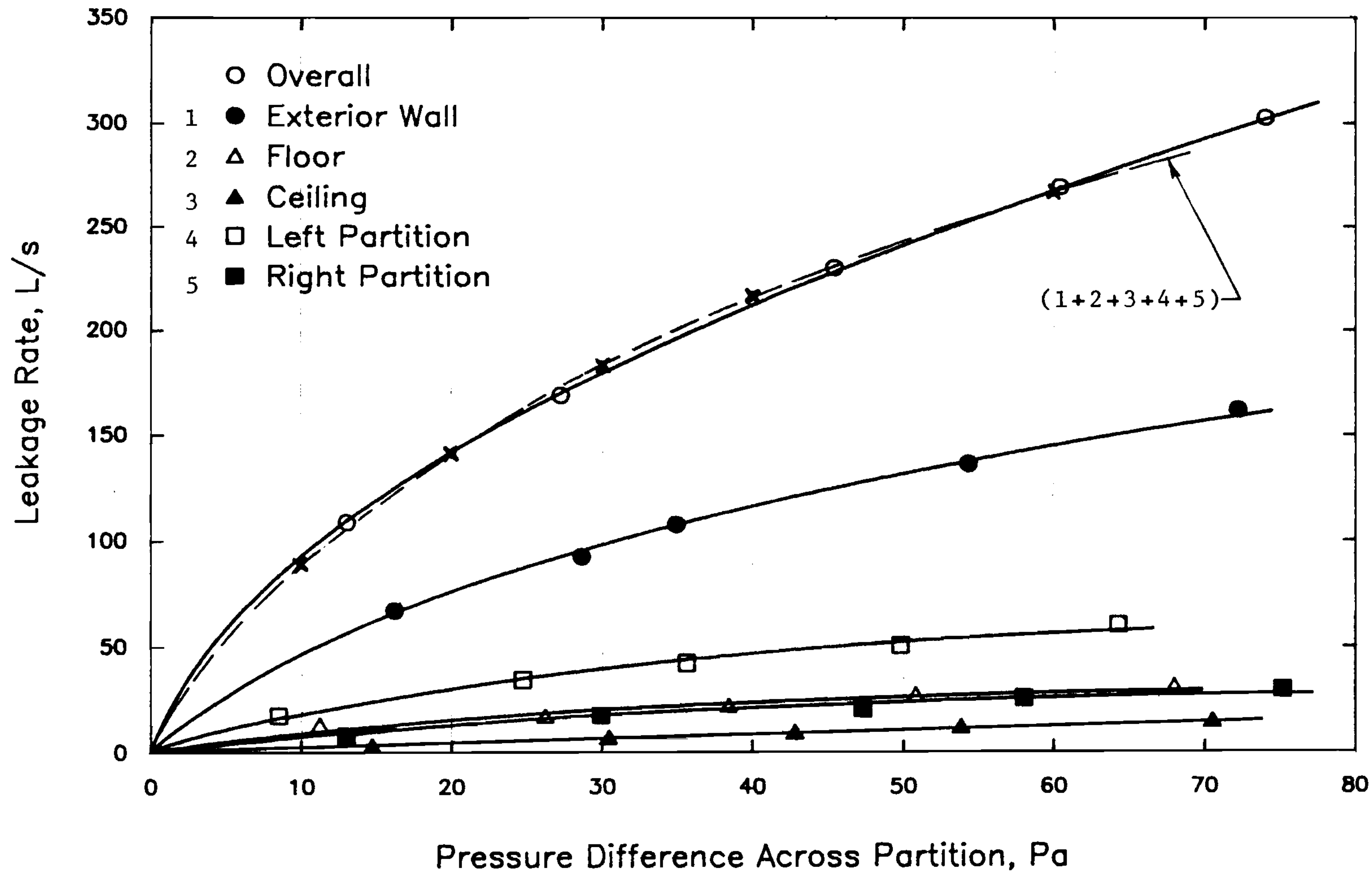


Figure 9 Overall and partition air leakages for Apartment 307

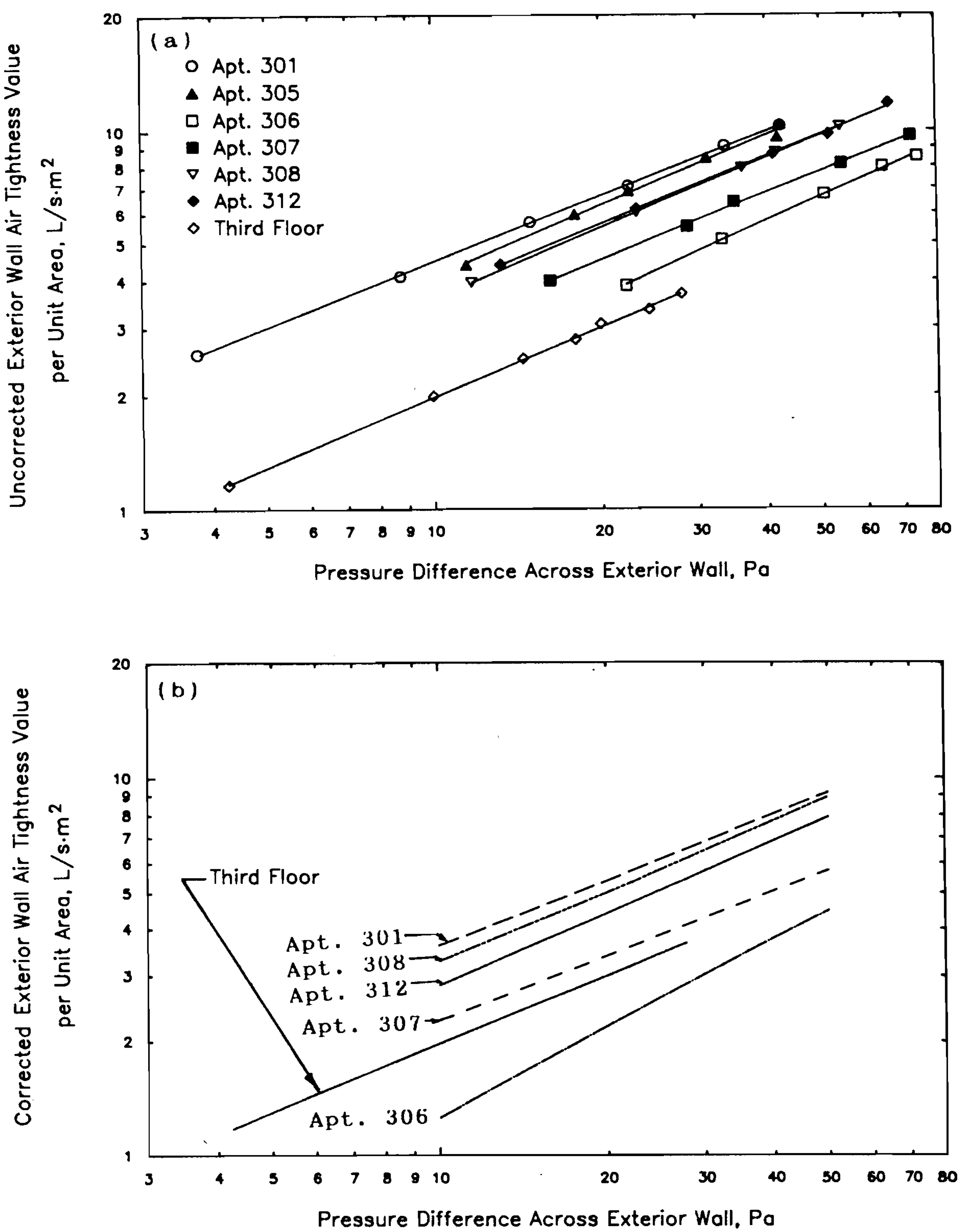


Figure 10 Air tightness values of exterior walls of individual apartment units

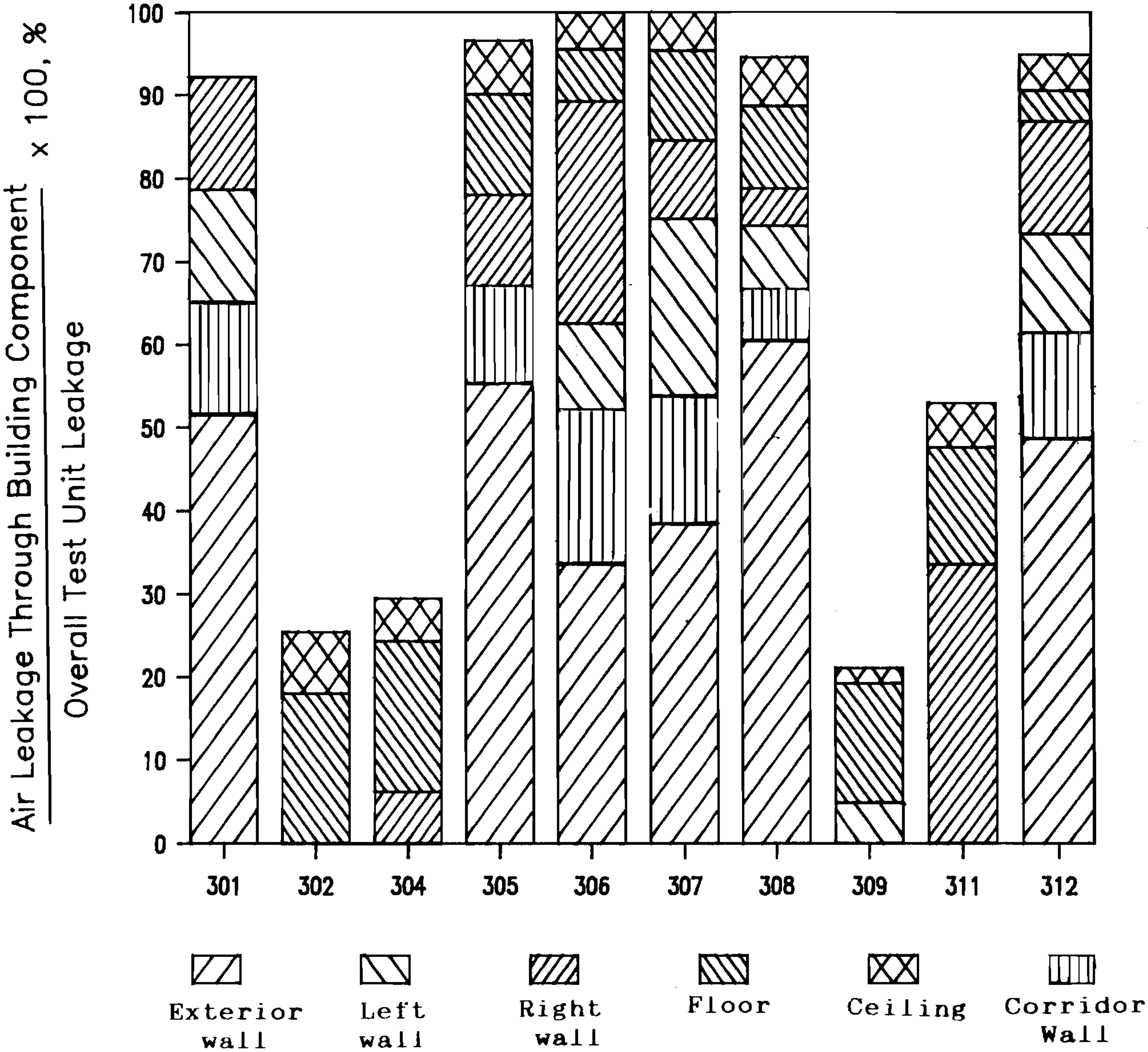


Figure 11 Ratio of component air leakage to overall leakage for individual apartment units, ΔP=50 Pa

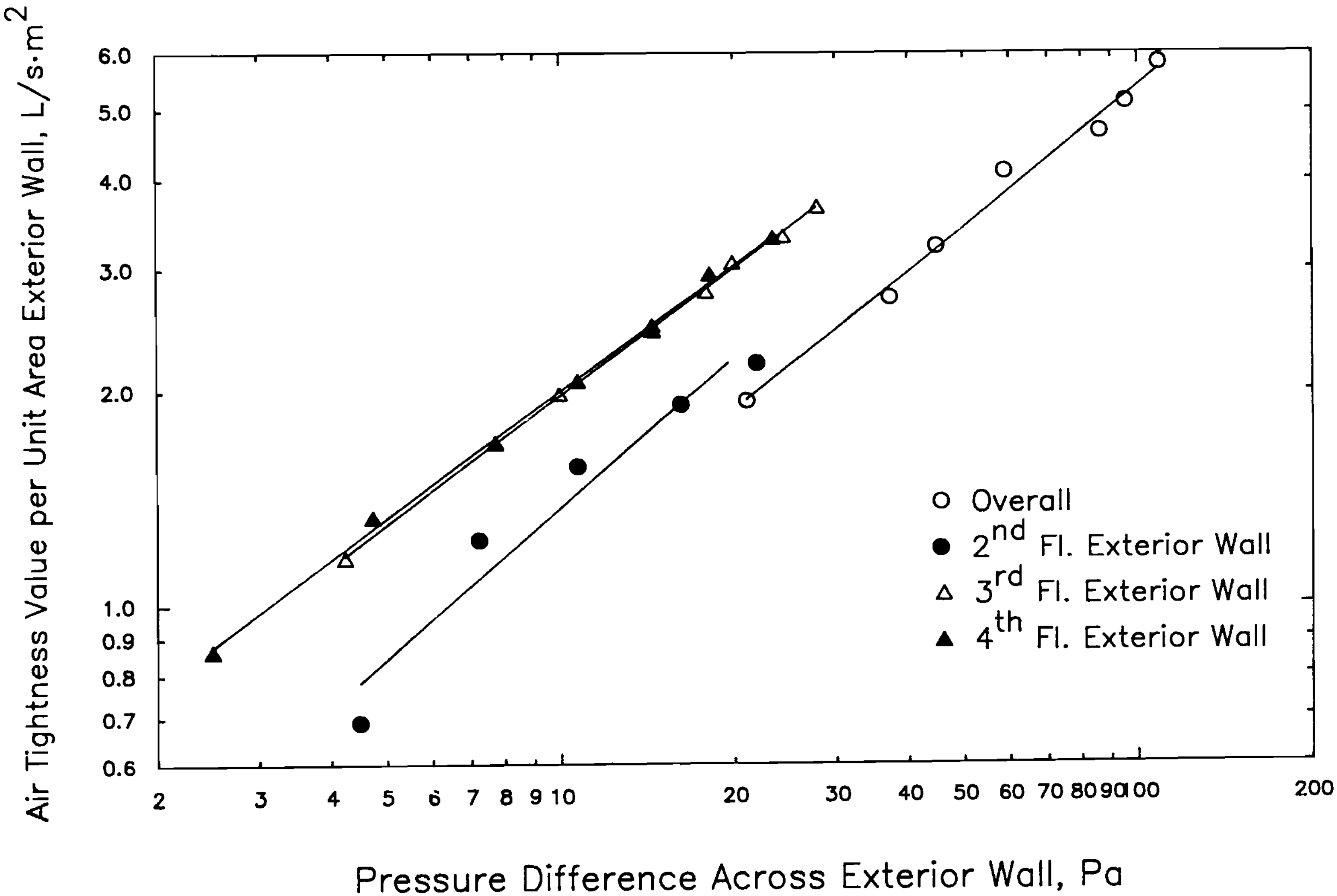


Figure 12 Overall and individual floor exterior wall air tightness values

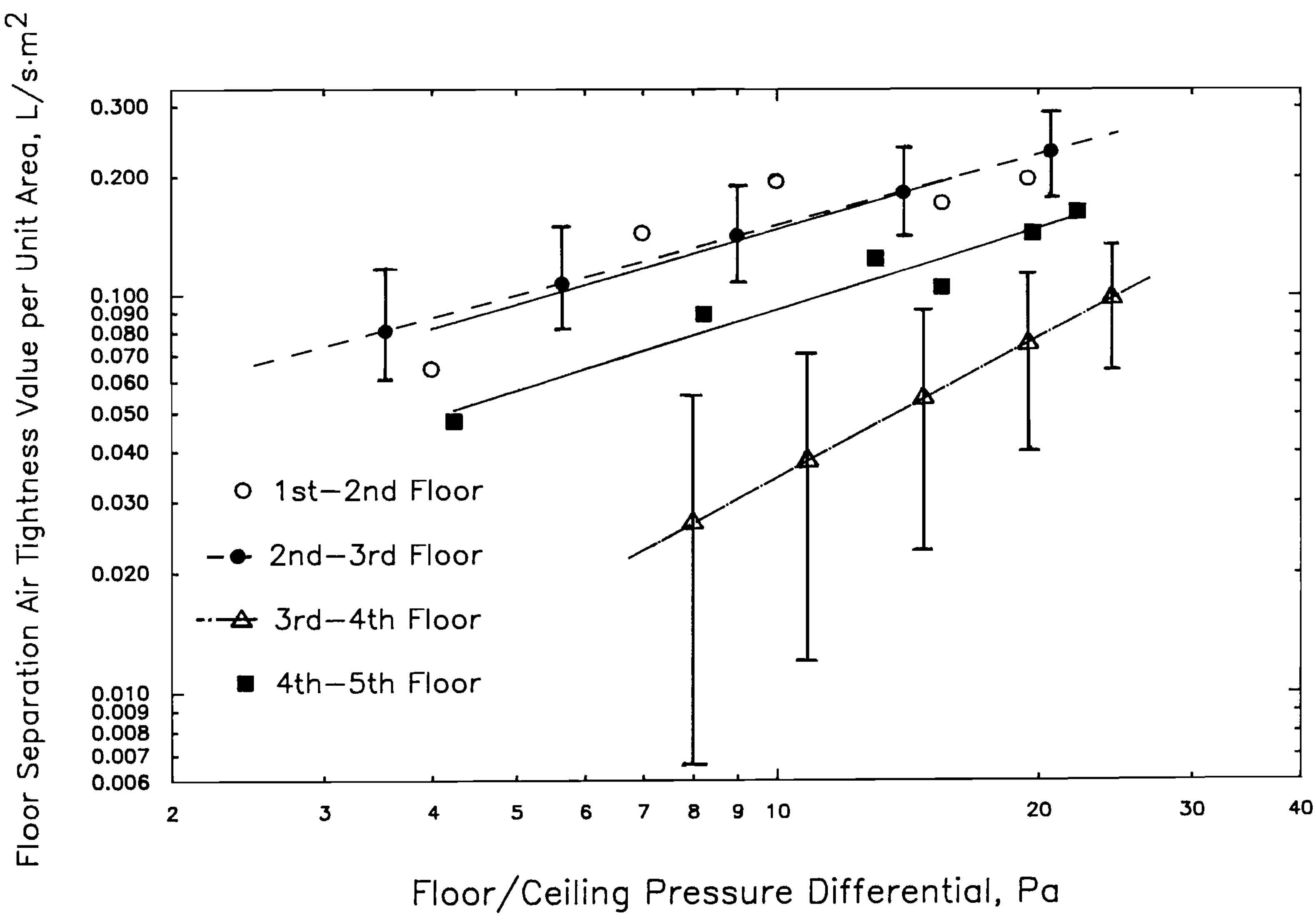


Figure 13 Air tightness values for floor separations

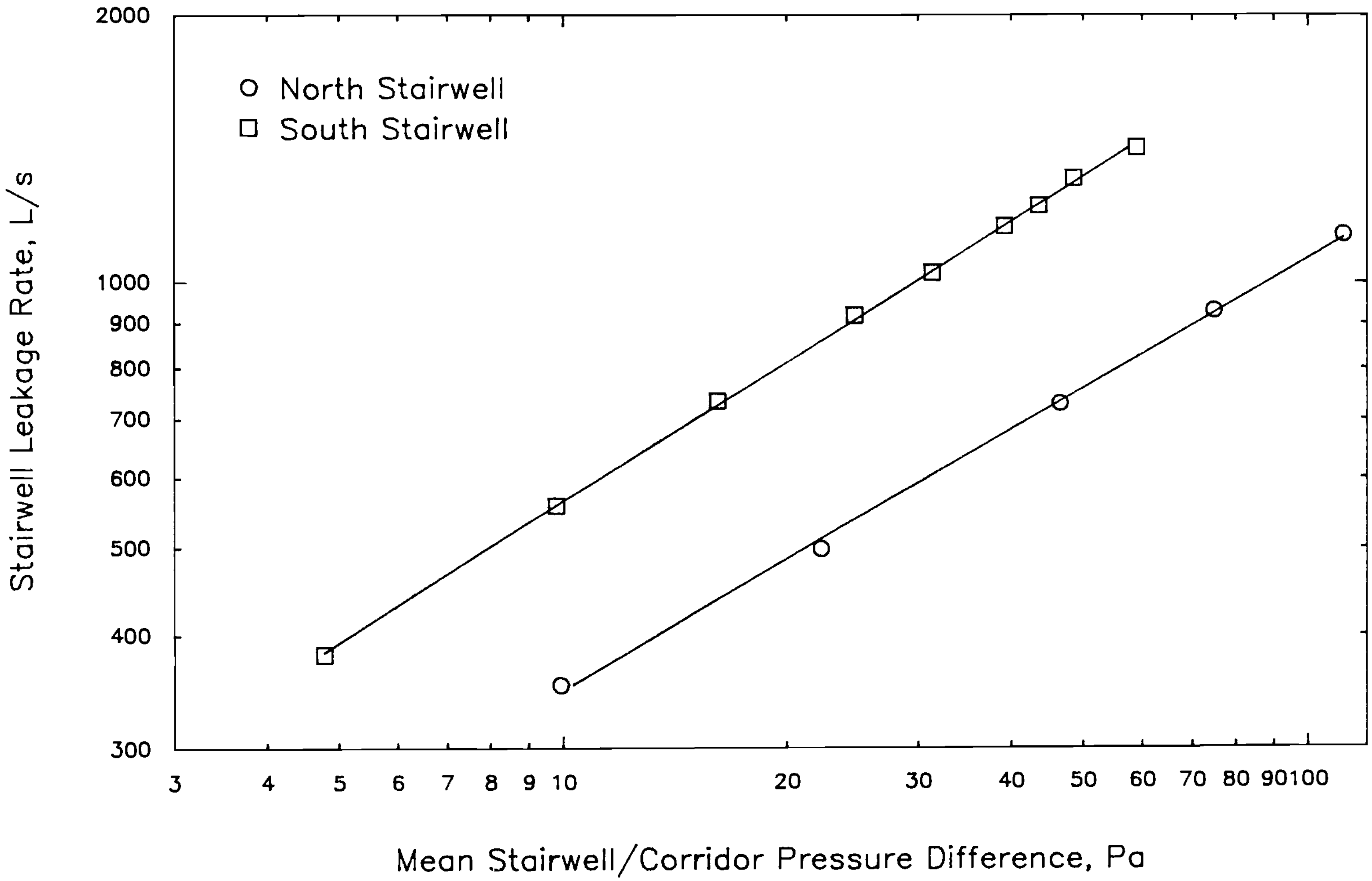


Figure 14 Air tightness values for stairshafts

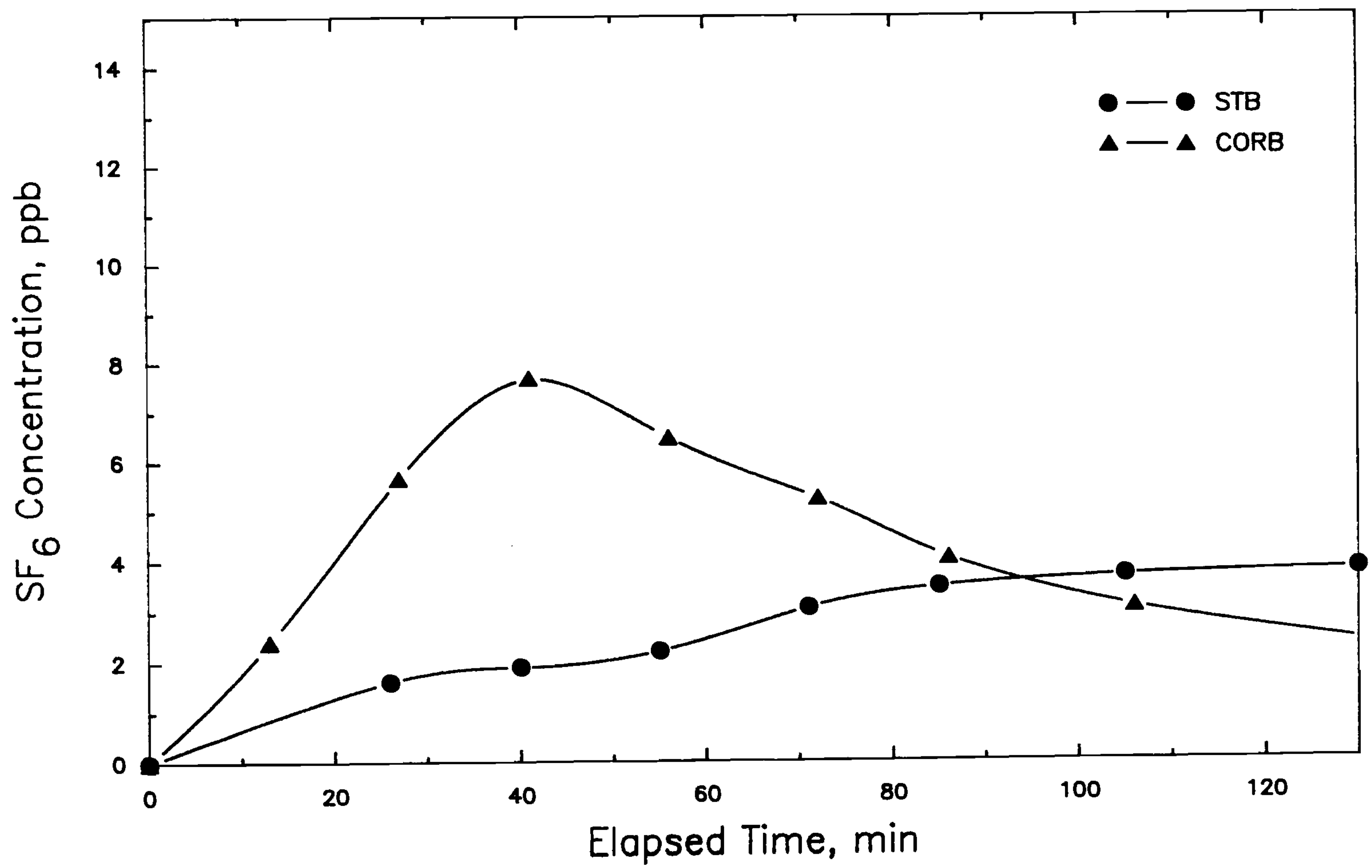


Figure 15 Air flow patterns for basement with tracer gas injected into garbage room, winter test

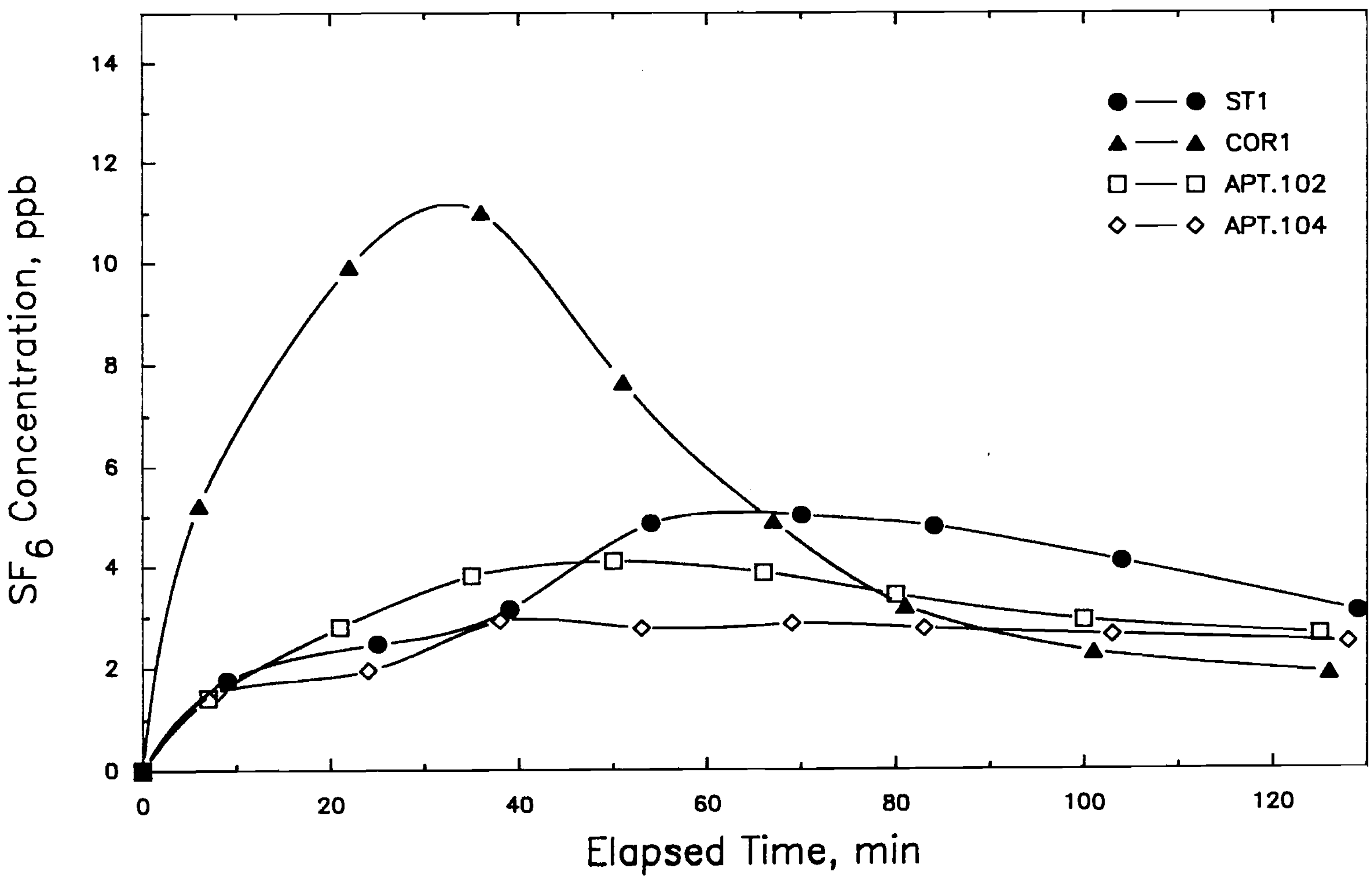


Figure 16 Air flow patterns for ground floor with tracer gas injected into garbage room, winter test

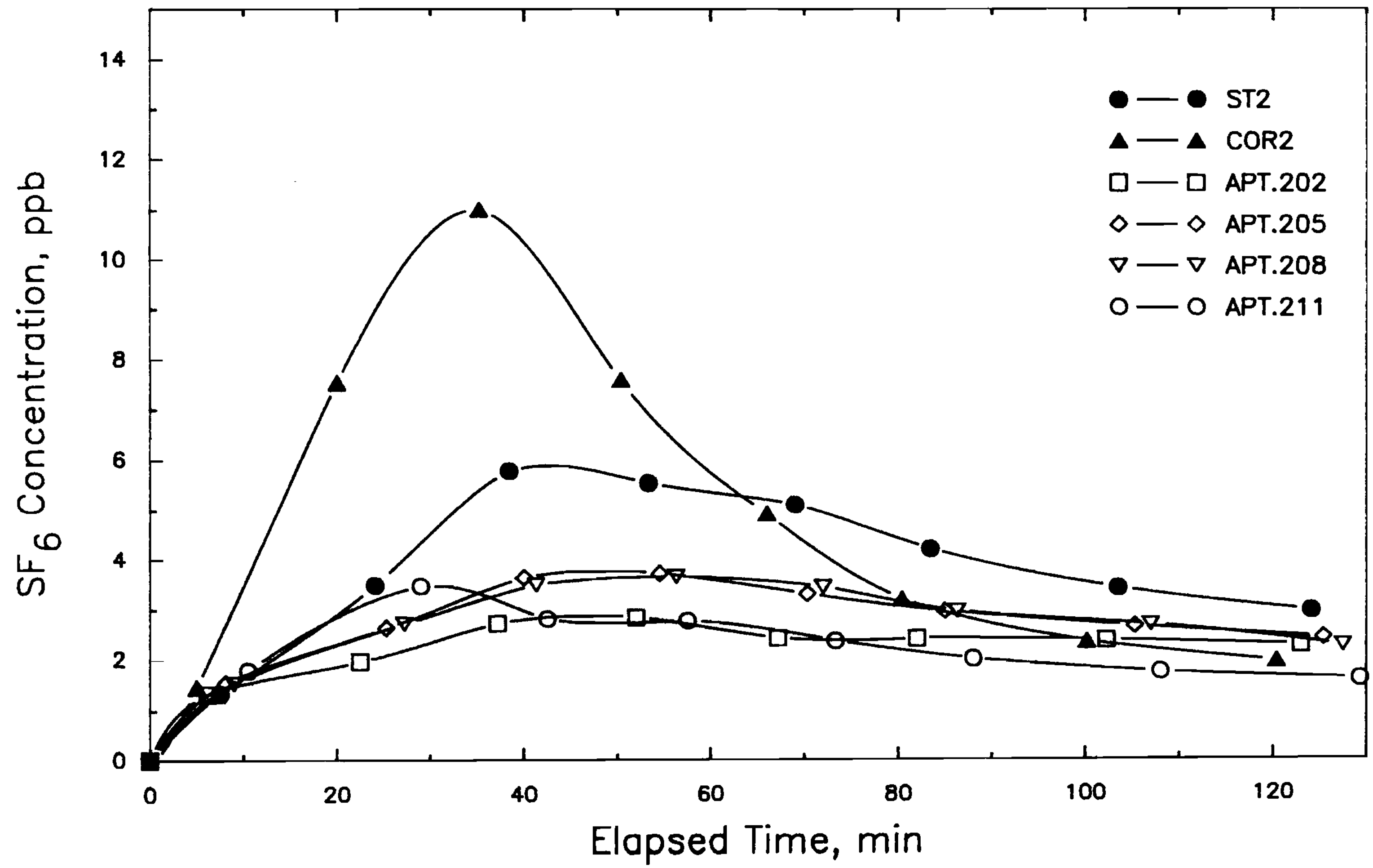


Figure 17 Air flow patterns for second floor with tracer gas injected into garbage room, winter test

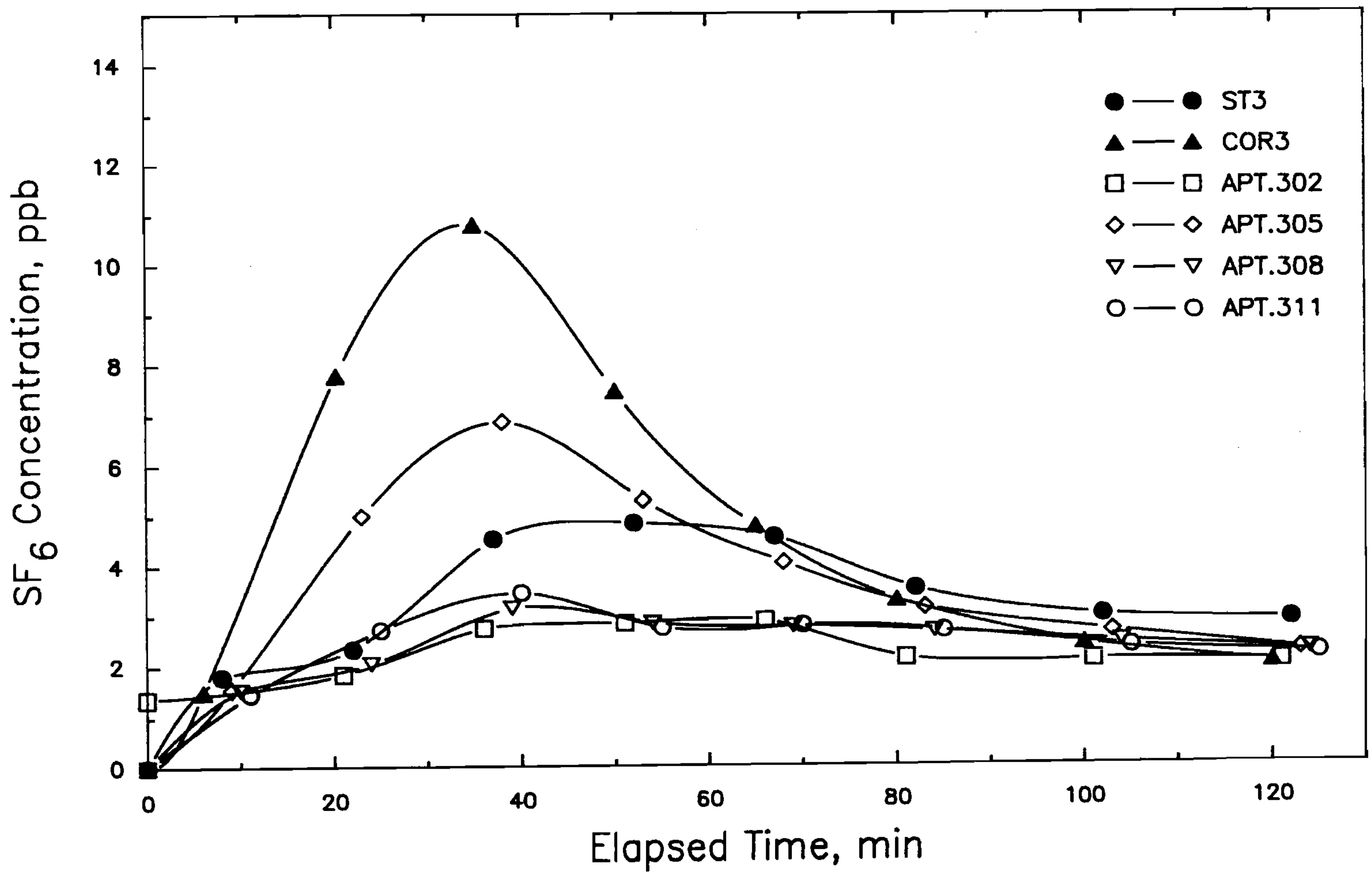


Figure 18 Air flow patterns for third floor with tracer gas injected into garbage room, winter test

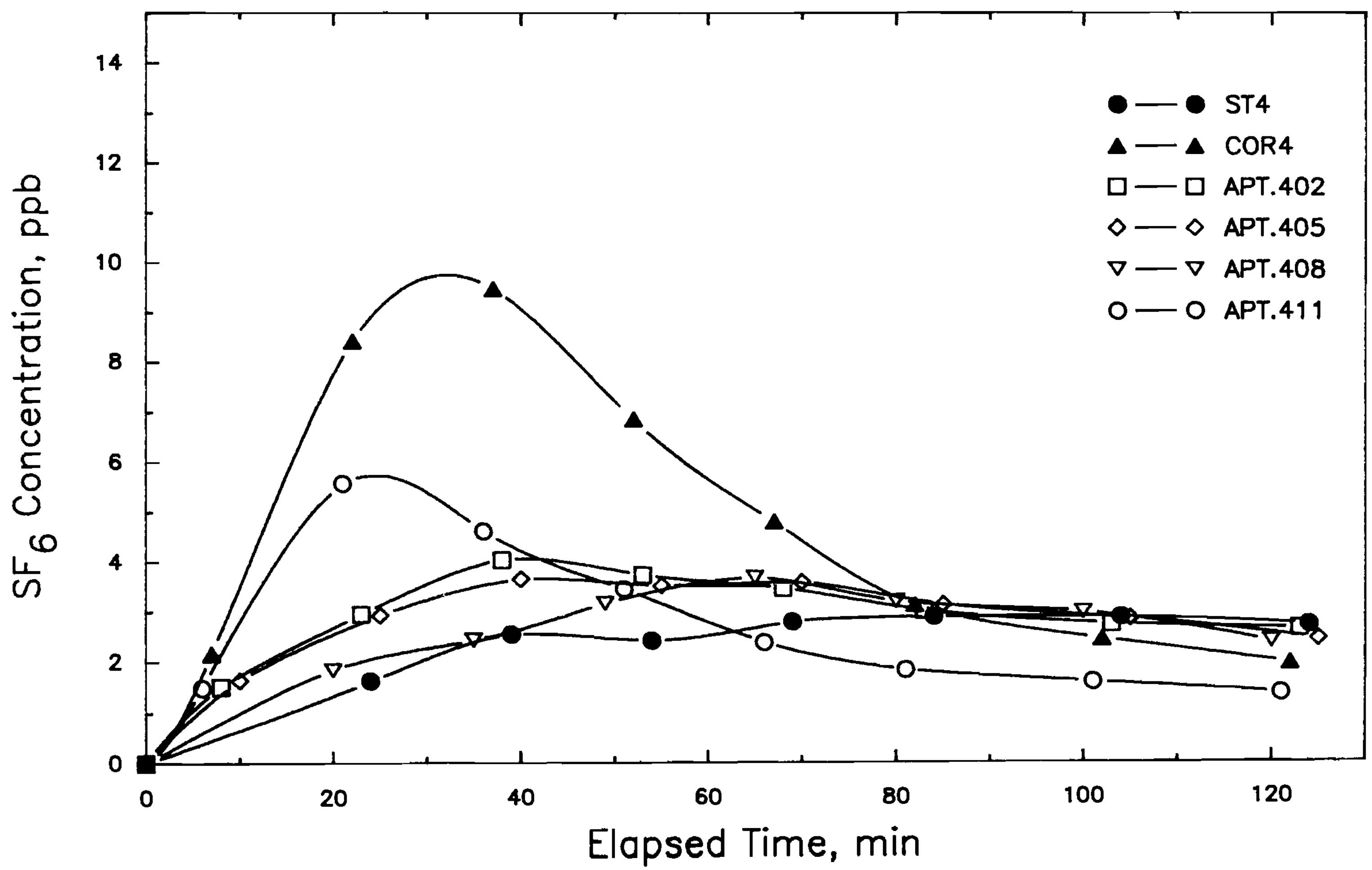


Figure 19 Air flow patterns for fourth floor with tracer gas injected into garbage room, winter test

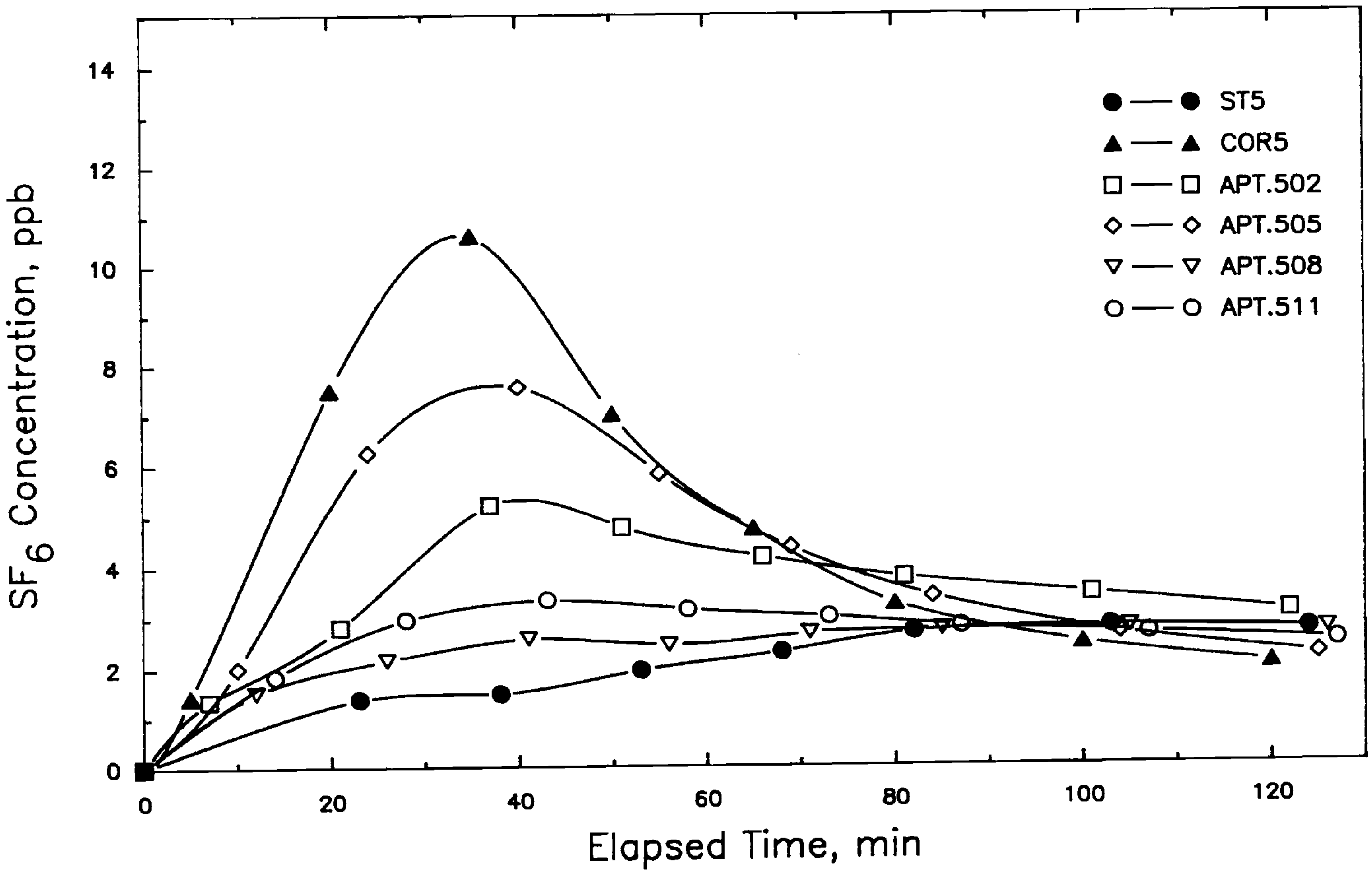


Figure 20 Air flow patterns for fifth floor with tracer gas injected into garbage room, winter test

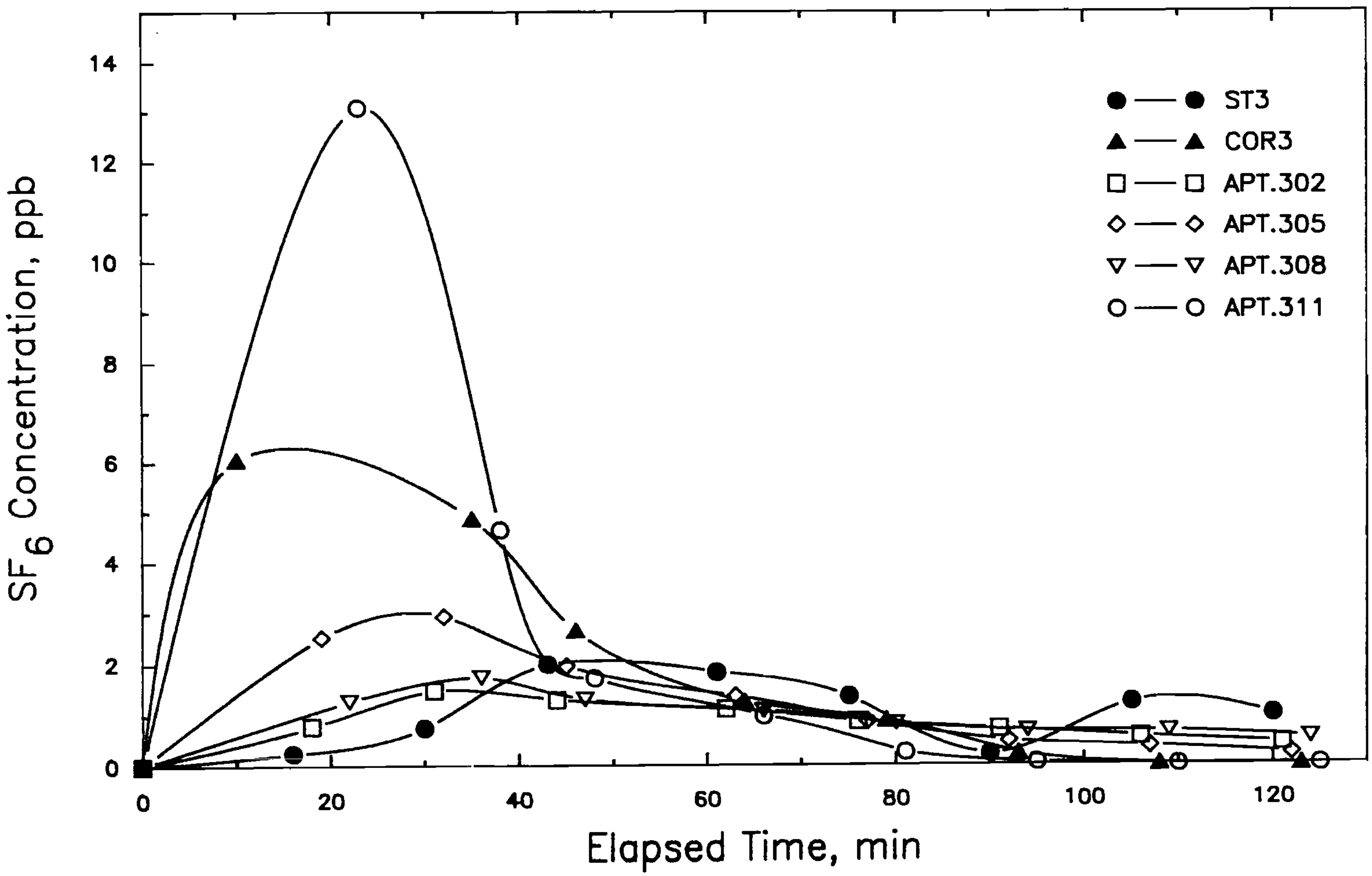


Figure 21 Air flow patterns for third floor with tracer gas injected into garbage room, summer test

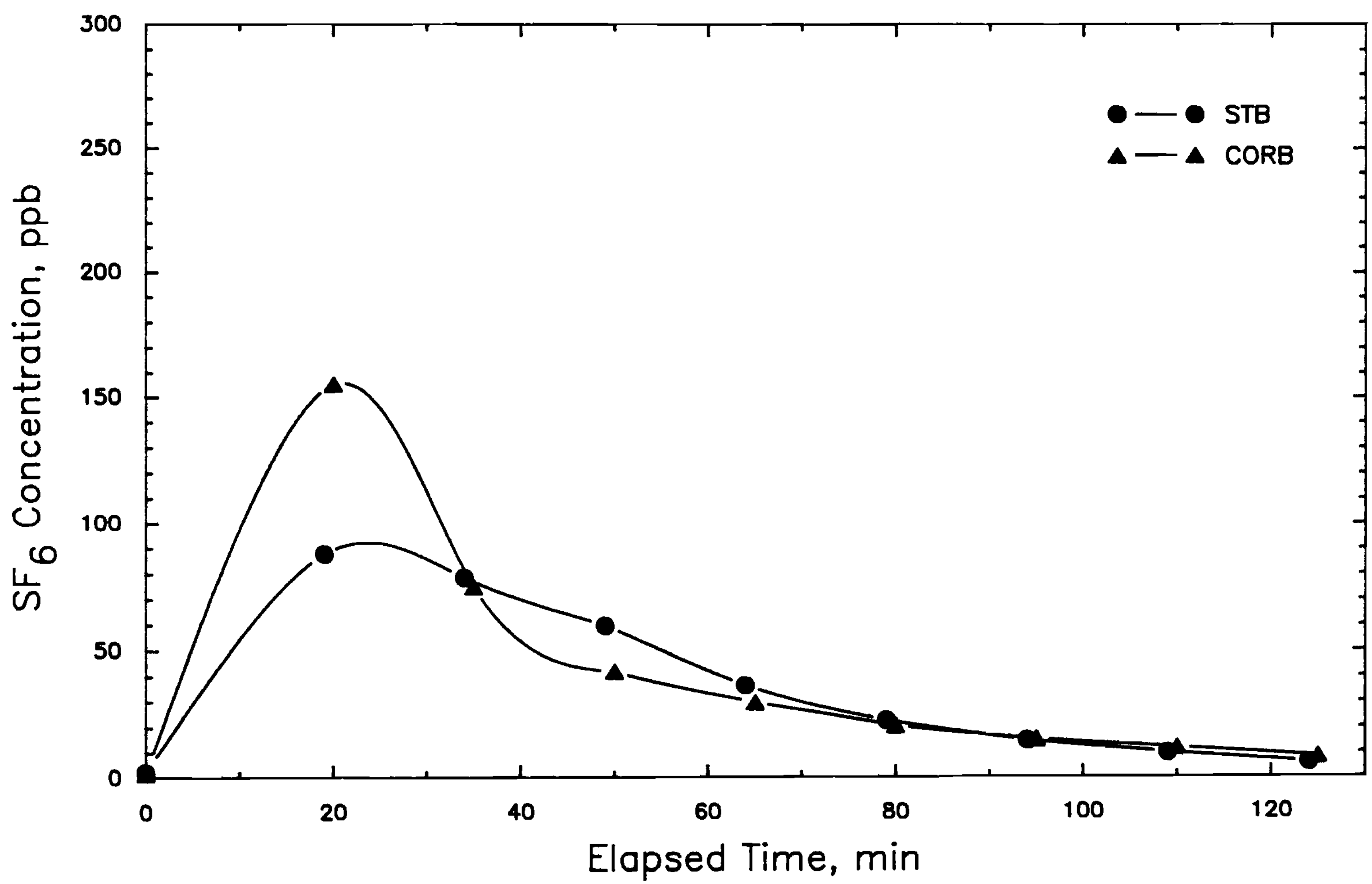


Figure 22 Outdoor air distribution patterns for basement

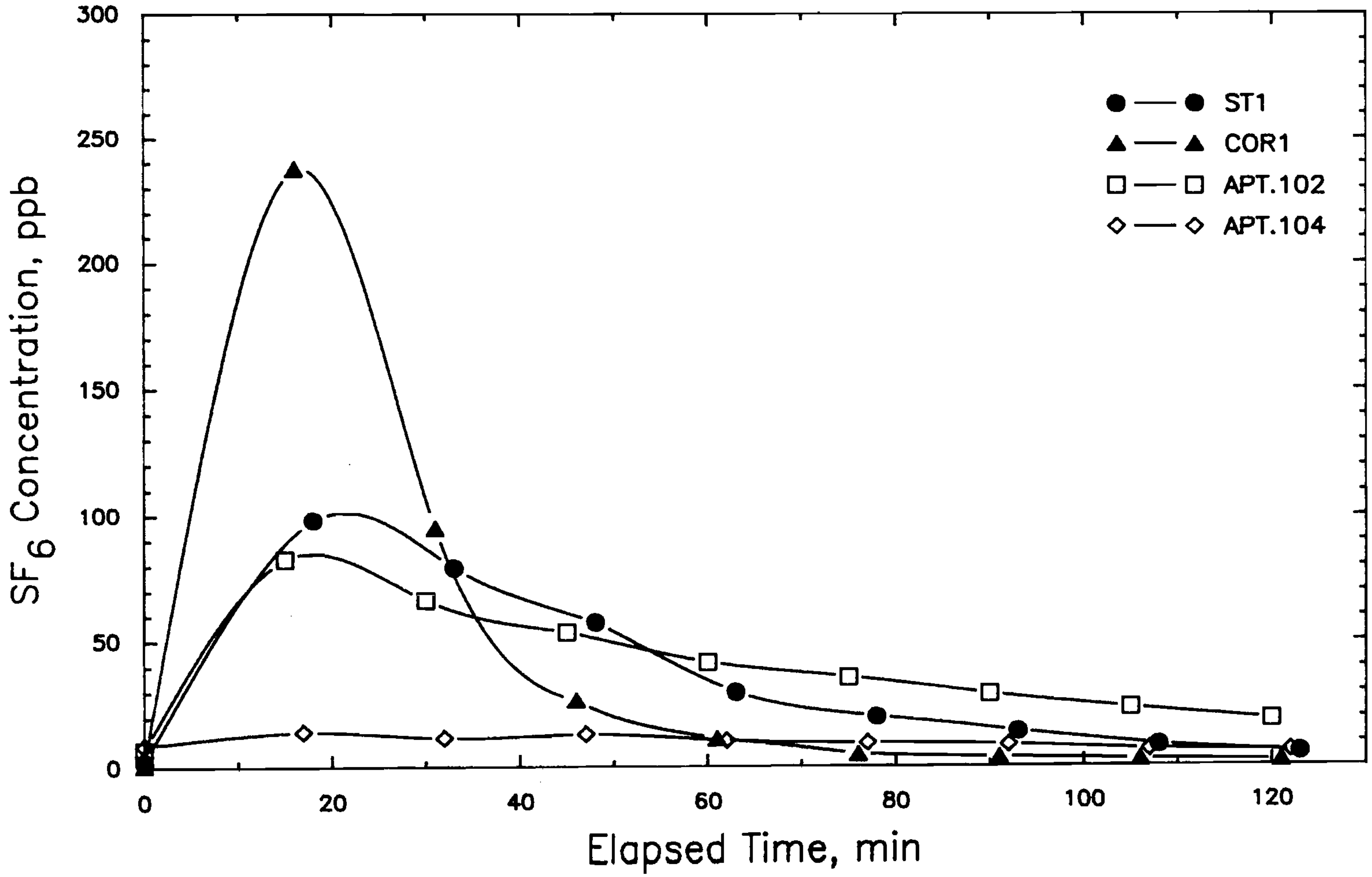


Figure 23 Outdoor air distribution patterns for ground floor

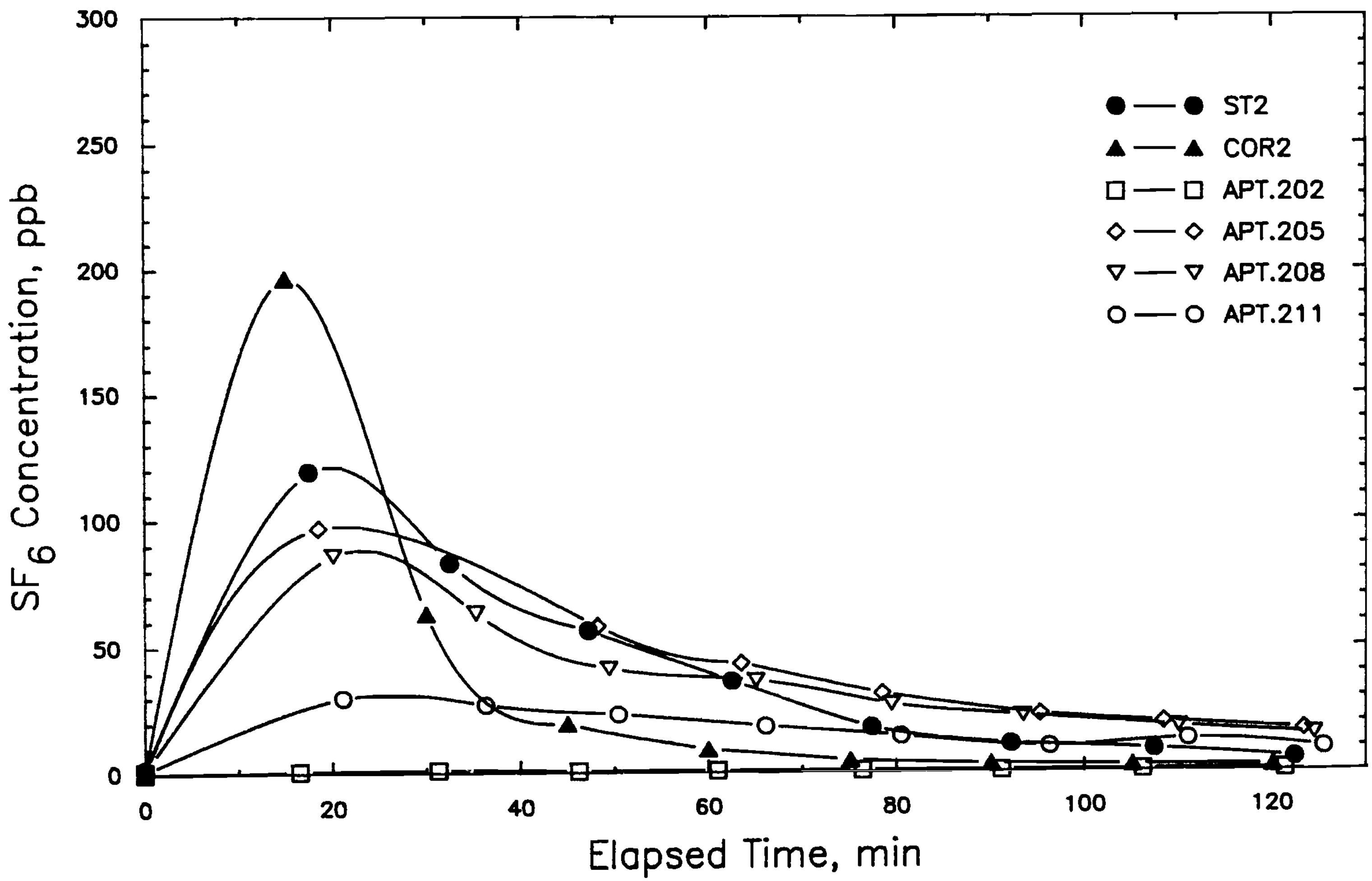


Figure 24 Outdoor air distribution patterns for second floor

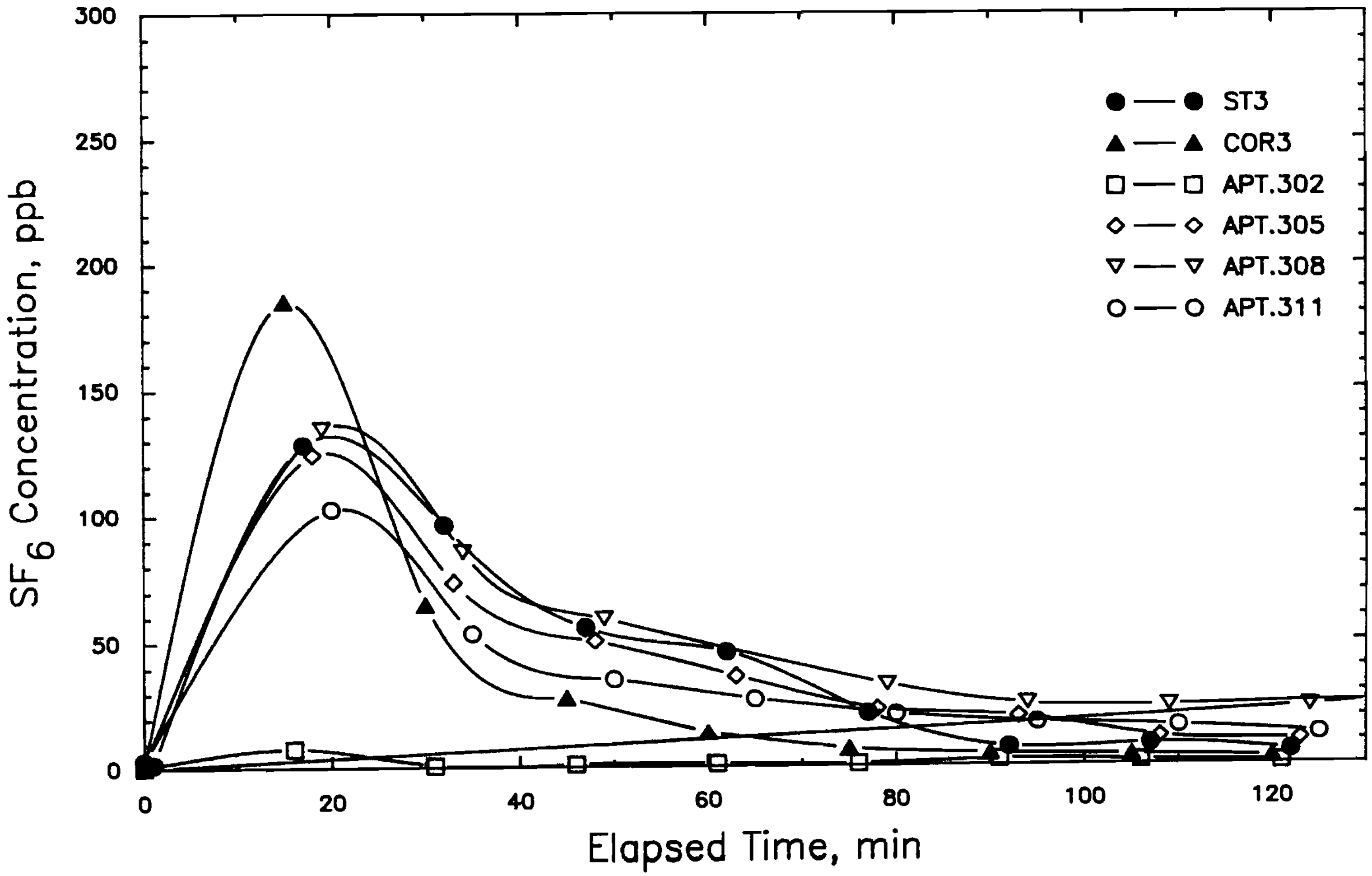


Figure 25 Outdoor air distribution patterns for third floor

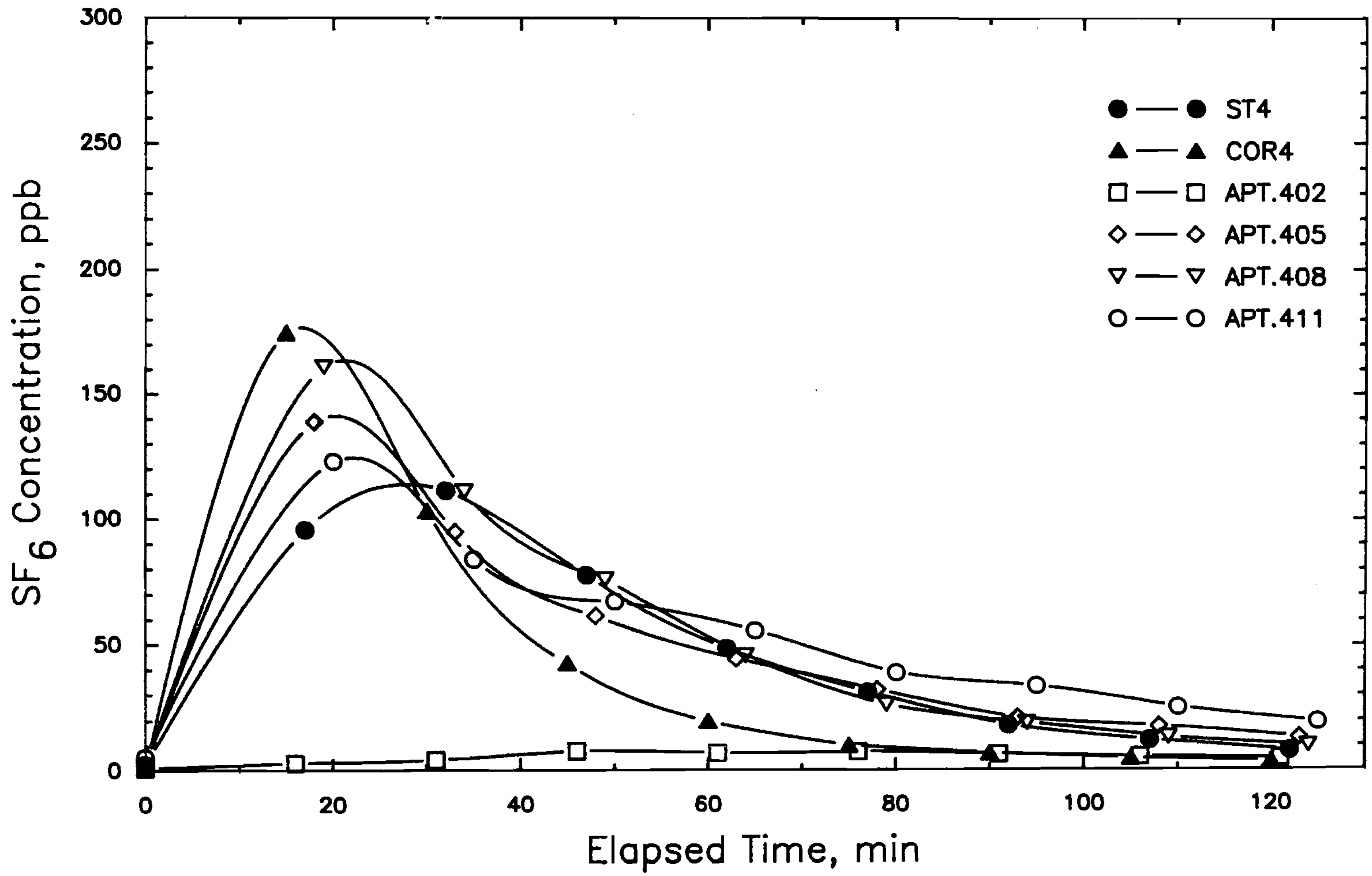


Figure 26 Outdoor air distribution patterns for fourth floor

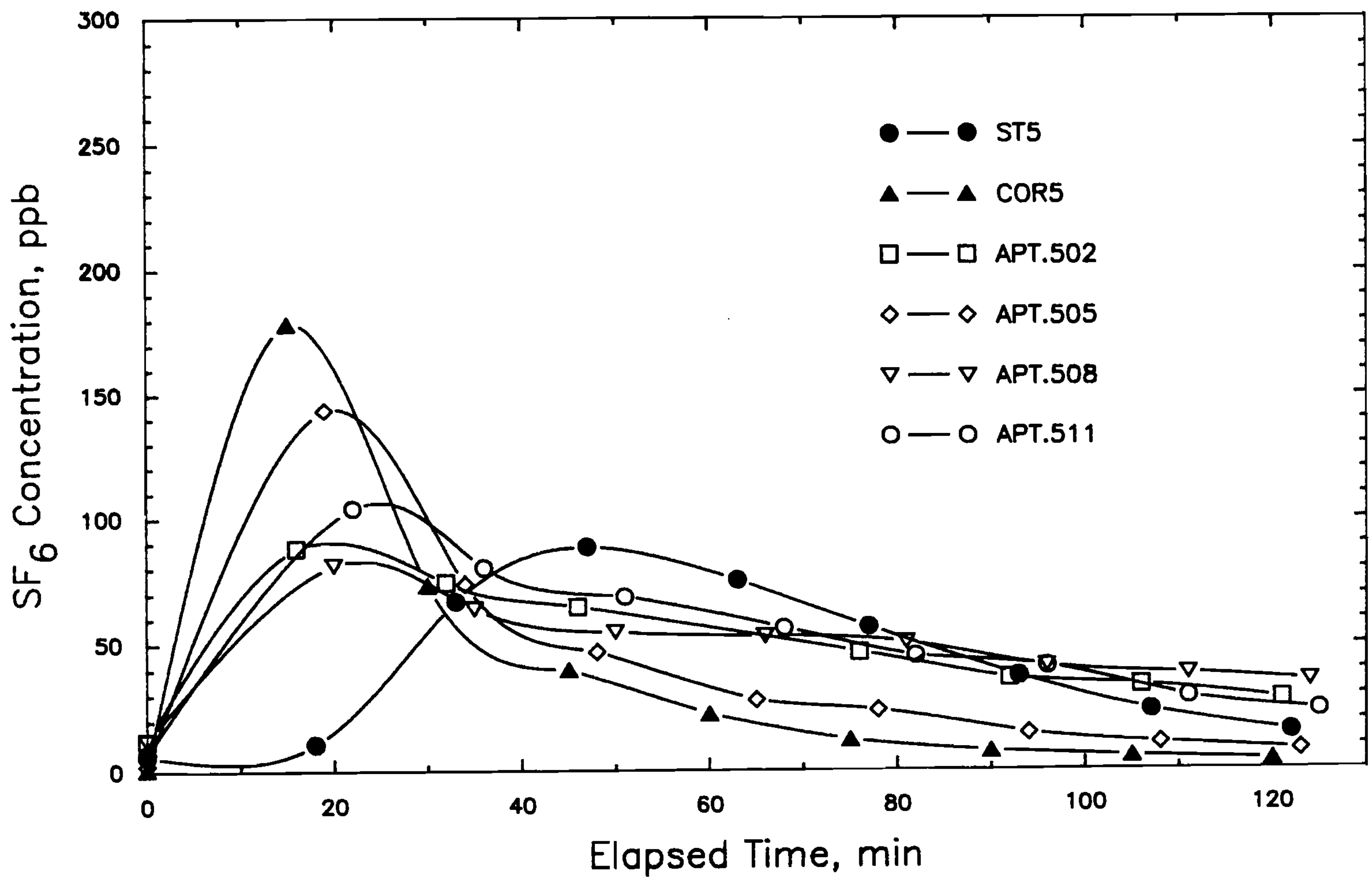


Figure 27 Outdoor air distribution patterns for fifth floor