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Multizone Infiltration Measurements in Homes and Buildings Using a Passive Perfluorocarbon Tracer Method

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ABSTRACT

A miniature passive perfluorocarbon tracer system was successfully applied to the determination of air infiltration and exfiltration rates from each zone of a multizoned structure, as well as the air exchange rates between zones in homes, multiple unit condominiums, naturally ventilated apartment buildings, and large commercial buildings with multiple air-handling systems. Use of the multizone technique in indoor air quality assessments and air-handling system stratification studies appears to be quite feasible with the availability of this measuring system.

INTRODUCTION

The scientific community performing studies of indoor air quality (IAQ), energy consumption, and weatherization of homes and buildings has proposed models and methods of using tracer gases in solutions of those models for determining air infiltration rates in those structures considered as single, well-mixed chambers or zones (Dietz and Cote 1982; Kronvall 1981; Hunt et al. 1980).

It was recognized that many larger, more complex buildings, especially those with multiple-zoned heating, ventilating, and air-conditioning (HVAC) systems were not effectively represented as single, well-mixed zones (I'Anson et al. 1982; Perera 1982; Dietz et al. 1984). Even one- and two-story homes with basements realistically can only best be represented by models that recognize the building as multiple-connected zones, each of which is well mixed (Dietz et al. 1983; Hernandez and Ring 1982). In certain cases, a room or zone may not be well mixed; stratification can occur in unusually tall rooms (Maldonado and Woods 1982). In buildings with air-handling equipment, a stratified zone near the ceiling can lead to short-circuiting of supply air to return air ducts, preventing some of the fresh air intake from mixing with the breathing zone (Janssen 1984).

Multizone modeling for addressing these different physical situations was not seriously considered, primarily because there was no convenient and practical measurement technology. Recently, Brookhaven has developed a new perfluorocarbon tracer (PFT) passive monitoring system (Dietz et al. 1985) for multizone infiltration and air exchange measurements indoors and, through the capability of the system, is developing modeling concepts for measuring and quantifying airflow distribution in structures from homes to multistory commercial buildings equipped with multiple air-handling systems.

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Following a brief description of the PFT methodology, this paper shows the application of the technology to multizone flow characterization of a two-story house with a basement, discusses some shortcomings associated with considering that home only as a single zone, and demonstrates the use of the system in characterizing multiple-connected condominium units. In addition, some modeling concepts for large commercial and apartment buildings are described and some field results are presented.

THE MEASUREMENT METHODOLOGY

The details of the Brookhaven Air Infiltration Measurement System (BNL/AIMS) are described elsewhere (Dietz et al. 1984; 1983; 1985). The principal of AIMS is based on the applicable steady-state assumption that over several days the average concentrations (e.g., in pL/L or nL/m^3) of a tracer vapor in a single-zone building is equal to the emission rate of the tracer source (e.g., in nL/h), divided by the air leakage or infiltration rate (e.g., in m^3/h). Knowing the rate from deployed passive PFT sources and measuring the average concentration with miniature passive samplers then provides a means to calculate the air leakage rate.

Although the BNL/AIMS is a powerful technique for simply, inexpensively, and non-obtrusively determining the air exfiltration rate in a single-zone building, its real potential is in application to the determination of air exfiltration rates from each zone and air exchange rates between zones in multizoned homes and buildings. Typically, homes consist of up to three-zone types. For example, a two-story house with a basement or crawl space would be modeled as a three-zone building, with one tracer type in the basement, a different one on the main floor, and a third type on the second floor. With up to four PFT types currently available and measurable from the same single passive sampler, almost any configuration can be handled using a previously described modeling theory (Dietz et al. 1985; Sinden 1982).

SMALL BUILDING FLOW CHARACTERIZATION

The results of applying the BNL/AIMS technique to a two-story home with a basement, a four-unit single-story apartment complex, and a four-unit two-story condominium unit are described here. Implications on IAQ assessments and shortcomings to single- and two-zone approaches to a three-zone home are discussed.

Brookhaven House

The unoccupied Brookhaven House, completed in September 1980 for energy conservation research, was specially equipped to reduce air infiltration. Forced hot air was provided to the first floor with vents in the ceiling to provide natural draft to the second floor, where the return air grille was located. The basement was isolated from the first floor by a door that was closed at all times; the first and second floors were connected by an open staircase.

BNL/AIMS Measurement Results. Table 1 provides the concentration results for the three PFTs deployed, one type per zone (i.e., floor), and Figure 1 presents the three-zone calculated flow rates. The tracer concentration was the highest in the zone in which it was deployed, a necessary, but not sufficient condition for all flow rates to be computed as positive values; the standard deviation of the measurements was generally within ±10% or better, indicating that uniform tagging of each zone was achieved.

Two changes that altered the flow characterization of the house were quantified by this measuring system.

Effect of Kitchen Range Vent. The flow patterns in Figure 1 indicated that of the air leaving the basement, 68 + 3 + 43 or 114 m^3/h, about 60% entered the first floor; after a kitchen range vent, which was open to the basement, was plugged, subsequent measurements showed only about 44% exfiltrating from the basement to the first floor.

Effect of Air-To-Air Heat Exchanger. This window-type unit, installed on the first floor, was left on high fan speed for two measuring periods and off for two during the winter of 1983/84. As shown in Table 2, there was no statistical effect on the infiltration rates into the second floor or basement. The first floor, however, showed a significant increase in infiltration rate, 99 ± 22 m^3/h (143 ± 58%), i.e., in excellent agreement with the rated capacity of 120 m^3/h.

Concentration Distribution for Different Source Locations. The concentrations expected on each floor of the Brookhaven House for a 1000 nL/h source alternatively located in each of the zones are shown as cases 1-3 in Table 3. For a source on the second floor, the concentration on the first floor was less than half that on the second; located on the first floor, the levels were only slightly lower on the second floor compared to the first; located in the basement, the concentration on the first or second floors was about half that in the basement.

Impact on IAQ Studies. For a steady-state combustion sources such as an unvented space heater located on the first floor (case two), it can generally be concluded that someone sleeping in a bedroom on the second floor will be exposed to a slightly reduced pollution level compared to that on the first floor (reactive pollutants excluded).

If radon concentrations measured on the first floor and basement were in the proportion of 4.6 to 9.6 (case 3), then the three-zone model would show that the radon source was entirely in the basement; a greater ratio would imply a radon source in the living zone (e.g., use of radon-containing well water) as well as in the basement (e.g., soil gas penetration (Bruno 1983). The source rates can be determined by the three-zone model.

Single Zone ACH. To perform a single-zone measurement of the air changes per hour (ACH) in a multizone house using a single, constant emission rate tracer source such as SF_6 (Tolzke et al. 1984), popular because of the simplicity of the sampling and analytical equipment, requires an approach to equalize concentrations in each zone to minimize errors in the determination (Dietz et al. 1985; Sinden 1982); previous modeling has shown that this requires a source strength in each zone in proportion to the infiltration rate in that zone, which is the principal of the automated multizone constant-concentration approach (Sinden 1982). However, the single-zone, uniform concentration (5.9 nL/m^3, case 4) is not readily attained by a single source located in any one zone (cases 1-3).

The computed source rates for equal concentrations in the whole house (case 4) and the living zone (case 5), shown in Table 3, indicate that a good compromise for the former is a 50-50 distribution between the basement and first floor and, for the latter, a source only on the first floor. For researchers who want to perform a basement-living zone, two-zone evaluation of a two-story house, important, for example, in radon IAQ studies, it is apparent that one type of source in the basement (case 3) and one type of source in the living zone, but only on the first floor (case 5), would provide an effective approach to a uniform concentration in each zone. Note, however, that this approach cannot give the correct second floor concentration for a source on that floor; only a three-zone (case 1) approach would suffice.

Quadraplex Housing Unit

Located in Yuma, Arizona, this earth-sheltered passive solar-gain building consisted of four individual apartment units, each approximately 900 ft^2 (84 m^2) in size, arranged in a rectangular fashion as shown in Figure 2. Being monitored under the Solar in Federal Buildings Program (SFBP), each unit was considered a separate zone and was, therefore, tagged with one type each of the four available PFTs. The AIMS technique was deployed from February 3 to March 7, 1984.

Listed in Table 4 are the emission rates of the dual sources used in each of the four units and the concentrations found for each of the four tracers on each passive sampler. First it is noted that the concentration of the tracer deployed in a unit, e.g., PDCH* in unit 1, was

Note: m^3 = 35.31 ft^3; L = 61.02 in^3; nL = 10^{-9}L; pL = 10^{-12}L

*Tracer codes: PDCB - perfluorodimethylcyclobutane
PMCP - perfluoromethylcyclopentane
PMCH - perfluoromethylcyclohexane
PDCH - perfluorodimethylcyclohexane

always higher in the master bedroom than the rest of the unit. Apparently, with only one window, no doors, and a source deployed in that room, there was a bias in the concentration distribution compared to the other rooms, which generally had uniformly lower concentrations.

It was also found, of course, that the concentration of a particular tracer was always highest in the unit in which it was deployed. For units 1 and 3, the concentration of the unit tracer was next to the highest in the adjacent unit with the largest common wall and lowest in the diagonally adjacent unit. Units 2 and 4 had just a slight variation to that general observation.

A material balance solution gave the internal flow rates shown in Figure 2 and tabulated in Table 5. Compared to the infiltration and exfiltration rates, which ranged from 30 to almost 60 m^3/h, the air exchange rates were quite low, ranging from 0.007 to 2.1 m^3/h with a median value of 0.17 to 0.42 m^3/h. Based on our observations of floor-to-floor air exchange rates in multistory houses and buildings, these rates are quite low--about 2 orders of magnitude. Thus, the units are essentially isolated from each other.

In terms of air changes per hour, the values ranged from 0.12 to 0.22 h^{-1}, not unreasonably low for energy efficient structures, as we have seen average values in typical housing from 0.4 to 0.5 and in tight houses from 0.2 to 0.25 h^{-1} (Dietz et al. 1985).

The exfiltration and infiltration rates were nearly identical in units 1, 2, and 3, averaging about 35 m^3/h; unit 4 was about 60% higher. One possible reason may be the prevailing wind direction. It is noted that the infiltration into Unit 2 was greater than the exfiltration rate (cf. Figure2). There was a net flow from unit 2 to units 3, 4, and 1. Also there was a net flow from unit 3 to 4 and unit 1 to 4, and the exfiltration rate was greatest from unit 4 as well as having the largest exfiltration to infiltration rate ratio. Thus, it would appear that unit 4 was being subjected to a wind-induced "stack" effect or slightly reduced barometric pressure, resulting in net internal flow from the northwest to the southeast.

Four-Unit Condominium Building

For a two-week period, on Long Island, from November 18 to December 2, 1984, a four-zone BNL/AIMS measurement was performed in a two-story building constructed in 1978 containing four units, each with a living area of about 800 ft^2 (74 m^2). All the units had magnetic seals on the doors and were equipped with storm windows and doors, with the exception of unit 2, which had neither. Prior to the test, the interlock seals on both the main windows and the storm windows in unit 1, an upper unit, were adjusted for a tight fit. Each unit was separately tagged with a single PFT source and sampling was performed with two passive samplers with the exception of unit 1, which had three; the standard deviation of the concentrations in unit 1 averaged about ±9%.

As shown in Figure 3, the air infiltration rates in the two lower units were about equal at 115 m^3/h, equivalent to an infiltration ACH of 0.71 h^{-1}. However, the infiltration rates in the two upper units were quite different from each other, with values of 56 and 149 m^3/h for units 1 and 4, respectively, equivalent to infiltration ACH values of 0.32 and 0.85 h^{-1}, respectively; the whole building ACH was 0.65 h^{-1}.

The air exchange between units on the same floor, both upstairs and downstairs, was quite low, less than about 2 m^3/h. However, there was a significant stack effect, with the flow from the downstairs units to the upstairs units ranging from 27 to 32 m^3/h and the reverse flows only 3 to 4 m^3/h; even two of the diagonally-paired units, units 1 and 3, exhibited a similar stack effect.

Unlike the previous quadraplex building, these units could not all be treated as isolated from each other. As summarized in Table 6, the total in-flow in the first floor units was not much greater than the infiltration rate; thus, units 2 and 3 were essentially autonomous. The upstairs units, however, were moderately (unit 4) to significantly (unit 1) affected by the flow from downstairs units. The relative leakiness of all but unit 4 were about the same; unit 4 had a 65% higher leakiness than unit 1, which appeared to have benefited slightly compared to units 2 and 3 in regard to the weatherizing of the windows. Unit 4 appears to need weatherization.

MULTIZONE INFILTRATION IN LARGE BUILDINGS

Very little determination of the actual airflow patterns in large industrial, commercial, and apartment buildings has been accomplished, primarily because the measuring tehchnology has not been available to accommodate the multizone nature of these buildings. The multiple PFT capability in the BNL/AIMS methodology can now change that situation.

This section will present building internal airflow models to establish measurement and analysis protocols for the following types of situations:

1. Natural infiltration in large buildings without HVAC systems
2. Natural and mechanical ventilation in large buildings with HVAC systems
3. Performance certification of air handling equipment in large buildings

The beneficiaries of such protocols would include:

1. Local and federal agencies responsible for effecting energy savings in low-cost and older naturally ventilated buildings
2. Building and HVAC designers, installers, and operators
3. Local agencies responsible for setting and evaluating performance standards and indoor air quality

Naturally Ventilated Buildings

A simplified multitracer (SMT) method is proposed for multistory, naturally ventilated buildings to measure the infiltration and exfiltration rates of each floor, the air exchange rates between floors, and the total building infiltration rate. Only three PFT types are needed if the following assumptions hold:

1. Each floor is a single well-mixed zone, and
2. There is negligible direct airflow between nonadjacent floors.

The latter has generally been shown to be the case in naturally ventilated buildings. Any central stairwell can be treated as an independent fourth zone.

Assumption 1 is generally not valid, since each floor is usually divided into several apartments or office complexes. However, by adjusting the PFT source strength in each apartment in proportion to its respective floor area, this assumption can be approximated.

As shown in Figure 4, the PFT sources are deployed as follows: Each apartment on floor one receives PFT type one; similarly, floor two, PFT type two and floor three, PFT type three. Floor four receives PFT type one again, and the sequence repeats. Mathematically, it can be shown that each of the floor infiltration, exfiltration, and air exchange rates can be solved, exactly, from multiple sets of three simultaneous equations.

This technique has been field-implemented in a 2300 m^3 three-story plus basement solar energy laboratory in Lausanne, Switzerland, during which simultaneous measurements of the air infiltration rate into each floor were also determined by a constant concentration technique (Scartezzini et al. 1984). These results plus subsequent measurements as a four-zone building using four different PFTs are underway and will be evaluated.

The advantages of the SMT approach are the simplicity of field equipment and personnel needs, the direct determination of between floor air exchange (necessary for IAQ studies involving different users on different floors), and a direct measure of the magnitude of the stack effect (i.e., the air exchange rate up divided by that down). A disadvantage of this technique is the practical consideration of requiring access to every apartment or office complex on every floor. In certain office building situations this may be feasible, but in apartment buildings this is practically infeasible.

The Core Apartment Procedure (CAP). An alternative to the SMT method is to select one apartment on one floor as a core unit; it would receive PFT 1. Any other apartment(s) on the same floor sharing a common wall to the core apartment would be tagged with PFT 2. Lastly, the apartment directly below the core apartment would receive PFT 3 and that above, PFT 4. This

four-zone measurement would then provide an estimate of the fresh air into and out of the apartment, exchange between apartments on the same floor, and the stack effect (exchange between apartments in the vertical). Repeating this at one or two other elevations in the same building would allow a reasonably complete picture for the whole building, to be drawn from access to only a limited number of apartments. Note that when selecting the PFTs for deployment in this and any other vertically arranged three- or four-zone study, the proper choice from the highest to the lowest zone in a three-zone study is PDCB, PMCH, and PDCH; in a four-zone study, the order is PDCB, PMCP, PMCH, and PDCH.

This procedure was demonstrated for a two-week period, the second half of November 1984, in three New York City five-story apartment buildings currently undergoing weatherization to reduce air infiltration. This field experience corroborated the suspicion of difficulty in implementing the SMT approach; it was only possible in one case to nearly achieve the CAP protocol, the deterrents having been (1) people not home during deployment and recovery, (2) "lost" sources and samplers, (3) fear of the PFT system, and (4) no interest in cooperating.

In one building, a stack of three apartments was successfully tested. In another, two stacked apartments, 4E and 5E, plus an adjacent apartment, 4D, and the stairwell were tested; but the results were not completely unambiguous because both 4D and the stairwell were tagged with the same PFT-type source. The third building was successfully evaluated as a four-zone test, involving three stacked apartments and a stairwell.

The four-zone flow rates for the latter are shown in Figure 5, in which apartment 32 was the core apartment. First, there appears to be a modest to significant stack effect, with the flow upward in vertically adjacent apartments ranging from 36 to 80 m^3/h, not substantially less than the individual apartment "adjusted" infiltration rates (more on this shortly), whereas the flow downward was less than 1 m^3/h. In fact, for all three buildings, this downward flow was never greater than 2 m^3/h. It can also be seen that the upward flow from apartments 22 to 42 was 13 m^3/h, not insignificant as required by the previous SMT model.

The airflow through the stairwell was clearly upward, as indicated by the magnitude of the concentrations of the PFTs used in the three apartments with respect to the stairwell sampling locations on the first, third, and fifth floors; at slightly more than 500 m^3/h, the air infiltration rate corresponded to an ACH of 2.3 h^{-1}. There was also a modest air exchange between the stairwell and each of the apartments, ranging from 10 to 15 m^3/h into the apartments and 5 to 10 m^3/h out into the stairwell.

<u>CAP "Adjusted" Infiltration Rates.</u> Fresh air infiltration into the core apartment, apartment 32, was 98.1 m^3/h (Figure 5). But based on the non-adjacent vertical flow of 13.1 m^3/h from apartment 22 to apartment 42, the same amount can be assumed to be flowing from apartment 12 to apartment 32, which would have been counted in the modeling results as part of the 98.1 m^3/h fresh air rate, since there was no tracer in apartment 12, due to little downward flow. Based on measurements in another building, two other apartments might have contributed to apartment 32, namely, apartment 33 (adjacent on the same floor, about 1 m^3/h) and apartment 23 (diagonally adjacent downstairs, about 13 m^3/h), both estimated as fresh air rates.

Subtracting each of these other contributing flow rates (13 + 1 + 13 or 27 m^3/h) from the computed fresh air rate of apartment 32 (98 m^3/h) gives a net fresh air infiltration rate of 66 m^3/h. Dividing by the apartment volume, 215 m^3, gives a net infiltration ACH of 0.31 h^{-1}, about two-thirds of the originally calculated rate. In a similar way, the "adjusted" rate into apartment 42 is about 158 m^3/h (0.73 h^{-1}) and into apartment 22, 78 m^3/h (0.36 h^{-1}). Thus, the expected whole building living zone air infiltration rate is about 0.47 ± 0.23 h^{-1}.

Natural and Mechanical Ventilation

In HVAC-equipped buildings, the breathing zones, and, hence, the tracer zones, are defined by the sections of the building being serviced by each individual HVAC system. By placing a different tracer type in each separate HVAC supply air plenum, a multizone measurement of the total natural <u>and</u> mechanical infiltration into each zone can be obtained and, hence, an estimate of the performance of each system within that building.

The schematic representation of the 5,000,000 ft^3 (142,000 m^3) 15-story Portland Building in Oregon, Figure 6, demonstrates the utility of the method. Zones one and three had about the same fresh air rate (1.07 h^{-1}), but zone two was four-fold lower (0.25 h^{-1}), indicating a system imbalance and poorer IAQ in that zone (Dietz et al. 1984).

Based on the modeling approach represented by Table 3, it can be shown that, relative to the concentration in zone one of the Portland Building for a source in zone one, the concentration in zone two with the source in zone two is 71% higher and in zone three for a source in zone 3, +16%. Similarly, for an equal source strength in each zone, the concentrations in zones two and three relative to zone one are +38% and -29%, respectively. This means, for example, that for the same number of occupants in each zone, the CO_2 level above background would be 38% higher in zone two compared to zone one and 29% lower in zone three compared to one.

Note, however, that this approach does not distinguish the extent of natural infiltration from mechanical ventilation; the former may be significant in some buildings or in particular zones of buildings. If this were known, then there is the potential for energy savings.

An extention of the multizone model to the bizone-multizone model (BMM) is shown schematically in Figure 7. The model is called bizone because each air handling system is separated into two zones, the HVAC zone (i.e., the mixing plenum) and the breathing zone (i.e., the floor area serviced by the HVAC system). One type of PFT is placed in the supply air duct (PFT 1) to tag the breathing zone, and a different PFT is placed in the return air duct (PFT 2) to tag the HVAC zone.

With this approach the natural infiltration into the breathing zone can be distinguished from the mechanical ventilation provided by the HVAC zone and, similarly, for the exfiltration from the respective zones. However, because only four PFT types are currently available, only buildings with two HVAC systems can be accommodated with this modeling approach. Hence, there is a need for establishing more PFT types.

Performance Certification of Air-Handling Systems

A question arises as to what extent the occupants in the breathing zone of a building are benefiting from the fresh air being drawn into the HVAC system. Many buildings have air-handling systems equipped with ceiling supply and return air ducts, sometimes ingeniously concealed within ceiling lighting fixtures. Stale air can be exhausted at the ceiling or perhaps a portion of the supply or return air is vented.

A question among designers, installers, and operators of these systems is to what extent is the supply air mixed adequately within the breathing zone or, conversely, to what extent does stratification and short-circuiting of supply air to the return air vents occur?

An adaptation of the bizone-multizone model (BMM) has resulted in the HSM (HVAC stratification model). As shown schematically in Figure 8, the breathing zone (zone B) is serviced by the HVAC system (zone H) through ceiling vents, resulting in a non-dimensionally defined stratified zone (zone S) near the ceiling for this one-fan system.

In this case, as in the BMM case, only two PFT-types are required. One PFT is placed in the return air duct (PFT S_2) to tag the HVAC zone as before, but the other PFT-type is distributed throughout the breathing zone (PFT S_1). Sampling is then performed in the breathing zone, in the stratified zone (e.g., behind the return air vent), and in the HVAC zone (e.g., in the supply air duct).

Assuming that the mechanical exfiltration can occur from any one of the three zones, a solution of this model not only provides the natural and mechanical infiltration and exfiltration but also provides a direct measure of the efficiency of the HVAC system as given by:

	Mechanical Exfiltration		HVAC Efficiency	
Type	Zone	Rate	Absolute	Effective
1	H	R_{ME} ($R'_{ME} = 0$)	C_{1H}/C_{1B}	C_{1S}/C_{1B}
2	S	R'_{ME} ($R_{ME} = 0$)	C_{1S}/C_{1B}	C_{1S}/C_{1B}
3	B	$R_{NE} = R_{MI} + R_{NI}$ ($R_{ME} = R'_{ME} = 0$)	1.0	1.0

The assumption of the stratified zone having a uniform or representative concentration must be evaluated as well as field-testing this new model. Protocols for various building configurations must be established and the effectiveness and utility of the model, together with the multiple PFT system, must be demonstrated. Again, there is a need for more PFTs. Tests of this technique in a two-zone commercial building, each serviced by a separate HVAC system, in which stratification is possible in one zone but not in the others, are currently underway. In a similar way, a model for a two-fan system, in which the supply air and return air are balanced with separate fans, and stale air is eliminated by venting a portion of the return air, can also be developed and evaluated.

CONCLUSIONS

The multizone measurement of air infiltration and exfiltration rates from multizoned homes, as well as the air exchange rates between zones, provides a quantitative method for (1) assessing changes in the flow character due to specific physical changes and (2) determining the impact of pollution sources in different zones on the concentration in each zone.

Four-zone measurements in a single-story, four-apartment complex showed little interaction between the zones; each could have been treated as a single zone. The same type of measurements in a two-story, four-unit condominium, demonstrated the existence of a moderate stack effect; the upper units were significantly less like independent single-zone units when compared to those downstairs.

A core apartment procedure was established and field tested for evaluating the infiltration and multizone flow rates in multistory apartment buildings. It appears that selection of two or three "core" apartments, each included in part of a four-zone study of adjacent apartments, is sufficient to characterize the performance of these naturally ventilated buildings.

The BNL/AIMS passive PFT technology was successfully applied to a 15-story, 142,000-m^3, building serviced by three HVAC systems. Although there were differences in the fresh air infiltration rates provided by the system of as much as a factor of four, the spread between the zones with the lowest to the highest air pollution levels was about a factor of 1.7. Thus the multizone modeling concepts can be used to assess factors influencing IAQ in very large multiple-zoned buildings. Thus, there is a need to develop more PFTs than the four currently available.

With the perfluorocarbon tracer technology, it appears that simple schemes can be employed to distinguish natural infiltration from mechanical ventilation and to determine the efficiency of air-handling systems with respect to stratification and short circuiting of HVAC supply air.

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TABLE 1

BNL/AIMS Results for the Brookhaven House (3/29-4/2/83)

Zone	Vol., m^3	Source Rate, nL/h	Average Tracer Concentrations,[a] nL/m^3 PFT 1	PFT 2	PFT 3
1. 2nd Floor	215	3410	36.39 ± 3.11	13.63 ± 0.44	7.97 ± 0.08
2. 1st Floor	240	1878	15.40 ± 1.39	14.14 ± 1.46	8.00 ± 0.13
3. Basement	204	1734	4.17 ± 0.14	2.52 ± 0.06	16.63 ± 1.98

[a] Average of two passive samplers on each floor; PFT 1 was deployed in zone 1, etc.

TABLE 2

Effect of an Air-to-Air Heat Exchanger[a] (AX) on the Zonal Infiltration Rates in the Brookhaven House

AX Status[b]	Floor Infiltration Rates, m^3/h 2nd	1st	Basement	Whole House, ACH, h^{-1}
Off	18 ± 4	69 ± 9	75 ± 26	0.25 ± 0.06
On (Hi fan)	19 ± 28	168 ± 13	57 ± 15	0.37 ± 0.04
Change:	1 ± 32	99 ± 22[c] (143 ± 58%)	-18 ± 41	0.12 ± 0.10 (48%)

[a] Installed in a first-floor window.
[b] Average of two bi-weekly periods off and two on.
[c] Rated capacity on high fan speed was 120 m^3/h.

TABLE 3

Expected Zone Concentrations for One Type of Source in Different Locations of the Brookhaven House

Case	Calculation Basis	Source Location and Rate,[a] nL/h 2nd	1st	Bsmt	Calculated[b] Zone Concentrations, nL/m^3 2nd	1st	Bsmt
1	Source on 2nd floor	1000	-	-	10.8	4.5	1.2
2	Source on 1st floor	-	1000	-	7.3	7.5	1.3
3	Source in basement	-	-	1000	4.6	4.6	9.6
4.	Equal conc. on all flrs[c]	20	430	550	5.9	5.9	5.9
5.	Equal conc. in liv. zone[d]	42	958	-	7.4	7.4	1.3

[a] The source rates in cases 4 and 5 were proportioned according to the 3-zone infiltration rates in Figure 1 and computed 2-zone (2nd and 1st floor) infiltration rates, respectively.

[b] Calculated by normalizing the measured concentrations in Table 1 with the known source strengths.

[c] Source rates required to give equal concentrations in each zone; equivalent whole house ACH of 0.259 h^{-1}.

[d] Source rates required to give equal concentrations on each floor of the living zone (2nd and 1st floors); equivalent living zone ACH of 0.297 h^{-1}.

TABLE 4

PFT Concentrations in 4-Zone Quadraplex Housing Units
(Samplers Deployed for 33 Days)

Unit	Sampler No.	Location	PDCH (U1)[b] (2143 nL/h)	PDCB (U2) (4656 nL/h)	PMCP (U3) (4838 nL/h)	PMCH (U4) (3096 nL/H)
1	1672	Liv. Rm.	74.9	6.56	0.47	1.61
1	1649	Kitchen	69.5	6.65	0.25*	1.57
1	1666	Mas. Bdrm.	115.0*	7.83	0.52	1.79
1	1657	Sm. Bdrm.	64.1	6.49	0.53	1.46
	avg.		80.9 ± 20.1	6.88 ± 0.55	0.44 ± 0.11	1.61 ± 0.12
	avg.[a]		(69.4 ± 4.4)		(0.51 ± 0.03)	
2	1651	Mas. Bdrm.	0.177	135.3	1.56	0.0315
2	1635	Liv. Rm.	0.158	116.7	1.56	0.0309
	avg.		0.168 ± 0.010	126.0 ± 9.3	1.56	0.0312 ± 0.003
3	1643	Mas. Bdrm.	---	3.40	142.9	0.0242
3	1227	Liv. Rm.	0.018	3.07	124.6	0.0235
	avg.		0.018 ± 0.004	3.23 ± 0.17	133.8 ± 9.2	0.0239 ± 0.0004
4	1650	Liv. Rm.	2.58	0.63	0.99	57.3
4	1415	Kitchen	2.55	0.61	0.94	46.6
4	1452	Mas. Bdrm.	2.61	0.74	1.51*	81.7*
4	1319	Sm. Bdrm.	2.63	0.66	1.13	62.3
	avg.		2.59 ± 0.03	0.66 ± 0.05	1.14 ± 0.23	62.0 ± 12.7
	avg.[a]				(1.02 ± 0.08)	(55.4 ± 6.6)

[a]Average also computed excluding value with asterisk.

[b]Values in parentheses are the unit location tagged with that tracer and the average emission rate for the 2 sources deployed.

TABLE 5

Calculated Air Exchange and Infiltration Rates
in the Quadraplex Housing Units
(2/3/84 to 3/7/84)

	Air Exchange and Infiltration Rates, m^3/h			
	Unit 1	Unit 2	Unit 3	Unit 4
to Unit 1	----	1.68	0.090	0.90
to Unit 2	0.089	----	0.43	0.018
to Unit 3	0.007	0.93	----	0.015
to Unit 4	2.08	0.169	0.42	----
R_E[a]	31.3	36.2	36.7	58.3
R_I[a]	30.8	38.4	36.7	56.6
ACH_I, h^{-1}[b]	0.120	0.150	0.143	0.220

[a]R_E and R_I are the rates of air exfiltration and infiltration,

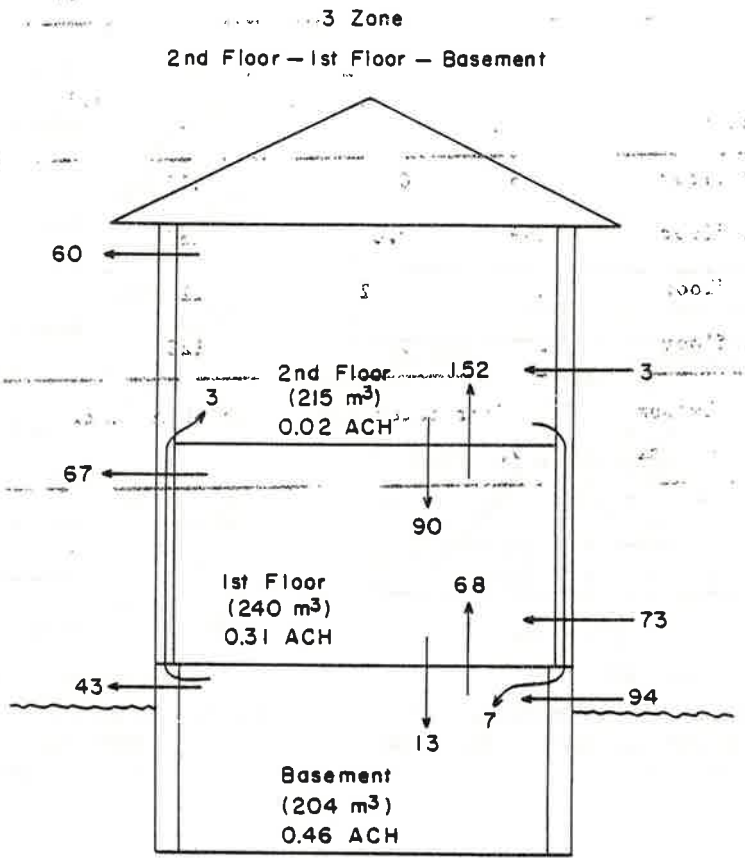
[b]ACH_I is R_I divided by the unit volume (257 m^3).

TABLE 6
Performance of the Long Island Condominium Building

Unit	Location	Infiltration Rate, m^3/h	Infiltration ACH, h^{-1}	Total inflow,[a] m^3/h	Leakiness[b] Relative to Unit 1
1	2nd floor	56	0.32	112	1.00
4	2nd floor	149	0.85	185	1.65
2	1st floor	116	0.72	121	1.08
3	1st floor	114	0.71	120	1.07

[a] Calculated by summing the four inlet flows into each unit.

[b] Based on the total in-flow.



BROOKHAVEN HOUSE

(All Flow Rates in m^3/h)

Figure 1. Distribution of flow rates in early spring

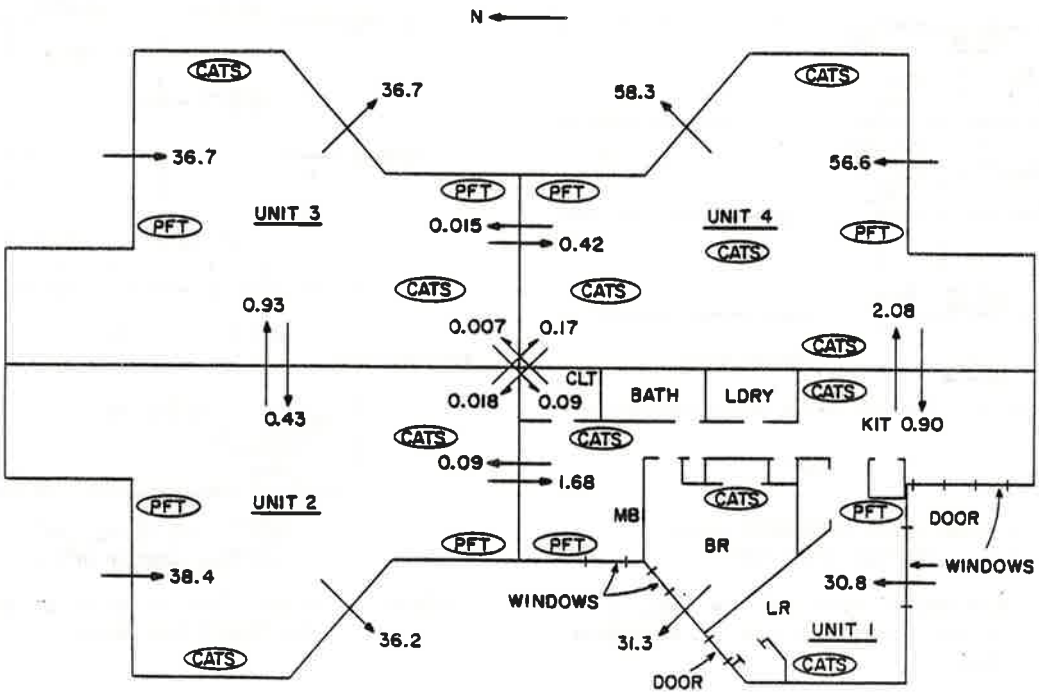


Figure 2. Plan view of quadraplex housing units. All flow rates in m^3/h

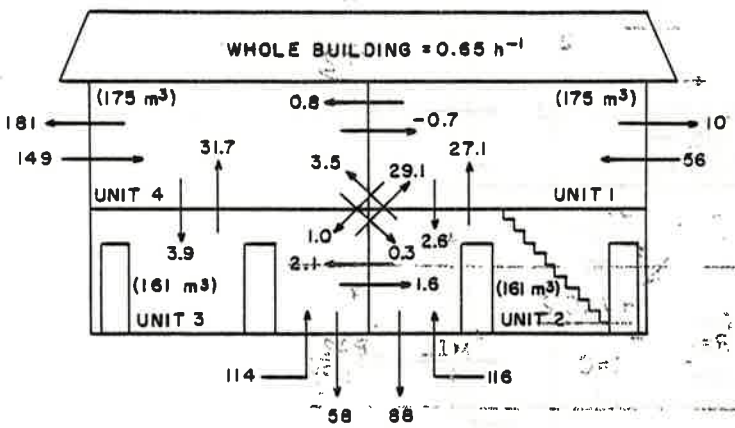


Figure 3. Elevation view of a four-unit condominium building. All flow rates in m^3/h

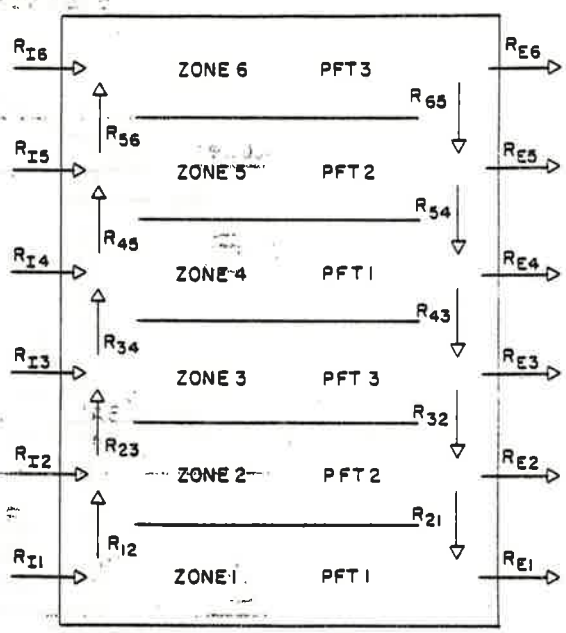


Figure 4. Simplified measurement technique (SMT) for determining natural infiltration in apartment buildings

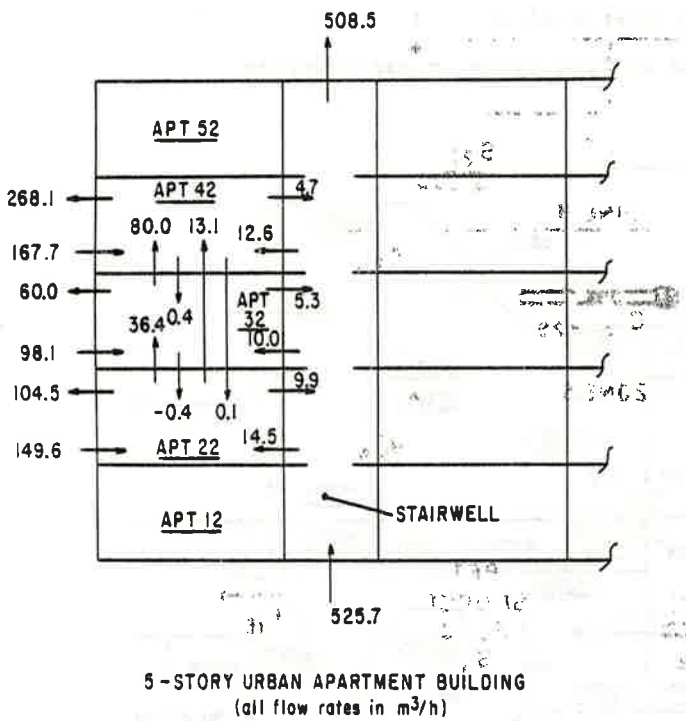


Figure 5. Elevation view of the results of the core apartment procedure (CAP)

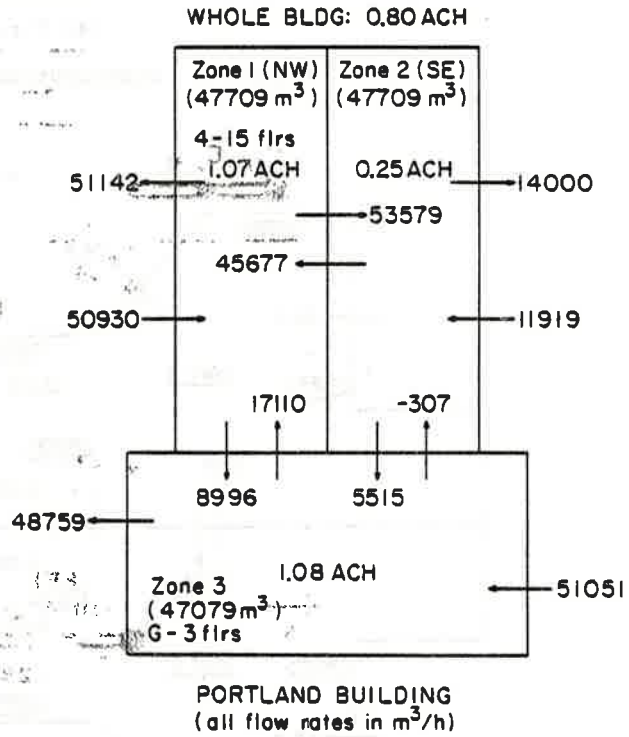


Figure 6. Flow distribution in the 15-story Portland building

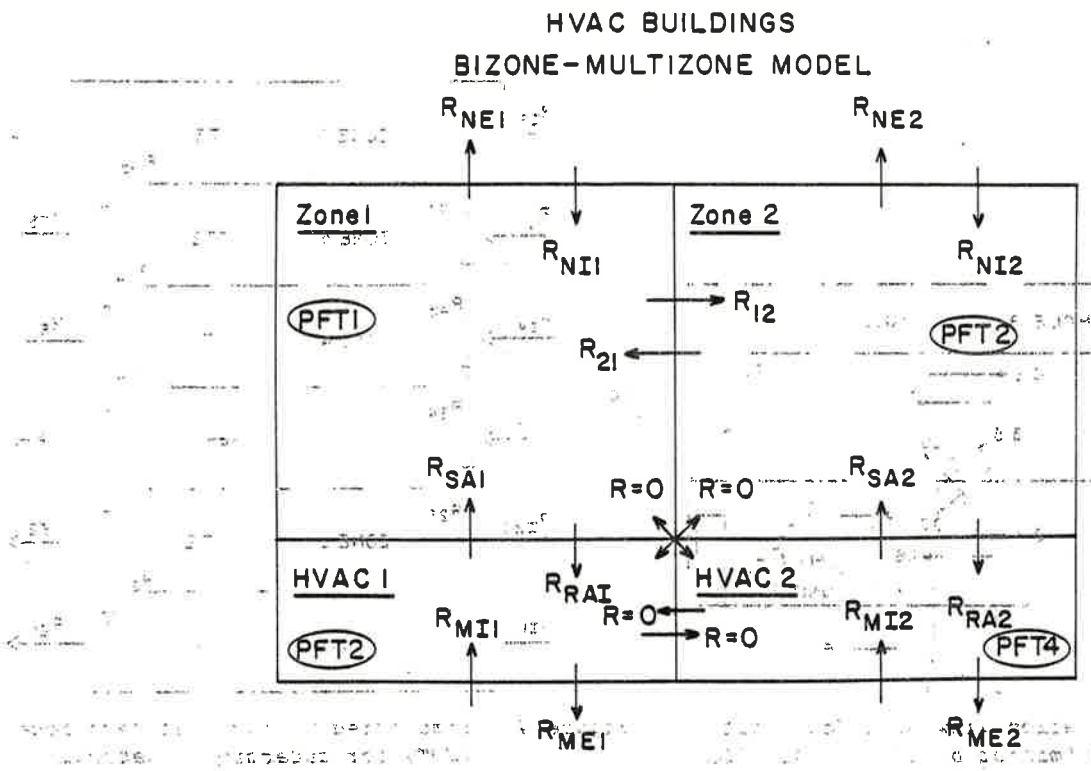


Figure 7. Schematic of the bizone-multizone model (BMM) for buildings with HVAC systems

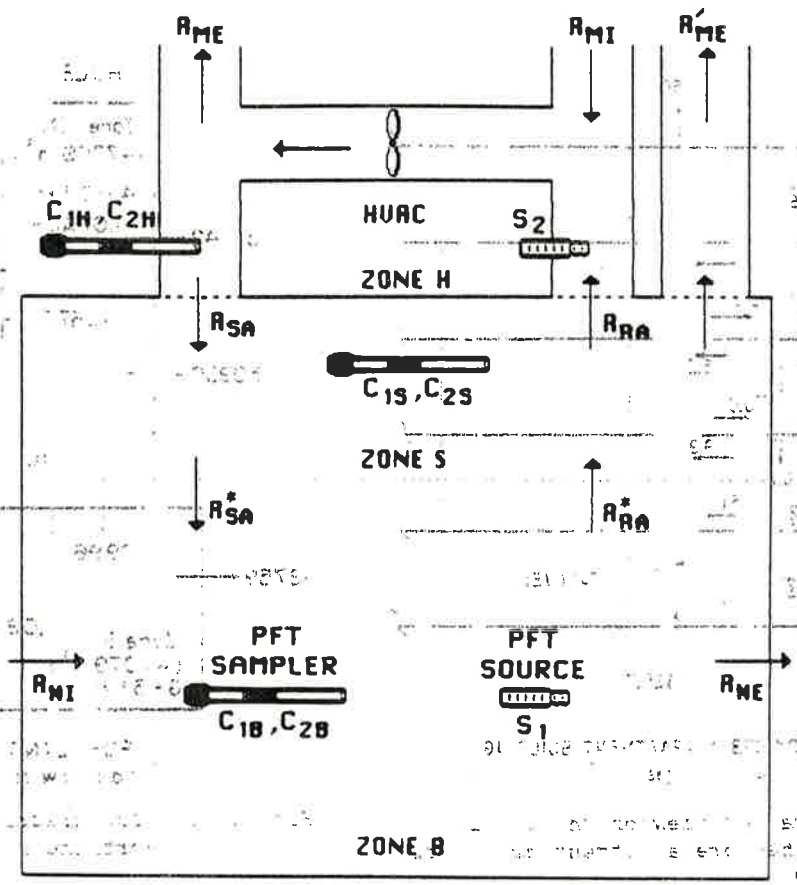


Figure 8. Quantifying stratification with the HVAC stratification model (HSM)