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Airflow
Tracers

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Final Report
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Air Infiltration and Interzonal Airflow Measurements in Research Houses

Prepared by
GEOMET Technologies, Inc.
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REPORT SUMMARY

SUBJECTS Lighting, appliances, and building energy systems / Air quality research

TOPICS

Air infiltration	Airflow
Residential energy use	Tracers
Indoor air quality	

AUDIENCE R&D and environmental engineers / Customer service representatives

Air Infiltration and Interzonal Airflow Measurements in Research Houses

Infiltration of outdoor air into residential buildings and air movement between conditioned and unconditioned airspaces can significantly affect energy use and indoor air quality. A study using four measurement methods provides detailed data on air infiltration and interzonal airflows and describes the performance characteristics of the measurement techniques.

BACKGROUND Energy conservation retrofits reduce air infiltration and heat loss in residential buildings but may adversely affect air quality by trapping indoor pollutants inside. Previous EPRI studies (reports EA/EM-4117 and EM-5896) document the effect of weatherization on whole-house concentrations of indoor pollutants, especially radon and radon progeny. An understanding of air infiltration and airflow rates from a multizone perspective would strengthen residential building energy use and indoor air quality modeling efforts. Multizone measurements identify airflow patterns among various zones or compartments within a house, including conditioned living areas and unconditioned spaces, such as attics and garages.

OBJECTIVES To gather detailed data on multizone air infiltration and airflow rates in residential buildings and to compare air infiltration and multizone airflow measurement techniques.

APPROACH Over the course of a year, researchers measured the rates of whole-house air infiltration, as well as interzonal airflow between the upstairs, downstairs, attic, and garage of two bilevel research houses. Researchers had already weatherized one of the houses for an earlier EPRI project (report EA/EM-4117). The unweatherized house served as the control. They used four different but complementary measurement techniques—sulfur hexafluoride tracer gas dilution, sulfur hexafluoride single tracer constant concentration, constant release of passive perfluorocarbon tracers, and constant release of multiple halocarbon tracers with real-time analysis.

RESULTS Whole-house air infiltration rates exhibited seasonal variations. For the control house, the wintertime rate reached 0.66 air changes per hour (ACH)—three times higher than the summer rate of 0.19 ACH. Air infiltration rates in the weatherized house measured 20–30% lower. A 40–60% variation in the downstairs air infiltration rate of the weatherized house is the primary cause of the difference in whole-house air infiltration rates.

Throughout the year, air moved at a higher average rate from the basement to the upstairs than in the reverse direction. These rates were 55% lower in the weatherized house than in the control house. Measurement of interzonal airflow rates between the upstairs and the attic showed the effectiveness of weatherization in reducing air losses resulting from the vertical temperature gradient in the house. The four methods used in the study provided comparable results for measurement of whole-house air infiltration rates.

EPRI PERSPECTIVE

This project developed a comprehensive database on infiltration and interzonal airflow rates for the two research houses. These data will provide valuable input for utility programs involving multizone modeling of indoor air quality and energy use in residential buildings. In addition, the presentation of results for the four measurement methods, including a comparison of the advantages, limitations, and applicability of each, will assist utilities in conducting measurement programs.

PROJECT

RP2034-1
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Contractor: GEOMET Technologies, Inc.

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Air Infiltration and Interzonal Airflow Measurements in Research Houses

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ABSTRACT

Four different but complementary methods--the tracer gas dilution method, single tracer constant concentration, passive perfluorocarbon tracers (constant release), and constant release of multiple halocarbon tracers with real-time analysis--were used to obtain detailed information on air infiltration and interzonal airflow rates in two bilevel research houses. The study included measurements of seasonal variations and differences between the houses, one of which was retrofitted in a previous EPRI study to reduce the air leakage area. Measurements showed that there had been little change in whole house infiltration rates during the 4 years since the retrofit. Differences between the houses with respect to whole house air infiltration rates were primarily the result of differences in downstairs air infiltration rates between the two houses. Zone-specific measurements indicated that downstairs infiltration rates were three to nine times higher than upstairs; infiltration rates were 30 to 60 percent lower in the downstairs of the retrofitted house than in the other house. The impact of the retrofit was also reflected by lower rates of airflow from the garage into the downstairs and from the upstairs to the attic. Airflows between the upstairs and downstairs of the houses exhibited seasonal variation due to stack effect action and operation of the central heating and cooling systems. Short-term interzonal airflow rates were as much as an order of magnitude higher than week-long average rates. Results of measurements with the different methods are also compared and discussed as they relate to advantages, limitations, and applicability of the methods in utility-sponsored measurement programs.

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David Harrje and David Bohac of Princeton University were responsible for the collection of constant concentration data at the research house. They provided the necessary instrumentation and analysis of the resultant data.

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SUMMARY

Infiltration of outdoor air and the patterns of air movement between conditioned and unconditioned airspaces can have a significant impact on energy use and air quality in residential dwellings. Energy conservation retrofit procedures can be implemented to reduce air infiltration and loss of heat from conditioned indoor airspaces, but these procedures may affect air quality.

The Electric Power Research Institute (EPRI), recognizing the importance of the quality of the indoor environment, has played an important role in the field of air infiltration and indoor air quality research. As part of the research effort, EPRI initiated an indepth study in 1982 of energy use, air infiltration, and air quality in the two contemporary research houses operated by GEOMET. Following a period of baseline monitoring, one house--the experimental house--was retrofitted for building tightness to reduce the leakage area and air infiltration rate. The other house--the control house--remained in its initial state of construction. Subsequent monitoring addressed the effect of the retrofit on energy use, air infiltration, and indoor air quality. The current study was initiated to obtain a fuller understanding of certain aspects of the original project. The objective of the research effort described in this report was to gain a detailed understanding of air infiltration and interzonal airflow rates in the houses from a multizone perspective that included both conditioned indoor airspaces and unconditioned zones such as the attic.

Four different but complementary measurement methods were used to measure air infiltration and interzonal airflow rates. Characteristics of the four methods are summarized in Table 1.

Table 1

CHARACTERISTICS OF THE MEASUREMENT METHODS

Method/Technique	Number of Tracers	Sampling Method	Averaging Period	Measurement Parameter(s)
Tracer dilution, sulfur hexafluoride (SF_6)	1	Continuous	Hour	Single-zone infiltration
Constant concentration (SF_6)	1	Continuous	Hour	Multizone infiltration
Perfluorocarbon tracers (PFT)/constant release	4	Passive	7-day	Multizone infiltration and interzonal airflows
Halocarbon tracers/ constant release	2	Continuous	Hour	Multizone infiltration and interzonal airflows

The tracer dilution method with sulfur hexafluoride (SF_6) as the tracer gas was used as the reference method for measurement of air infiltration rates for the whole house. Multizone air infiltration rates were measured with an automated constant concentration system in six zones defined in the control house. Two multiple tracer systems were used in a constant release mode: (1) passive perfluorocarbon tracers (PFTs) that were used to obtain week-long average measurements of air infiltration rates and interzonal airflow rates for the upstairs, downstairs, attic, and garage, and (2) an automated multiple tracer gas system using halocarbons and a "real-time" analyzer that was used to measure short-term variations in airflows between the two conditioned zones.

Whole house air infiltration rates measured by the SF_6 tracer dilution method exhibited seasonal variations similar to those measured in the previous EPRI study at the research houses. Winter rates of 0.66 air changes per hour (ACH) were approximately three times higher than the summer rates (0.19 ACH) in the control house. Air infiltration rates in the experimental house were 20 to 30 percent lower than in the control house. Differences between the houses were consistent with previous measurement results.

Differences in whole house air infiltration rates for the two houses were due mainly to differences in the infiltration rates for the downstairs zones. Constant concentration, PFT, and halocarbon methods all showed substantially higher infiltration rates downstairs than upstairs. The range in upstairs infiltration rates in the two houses during the year was rather narrow, from 0.07 to 0.32 ACH. Downstairs, week-long average infiltration rates ranged from 0.14 to 1.69 ACH. Downstairs rates were as much as seven times higher than upstairs rates in the control house. Infiltration rates were 40 to 60 percent lower in the downstairs of the experimental house than in the control house, reflecting the effectiveness of retrofit measures implemented downstairs. Upstairs infiltration rates differed by no more than 0.08 ACH between the houses during the year and were generally higher in the experimental house than in the control house.

Attic air infiltration rates were quite high, as expected. Rates ranged from 6.6 to 15.4 ACH and were generally above 9. Rates in the attic were not significantly different for the experimental and control houses.

Relatively low infiltration rates were measured for the garages; week-long average rates were less than 1.2 ACH throughout the year. Infiltration rates were lower for the garage of the experimental house than the control house, consistent with the fact that retrofit measures included adjustment of the garage doors in the experimental house.

PFT measurements indicated that there was very little airflow from the downstairs into the garage, but that substantial amounts of air entered the downstairs from the garage. In the control house, for example, the average airflow rate from the garage to downstairs was 67 m^3/h during winter. Airflow rates between the garage and downstairs were 30 to 60 percent lower in the experimental house than in the control house. This difference was consistent with the sealing of leakage areas in the wall and door between the two zones during the retrofit.

The effectiveness of retrofit measures to reduce air losses due to the stack effect was evident from measurement of airflow rates between the upstairs and the attic. Airflow from the upstairs to the attic in the experimental house was lower than in the control house during all seasons; in the winter, the airflow rate was nearly 60 percent lower in the experimental house.

Average interzonal airflow rates between the upstairs and downstairs of the houses during week-long measurement periods ranged from a low of 24 m^3/h in the spring to a high of 263 m^3/h during the winter. Average airflow rates from the basement to upstairs were higher than in the reverse direction throughout the year, and the rates were higher in the control house than in the experimental house. Measurements with the halocarbon system showed that short-term airflow rates were as much as an order of magnitude higher than the week-long average rates. Hourly airflow rates were related to the amount of time that the fan of the central forced-air heating/cooling system operated.

Results of measurements in this study further demonstrated the effectiveness of the retrofit procedures applied in the experimental house. Rates of infiltration in the downstairs of the experimental house were 40 to 60 percent lower than in the control house. Airflow rates were also lower from the garage to the downstairs in the experimental house. Retrofit procedures resulted in lower airflow rates from the upstairs to the attic in the experimental house and also impacted the rate of airflow from downstairs to upstairs.

The applicability and limitations of the various measurement methods were clearly demonstrated in this study. The four different measurement methods provided comparable results for measurement of whole house air infiltration rates. The constant concentration method indicated that the air infiltration rates of individual rooms upstairs were comparable, but that the downstairs infiltration rates were substantially higher than the upstairs rates. Zone-specific infiltration rates were also obtained with the two multiple tracer methods. Results of measurements in the upstairs and downstairs by the three methods generally compared well. The PFT method was advantageous in that it could be used for measurement of infiltration rates in the attic and garage in addition to the conditioned zones. However, a week-long exposure was required so that only long-term average infiltration and interzonal airflows could be measured. The halocarbon method, however, was capable of providing short-term measurements of infiltration and interzonal airflow rates.

Utilities can benefit from the results of this study by using the results as a basis for comparing the advantages, limitations, and applicability of the measurement methods as they relate to measurement requirements in utility-sponsored programs.

The comprehensive data base on infiltration and interzonal airflow rates available for the two research houses will prove valuable for multizone modeling of indoor air quality and for providing realistic inputs to energy-use modeling. Modeling efforts can be further strengthened by performing a series of similar tests in two or three additional types of residential structures.

Results of this study indicate that the multiple halocarbon tracer system is a valuable tool for measurement of short-term variations in infiltration and interzonal airflow rates. Further refinements and expansion of the system will prove valuable in the study of airflow patterns in residences.

Section 1

INTRODUCTION

BACKGROUND

Air exchange between indoors and outdoors is recognized to be an important parameter related to indoor air quality and energy use in buildings. Air that infiltrates into a building may contain significant concentrations of outdoor pollutants. This same air, however, can serve to dilute the concentration of pollutants generated indoors. Infiltrating air also directly impacts energy use in buildings because of the need to condition incoming air.

Airflows within a building can have a substantial impact on air quality and energy use in different areas or zones. As an example, although radon enters buildings primarily through the basement or lowest floor of the structure, concentrations of radon in the living space of a residence depend not only on the source strength in the basement, but also on the direction and magnitude of the airflows between the basement and the upstairs living space. Likewise, the movement of air from unconditioned or marginally conditioned spaces such as basements, attics, and attached garages affects energy use.

Improved building design, new construction practices, and retrofits for energy conservation purposes can achieve substantial decreases in air infiltration rates. Although these practices reduce energy consumption, they can adversely affect the quality of the air in indoor environments. The Electric Power Research Institute (EPRI), recognizing the importance of the quality of the indoor environment, played an early role in the field of air infiltration and indoor air quality research. Since the mid-1970s EPRI has conducted a number of research studies on the effects of air infiltration and weatherization on indoor air quality. These studies have included both field monitoring surveys and experimental testing in GEOMET's two research houses.

In 1982, EPRI initiated an in-depth study of energy use, air infiltration, and indoor air quality in GEOMET's research houses. The test site consists of two tight, well-insulated conventional residences located in the Washington, D.C. metropolitan area. The two homes are of identical thermal construction and are located on adjacent lots. Following a period of baseline monitoring that demonstrated the nearly identical characteristics of the two homes, one home was retrofitted for energy conservation by sealing of air leakage sites. With use of standard retrofit procedures, the one house, termed "experimental," was modified so that it was about 40 percent tighter than the "control" house following retrofit. Postretrofit monitoring was then performed to assess the effect of the retrofit on energy use, infiltration, and indoor air quality. The initial construction, preretrofit monitoring, and postretrofit monitoring periods constituted Phase I of the EPRI project (1).

During Phase I monitoring, air infiltration was measured by two different methods. The fan pressurization technique (blower door) was used at routine intervals during the test period to measure leakage area and to calculate air exchange rates under pressurized and depressurized conditions. Air exchange was also measured continuously by an automated tracer gas dilution method with sulfur hexafluoride (SF_6) as the tracer.

The nearly continual measurement of air exchange with the tracer gas dilution method provided a substantial data base for understanding temporal variations in air infiltration rates in the two houses on time scales ranging from hours to seasons. However, with this monitoring method, detailed spatial behavior such as thermal stratification and flow coupling among conditioned and unconditioned airspaces could not be adequately characterized. Therefore, additional testing to characterize air infiltration and interzonal airflows was conducted in this study.

METHODS FOR MEASUREMENT OF AIR EXCHANGE AND INTERZONAL AIRFLOWS

Fan Pressurization Technique

The fan pressurization technique, more commonly referred to as the blower door measurement, has found widespread use for measuring air leakage rates through the building envelope and estimating air exchange rates of residential dwellings. The blower door is a portable device consisting of a large fan and a pressure sensor. The fan is used to alter the pressure in the house and exaggerate air leakage in the building envelope. A standard practice for measuring air leakage by the fan pressurization method has been developed by the American Society for Testing and Materials (ASTM) (2). Measurements with the blower door are used to estimate leakage area (cm^2) and air exchange rates at 50 pascals. The measurements are not direct measurements of air exchange rates that would occur under natural conditions. This method, therefore, cannot be used to measure naturally varying air infiltration rates.

Tracer Gas Methods

Tracer gas methods have been widely used for many years to measure the air exchange rates of a variety of different types of buildings. There are three basic tracer gas techniques--tracer gas dilution, constant concentration, and constant release.

Tracer gas dilution methods using a single tracer are the simplest and most widely used techniques for air exchange measurements. The general method assumes that the interior space of the building is a single, uniformly mixed space. A quantity of tracer gas is injected and mixed throughout the building. As tracer-free outside air enters the building, the concentration of the tracer gas decreases due to dilution. Periodic measurements of the tracer gas concentration are used to calculate the building's average air infiltration rate. A standardized ASTM measurement procedure (3) exists for this widely used technique.

Constant concentration techniques employ automated systems to simultaneously measure the concentration of the tracer and to inject the appropriate quantity of tracer gas into the zone to maintain a predetermined constant concentration (4). With a single tracer gas, this technique can be used to measure air infiltration rates, but not interzonal airflows, for multiple zones within a single structure. At the GEOMET research houses, for example, air infiltration rates were measured in six different zones.

Constant release methods (sometimes referred to as constant injection) employ a precision system to release a tracer gas at well-controlled rates. Air exchange rates are related to the tracer gas release rate and changes in the absolute concentration of the tracer. The analytical system is similar to that used for tracer gas decay methods. This technique has not been widely used as a single tracer method.

A number of different tracer gases are available for use. Sulfur hexafluoride has been used widely in single tracer methods, but other inert gases including helium, carbon dioxide, and nitrous oxide have been employed as tracers. Halocarbons and perfluorocarbons have been used for both single and multiple tracer methods.

Because of the widespread use of single tracer gas methods for air exchange measurements, a variety of both active and passive release and sampling methods have been developed (5, 6). Fundamentals and applications of tracer gas methods for the measurement of air exchange have been presented in a number of published reviews (7, 8, 9).

Multiple Tracer Gas Methods

Single tracer gas methods are used to measure air exchange rates in buildings that can be treated as a single well-mixed zone. However, to determine air infiltration rates for multiple compartments of a building, multiple tracer gas techniques are generally employed. With these techniques, interzonal airflows can also be characterized.

Multiple tracer gas systems can be configured that use the tracer gas dilution method, the constant concentration method, or the constant release method. With the dilution method, a single unique tracer gas is released as a pulse in each zone to be monitored. I'Anson, Irwin, and Howarth et al. (10), for example, used three halocarbon gases as tracers to measure interzonal airflows by the dilution method. Other refrigerants and perfluorocarbons have also been used in measurement systems employing the dilution method (8).

Constant release techniques that have been developed using perfluorocarbons or refrigerants as the tracers have been reviewed by Lagus and Persily (8). One widely used method is the diffusion-based constant release system with up to four perfluorocarbon tracers (PFTs) developed at Brookhaven National Laboratory (BNL). The PFT system has been used in single-family residences, apartment buildings, and large commercial buildings (6, 11). The system uses a passive release system and passive sampling with capillary adsorption tubes. It has found widespread use for measurement of integrated air exchange rates and interzonal airflow rates over periods of several days to several weeks.

Researchers at the Lawrence Berkeley Laboratory (LBL) have described a constant release system employing SF_6 and five halocarbon tracer gases for measuring ventilation rates and ventilation efficiencies in large buildings (12). Automated systems were used for tracer gas release and sample collection; samples were returned to the laboratory for analysis by gas chromatography with an electron capture detector (GC-ECD).

OBJECTIVES AND SCOPE

The principal objective of this task was to characterize the air infiltration and interzonal airflow rates among the conditioned and unconditioned airspaces of the GEOMET research houses. This characterization included comparisons between the retrofitted experimental house and the control house as well as an assessment of seasonal differences.

A secondary objective of this task was to compare the performance of different air infiltration and interzonal airflow measurement techniques.

To address these objectives the following measurement methods for air exchange and interzonal airflows were employed at the GEOMET research houses:

- Fan pressurization method
- SF_6 dilution method
- SF_6 constant concentration method
- Multiple PFT (passive) constant release method
- Multiple halocarbon constant release method.

Each system was employed during different times of the year to determine seasonal variations in air infiltration and interzonal airflows. To the extent possible, measurement methods were used concurrently to compare their performance.

This report describes the results of the measurements at the GEOMET research houses. Section 2 describes the test site, measurement parameters, measurement methods, sampling locations, and quality assurance (QA) and quality control (QC) procedures.

Results are presented in Sections 3 (Fan Pressurization and Tracer Dilution Measurement Results), 4 (Constant Concentration Measurement Results), 5 (Passive Perfluorocarbon Tracer Measurement Results), and 6 (Multiple Halocarbon Tracer Measurement Results). Differences in air infiltration and interzonal airflows between the houses (and for different seasons) are discussed, and the measurement methods are compared. Section 7 summarizes the major findings. Conclusions and recommendations for future work in this area are made in Section 8.

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Section 2

MEASUREMENT METHODS

TEST SITE

The site for testing under this task consisted of the two GEOMET research houses. The houses, constructed in 1982 in a new subdivision approximately 35 km northwest of Washington, D.C., are bilevel wood-frame houses. The houses are of identical design and are located on adjacent lots. Details of the house construction and initial characterization have been presented by Nagda, Koontz, and Rector in a previous EPRI report (1). The floor plan of the houses, depicted in Figure 2-1, consists of a main living area and three bedrooms upstairs, and a downstairs area divided into an unfinished living area and an integral garage. The upper and lower levels are connected by an open stairway that has a door at the bottom entry to the unfinished living area. Both houses are modestly furnished, including beds, tables, bookshelves, sofa, and chairs. Each house contains a standard set of appliances including a gas range, electric water heater, washing machine, clothes dryer, dishwasher, refrigerator, and range-hood and bathroom exhaust fans. The houses are heated and cooled with an electric forced-air system. The houses are unoccupied, but activities are simulated in the houses for experimental purposes with use of standardized simulation protocols.

MEASUREMENT PARAMETERS AND METHODS

A mobile laboratory equipped with a large array of analytical instrumentation, support and calibration equipment, and data acquisition systems is situated between the two research houses. Sample lines extend from the houses to the

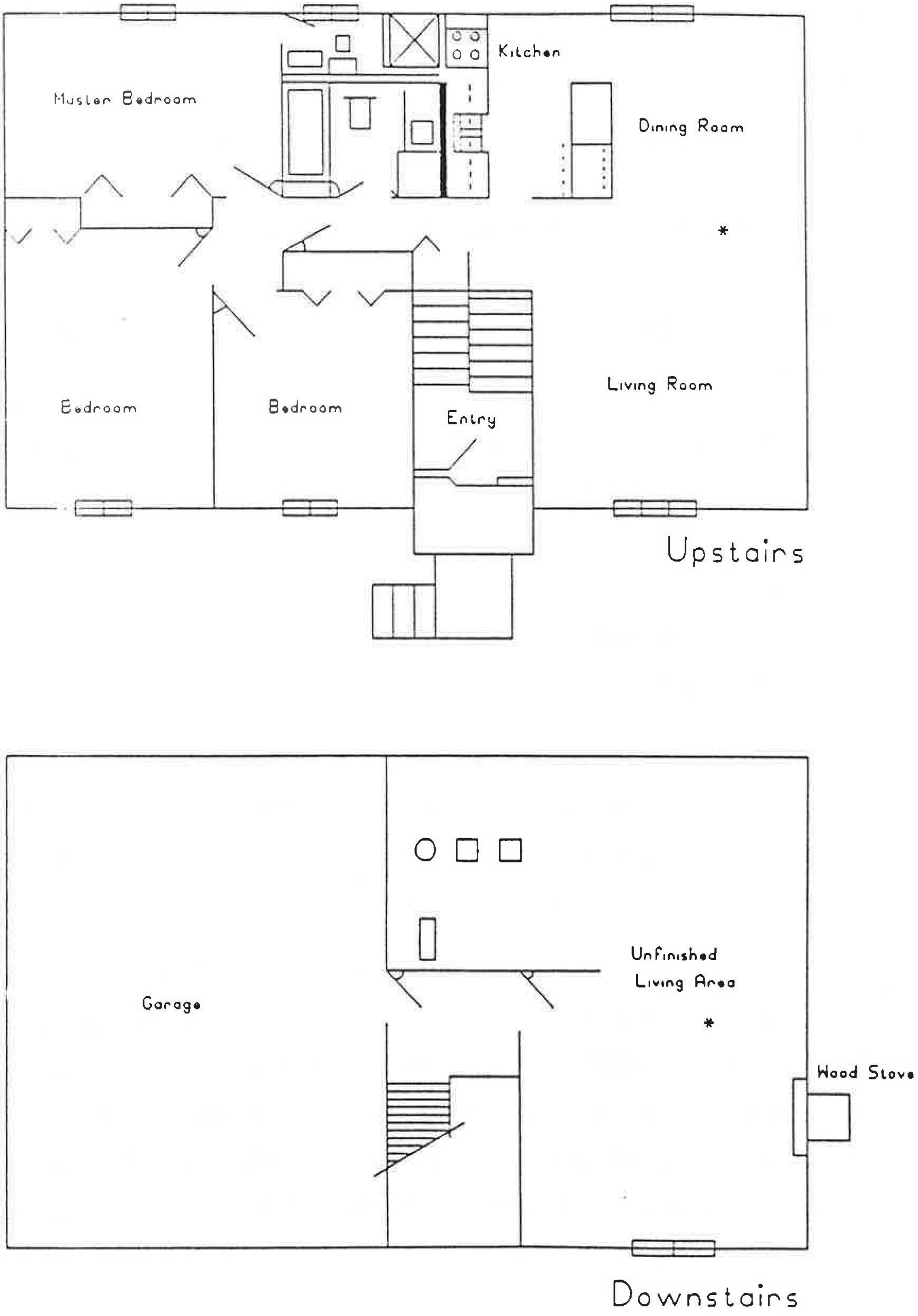

Figure 2-1. Floor Plan of the GEOMET Research Houses
(asterisk denotes sampling location in each zone)

laboratory to transfer gaseous substances to real-time monitors and to provide vacuum sources for samplers placed in the houses. Signal cables connect various sensors in the houses to the data acquisition system in the laboratory.

Five basic measurement zones were used during routine monitoring in the two research houses. Two zones, upstairs and downstairs, were defined within each house for a total of four zones, and the outdoors was defined as the fifth zone. Criteria and experimental tests used to define the zones have been reported previously (1). Locations of sensors and sampling probes at the indoor locations are depicted on Figure 2-1. Outdoor measurements were taken in the vicinity of the laboratory located between the houses.

Parameters monitored at the research houses fall into the following categories:

- Air exchange and interzonal airflow parameters
- Meteorological parameters
- Indoor environment parameters
- Air quality parameters
- Energy consumption parameters.

Measurement parameters and measurement techniques used at the GEOMET research houses are summarized in Table 2-1. Individual methods and instruments used conformed to standard or accepted measurement practices. References are provided in the table for further information on selected methods.

Outputs from measurement devices were recorded automatically with a PC-based data acquisition system (DAS); data were recorded on magnetic media. Measurement channels for meteorological and environmental parameters were scanned once each minute and hourly averages were recorded. Automated counters recorded measurements such as energy use, gas use, and precipitation. Pollutant and tracer gases were measured and recorded for each zone once every 15 minutes, as described in a previous report (1).

Table 2-1

SUMMARY OF MEASUREMENT PARAMETERS AND MEASUREMENT TECHNIQUES

Measurement Parameter	Measurement Technique[a]	
Air Exchange		
Fan pressurization	Blower door	(2)
Tracer gas (SF_6) dilution	Gas chromatography-electron capture detection (GC-ECD)	(3)
Constant Concentration (SF_6)	GC-ECD	(4)
Interzonal Airflows		
Constant release (multiple PFTs)	GC	
Constant release (multiple halocarbons)	GC-ECD	(5)
Meteorological		
Temperature	Thermistor	
Relative humidity	Thin film capacitance	
Wind speed/direction	Anemometer/vane	
Barometric pressure	Piezoresistance	
Solar radiation	Pyranometer	
Precipitation	Tipping bucket	
Indoor Environment		
Temperature	Thermistor	
Relative humidity	Thin film capacitance	
Air Quality		
Carbon monoxide (CO)	Nondispersive infrared (NDIR)	(6)
Carbon dioxide (CO_2)	NDIR	(7)
Nitrogen oxides (NO_x)	Chemiluminescence	(8)
Formaldehyde	Spectrometry	(9)
Particles	Filtration/impaction	(10)
Radon	Alpha scintillation	(11)
Radon progeny	Gross alpha counting	(12)
Energy Use		
Total energy use	Watt-hour meter	
Heating/cooling energy	Watt-hour meter	
Gas use	Dry gas meter	
Appliance use	Status transducer	

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[a] References are provided at the end of this section.

The tightness of each house was measured periodically with the fan pressurization technique. A blower door consisting of a flow-calibrated, variable-speed fan was mounted in the front entry door to pressurize and depressurize the house through prescribed pressure increments, according to standardized ASTM procedures (2).

Air infiltration was measured by tracer gas dilution, constant concentration, and constant release methods. The tracer gas decay method, based on ASTM method E471-80 (3) and described previously (1), was used on a nearly continual basis to measure whole house air infiltration rates for the two houses. The GEOMET system consists of an automated release system that injects SF_6 into each house once every 6 to 12 hours. An automated sampling system cycles on 3-minute intervals through each of the five zones, so that SF_6 is measured in each zone once every 15 minutes. Indoor sampling locations are those depicted in Figure 2-1. The logarithmic decay in SF_6 concentration with respect to time was used to determine the average hourly air infiltration rate in air changes per hour (ACH).

The constant concentration tracer gas (CCTG) system used in this study was configured by researchers from Princeton University. The system consists of a gas chromatograph with an electron capture detector, a series of sampling and injection lines, an auxiliary pump, and a microcomputer-based measurement and control system (4). A single tracer gas, SF_6, is maintained at a constant concentration in all measurement zones. To accomplish this the SF_6 concentration is measured, the SF_6 injection rate needed to maintain a constant SF_6 concentration is automatically calculated, and then tracer gas is injected by the system in each zone. Six zones, five upstairs and one downstairs, that were defined for the GEOMET research house are depicted in Figure 2-2. As depicted in the figure, each zone includes an injection point and a sampling point plus a small fan used to mix the tracer gas within the zone. Because only one analytical system was available, constant concentration measurements were performed only in the control house.

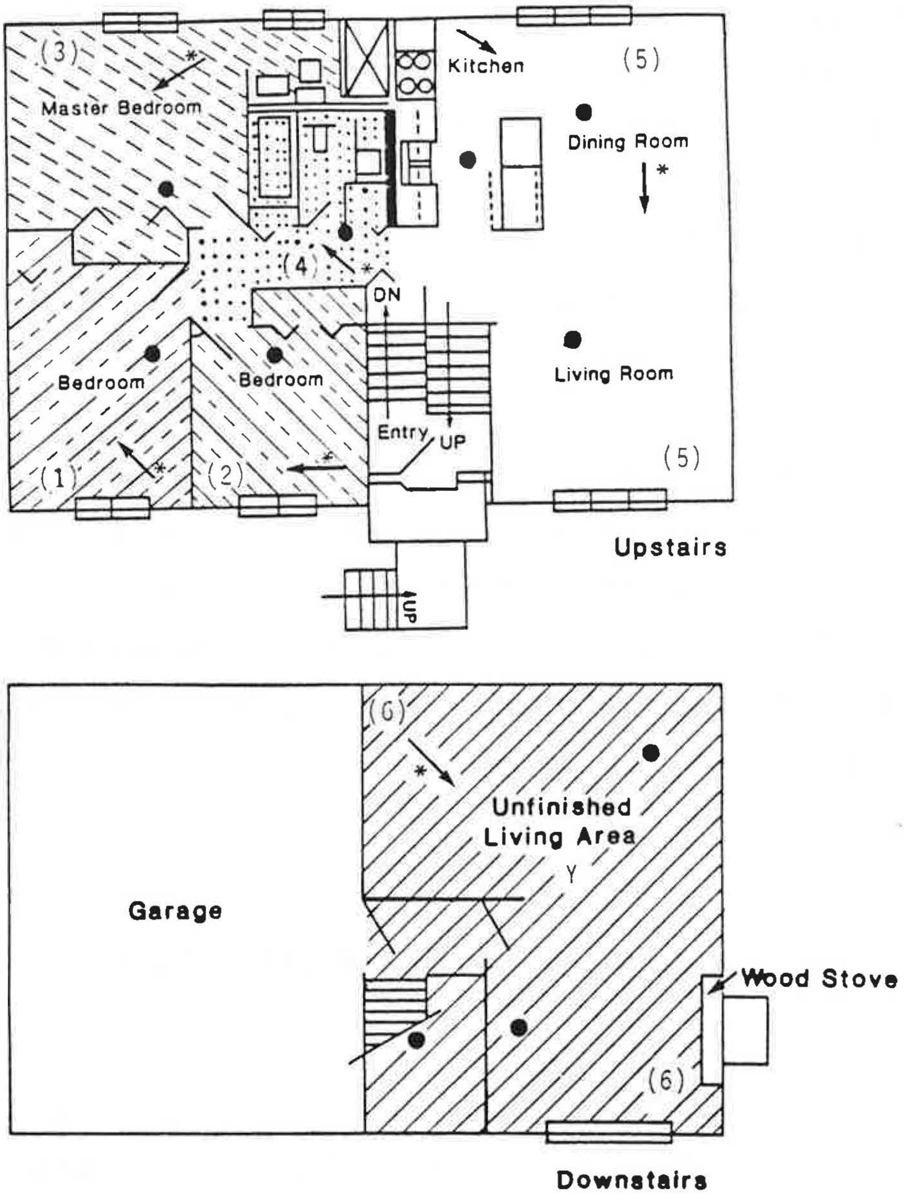

Figure 2-2. Floor plan of the control house with six zones defined for constant concentration measurements. SF_6 injection points (*), mixing fans (→), and sampling points (•) are shown for each zone.

Two different systems for constant release of multiple tracers were used in this study to measure air infiltration rates and interzonal airflows. The passive PFT method developed at BNL (5) was used to measure air exchange and interzonal airflows between both conditioned and unconditioned airspaces. The BNL technology consists of miniature PFT sources that release the tracer at a constant, temperature-dependent rate and capillary adsorption tubes for passive sampling. PFT sources were deployed in each room according to standardized BNL protocols. The passive samplers were deployed for a period of 7 days to ensure collection of sufficient quantities of tracer from all zones. The tracers used and zones of deployment are summarized in Table 2-2. As indicated in the table, the measurement zones included the attic and garage, in addition to the conditioned interior zones. A single sampler was placed near the center of each zone, except in the upstairs of the house for which one sampler was placed at the living room probe site (Figure 2-1) and a second sampler was placed at the end of the hallway centered on the entrances to the three bedrooms. PFT sources and samplers were supplied by BNL, and sampler analysis was performed by BNL.

Table 2-2

PERFLUOROCARBON TRACERS AND ZONES OF DEPLOYMENT
IN THE RESEARCH HOUSES

Tracer	Zone
Perfluorodimethylcyclohexane (PDCH)	Upstairs
Perfluoromethylcyclohexane (PMCH)	Downstairs
Perfluorodimethylcyclobutane (PDCB)	Garage
Perfluoromethylcyclopentane (PMCP)	Attic

The second constant release system used in the study was a constant multiple halocarbon tracer gas release system with a continuous tracer gas analyzer. The system was used to calculate near real-time air infiltration rates and interzonal airflows in the conditioned airspaces of the research house. The halocarbon tracers selected for the two-zone measurements were halocarbon 114 ($C_2Cl_2F_4$--dichlorotetrafluoroethane) and halocarbon 13B1 ($CBrF_3$--bromotrifluoromethane). Both halocarbons are nontoxic at the parts per million (ppm) level concentrations used in this study (threshold limit value of 1000 ppm), are gases at room temperature, and can be easily separated and detected with the GC-ECD used for analysis.

Halocarbon 114, at a tank (source) concentration of 2.2 percent in air, was released in the upstairs of the house and 13B1 (source concentration of 0.4 percent in air) was released downstairs. The release system consisted of the compressed gas cylinder, a two-stage pressure regulator, a sintered stainless steel filter element, and variable lengths of 0.010-inch inside diameter capillary tubing downstream of the regulator. Tracer gas was released at a single point in each room as depicted in Figure 2-3. Release rates were controlled by adjusting the length of the capillary tubing and pressure. Flow rates for release ranged from 20 to 100 cm^3/min in each room and were adjusted to provide volume-weighted release rates proportional to the volume of each room. Concentrations of the tracer gases in the house ranged from 0.2 to 4 ppm during use of the system.

Air samples were collected sequentially from the upstairs and downstairs once every 7.5 minutes with an automated sampling system. Samples were collected at a single site downstairs and through a two-port manifold upstairs (Figure 2-3).

The analytical system consisted of a Perkin-Elmer Sigma 300 GC-ECD with a 10-port Valco sampling valve. SF_6 and the halocarbons were separated on a 15-foot by 1/8-inch stainless steel column containing Porapak Q (80/100 mesh). Operating

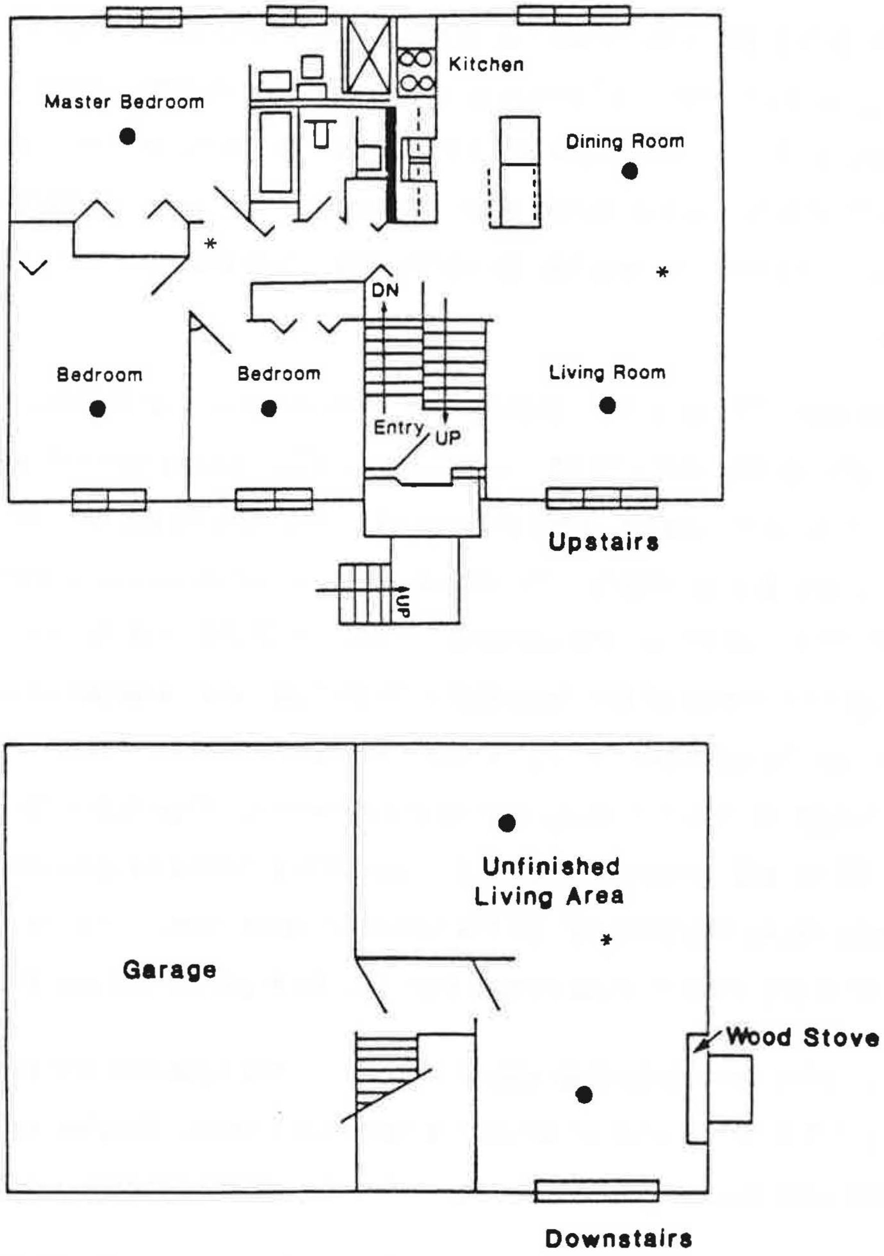

Figure 2-3. Floor plans for the GEOMET research houses indicating halocarbon release points (•) and sampling sites (*).

conditions included column temperature of 165°C, injector temperature of 175°C, detector temperature of 300°C, column flow rate of 30 cm^3/min, and makeup air at 30 cm^3/min. Retention times were 1.1 minutes for air, 1.5 minutes for SF_6, 2.3 minutes for 13B1, and 5.9 minutes for 114. Calibration curves were developed for each tracer gas by performing multipoint calibrations, using standards prepared by dilution methods.

Infiltration, exfiltration, and interzonal airflow rates were calculated using algorithms drawn from the multiple chamber description of the mass balance (13,14). The mass balance for the two-zone case of the research houses was expressed through the following equations:

$$V_1 \frac{dC_{11}}{dt} = S_1 + Q_{21} C_{12} - Q_{12} C_{11} - Q_{10} C_{11} \qquad (2\text{-}1)$$

$$V_2 \frac{dC_{22}}{dt} = S_2 + Q_{12} C_{21} - Q_{21} C_{22} - Q_{20} C_{22} \qquad (2\text{-}2)$$

$$V_1 \frac{dC_{21}}{dt} = Q_{21} C_{22} - Q_{12} C_{21} - Q_{10} C_{21} \qquad (2\text{-}3)$$

$$V_2 \frac{dC_{12}}{dt} = Q_{12} C_{11} - Q_{21} C_{12} - Q_{20} C_{12} \qquad (2\text{-}4)$$

$$Q_{10} + Q_{12} = Q_{01} + Q_{21} \qquad (2\text{-}5)$$

$$Q_{20} + Q_{21} = Q_{02} + Q_{12} \qquad (2\text{-}6)$$

where

C_{ij} = tracer i concentration in zone j, ppm (ml/m^3)
S_i = tracer i release rate into zone i, ml/h
Q_{ij} = transport from zone i to zone j, m^3/h
V_i = volume of zone i, m^3 .

For calculation of airflows, the derivative was applied to the time-varying tracer gas concentrations. Similar expressions were employed by BNL to calculate average interzonal flows from the PFT experiments; the steady-state condition was assumed, which reduces the derivative, dC/dt, to zero (5).

QUALITY ASSURANCE AND QUALITY CONTROL

A program of routine procedures was implemented during the study at the GEOMET research house site to control the quality of all data collected. These procedures were described in detail in the final report for the EPRI Phase I testing (1) and are also summarized here. In addition to the routine QC procedures, external performance audits of the measurement system at the GEOMET research houses were conducted during the period of this study. External audits were conducted by PEI Associates, Inc., in February 1985 (15) and February 1986 (16), and by Research Triangle Institute in September 1987 (17).

Routine QC Procedures for Measurement Devices

Routine procedures for measurements of SF_6 and halocarbon tracer gases included daily checks of sampling system airflows and appropriateness of data, and routine multipoint calibrations with standard gas concentrations. Data were collected with an automated PC-based data logger, but strip charts were used routinely as a backup and for QC verification checks. Multipoint calibrations consisted of inputs of zero air and at least four upscale points.

Measurements with thermistors, relative humidity sensors, and meteorological instrumentation were verified on a daily basis for appropriateness. Span checks consisting of colocated measurements with reference devices were performed on a quarterly basis. Multipoint calibrations for these relatively stable devices were performed annually or more frequently, depending on results of the span checks. QC procedures for these devices have been described more completely in the previous EPRI report (1).

Quality Assurance Objectives and System Performance

Quality assurance objectives based on acceptable precision, accuracy, and completeness levels have been defined for measurements made in GEOMET's Indoor Environment Division programs (18). The performance of the measurement devices at the research houses was assessed on a periodic basis through multipoint calibrations, zero checks, and span checks.

As part of the QA program, performance of the measurement system was evaluated through an annual performance audit. The audit, performed by an external auditing organization, assesses the accuracy of measurement devices. Pollutant and SF_6 analyzers, for example, are challenged by the auditor with known concentrations of National Bureau of Standards (NBS)-traceable calibration gases.

The performance of other devices such as thermistors, humidity sensors, and meteorological instruments is measured by comparisons to NBS-traceable reference devices.

The accuracy of selected measurement devices is highlighted in Table 2-3, which presents QA objectives and corresponding results from the 1986 audit. As indicated in the table, the performance of the measurement devices exceeded QA objectives except for the relative humidity sensors. Subsequent adjustments and calibrations, however, rectified the problem with the thin film capacitance sensors used to measure humidity. Outdoor measurement parameters showed good agreement with the auditor's measurements.

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Table 2-3

SUMMARY OF THE ACCURACY OF MEASUREMENT DEVICES COMPARED WITH QUALITY ASSURANCE OBJECTIVES[a]

Measurement Parameter	QA Objectives	Actual Performance
SF_6	±10%	+7.8%
NO_x	±10%	-2.2%
CO	±10%	+2.6%
CO_2	±10%	-2.6%
Radon[b]	±15%	-7%
Wind speed	±2.2 mph	+0.9 mph
Wind direction	±9°	±0°
Barometric pressure	±2 mbar	+0.01 mbar
Solar radiation	±0.1 $cal/cm^2/min$	+0.05 $cal/cm^2/min$
Temperature[c]	±2.5 °C	-0.2 °C
Relative humidity[c]	±5%	-13.6%

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[a] Performance based on accuracy measured in 1986 performance audit (16).

[b] Based on Department of Energy interlaboratory comparison exercise.

[c] Average for subset of nine sensors.

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Section 3

FAN PRESSURIZATION AND TRACER DILUTION MEASUREMENT RESULTS

During the previous study conducted for EPRI at the GEOMET research houses, fan pressurization measurements were performed over an 18-month time span that included the preretrofit and postretrofit periods. Air exchange measurements by the automated tracer gas (SF_6) dilution method were also performed on a nearly continuous basis. In this study, a similar series of measurements was conducted. This section describes the more recent measurements, conducted in 1986 and 1987, and compares them to the measurements conducted in the 1983 to 1984 period.

FAN PRESSURIZATION MEASUREMENTS

The initial series of fan pressurization measurements conducted during a 6-month period following construction of the two GEOMET research houses showed that the air leakage rates were similar in the two houses. Average air exchange rates at 50 pascals, calculated from the blower door measurements, were 10.6 ± 0.3 ACH for the control house and 10.1 ± 0.2 ACH for the experimental house (1). Following the retrofit to reduce leakage areas in the experimental house, average air exchange rates were 10.8 ± 0.1 ACH in the control house and 6.5 ± 0.2 ACH in the experimental house. Thus, after the retrofit, the experimental house was about 40 percent tighter than the control house on the basis of the 50 pascal flow rate measured with the blower door.

During 1986, blower door measurements were performed during a 9-month period to determine if the air leakage characteristics of the houses had changed since the retrofit of the experimental house in 1983. A time series of the blower door measurement results is shown for the two houses in Figure 3-1. Average air

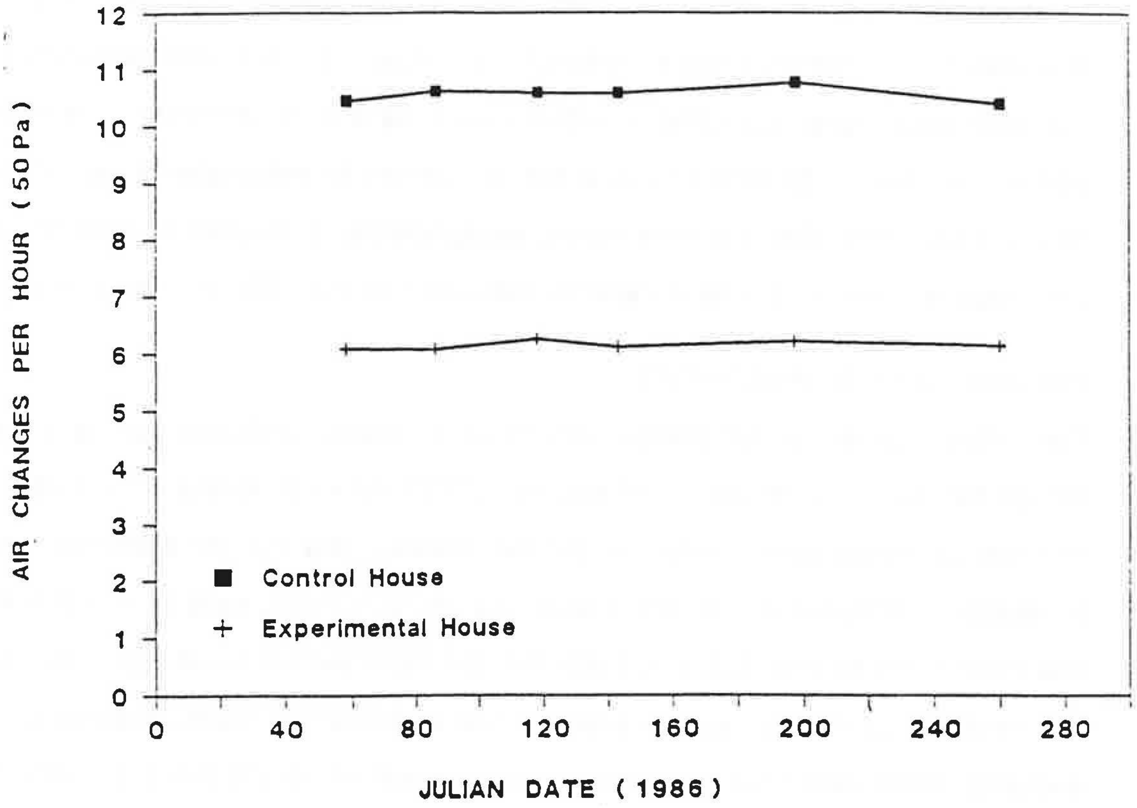

Figure 3-1. Results of Blower Door Measurements Conducted in 1986 (expressed as air changes per hour at 50 pascals.)

exchange rates at 50 pascals during the period were 10.6 ± 0.1 ACH in the control house and 6.1 ± 0.1 ACH in the experimental house and were comparable to the measurements performed in 1984. As in the previous (1984) series of measurements, the blower door results did not vary with season. These results also indicate that there has not been a substantial change in the air leakage characteristics of the two houses.

SF_6 TRACER DILUTION MEASUREMENTS

Throughout the period of the initial phase (Phase I) of the EPRI study at the GEOMET research houses, air infiltration rates were measured on a nearly continuous basis by the automated SF_6 tracer gas dilution method. These measurements have continued during the current (Phase II) study period.

In Phase I, average air exchange rates of the houses were shown to vary substantially across seasons. As shown in Table 3-1, average air exchange rates in the control house were 0.15, 0.29 and 0.61 ACH in the summer, fall, and winter, respectively. The table also shows that, as a result of the retrofit, air exchange rates were approximately 24 percent lower in the experimental house than in the control house following the retrofit.

To compare air exchange rates between Phase I (1984) and Phase II (1986-1987), 3 weeks of measurements during Phase II were selected during which the houses were configured and operated in a manner identical to that of Phase I; during these periods, occupancy was simulated according to the Phase I protocols and thermostat settings were replicated. Data for these 3 weeks are also presented in Table 3-1. Although outdoor conditions (indicated by indoor-outdoor temperature difference [ΔT] and wind speed) were not identical, the air exchange rates measured during the two periods were quite similar for the winter and summer seasons. Measurements during the transition seasons (spring and fall) were not as similar because of large differences in outdoor conditions for the two measurement periods. Results

Table 3-1

AVERAGE AIR EXCHANGE RATES MEASURED IN THE CONTROL AND EXPERIMENTAL HOUSES IN 1984 AND 1986-87

	ΔT[b] (°F)	Wind-speed (mi/h)	Air Exchange Rate (ACH)[a] Control House	 Experimental House	 Percent Difference[c]
Phase I (1984)[d]					
Summer	2.8	2.5	0.15 ± 0.07	0.11 ± 0.05	24
Fall	18.5	3.8	0.29 ± 0.09	0.22 ± 0.08	22
Winter	45.5	4.9	0.61 ± 0.15	0.46 ± 0.13	25
Phase II (1986-1987)					
Summer	7.3	2.6	0.17 ± 0.07	0.13 ± 0.05	24
Spring	25.6	5.2	0.49 ± 0.18	0.33 ± 0.11	33
Winter	44.9	2.9	0.66 ± 0.14	0.49 ± 0.13	26

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[a] Air change per hour (ACH); average ± standard deviation.

[b] Indoor-outdoor temperature difference.

[c] ([Control House - Experimental House]/Control House) x 100; calculations based on values measured to three decimal places to enable more precise calculation.

[d] Reference (1).

of the Phase II measurements were consistent with those of Phase I in that they showed substantial seasonal differences in air exchange rates. Differences between the control and experimental houses were also comparable during the winter and summer measurement periods; during both Phase I and Phase II measurement periods, the difference was 24 to 26 percent.

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Section 4

CONSTANT CONCENTRATION MEASUREMENT RESULTS

The constant concentration tracer gas (CCTG) system was deployed in the control house for periods of 1 to 2 weeks each during summer, winter, and spring to measure the infiltration rates of six zones. The zones defined were the master bedroom, bedroom 1, bedroom 2, hallway, kitchen/living room/dining room (KLD), and downstairs. As described in a previous section, the CCTG system used a single tracer (SF_6). Therefore, the system was used only to measure infiltration rates; interzonal airflows (i.e., airflows between zones) could not be measured with the system. The objective of the CCTG multizone air infiltration measurements was to determine specific air infiltration rates for each of the six zones under different meteorological conditions.

ROOM INFILTRATION RATES

Variations in air infiltration rates among different rooms in the house can be expected because of variations in air leakage sites at different parts of the house due to building design and construction practices. Infiltration rates in individual rooms may also vary due to the orientation of the room with respect to wind, and location of the room with respect to perimeter walls.

An example of the type of zonal air infiltration rates measured with the CCTG system is presented in Figure 4-1. A time series of air exchange rates for rooms on the first floor of the control house is shown for a 4-day period in the winter of 1987. As shown in the figure, air infiltration rates were lowest in the KLD zone. Air exchange rates were somewhat higher in the three bedrooms, and highest in the hallway where the attic access door is located; the zone also includes a

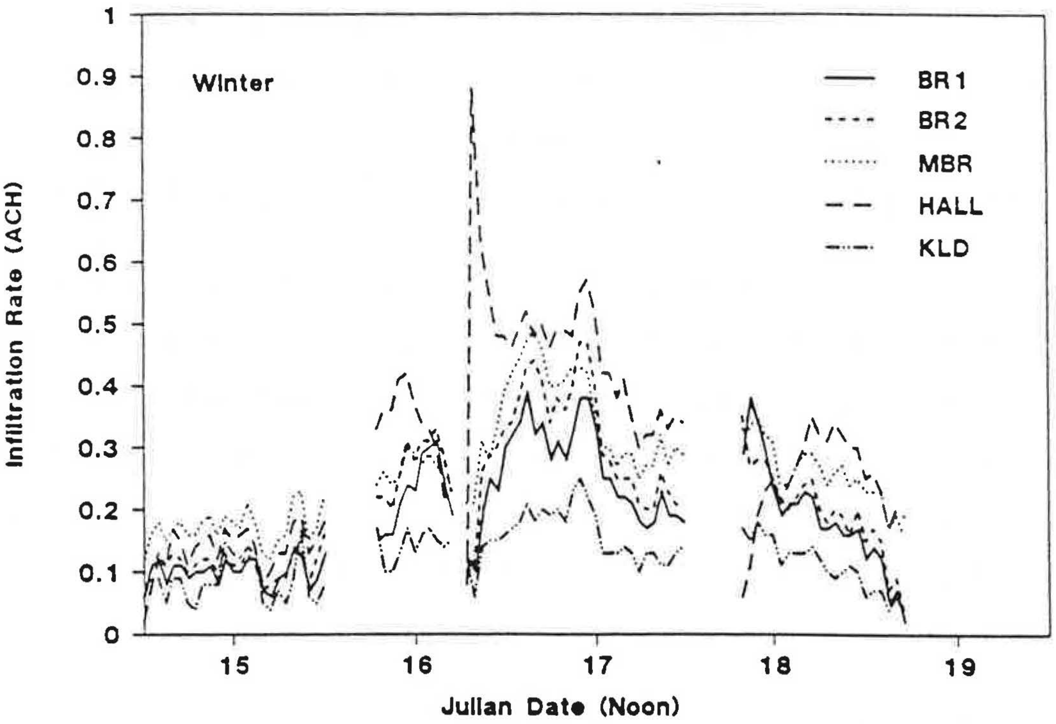

Figure 4-1. Example of CCTG measurements of air infiltration rates for individual rooms in the control house during winter 1987.

bathroom with an exhaust fan, although it was not operated during the measurement period. Rates of air exchange varied from less than 0.05 ACH to nearly 0.9 ACH in the five upstairs zones during this period. As shown in Figure 4-1, short-term variations in infiltration rates were generally small, except in the hall.

The variability of room-specific air infiltration rates can be seen clearly by plotting the frequency of air infiltration rates for the individual rooms, as presented in Figure 4-2. As shown in the figure, the air infiltration rates in the KLD zone did not exceed 0.4 ACH and were generally less than 0.2 ACH. Even in the hallway, where the highest infiltration rates were measured, most rates were less than 0.4 ACH. During this period, the average indoor/outdoor temperature difference (ΔT) was 23.2 ± 7.6°F and the wind speed averaged 2.7 ± 1.6 mi/h.

Seasonal differences in room-specific infiltration rates can be seen by comparing summer measurements, depicted in Figure 4-3, and the winter data depicted in Figure 4-2. During the summer measurement period, the ΔT was only 4.9 ± 7.2°F and the average wind speed was 3.1 ± 2.2 mi/h. Room infiltration rates were typically below 0.2 ACH. Unlike the winter case where the rates differed in each room, infiltration rates were quite similar for the five upstairs zones during the summer tests.

UPSTAIRS VERSUS DOWNSTAIRS INFILTRATION RATES

During Phase I of the EPRI project, air infiltration rates for the houses were measured by the SF_6 dilution method. Measurements of SF_6 in the upstairs and downstairs zones indicated more rapid dilution of SF_6 in the downstairs. When measurements were performed with the heating, ventilation, and cooling (HVAC) circulation fan off to minimize interzonal airflows, the estimated air infiltration rate for the downstairs was approximately 0.1 ACH higher than upstairs. Although this was not intended as a method for precisely measuring zonal infiltration rates, it was an indicator of differences between upstairs and downstairs.

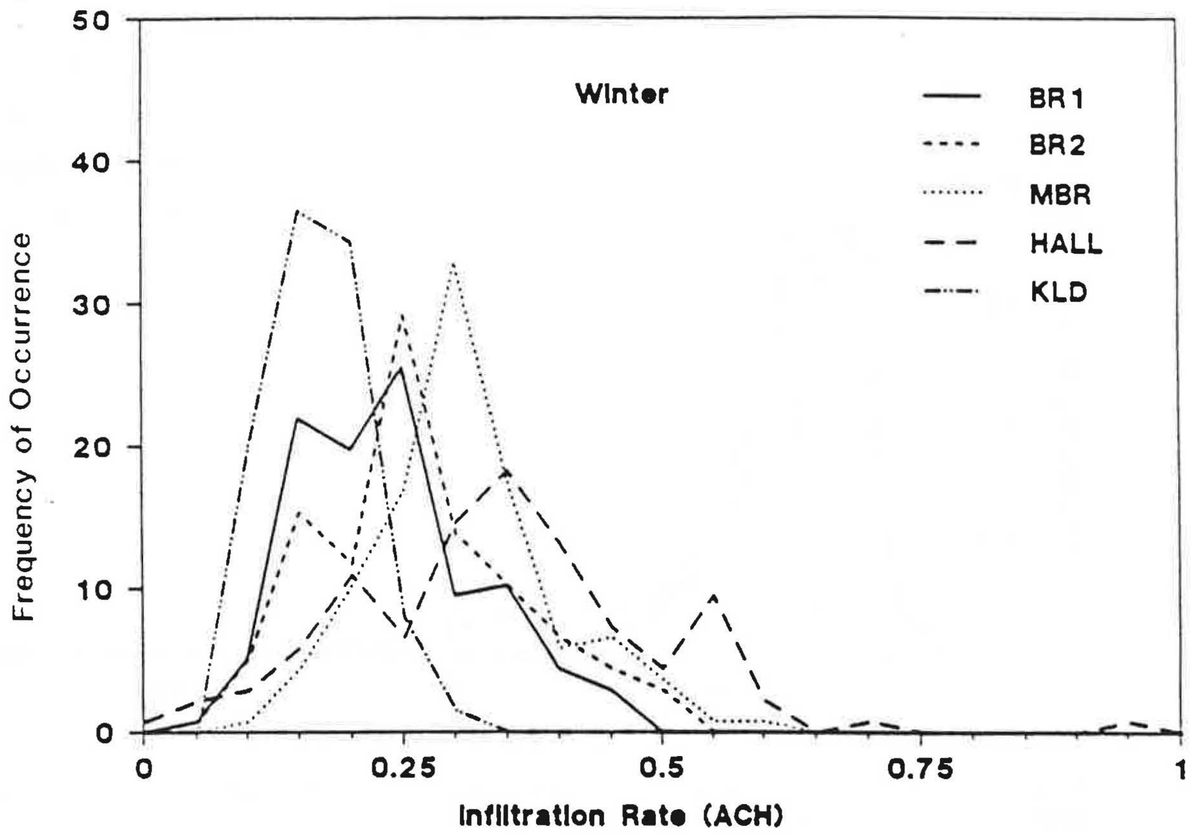

Figure 4-2. Frequency of room infiltration rates for five rooms in the upstairs of the control house, winter 1987.

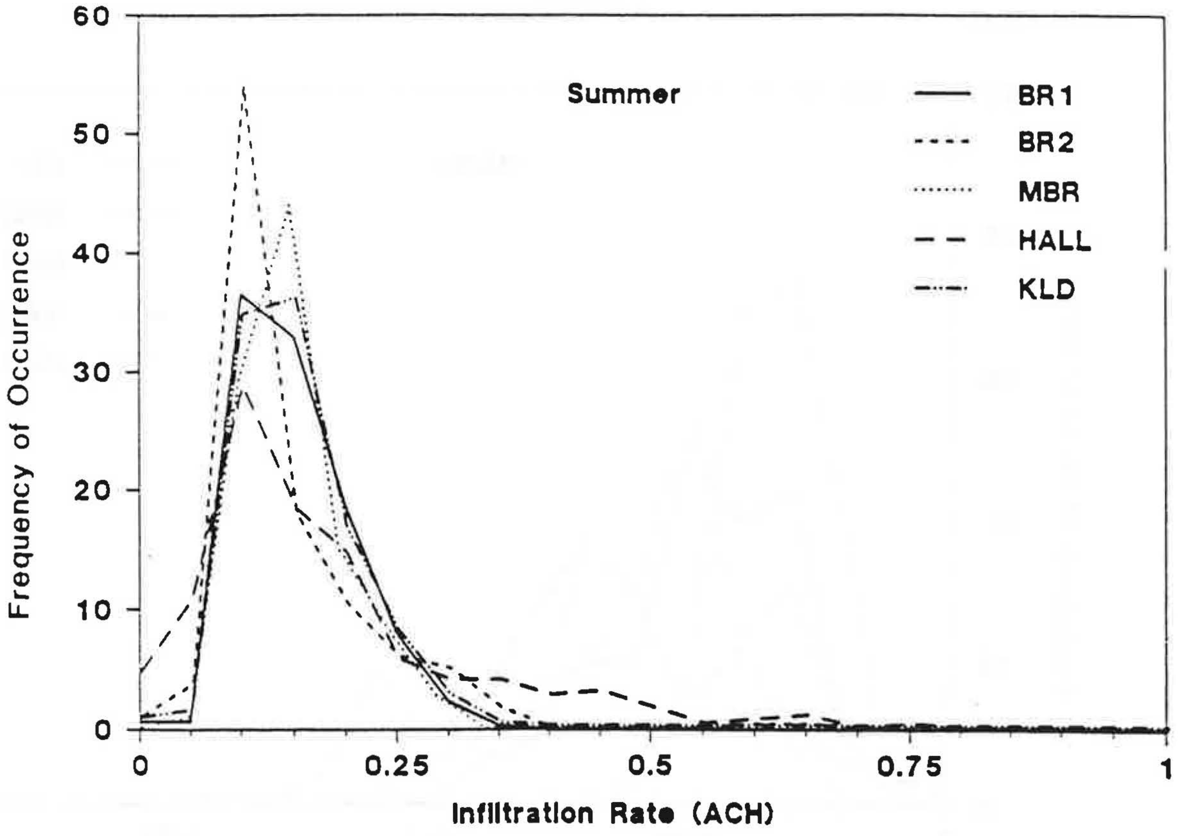

Figure 4-3. Frequency of room infiltraiion rates in five rooms in the upstairs of the control house, summer 1986.

Measurements with the CCTG system showed large differences between the infiltration rates for the upstairs and downstairs of the control house (Table 4-1). During the 8-day winter measurement period, the average downstairs infiltration rate was 1.18 ACH compared to an infiltration rate of only 0.18 ACH upstairs. During this period, downstairs infiltration rates ranged from approximately 0.6 to 1.6 ACH, while the upstairs infiltration rate never exceeded 0.45 ACH. The ratio of upstairs to downstairs infiltration rates was 6.5 during this period. Similar differences between upstairs and downstairs infiltration rates were observed in the spring and summer, although the magnitude of the differences was not as large as during winter. Ratios of downstairs to upstairs infiltration rates were 4.8 in spring and 3.9 in summer. The magnitude of the difference was clearly related to outdoor conditions, with the largest absolute difference in infiltration rates occurring in winter, with a difference of 1.0 ACH.

Table 4-1

AIR INFILTRATION RATES MEASURED IN THE CONTROL HOUSE FOR THE UPSTAIRS, DOWNSTAIRS, AND WHOLE HOUSE

Season	ΔT (°F)	Windspeed (mi/h)	Average Air Infiltration Rate (ACH)[a] Upstairs	Downstairs	House
Spring	13.9	6.3	0.15	0.72	0.37
Summer	4.9	3.1	0.10	0.39	0.20
Winter	23.2	2.7	0.18	1.18	0.57

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[a] Average error of the air infiltration rate estimate is approximately 5 percent (reference (1)).

The high downstairs infiltration rate in winter resulted in a whole house air infiltration rate of 0.57 ACH, which was consistent with SF_6 dilution measurements in the control house under similar conditions (see Table 3-1). Whole house infiltration rates measured with the CCTG system in spring and summer were also consistent with SF_6 measurements.

The CCTG measurements show that variations in whole house air infiltration rates are primarily a function of the downstairs infiltration rates. As shown in Table 4-1, seasonal differences in the average upstairs air infiltration rates were small, differing by only 0.08 ACH between winter and summer. Downstairs infiltration rates, however, differed by 0.79 ACH between winter and summer.

The higher air infiltration rates measured in the downstairs of the control house were consistent with observations made during the retrofit of the experimental house. Many of the air leakage sites that were sealed in the experimental house during the retrofit were in the downstairs. The high downstairs infiltration rates during the winter were also consistent with anticipated upward airflows due to stack effect action.

The low infiltration rates measured in the upstairs of the house, less than 0.2 ACH on the average even during winter, may have a significant impact on air quality in a house. There are many potential sources of contaminants in the upstairs of a house, including building materials, gas ranges, and a wide array of consumer products. Because of the low air infiltration rates, concentrations of contaminants released into the upstairs airspace may remain elevated for extended periods.

EFFECT OF WIND SPEED, WIND DIRECTION, AND ΔT

Wind speed and ΔT are known to be major driving forces for air infiltration. These factors and the relationships that underlie mathematical models of air infiltration have been reviewed by the Air Infiltration Centre (2,3) and were summarized in the final report of Phase I work on this EPRI project (4).

In Phase I, two types of air infiltration models were developed for the two houses. The first was of the general form:

$$\nu = a + b \cdot |\Delta T| + c \cdot V \quad , \qquad (4\text{-}1)$$

where ν is the air infiltration rate (ACH)

ΔT is the indoor-outdoor temperature difference (°F)

V is the windspeed (mi/h)

a, b, and c are parameters to be estimated by least-squares techniques (i.e., regression analysis) .

The second type of model was the infiltration algorithm used in the EMPS model (5) for energy consumption:

$$\nu = \beta_o/\sqrt{T_o} \cdot (h \cdot 0.058 \cdot |\Delta T| + 0.361 \cdot V^2)^{1/2} \quad , \qquad (4\text{-}2)$$

where h is the neutral height, assumed by the EMPS model to be one-half the height of each indoor space, and β_o is a constant to be estimated by the user.

Using the Phase I SF_6 dilution measurement results, it was found that the first model had a higher predictive power than the algorithm used in EMPS. The simple linear model had R^2 values of 0.89 for the control house and 0.83 for the experimental house (4). The algorithm used in EMPS had R^2 values of 0.60 to 0.70. Various modifications of the first model were also considered, including use of a squared term for wind speed, separate regression equations for negative and positive ΔT conditions, and a dummy variable to measure wind direction effects. None of the modifications, however, had any substantial impact on the predictive power of the model (4).

Harrje, Bohac, and Fortmann (6) also used the first model (equation 4-1) and various modifications of the model with the constant concentration data from the control house to predict air infiltration rates for the house. Using the simple model (4-1) that specifies a linear additive relationship with ΔT and wind speed, the R^2 values were 0.71, 0.85, and 0.78 for the summer, winter, and spring data sets, respectively. For the total data set ($n = 480$) the R^2 value was 0.79. A scatter plot illustrating the agreement between predicted and measured air infiltration rates is depicted in Figure 4-4. As in the previous EPRI study reported by Nagda et al. (4), more complex models that included wind direction did not substantially improve the predictive power of the model.

Because the CCTG system provides infiltration data for individual zones, the model can also be applied to individual zones. As an example, regression analyses were performed for the downstairs zone during the summer period. With the linear additive model (equation 4-1), an R^2 value of 0.74 was obtained. Because the downstairs zone is shielded from the wind on the garage side and has windows on only one side, wind direction may be a major factor impacting air infiltration.

The effect of wind direction was examined by adding a $(\cos(\theta - \theta_0))$ term to the model. The results of the regression analysis with this model gave an R^2 value of 0.83, a substantial increase over the value of 0.74 for the model without the direction term. The relationship between predicted and measured air infiltration rates is depicted graphically in Figure 4-5. The value of θ_0 was estimated to be 34 ± 5°, a direction that corresponds to wind impinging on the front of the house, where the windows are located.

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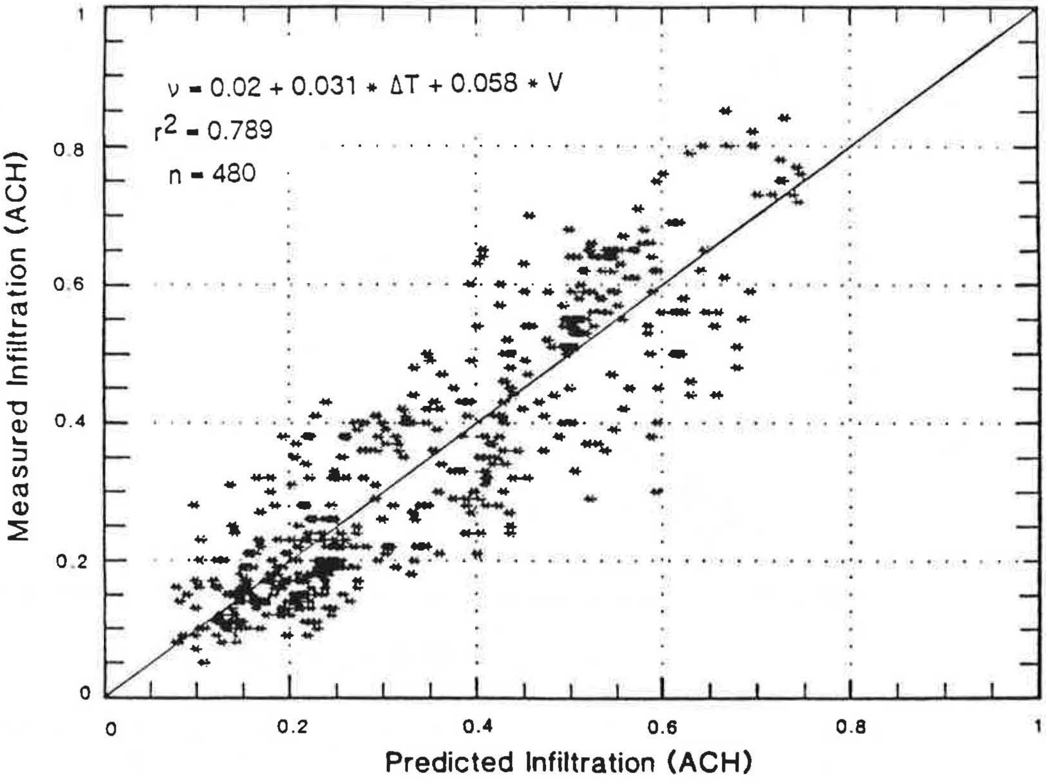

Figure 4-4. Scatter plot of the total data set illustrating the agreement between predicted and measured air infiltration rates (reference: Harrje et al. (4)).

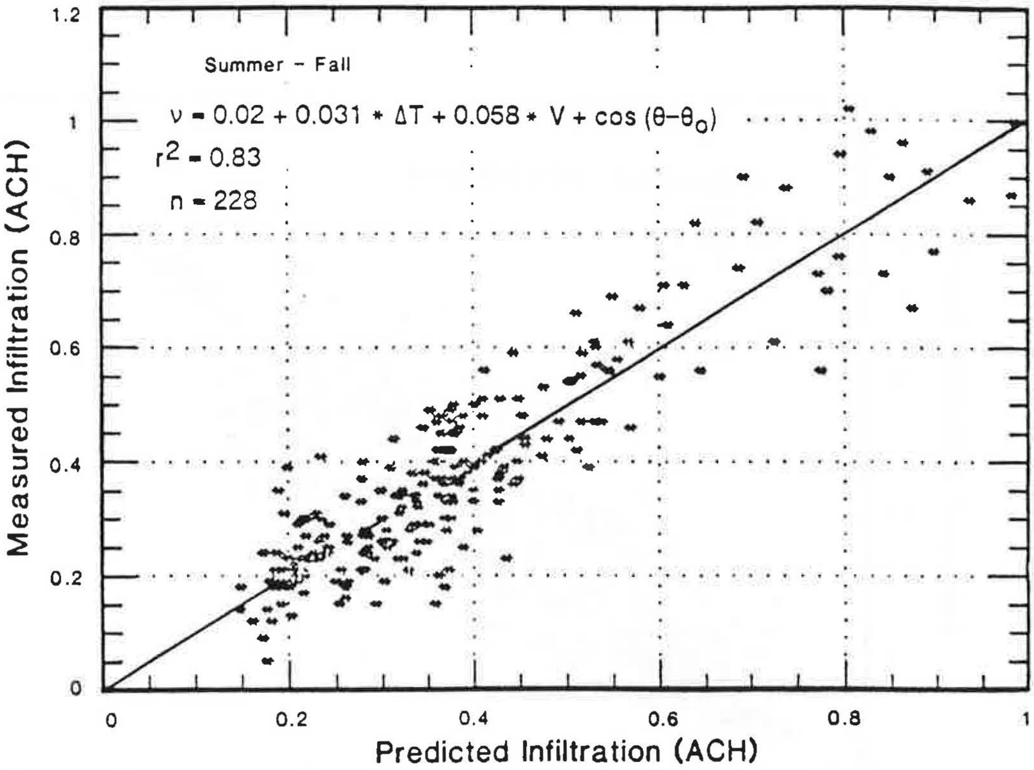

Figure 4-5. Scatter plot of the measured air infiltration and predicted air infiltration using downstairs data and the linear model with wind direction (reference: Harrje et al. (4))

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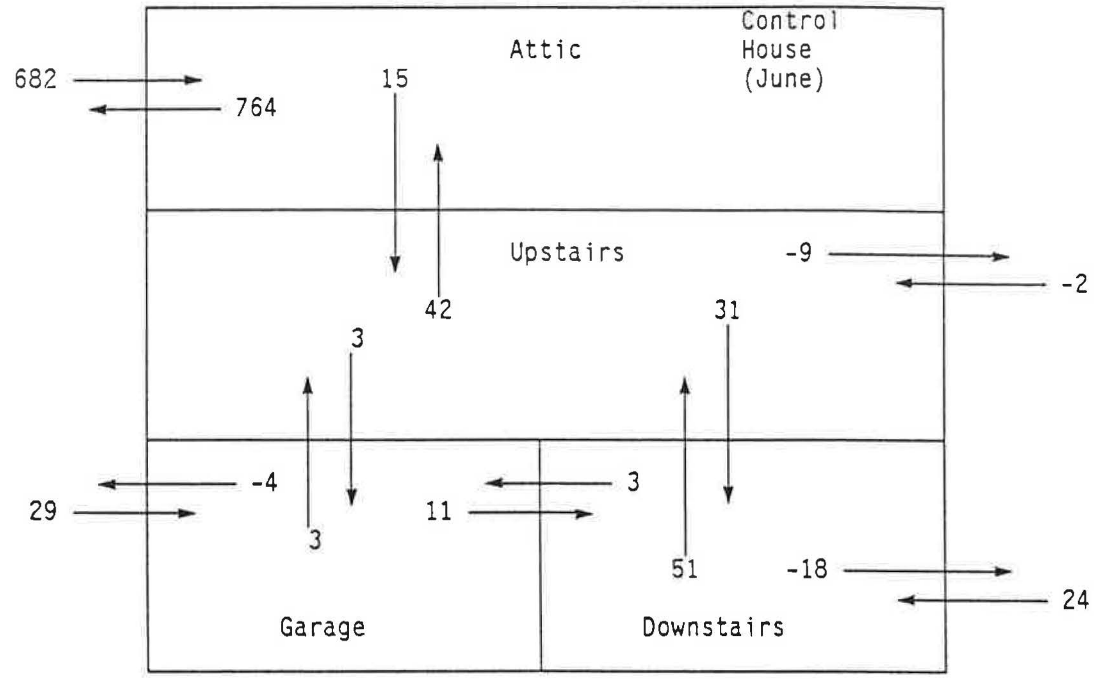
Section 5

PASSIVE PERFLUOROCARBON TRACER MEASUREMENT RESULTS

INTRODUCTION

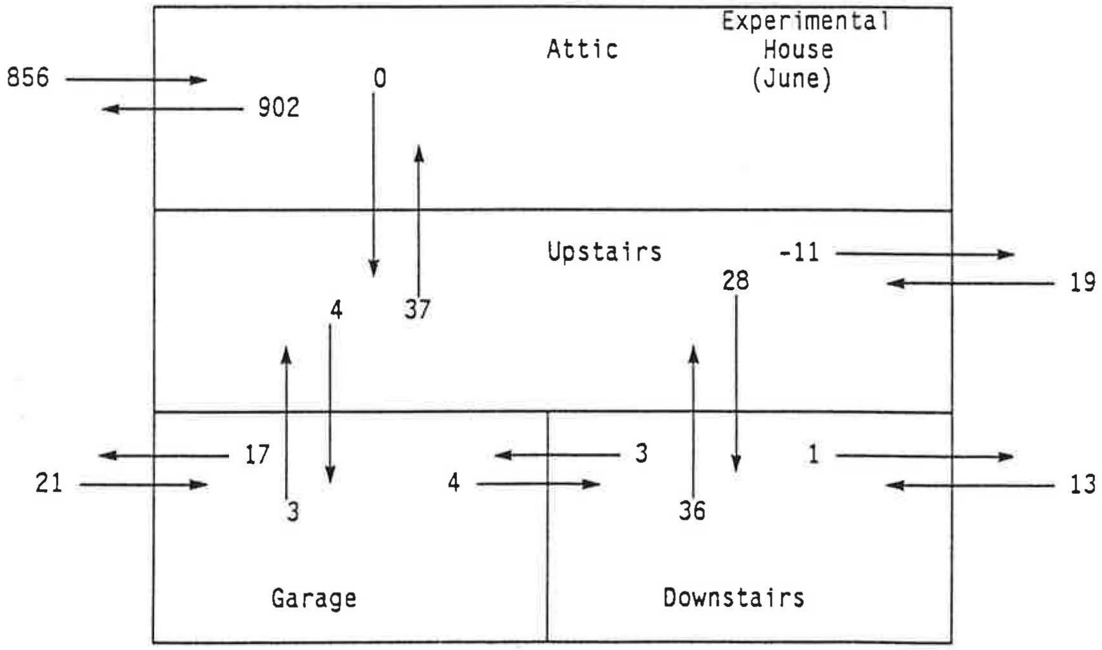
The passive perfluorocarbon tracer (PFT) system developed at the Brookhaven National Laboratory (1) was used in both research houses in this study to assess the seasonal variation of infiltration rates and interzonal airflows, and to further characterize differences between the two houses. PFT measurements were performed for week-long exposure periods in August 1985, March 1986, January 1987, and June 1987. Measurements were made in four zones--upstairs, downstairs, attic, and garage. Four zones are currently the maximum that can be measured simultaneously with the BNL PFT system. The primary objective of the four-zone PFT measurements was to obtain a more detailed characterization of the air infiltration rates for individual zones and the airflows between conditioned and unconditioned airspaces in the research houses. Some comparisons of results with PFT and other measurement methods are presented in this and the following section.

With the four-zone PFT measurement system, infiltration and exfiltration rates are calculated for each zone and interzonal airflows are measured in both directions between all zones, resulting in a total of 20 airflow rates for each set of measurements in each house. Results of the PFT measurements in the two research houses during the four week-long measurement periods are depicted in Figures 5-1 to 5-4. Values depicted in the figures are the average airflow rates (m^3/h) during the week-long periods. The figures will be referred to in the following discussion that describes various aspects of the measurements.



Garage to attic: 24
Attic to garage: -2

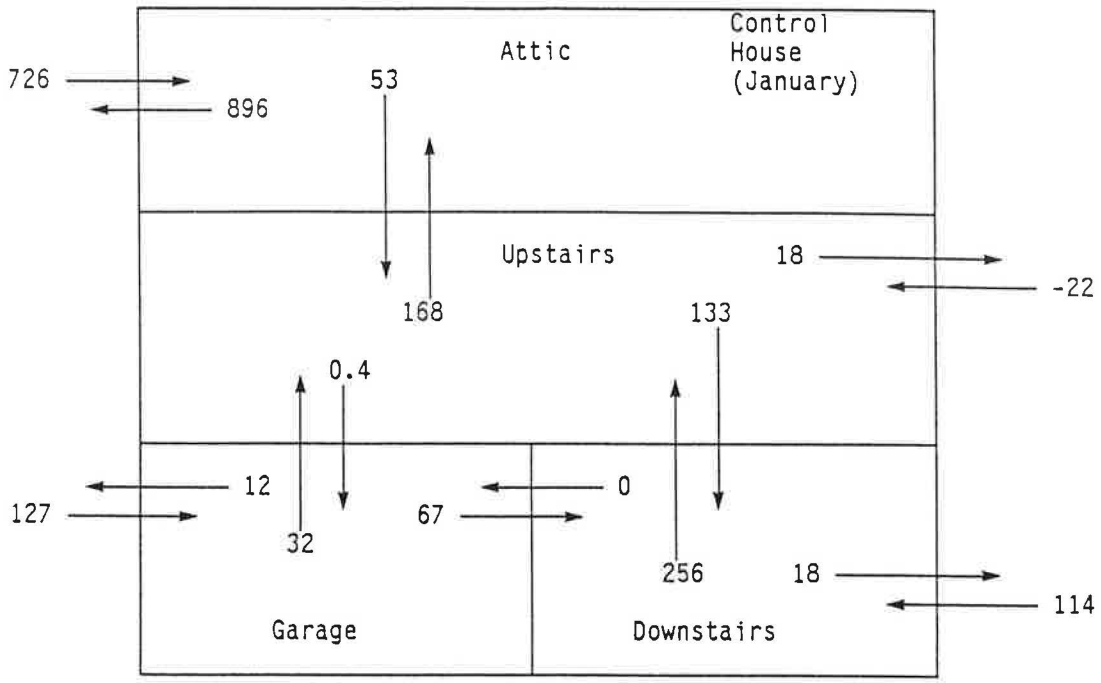
Downstairs to attic: 38
Attic to downstairs: 9



Garage to attic: 4
Attic to garage: 0

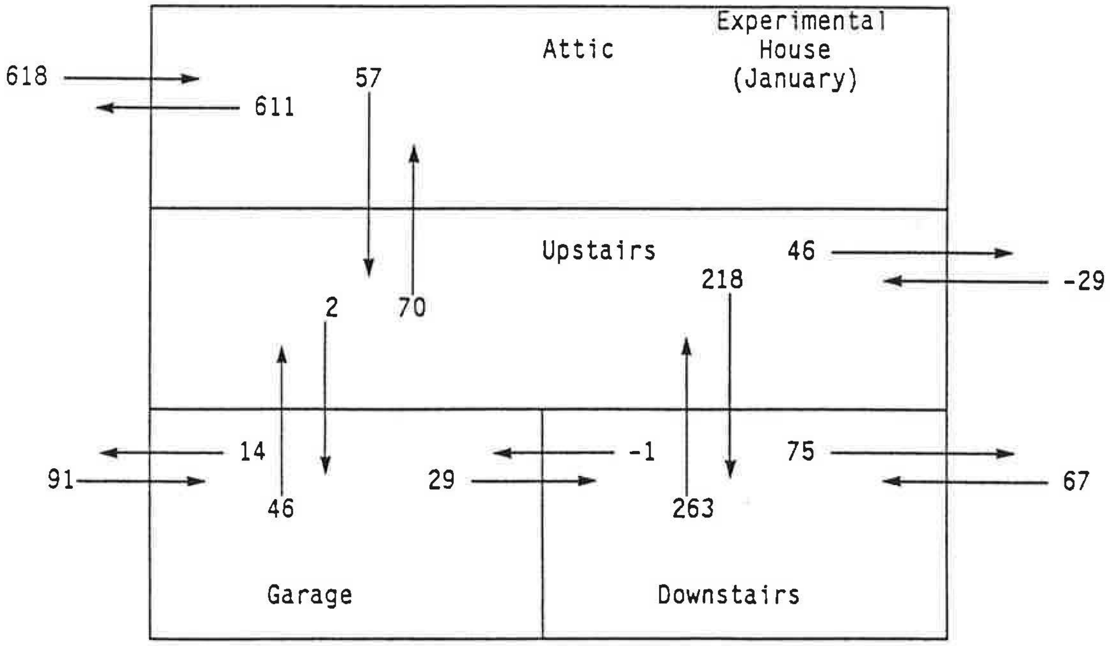
Downstairs to attic: 6
Attic to downstairs: 0

Figure 5-2. Airflow rates (m^3/h) measured with PFTs in the control and experimental houses in June 1987.



Garage to attic: 15
Attic to garage: 0

Downstairs to attic: 58
Attic to downstairs: 17



Garage to attic: 2
Attic to garage: 0

Downstairs to attic: -8
Attic to downstairs: 15

Figure 5-4. Airflow rates (m^3/h) measured with PFTs in the control and experimental houses in January 1987.

AIR INFILTRATION RATES

Air Infiltration Rates for the Conditioned Spaces

At the simplest level, PFT measurements can be used to estimate the air infiltration rate for the whole house by use of a single tracer. In this study, four-zone measurements were performed that included both conditioned and unconditioned airspaces (garage and attic). As shown in Figures 5-1 to 5-4 there were a number of cases when negative airflows were calculated from the four-zone PFT measurements. Negative airflows, which are theoretically impossible, occur as a result of errors associated with tracer release rates, sampling rates, and tracer analysis. They are more likely to occur in a four-zone measurement case than in a single or two-zone measurement case because of the greater number of airflows that enter into the calculation, each of which has associated measurement error. For the calculation of airflow rates measured with a single capillary adsorption tube, BNL sets the standard deviation in the PFT source release rate at 10 percent, and the standard deviation in the volume measurement is set at 5 percent. In the four-zone case the measurement errors can be quite large. For the March measurement in the control house, for example, the upstairs infiltration rate of 15 m^3/h had a standard deviation of 12 m^3/h. The downstairs infiltration rate of 89 m^3/h, however, had a standard deviation of only 15 m^3/h. Other examples of measurement errors are included in the following discussion.

Recognizing that the error associated with the PFT measurement increases with an increasing number of zones, the PFT measurement results were recalculated for a two-zone case restricted to the conditioned airspaces. These values were then used to calculate the whole house air infiltration rates presented in Table 5-1. Air infiltration rates measured with PFTs showed seasonal variations consistent with average indoor-outdoor temperature differences (ΔT), with the lowest rates occurring in June. Differences in air infiltration measurement results between the two houses were consistent with previous measurements at the houses, with lower rates occurring in the experimental house. The air infiltration rates for

For the estimation of whole house air infiltration rates, the week-long passive PFT measurements compared favorably with the real-time SF_6 dilution measurements integrated over the period. The difference between PFT and SF_6 measurement results ranged from -15 to +14 percent with an average absolute difference of 6.7 percent for the control house and 13 percent for the experimental house (Table 5-1). The PFTs slightly over-predicted the winter air exchange rates, but the differences from SF_6 measurements were less than 14 percent and were not statistically significant.

Upstairs Versus Downstairs Air Infiltration Rates

Like the constant concentration method, PFT measurements can be used to estimate infiltration rates of individual zones. This is accomplished by releasing a different tracer gas in each zone. To compare air infiltration rates for the upstairs and downstairs (conditioned zones), the PFT four-zone measurement data were recalculated for the two-zone case using only the concentration of the upstairs and downstairs tracers to reduce measurement error, as described above.

PFT measurements of air infiltration rates for the upstairs and downstairs zones were consistent with previous SF_6 dilution measurements and constant concentration measurements that showed higher rates downstairs. As shown in Table 5-2, infiltration rates in the downstairs were as much as 7 times higher than upstairs. In the control house, downstairs infiltration rates were 4.4 to 7 times higher than upstairs throughout the year and showed a maximum absolute difference of 1.45 ACH during the winter. By comparison in the experimental house, air infiltration rates downstairs were only 1.4 to 3.4 times higher than upstairs. This difference between the houses is consistent with the lower leakage area measured with the blower door in the experimental house and the focus of energy conservation retrofit procedures on the downstairs of the experimental house.

The comparison between the two houses, expressed in Table 5-2 as the "percent difference," clearly shows that the houses differ in terms of air infiltration due the experimental house were 34, 31, 35, and 28 percent lower than for the control house during the four measurement periods. This difference was greater than the 22 to 25 percent difference observed in Phase I, and also larger than calculated from concurrent SF_6 measurements. As shown in Table 5-1, based on the SF_6 measurements, the houses differed by 33, 24, 21, and 26 percent during the four measurement periods, differences that were quite comparable to the Phase I results.

Table 5-1

WHOLE HOUSE AIR INFILTRATION RATES MEASURED WITH
PFTs AND THE SF_6 DILUTION METHOD

		Air Infiltration Rate (ACH)[a]		
Season (ΔT)[b]	Method	Control House	Experimental House	Percent Difference[c]
Spring (25.6 °F) (March)	PFT	0.50	0.33	+34
	SF_6	0.49	0.33	+33
Summer (7.3 °F) (June)	PFT	0.16	0.11	+31
	SF_6	0.17	0.13	+24
Summer (-2.5 °F) (August)	PFT	0.20	0.13	+35
	SF_6	0.19	0.15	+21
Winter (44.9 °F) (January)	PFT	0.75	0.54	+28
	SF_6	0.66	0.49	+26
PFT/SF_6 Difference (%)[d]		6.7	13.0	

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[a] Air changes per hour.

[b] Indoor-outdoor temperature difference (°F).

[c] ([Control House - Experimental House]/Control House) x 100.

[d] Absolute percent difference: ($|PFT-SF_6|/SF_6$) x 100.

primarily to the higher air infiltration rates in the downstairs of the control house. Downstairs infiltration rates in the control house were 39 to 60 percent higher than in the experimental house. However, except for the spring measurement, upstairs air exchange rates were actually higher in the experimental house than in the control house. Although the upstairs air infiltration rates differed between the houses by as much as 67 percent when the rates were low in June, the absolute difference between the houses was always less than 0.1 ACH for the upstairs area.

Table 5-2

AIR INFILTRATION RATES OF UPSTAIRS AND DOWNSTAIRS ZONES
OF THE GEOMET HOUSES (PFT MEASUREMENTS)

	Air Infiltration Rate (ACH)					
	Control House		Experimental House		Percent Difference[a]	
Season	Upstairs	Downstairs	Upstairs	Downstairs	Upstairs	Downstairs
Spring (March)	0.23 ±0.24[b]	1.01 ±0.90	0.18 ±0.19	0.62 ±0.55	+22	+39
Summer (June)	0.06 ±0.07	0.35 ±0.31	0.10 ±0.10	0.14 ±0.12	-67	+60
Summer (August)	0.09 ±0.09	0.41 ±0.36	0.10 ±0.11	0.19 ±0.16	-11	+54
Winter (January)	0.24 ±0.30	1.69 ±1.47	0.32 ±0.39	0.96 ±0.17	-33	+43

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[a] ([Control House - Experimental House]/Control House) x 100.

[b] Standard deviation assigned based on estimated source release and sampling errors.

The high air infiltration rates measured with the PFTs in the downstairs of the control house were consistent with constant concentration measurements. PFT measurements were not performed concurrently with constant concentration measurements, but relative comparisons can be made with the two data sets shown in Table 5-3. Despite different measurement conditions, as indicated by the ΔT values, the PFT and constant concentration measurements were similar during each season. For example, when the average ΔT for the summer measurements differed by less than 2.5°F, the measurement results differed by less than 0.04 ACH for the two measurement methods. The ratios of the downstairs to upstairs air exchange rates ranged from 3.9 to 6.5 for the CCTG measurements, which were comparable to ratios of 4.4 to 7 with the PFTs. The PFT data, like the CCTG data discussed in Section 4, clearly show that air infiltration into the downstairs zone of the research houses, particularly the control house, is the primary determinant of the air infiltration rate for the whole house. This is especially true during winter when the stack effect results in large upward flows of air from the downstairs.

Table 5-3

COMPARISON OF PFT AND CONSTANT CONCENTRATION MEASUREMENTS
OF UPSTAIRS AND DOWNSTAIRS AIR INFILTRATION RATES IN THE CONTROL HOUSE

			Air Infiltration Rate (ACH)		
Season	Method	Delta T (°F)	Upstairs	Downstairs	House
Spring (March)	PFT CCTG	25.6 13.9	0.23 0.15	1.01 0.72	0.50 0.37
Summer (August)	PFT CCTG	2.5 4.9	0.09 0.10	0.41 0.39	0.20 0.20
Winter (January)	PFT CCTG	44.9 23.2	0.24 0.18	1.69 1.18	0.75 0.57

Air Infiltration Rates for Unconditioned Airspaces

In this study, air infiltration rates were also measured for the unconditioned attic and garage airspaces. Attic infiltration rates (Table 5-4), as expected, were quite high since the attic has soffit vents and a continuous ridge vent. Rates were above 9 ACH during all but the August measurement period, when the rates were only 6.6 and 8.0 ACH. The reason for the lower air infiltration rates in August is not clear since the average ΔT between the attic and outdoors was 10.6°F in June and 15.3°F in August, and the average wind speed was not substantially lower in August. Differences between the houses were not significant since, in all cases, the standard deviation of the measurements was greater than 1 ACH and was as high as 5 ACH for the spring measurement.

Table 5-4

AIR INFILTRATION RATES OF UNCONDITIONED AIRSPACES OF THE GEOMET RESEARCH HOUSES (PFT MEASUREMENTS)

	Air Infiltration Rate (ACH)			
	Control House		Experimental House	
Season	Attic	Garage	Attic	Garage
Spring (March)	9.92	0.58	14.93	0.44
Summer (June)	10.18	0.27	12.78	0.20
Summer (August)	6.62	0.08	8.01	0.11
Winter (January)	10.84	1.18	9.23	0.84

The air infiltration rates measured for the integral garages were quite low (see Table 5-4). During the summer, infiltration rates were less than 0.3 ACH. Even in January, when average outdoor temperatures were 17.7°F, the infiltration rates of the garages were only 1.18 and 0.84 ACH for the control and experimental houses, respectively. Generally, the garage rates were lower than those measured in the conditioned downstairs zone (Table 5-2). This was unexpected because the garages are not insulated and have standard garage doors with no special provisions to reduce air infiltration. The driving force for infiltration of air into the garage, however, is low due to the lower temperature differential between the garage and outdoors. In the summer the ΔT was only -1 to 3.4°F and in the winter the ΔT was 16.9°F for the garages compared to 44.9°F for the conditioned indoor airspaces. It should be recognized, however, that because of the garage doors and uninsulated walls, wind speed and direction may have substantial impact on short-term infiltration rates. Average air exchange rates, as measured by the week-long PFTs, however, are low for the garages.

The air infiltration rates for the garage of the experimental house were generally lower than for the control house. Although the difference was not substantial, it may be the result of garage door adjustments that were included in the retrofit procedures.

Low air infiltration rates in the garage may have significant ramifications with respect to air quality in the garage and occupant exposure to substances such as solvents. Garages are often used as workplaces for activities such as painting, hobbies that utilize solvents, and vehicle maintenance. Although garage doors may be opened during the summer and the garage may be heated in the winter, thereby increasing infiltration rates, there may be periods during spring and fall when occupants spend extended periods in the garage under conditions of low air exchange. During these periods, occupants could experience high exposures to gasoline vapors and solvents used in work or hobby activities.

INTERZONAL AIRFLOW RATES

Airflows Between Conditioned and Unconditioned Airspaces

Airflows between conditioned and unconditioned airspaces are important because of their effect on ventilation and heat loss from conditioned zones. Information on interzonal airflows between zones can help to refine our understanding of heat losses from conditioned spaces, redistribution of heat among conditioned zones, and space-conditioning requirements. The four-zone PFT measurements provided estimates of the flows between the attic and garage areas and the conditioned indoor airspaces.

Average airflow rates between the garage and the downstairs, based on week-long PFT measurements for four periods, are presented in Table 5-5. During all seasons, there was very little airflow from the downstairs to the garage, being less than 6 m^3/h in all cases. During spring and winter, however, there was substantial movement of air from the garage into the downstairs. In the control house, an airflow rate of 67 m^3/h was measured in January. Air infiltrating from the garage was "conditioned" to some extent. During the winter period, the average temperature in the garage was 34.6°F compared to an outdoor temperature of 17.7°F.

This higher air temperature may have resulted from solar gains during the day and heat gains from the conditioned spaces (note in Figures 5-1 to 5-4 that there was a small amount of airflow from both the downstairs and upstairs into the garage). The energy cost, therefore, to condition air infiltrating from the garage will not be as high as for air infiltrating directly from outdoors through the other three walls of the downstairs.

Consistent with the lower leakage area of the experimental house, lower rates of air infiltration were observed from the garage into the downstairs. Airflow rates between these zones in the experimental house ranged from 33 to 64 percent lower than in the control house, reflecting the effect of retrofit actions such as sealing the sill plate and caulking around the door connecting the garage and downstairs.

Table 5-5

RATES OF AIRFLOWS BETWEEN THE GARAGE AND DOWNSTAIRS OF THE GEOMET HOUSES (PFT MEASUREMENTS)

Season	Airflow Rate (m^3/h)			
	Control House		Experimental House	
	Downstairs to Garage	Garage to Downstairs	Downstairs to Garage	Garage to Downstairs
Spring (March)	0.4	32.0	1.2	20.3
Summer (June)	3.0	11.0	3.0	4.0
Summer (August)	5.5	7.3	4.1	4.7
Winter (January)	0	67.0	0	29.0

From an indoor air quality perspective, infiltration of air into the house from the garage is significant. In most garages there are numerous sources of volatile contaminants including gasoline vapors, paints, and various solvent-based products. The garage, therefore, can represent a source of pollutants that continually infiltrate the house. As the data of this study show, the extent of infiltration of air from the garage, however, can be reduced by retrofit procedures that eliminate or reduce leakage area.

Airflow rates between the attic and the upstairs conditioned airspaces are presented in Table 5-6 for the two research houses. Also included in the table are the estimated standard deviations of the measurements; measurement errors ranged from approximately 20 to 100 percent. In both houses, airflows from the upstairs to the attic were always higher than in the reverse direction. The magnitude of the airflow from the upstairs to the attic was clearly related to the difference in temperature between the two zones, particularly in the control house, with the highest airflow rate occurring during the winter. In the experimental house, where retrofit procedures tightened the seal of the attic access door and sealed various penetrations between the attic and upstairs, the airflows to the attic were lower and not as clearly related to the temperature difference. Differences between the two houses were substantial only during the colder March and January periods when the attic temperatures were lower than those in the upstairs conditioned airspace. This was consistent with the upward movement of air due to the stack effect.

Table 5-6

RATES OF AIRFLOWS BETWEEN THE ATTIC AND THE UPSTAIRS
OF THE GEOMET HOUSES (PFT MEASUREMENTS)

			Airflow Rate (m^3/h)			
	Control House			Experimental House		
Season	ΔT (°F)[a]	Upstairs to Attic	Attic to Upstairs	ΔT (°F)[a]	Upstairs to Attic	Attic to Upstairs
Spring (March)	11.8	92 ±42[b]	26 ±12	5.5	21 ±10	1 ±0.4
Summer (June)	-8.8	42 ±14	15 ±4	-9.9	37 ±10	0 ±0
Summer (August)	-12.8	19 ±6	12 ±4	-10.8	15 ±4	8.4 ±2
Winter (January)	32.5	168 ±44	53 ±12	37.3	70 ±19	57 ±26

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[a] Upstairs-attic temperature difference.

[b] Standard deviation based on estimates of source release and sampling errors.

Airflows from the attic to the downstairs in the control house followed a trend related to temperature difference, with the highest airflows in March and January. In the experimental house there was little airflow from the attic to the upstairs, except in winter. Differences between the two houses show that the attic and upstairs are more strongly coupled in the control house than in the experimental house due to the sealing of penetrations and leakage sites in the experimental house during the retrofit. During the winter, the large temperature difference was apparently a sufficient driving force for movement of the air from the attic to the upstairs even in the experimental house, probably through small leakage sites that were not identified in the retrofit. However, the retrofit did seal the larger leakage sites, thereby substantially reducing upward airflow due to the stack effect in the experimental house.

Airflows Between the Upstairs and Downstairs

Average airflows between the conditioned upstairs and downstairs airspaces during week-long PFT measurement periods ranged from 24 to 263 m^3/h (Table 5-7), with estimated measurement errors ranging from 17 to 33 percent, as indicated by the standard deviations included in the table. In both houses, the rate of airflow from the downstairs to the upstairs showed seasonal variation that may be related to the stack effect.

The rate of airflow between the upstairs and downstairs will be influenced jointly by the stack effect, resulting in a net upward movement of air, and by operation of the central air handler which promotes airflow in both directions. As shown in Table 5-8, the air handler, in response to heating or cooling demand, operated between 19 and 43 percent of the time during the measurement periods. Airflow rates between the upstairs and downstairs were related to the percent of time that the air handler operated, with the lowest airflow rates measured in June when the air handler was only on 19 percent of the time. The magnitude of the interzonal airflow rates, however, was not directly proportional to the amount of time that the air handler operated. Although the air handler operated twice as long in winter compared to summer, the upward airflows were five to eight times greater in winter than in summer.

Table 5-7

AIRFLOW RATES BETWEEN THE UPSTAIRS AND DOWNSTAIRS OF THE GEOMET HOUSES (PFT MEASUREMENTS)

	Airflow Rate (m^3/h)			
	Control House		Experimental House	
Season	Downstairs to Upstairs	Upstairs to Downstairs	Downstairs to Upstairs	Upstairs to Downstairs
Spring (March)	104 ±22[a]	39 ±9	53 ±9	24 ±5
Summer (June)	51 ±13	31 ±9	36 ±8	28 ±8
Summer (August)	85 ±22	40 ±11	47 ±10	36 ±11
Winter (January)	256 ±55	133 ±35	263 ±72	218 ±71

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[a] Standard deviation based on estimates of source release and sampling errors.

The airflows between the conditioned zones, however, cannot be viewed in isolation from the airflows between other parts of the house. Such an approach is too simplistic and fails to address the complexity of the flow patterns in the houses. To understand the total flow pattern it is necessary to consider other interzonal airflows, such as from the upstairs to the attic. Figure 5-4, for example, shows the flows in the two houses during January. As shown in the figure, the airflow rate from the downstairs to the upstairs was similar in the two houses. During the measurement period, the air handler operated about 40 percent of the time in each house. Similar upward and downward airflow rates between upstairs and downstairs in the experimental house suggest that the operation of the air handler was the primary factor affecting the airflows during this period. But, in the control house, the downward airflow rate was much less than the upward airflow rate. Differences between the two houses, with respect to airflow rates from the upstairs to the downstairs, appeared to be related to airflows to the attic in the control house. The rate of airflow from the upstairs to the attic in the control house was 169 m^3/h compared to 70 m^3/h in the experimental house. In the control house, therefore, air exfiltrated from the upstairs due to the stack effect, rather than being returned to the downstairs by the air handler.

Table 5-8

PERCENT OF TIME THAT THE CENTRAL AIR HANDLER
OPERATED DURING PFT MEASUREMENT PERIODS

	Percent of Time Air Handler On	
Season	Control House	Experimental House
Spring (March)	21	19
Summer (June)	19	19
Summer (August)	32	28
Winter (January)	43	40

Interzonal airflow measurements performed with the PFTs further demonstrated the impact of the retrofit on airflow patterns in the research houses. As discussed in this section, retrofit procedures that reduced losses of air from the conditioned zones due to the stack effect also impacted the airflow patterns within the conditioned airspaces. The data also showed that there was substantial interzonal airflow related to operation of the central air handler. The magnitude of the airflow during HVAC operation will directly impact air quality in the houses by redistribution of contaminants within the conditioned zones. Average integrated measurements of interzonal airflows, such as those obtained with the PFTs, can assist in the prediction of contaminant migration between zones, particularly for contaminants released at constant rates from continuous sources.

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Attempts to measure flows between conditioned and unconditioned airspaces would have required a substantially larger investment of resources in the analytical system.

ZONE-SPECIFIC INFILTRATION RATES

An example of infiltration rates measured with the multiple halocarbon system for the upstairs, downstairs, and the whole house (conditioned spaces) is depicted in Figure 6-1. During a 12-hour period in March (midnight to noon), the downstairs infiltration rates ranged from 0.45 to 1.30 ACH and averaged 0.93 ± 0.26 ACH. The infiltration rates upstairs ranged from 0.09 to 0.33 ACH and averaged 0.22 ± 0.08 ACH. The higher downstairs infiltration rates were consistent with other measurement results. For example, PFT measurements conducted under similar outdoor conditions yielded a week-long average downstairs infiltration rate of 0.62 ACH and an upstairs rate of 0.18 ACH. Although the March halocarbon and PFT measurements were not concurrent, results with the methods were comparable, both methods measuring downstairs infiltration rates three to four times higher than upstairs.

Also shown in Figure 6-1 are data on wind speed and indoor-outdoor temperature difference during the period. The figure suggests that the downstairs infiltration rate was more closely related to ΔT than wind speed. The infiltration rate dropped from 1.3 to 0.45 during the 0700 to 1200 period when the ΔT decreased. The upstairs infiltration rate increased during this period, a period of increasing wind speed. An increase upstairs in response to wind speed would be consistent with the fact that the upstairs has a greater exposed perimeter wall area that includes windows and other potential leakage sites.

During a 1-week period in June, rates of air infiltration into the upstairs and downstairs of the experimental house were measured concurrently with both the halocarbon multiple tracer system and the passive PFT system. The PFT measurement

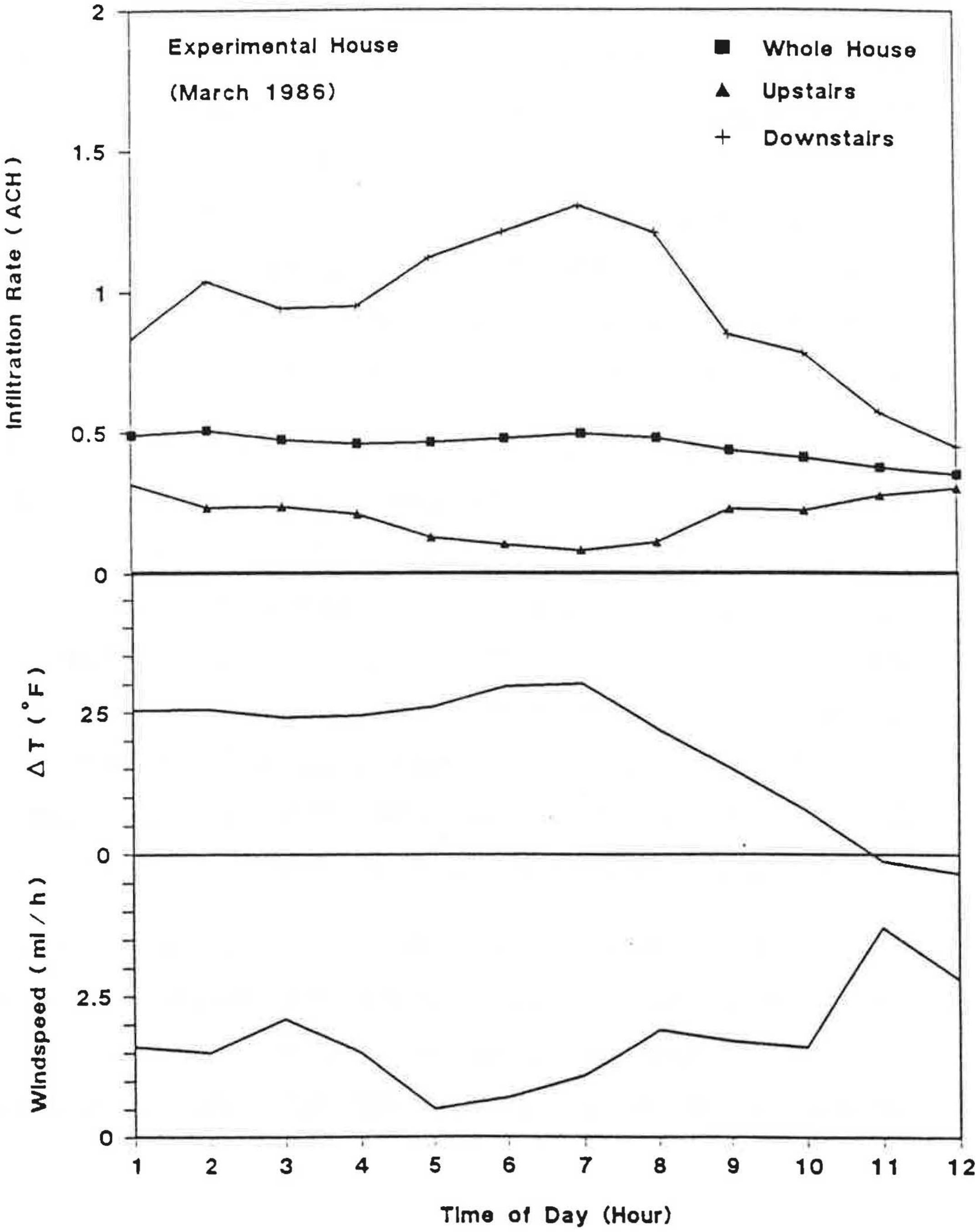


Figure 6-1. Air infiltration rates measured with halocarbon tracers in the experimental house related to ΔT and wind speed (March).

provided a week-long average measurement that was compared to an average calculated from hourly halocarbon measurements during the period. Upstairs infiltration rates measured with the halocarbons ranged from 0.05 to 0.18 and averaged 0.07 ACH.

Downstairs rates ranged from 0.08 to 0.68 and averaged 0.27 ACH. The week-long PFT measurements yielded infiltration rates of 0.10 ACH upstairs and 0.14 ACH downstairs. Upstairs infiltration rates for the two methods were quite similar. But there was an almost two-fold difference in the average downstairs rates measured by the two methods. Additional measurements with both PFTs and halocarbons, particularly during winter when infiltration rates are higher, will be required to determine the reason for this difference.

Measurements of whole house air infiltration rates with the multiple halocarbon tracer system were also compared to concurrent SF_6 dilution measurement results. For example, during the period depicted in Figure 6-1, the average whole house air infiltration rates measured with the halocarbons averaged 0.45 ± 0.05 ACH. This was 0.23 ACH higher than the estimated rate of 0.22 ± 0.07 ACH based on SF_6 measurements. In a subsequent measurement period, whole house air infiltration rates measured with halocarbons ranged from 0.24 to 0.40 ACH with an average of 0.27 ACH. SF_6 measurements yielded rates from 0.39 to 0.71 ACH (average of 0.41 ACH), averaging 35 percent higher than rates from the halocarbon measurements.

The disparity between the two measurement methods was inconsistent across tests, with halocarbons exhibiting a positive bias in one test and a negative bias in the other. This disparity was further examined during an extended period of summer measurements when the SF_6 dilution, multiple halocarbons, and PFT methods were used concurrently. During the week-long period the following average whole house air exchange rates were measured by the three methods:

- SF_6 dilution -- 0.13
- Halocarbons -- 0.14
- PFTs -- 0.11.

For the week-long period there was excellent agreement between the three methods. The relationship between SF_6 and halocarbon estimates of whole house air infiltration was further investigated by comparing hourly average rates. However, linear regression techniques indicated that hourly average rates were not well correlated (R^2 value of less than 0.1). Closer examination of the data indicated that not only were there periods when the halocarbons showed a positive bias with respect to SF_6 measurements, but there were also periods of negative bias, as well as periods of good agreement. During this period, SF_6 was injected into the house once every 12 hours. This practice facilitated calculation of 8-hour average air infiltration rates (the first 2 and last 2 hours were ignored to account for mixing and low concentrations, respectively). Comparisons of 8-hour average air exchange rates yielded R^2 values ranging from 0.004 to 0.93 (average R^2 value of 0.43) for twelve 8-hour periods. Halocarbons exhibited a negative bias in 5 of the 12 periods.

The close agreement in week-long average air infiltration measurements by the three methods and the lack of correspondence for hourly average rates measured by SF_6 and halocarbons raise questions concerning measurement errors and assumptions inherent in the use of the constant release method. Use of the mass balance approach to calculate airflow rates assumes that the tracer gas mixes thoroughly and instantaneously within the release zone, and that the tracer gas concentration can be characterized by a single value. If this is not true, measurement errors result, the magnitudes of which are related to the degree of imperfect mixing. To minimize this error, one alternative is to enhance mixing within each zone by placing fans in the zone. This approach, however, compromises natural conditions and may affect normal airflow rates into and out of the zone. A second alternative is to lengthen the measurement period to ensure that the measurements during the period are representative of steady-state tracer concentrations in the zone.

It is difficult to quantify the length of the period required to achieve equilibrium of tracer gas concentrations within a zone during constant tracer release. The period, however, can be estimated based on the length of time required to reach steady-state tracer concentrations following initiation of release. As shown in Figure 6-2, tracer gas concentrations in the two zones of the research house reached steady-state concentrations 3 to 5 hours after initiation of release in the downstairs and upstairs, respectively. During the period depicted, the furnace fan operated only from 1830 to 1900 (the first 30 minutes of the release period), then was off until midnight. The data depicted in Figure 6-2 suggest that for tracer measurements with the halocarbon system as configured in this study, averaging periods used to calculate infiltration rates may need to be greater than 3 to 5 hours during periods with little mechanical mixing by the HVAC system. As an alternative to use of longer averaging times, small fans, such as those used with the constant concentration system, could be added to the system to promote mixing. A more attractive alternative to address the problem of imperfect mixing is the addition of a substantially larger number of tracer gas release points in each room. Unlike the use of mixing fans, this approach will not affect interzonal airflows, the measurement of which is the primary objective with the multiple halocarbon system.

INTERZONAL AIRFLOW RATES

The multiple halocarbon tracer system provides a method for measurement of short-term changes in interzonal airflow rates that can be related to changing indoor and outdoor conditions. An example of interzonal airflow rates measured in

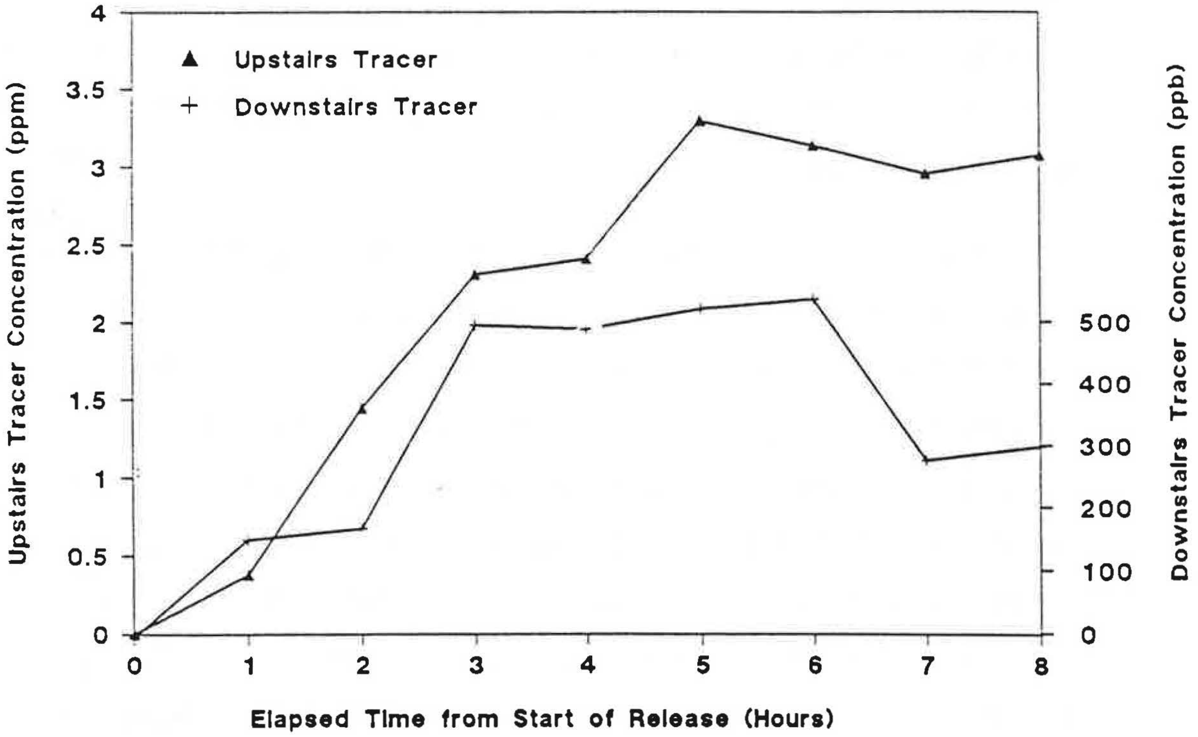


Figure 6-2. Time needed to reach steady-state tracer gas concentrations following initiation of release.

the experimental house is presented in Figure 6-3. During this wintertime measurement period, the basement door was closed and the central forced-air furnace operated in response to calls for heat by the thermostat. Interzonal airflow rates during the period ranged from 33 to 220 m^3/h, but were generally between 100 and 120 m^3/h during the period from 8 p.m. to noon of the next day. Interzonal airflow rates were not proportional to the percent of time that the HVAC fan operated, but, as shown in Figure 6-3, there was a clear relationship. Rates were highest during the 8 p.m. to noon period when the HVAC fan operated approximately 40 percent of the time. In the afternoon, when the HVAC fan operated less than 20 percent of the time, the interzonal airflow rates were substantially lower. Airflow rates were nearly identical in both the upward and downward direction.

Another example of interzonal airflows, presented in Figure 6-4, shows airflow rates under moderate winter conditions when the basement door was open. Airflow rates from upstairs to the downstairs ranged from 49 to 591 m^3/h, the highest flow rate occurring during the hour when the HVAC fan operated over 60 percent of the time. Airflow rates in the upward direction were only slightly higher than in the downward direction, suggesting that upward airflow due to the stack effect was minimal during this period or countered by HVAC operation. The figure shows that the interzonal airflow rates were related to the extent of HVAC fan operation when the basement door was open. Airflow rates were substantially higher with the basement door open than during January when the door was closed (Figure 6-3), even though the HVAC fan operated less than half as much during March as during the January period.

The relationship between HVAC fan operation and interzonal airflow rates is shown most dramatically in Figure 6-5, which depicts a 6-day period of halocarbon measurements in June. Because of moderate temperatures during the first 2 days, there was little HVAC operation and interzonal airflow rates were below 100 m^3/h.

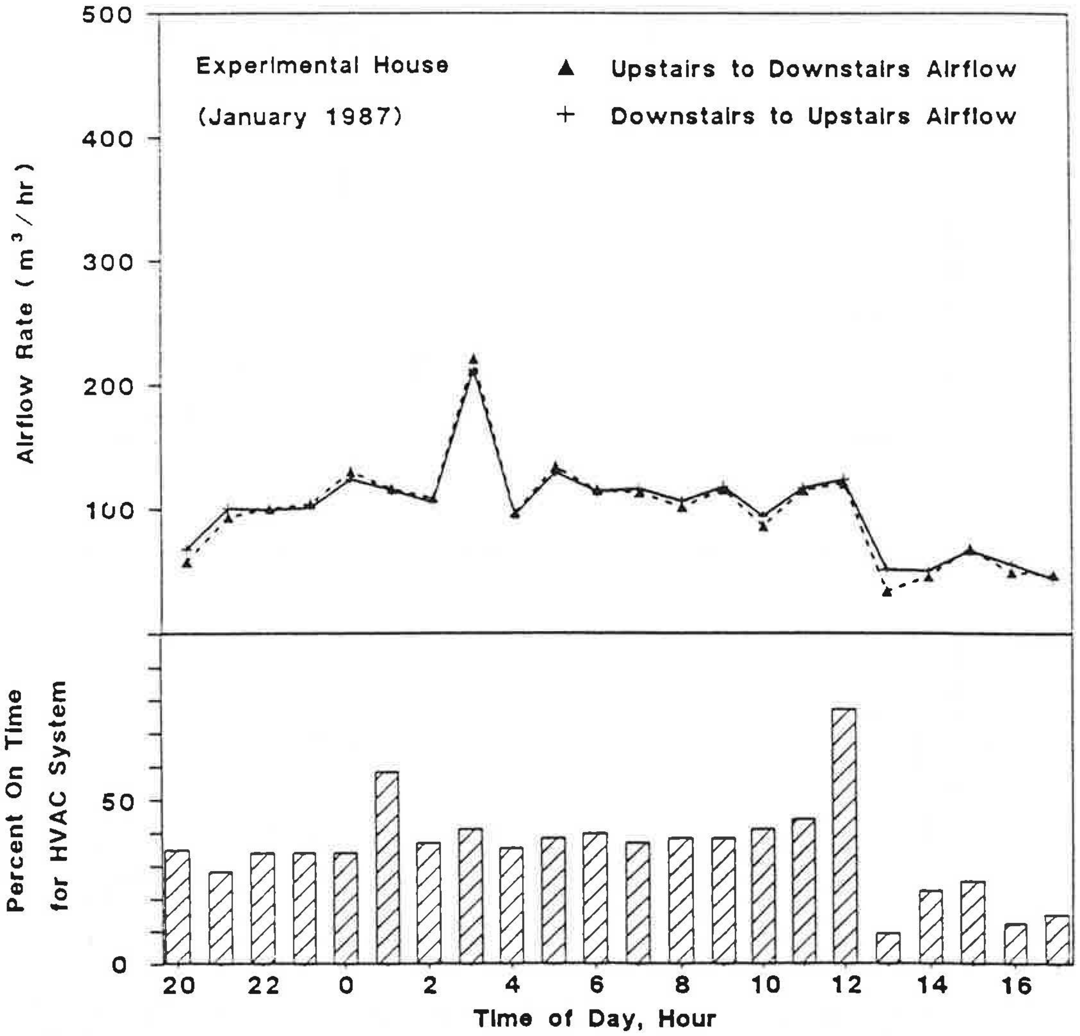


Figure 6-3. Interzonal airflow rates measured with halocarbon tracers in January in the experimental research house, downstairs door closed. (The lower portion of the figure depicts the percent of each hour that the furnace fan was operating.)

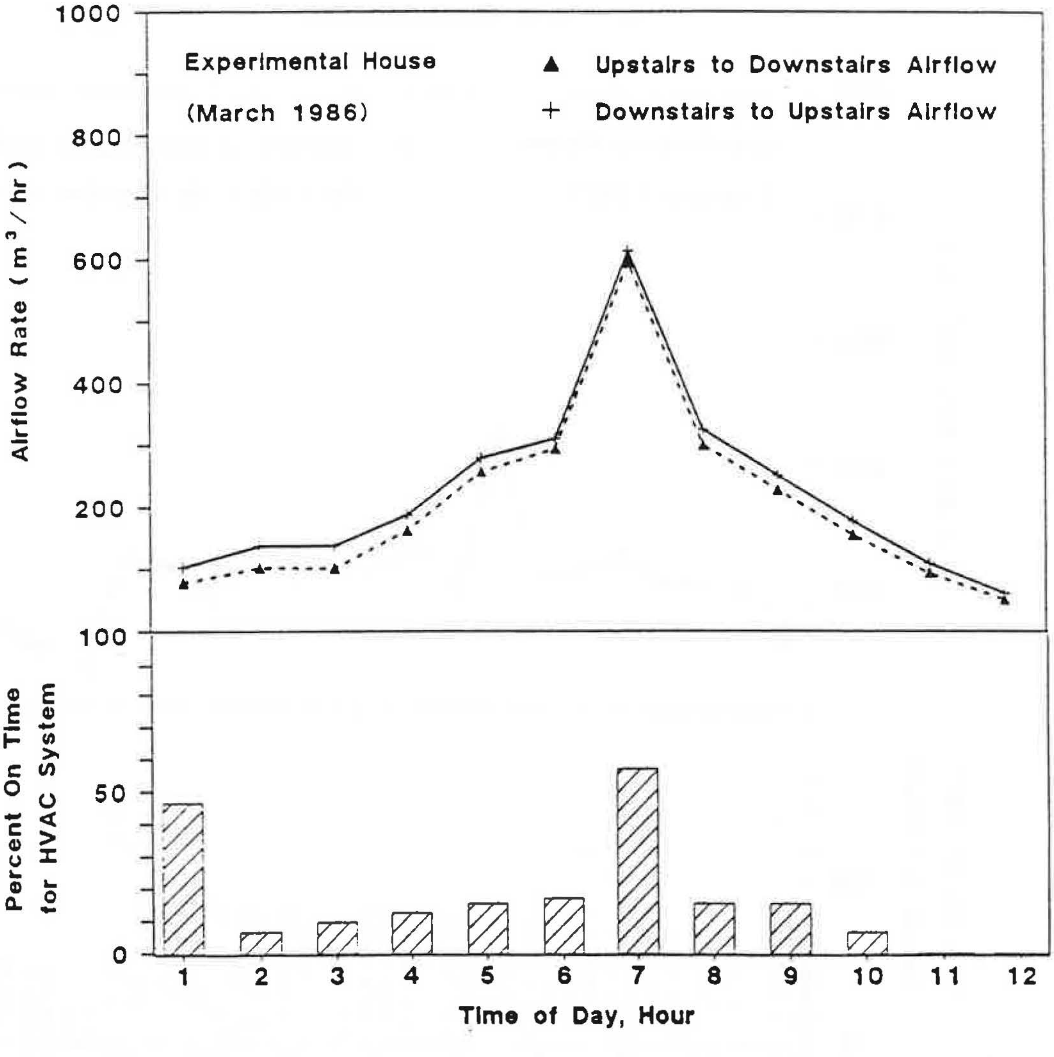


Figure 6-4. Interzonal airflow rates measured with halocarbon tracers in March in the experimental research house, downstairs door open. (The lower portion of the figure depicts the percent of each hour that the furnace fan was operating.)

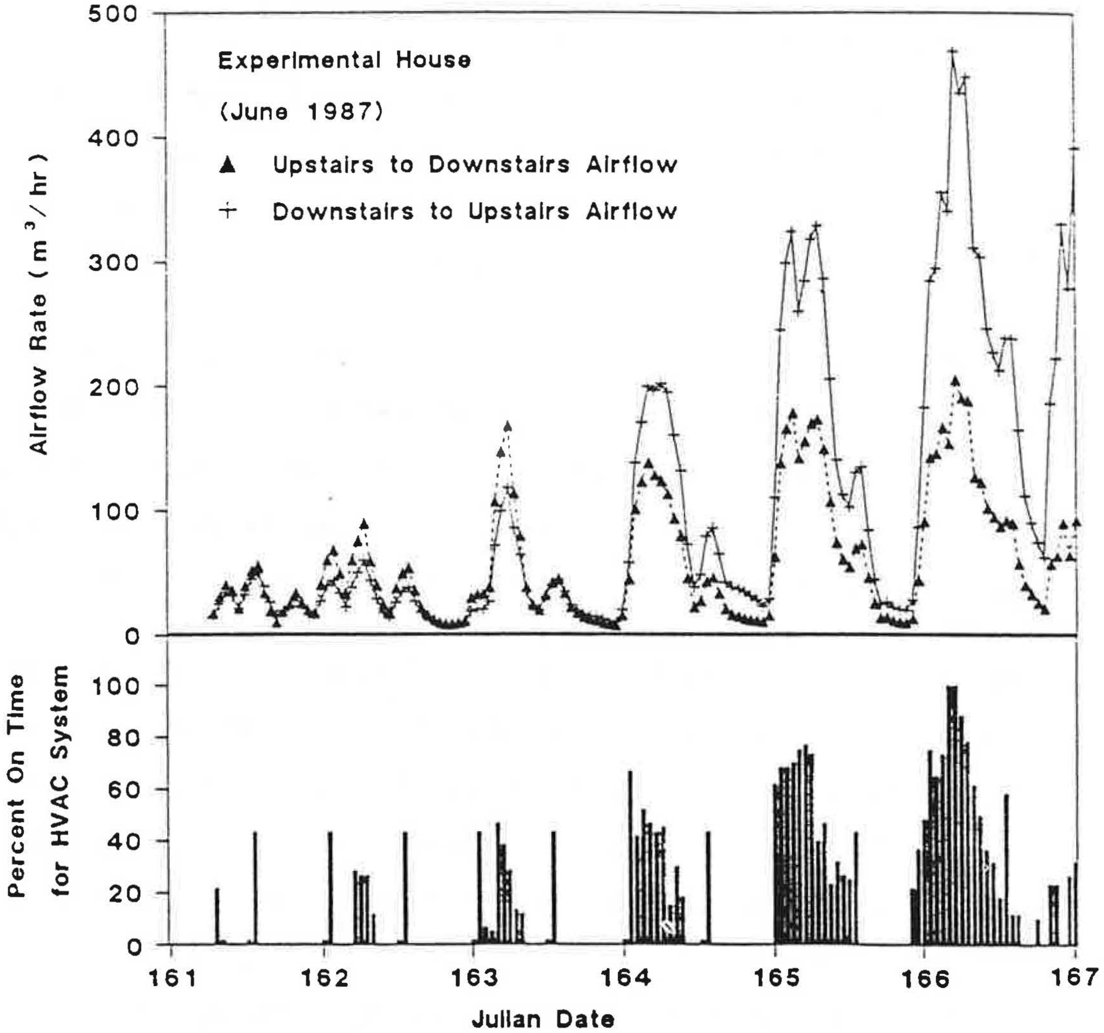


Figure 6-5. Interzonal airflow rates in the experimental house during air conditioner operation, June 1987.

As outdoor temperatures increased and the air conditioner ran more frequently, the interzonal airflow rates increased, with peak airflow rates occurring in the late afternoon and early evening hours. As shown in Figure 6-5, the highest flow rates, over 440 m^3/h in the upward direction and over 200 m^3/h in the downward direction, occurred on the day of highest air conditioner fan activity. During the period, interzonal airflow rates were highly correlated with the percent of time the fan was on; R^2 values were 0.7 for upstairs to downstairs airflow rates and 0.63 for the relationship between downstairs to upstairs airflow rates and percent of time that the air conditioner fan was on.

Figure 6-5 shows that during periods with little fan operation, the airflow rates were similar in both directions. However, when the fan operated for a greater percent of time, the flow from the downstairs to upstairs was greater than in the opposite direction. This result was different from the wintertime situation (depicted in Figure 6-3), when the flow rates were similar in both directions.

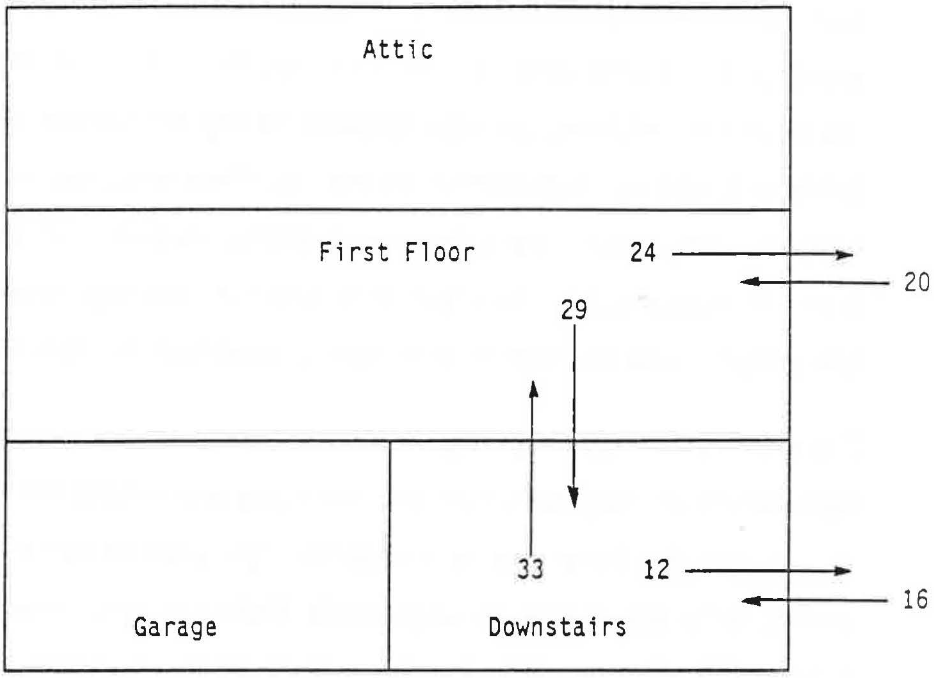
During the period depicted in Figure 6-5, limited simulation of appliance activity was performed. The simulations included operation of the shower, shower exhaust fan, clothes dryer, gas range, and range fan. The effects of appliance operation, however, could not be detected because the effect of the air conditioner's central fan impacted the interzonal airflows so strongly. During a different measurement period, however, operation of the clothes dryer (downstairs) for 40 minutes resulted in a two-fold increase (45 to 80 m^3/h) in the rate of airflow from the upstairs to the downstairs. The capability of the system to measure short-term changes in interzonal airflows during operation of appliances will require additional testing under a wider range of conditions in the house.

COMPARISON OF PFT AND HALOCARBON RESULTS

The passive PFT measurement method was compared to the multiple halocarbon tracer method by use of the two methods concurrently during a 1-week period in June. Hourly halocarbon measurements for the period were integrated for comparison with the PFT results. The six airflow rates measured in the conditioned zones are depicted in Figure 6-6. As described earlier in this section, whole house air exchange rates were comparable for the two methods. The PFT method over-predicted the upstairs infiltration rate compared to the halocarbon system, but the difference was not substantial at the low flows measured in the summer. The PFT-measured infiltration rate for the basement, however, was about half that measured with the halocarbons. As shown in Figure 6-6, average interzonal airflows between the upstairs and downstairs were nearly identical for the two methods.

The passive PFT system performed well compared to the halocarbon system for measurement of long-term infiltration rates and interzonal flows and is well-suited for long-term measurements. The ease of use of the system makes it particularly applicable to large-scale field surveys. However, as the data presented in this section indicate, short-term variations in infiltration rates and interzonal airflows can be substantial. During the period of concurrent PFT and halocarbon measurements, interzonal airflow rates were as high as 440 m^3/h, whereas average rates were only 27 to 34 m^3/h. The choice between the passive PFT system and the multiple halocarbon system as the measurement method will be determined by the integration period required to meet project objectives. To understand the general distribution and movement of indoor pollutants having a constant source, long-term average measurements may be adequate. For pollutants released from point sources or for short-time periods, however, pollutant movement and distribution within a residence must be characterized on a substantially shorter time basis such as that attained with the halocarbon system.

PFT Measurements



Halocarbon Measurements

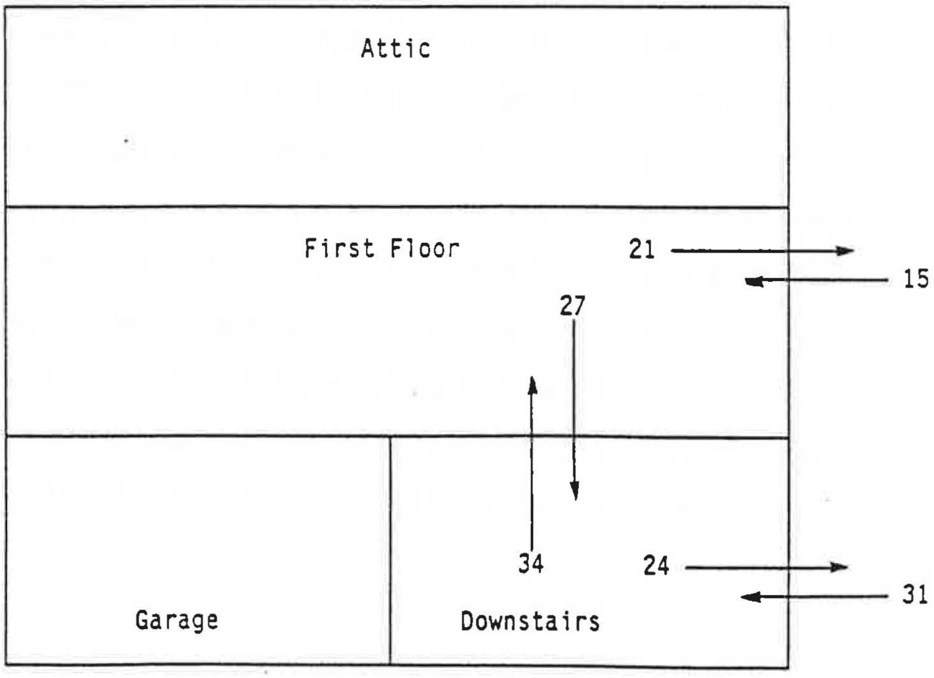


Figure 6-6. Comparison of PFT and halocarbon measurement results for a week-long period in June (rates in m^3/h).

Section 7

MAJOR FINDINGS

In this section, major findings concerning air infiltration rates and interzonal airflows in the GEOMET research houses are summarized and discussed. This section also includes a comparison of the measurement methods used in the study.

HOUSE TIGHTNESS AND SEASONAL AIR INFILTRATION RATES

Blower door measurements conducted during 1986 to assess leakage area and tightness of the research houses indicated that there had been little change since the initial measurements in 1984. Equivalent leakage areas were calculated to be 699 ± 37 cm^2 in the control house and 398 ± 27 cm^2 in the experimental house. These values were slightly lower, but not significantly different from the Phase I measurements.

The calculated air exchange rates at 50 pascals were 10.6 ± 0.1 ACH for the control house and 6.1 ± 0.1 ACH for the experimental house. This compared to 10.8 ± 0.1 ACH and 6.5 ± 0.2 ACH for the control and experimental houses, respectively, during Phase I.

As in Phase I, whole house air infiltration rates were shown to vary seasonally during the Phase II measurement period. Average air infiltration rates for the control house, for example, were 0.49, 0.17, and 0.66 ACH during spring, summer, and winter measurement periods, respectively. Infiltration rates measured in this study were quite similar to previous (Phase I) measurements during periods when outdoor conditions were similar in terms of temperature and wind speed. Average infiltration rates for the winter measurement period, for example, were 0.66 ± 0.14 ACH in this study compared to 0.61 ± 0.15 ACH during Phase I.

Both blower door measurements and SF_6 dilution measurements showed that there had been little change in the air leakage characteristics and whole house air infiltration rates during the period since the initial measurements.

UPSTAIRS AND DOWNSTAIRS AIR INFILTRATION RATES

Infiltration rates for the upstairs and downstairs of the research houses were measured by constant concentration, passive PFT, and multiple halocarbon methods.

Infiltration rates were substantially higher downstairs than upstairs in both houses during all seasons (Table 7-1). Upstairs infiltration rates ranged from 0.07 to 0.32 ACH over the year in the two houses, with the lowest rates measured in the summer. Upstairs infiltration rates did not differ significantly between the two houses; in some cases, they were higher in the experimental house than in the control house.

Table 7-1

INFILTRATION RATES OF THE UPSTAIRS AND DOWNSTAIRS OF THE GEOMET RESEARCH HOUSES MEASURED WITH CONSTANT CONCENTRATION AND CONSTANT RELEASE METHODS

		Air Infiltration Rate (ACH)			
		Control House		Experimental House	
Season	Measurement Method[a]	Upstairs	Downstairs	Upstairs	Downstairs
Spring	CCTG	0.15	0.72	--	--
	PFT	0.23	1.0	0.18	0.62
	MHT	--	--	0.22	0.93
Summer	CCTG	0.10	0.39	--	--
	PFT	0.06	0.35	0.10	0.14
	MHT	--	--	0.07	0.27
Winter	CC	0.18	1.18	--	--
	PFT	0.24	1.69	0.32	0.96
	MHT	--	--	0.10	0.73

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[a] CCTG: Constant concentration; PFT: Passive perfluorocarbon tracers; MHT: Active multiple halocarbon tracers.

Downstairs infiltration rates were approximately 3 to 7 times higher than those upstairs in the control house, depending on the season of the measurement. The difference between upstairs and downstairs was greatest in both houses during the winter. There was a substantial difference between the two houses with respect to the downstairs infiltration rates as measured with PFTs; infiltration rates for the downstairs of the experimental house were 40 to 60 percent lower than in the control house. During the winter, the infiltration rate in the downstairs of the control house was 0.73 ACH higher than for the experimental house.

The higher downstairs infiltration rates, as well as the differences in the infiltration rates between the two houses, are consistent with the details of construction of the houses and the reduction of leakage area by the retrofit measures applied in the experimental house. A number of the retrofit measures targeted leakage sites in the downstairs area of the house containing the sill plates, the wood stove insert, numerous pipe and wire penetrations, and the wall of the integral garage.

High infiltration rates in the downstairs of a house will impact energy use, occupant comfort, and air quality. If the downstairs is used as a living area, energy requirements will be increased to achieve an acceptable level of comfort. In a house with a central HVAC system and a single thermostat located upstairs, it may be difficult to achieve acceptable temperatures in the downstairs if the air infiltration rate is substantially higher than that upstairs. The impact of downstairs infiltration rates on air quality may be either positive or negative. Under certain conditions, higher infiltration rates may dilute downstairs concentrations of contaminants, such as radon. On the other hand, high downstairs air infiltration rates in combination with upward airflows due to the effect of stack action may promote transport of contaminants from the basement to the upstairs living area.

ATTIC AND GARAGE AIR INFILTRATION RATES

As expected, attic infiltration rates were quite high, but were much less variable than the infiltration rates for the conditioned airspaces. Infiltration rates ranged from 6.6 to 15 ACH and were above 9 ACH in both houses during three of the four measurement periods. Infiltration rates were slightly lower for the attic of the control house during spring and summer, but the differences between the houses were not significant.

The air infiltration rates for the garages were remarkably low. During the summer, the rates were less than 0.3 ACH. In the winter, the rates were 1.2 and 0.8 ACH in the control house and experimental house, respectively, and were lower than the infiltration rates of the corresponding conditioned downstairs zones during the same period. With the exception of the August measurement, the garage infiltration rate was lower in the experimental house than in the control house. This difference is probably the result of retrofit measures such as adjustment of the seal of the garage door.

Low infiltration rates into the garages, although attractive from an energy use viewpoint may result in indoor air quality problems in some cases. During spring and fall, particularly when the garage door would typically be closed and there would be no requirement for auxiliary heat in the garage, homeowners working in the garage may be exposed to high levels of contaminants due to the low air infiltration rates. In addition to gasoline vapors from stored vehicles, a variety of noxious compounds may be generated in garages due to work or hobby activities. The data from this study suggest that additional ventilation in the research house garages would be warranted during much of the year if pollutant sources were frequently activated in this area.

AIRFLOWS BETWEEN CONDITIONED AND UNCONDITIONED ZONES

PFT measurements showed that there was very little airflow from either the upstairs or downstairs conditioned zones to the unconditioned integral garage;

rates were less than 6 m^3/h in all cases. There was, however, substantial airflow from the garage into the downstairs. Airflow rates were 67 and 29 m^3/h for the control and experimental houses, respectively, during the winter. Airflow rates between the garage and downstairs were 33 to 64 percent lower in the experimental house, reflecting the effectiveness of retrofit measures implemented at the garage/downstairs interface. The relatively high rate of airflow from the garage into the downstairs may be significant because it represents a source of pollutants from stored vehicles and products used and stored in the garage.

The ability of retrofit measures to reduce the stack effect was demonstrated by measurements of airflow rates from the upstairs to the attic. During all three measurement seasons, the airflow to the attic was lower in the experimental (retrofitted) house than in the control house. There was also little downward airflow from the attic into the upstairs in the experimental house during spring and summer. In the winter, the airflow in this direction was similar for the two houses. This finding suggests that there are still many small leakage sites in the upstairs/attic interface that allow downward airflow under conditions of large temperature differences between the attic and upstairs during the winter. Heat losses due to the effect of stack action are an important component of the energy budget of a house. However, as this study shows, they can be effectively reduced by retrofit procedures.

AIRFLOWS BETWEEN UPSTAIRS AND DOWNSTAIRS

Interzonal airflow rates were measured with PFTs to obtain week-long average rates and with multiple halocarbon tracers to obtain short-term, hourly rates. Average one-week airflow rates ranged from a low of 24 m^3/h from the upstairs to the downstairs in the experimental house (during spring), to a high of 263 m^3/h from the downstairs to the upstairs in the control house (during winter). The average airflow rates were always higher in the upward direction than in the downward direction. Airflow rates were generally higher in the control house than in the experimental house, except during winter when the furnace fan operated over 40 percent of the time during the measurement period.

The average week-long airflow rates were shown to be as much as an order of magnitude lower than those during selected hourly periods, as measured with the multiple halocarbon tracers. During a summer measurement period, for example, week-long average airflow rates were only 27 to 34 m^3/h in the experimental house, but hourly measurements as high as 440 m^3/h were measured during periods when the central HVAC fan operated extensively. Hourly interzonal airflow rates measured with the halocarbon system correlated well (R^2 of 0.7) with the percent of time that the central HVAC operated during the hour.

The magnitude of the interzonal airflows within the house will have a strong impact on the distribution of air contaminants generated indoors. Results obtained with the halocarbon system suggest that there can be substantial variation in airflow rates. For contaminants released intermittently for short periods, contaminant concentrations both in the release area and other areas of the house will be a function of the airflows in the house. High airflow rates, for example, during HVAC operation will serve to dilute the concentration at the release site, lowering the user's exposure. On the other hand, distribution of the contaminants will increase passive exposure by nonusers. Measurement of interzonal airflow rates and characterization of their variation should prove valuable in the assessment of both active and passive exposure to contaminants generated indoors.

DIFFERENCES BETWEEN THE CONTROL AND EXPERIMENTAL HOUSES

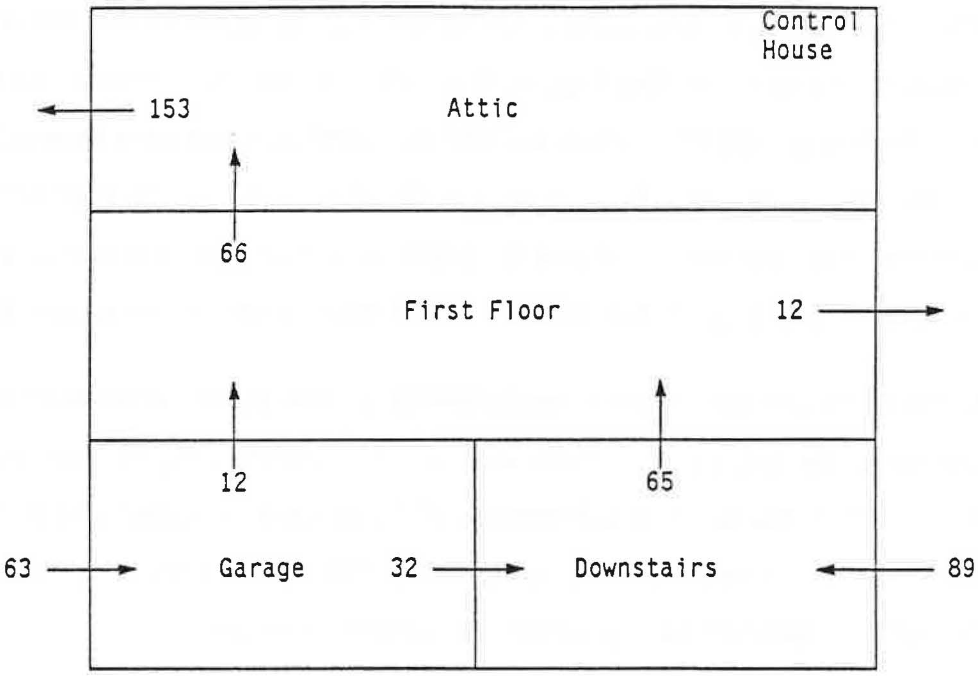
Differences between the two houses, as highlighted in the previous discussion, were consistent with Phase I measurements and the effects of retrofit measures on the tightness of the experimental house.

The effect of the retrofit on air infiltration and interzonal airflow rates in the two houses is shown in Figure 7-1, which depicts the direction and magnitude of the net airflows in the houses during March 1986, based on PFT measurement results. As shown in the figure, the direction of the airflows was the same for both houses during the period but the net airflow rates were generally much higher in the control house. The figure clearly shows the high rate of infiltration of air into the downstairs, movement upward, and loss from the attic, with the rates being substantially higher in the control house than in the experimental house.

Whole house air infiltration measurements by the SF_6 dilution method showed that the rates for the control house were 24 to 33 percent higher than those for the experimental house. The differences of 24 percent in summer and 26 percent in winter measured in this study were nearly identical to the differences of 24 and 25 percent measured during summer and winter in Phase I.

The differences in whole house air infiltration rates between the houses were mainly due to differences in infiltration rates for the downstairs of the houses, as demonstrated in the example depicted in Figure 7-1. Average infiltration rates for the downstairs of the experimental house were 39 to 60 percent lower than those measured in the control house during the week-long PFT measurement periods. Differences between the houses were related to indoor-outdoor temperatures and were largest in the winter, as depicted in Figure 7-2. Upstairs infiltration rates in the experimental house generally were slightly higher than in the control house.

Differences between the houses associated with the retrofit measures implemented in the experimental house during Phase I were also observed in the measurements of airflows between the conditioned and unconditioned zones. As shown in Figure 7-3, airflows from the upstairs to the attic were similar in the two houses during summer, but differed substantially during spring and winter. During the winter,



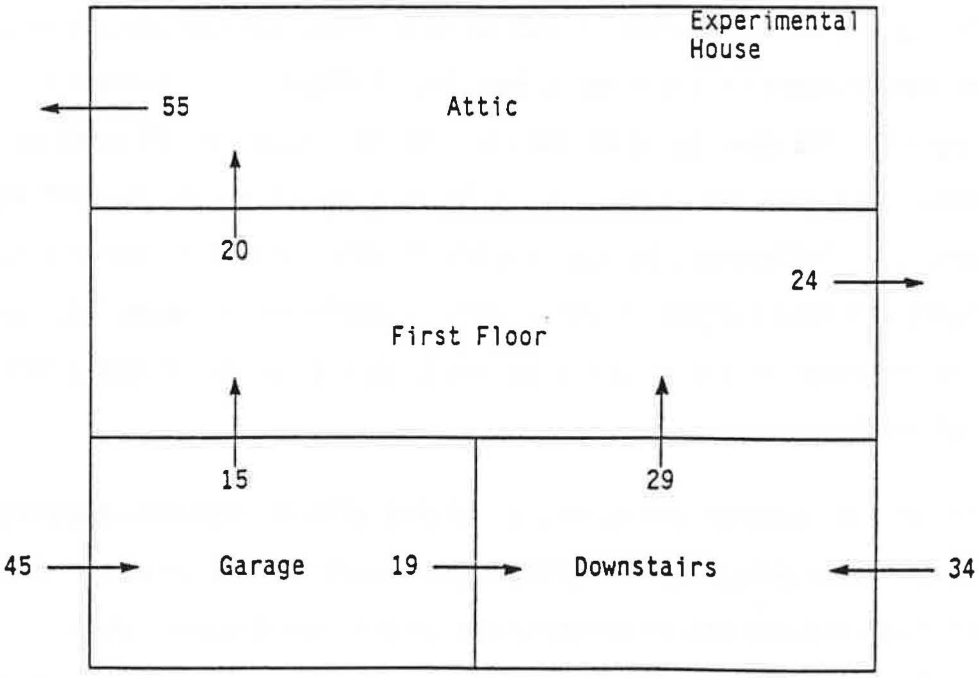


Figure 7-1. Direction and magnitude (m^3/h) of net airflows in the control and experimental houses measured with PFTs in March 1986.

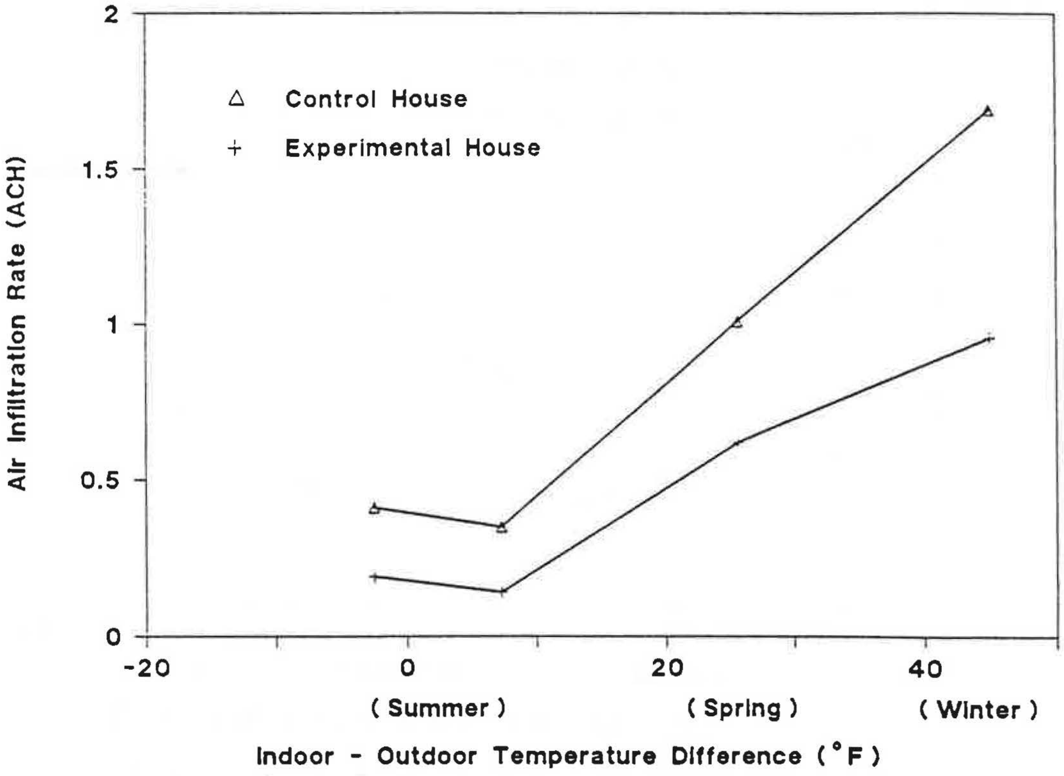


Figure 7-2. Effect of retrofit on air infiltration rates in the downstairs of the research houses during the year.

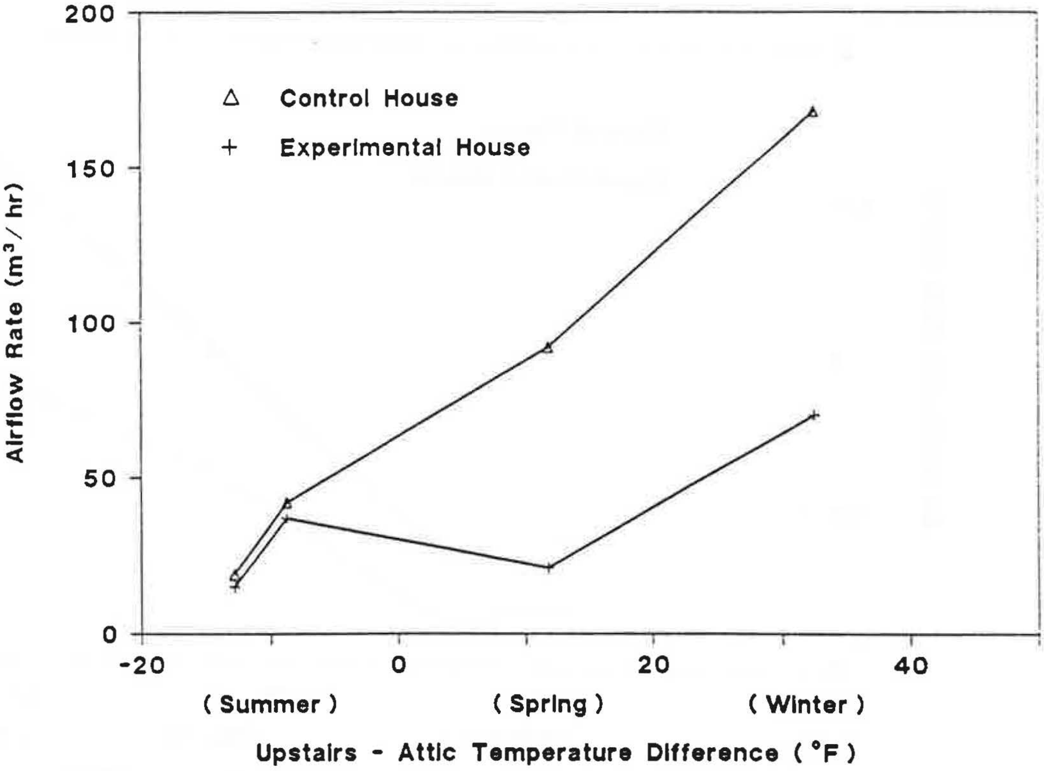


Figure 7-3. Effect of retrofit on the rates of airflow from the upstairs to the attic in the research houses during the year.

airflows from the upstairs to the attic were nearly 60 percent lower in the experimental house than in the control house.

Although neither house exhibited significant movement of air from the upstairs or downstairs into the garage, infiltration of air from the garage into the downstairs was substantially higher in the control house. In the winter, this airflow rate was over two times greater (67 versus 29 m^3/h) in the control house than in the experimental house.

COMPARISON OF MEASUREMENT METHODS

The four measurement methods used in this study--SF_6 dilution, constant concentration, passive PFTs (constant release), and constant release of multiple halocarbon tracers--were compared under a variety of conditions. Results of whole house measurements of air infiltration by the constant concentration and multiple tracer methods were referenced to the SF_6 dilution results. As shown in Table 7-2, the passive perfluorocarbon tracers generally showed good agreement with the SF_6 measurements. For the winter samples, PFTs over-predicted the air infiltration rate. SF_6 dilution and constant concentration measurements could not be performed concurrently. However, as discussed in Section 4, the results were fairly comparable when evaluated in light of differences in ΔT values for each measurement period.

The halocarbon method compared favorably with SF_6 measurements for a week-long period in June, but exhibited both positive and negative differences when compared on an hourly basis. As discussed in Section 6, hourly average whole house measurements by halocarbons did not correlate well with hourly SF_6 measurements, possibly due to imperfect mixing.

Table 7-2

COMPARISON OF METHODS FOR THE MEASUREMENT OF WHOLE HOUSE AIR INFILTRATION RATES

		Air Infiltration Rate (ACH)[a]	
Season	Method[b]	Control House	Experimental House
Spring	SF_6	0.49	0.33
	PFT	0.50	0.33
	CCTG	0.37	--
	MHT	--	0.47
Summer	SF_6	0.17	0.13
	PFT	0.16	0.11
	CCTG	0.20	--
	MHT	--	0.14
Winter	SF_6	0.66	0.49
	PFT	0.75	0.54
	CCTG	0.57	--
	MHT	--	0.32

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[a] SF_6 and PFT measurements performed concurrently; summer PFT and halocarbon measurements concurrent; other measurements not concurrent.

[b] CCTG: Constant concentration tracer gas; MHT: multiple halocarbon tracers.

The constant concentration method provided data on room- and zone-specific air infiltration rates. Data collected with this method were compared to the multiple tracer results presented previously in Table 7-1 in this section. Although PFT and constant concentration measurements were not concurrent, the data were quite comparable and indicated similar magnitudes of differences between the infiltration rates for the upstairs and downstairs of the control house.

PFT and halocarbon measurements, performed concurrently in the summer, yielded comparable results for the upstairs, but the downstairs infiltration rate measured with PFTs was only about half that measured with the halocarbons.

The passive PFT week-long measurement of interzonal airflows for the conditioned zones was quite comparable to the week-long integrated airflow rates measured with the multiple halocarbon system. For the week of concurrent measurements, the average airflow rates between upstairs and downstairs differed by no more than 2 m^3/h at airflow rates of 27 to 34 m^3/h. The halocarbon method, however, showed that short-term airflow rates could be as much as an order of magnitude higher than the week-long averages measured with the PFTs.

The selection of a system for measurement of air infiltration rates and interzonal airflow rates depends on many factors. Each method has specific applications, advantages, limitations, and costs that must be considered. Some of these factors are summarized in Table 7-3 for the four measurement systems used in this study. Although it is beyond the scope of this report to present a lengthy discussion on these factors, they are presented to highlight advantages and disadvantages of the various systems. The results of this study provide a basis for evaluating each method in terms of its specific application, the parameters that are measured with the method, and the type of output that can be obtained.

Table 7-3

COMPARISON OF FACTORS RELATED TO THE SELECTION OF METHODS FOR AIR INFILTRATION AND INTERZONAL AIRFLOW MEASUREMENTS

	Method			
Factor	SF$_6$ Dilution	Constant Concentration (SF$_6$)	Perfluorocarbon Tracers	Halocarbon Tracers
Release method	Periodic release	Automated periodic release	Constant (passive)	Constant (active)
Sampling method	Active (pump)	Active (pump)	Passive	Active (pump)
Number of zones	1	Up to 10	Up to 4	Up to 10[a]
Type of measurement	Infiltration	Infiltration	Infiltration/ interzonal	Infiltration/ interzonal
Type of output	Short-term	Short-term	Long-term	Short-term
Application for large field studies	Applicable	Limited	Applicable	Limited
Capital equipment costs	<$10 K	$10 K-20 K	$10 K-20 K	$10 K-15 K
User equipment required	Release/ sampling system	Fully automated system	Passive sources and samplers	Release/ sampling/ analytical system
Relative user cost	Low	Moderate	Moderate	Moderate
Ease of use	Easy	Complex	Easy	Complex

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[a] Number of zones depends on the configuration of the analytical system.

For measurements of whole house air infiltration rates in residences, the SF_6 dilution method and the passive perfluorocarbon method with a single tracer are the most attractive methods. Both methods are relatively easy to use in field monitoring programs because the samples can be collected in the field and returned to the laboratory for analysis. The methods are complementary; PFTs provide long-term average measurement results, while SF_6 measurements yield short-term rates that can be related to activities in the home as well as variations in outdoor conditions.

Constant concentration methods with a single tracer can provide highly detailed data on room- or zone-specific infiltration rates. Because measurements can be performed in up to 10 zones, the method can provide information that cannot be obtained with the four perfluorocarbon tracers. Although the halocarbon method can use a potentially unlimited number of tracers, analysis costs and time will preclude use of as many as 10 tracers. Additionally, the relatively short-term measurements that can be obtained with the constant concentration system provides a level of detail on infiltration rates that cannot be obtained with the passive PFT method.

The results of this study demonstrate the applicability of the PFT and multiple halocarbon tracer methods. The passive PFT method was particularly applicable to the measurement of interzonal airflows between conditioned and unconditioned airspaces. The halocarbon method, with a nearly real-time analysis system, was not as applicable for this measurement because the detector of the gas chromatograph does not have a wide enough analytical range to accommodate the large differences in tracer concentrations that occur between conditioned and unconditioned zones. For measurements within the conditioned zones, the multiple halocarbon system was particularly applicable. As the results show, the system provided a higher level of measurement detail than could be obtained with the PFTs.

Section 8

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Four complementary methods of measuring air infiltration and interzonal airflow rates were used to obtain a more detailed understanding of airflow patterns in the research houses. Testing was conducted under highly controlled conditions so that seasonal variations and differences between the houses could be determined. The performance of the measurement methods was compared where possible for spring, summer, and winter measurements. Based on the results of these measurements, the following conclusions have been reached:

- The tightness of the houses and the air infiltration rates have not changed substantially over the 4-year period since the initial monitoring.
- The air infiltration rate of the experimental house continued to be approximately 20 to 30 percent lower than the control house.
- The air infiltration rate into the downstairs of the houses was substantially higher than that upstairs; in the control house, it was 4 to 7 times greater.
- The air infiltration rate of the downstairs of the experimental house was 40 to 60 percent lower than the control house, reflecting the effectiveness of the retrofit measures.
- Rates of air infiltration into the garage were quite low, below 0.6 ACH in summer and spring. Supplemental ventilation in the garage may be warranted to prevent exposure to noxious gases that can be released during certain types of work or hobby activities.
- Airflow rates from the garage to the downstairs were higher in the control house than the experimental house, consistent with anticipated effects of retrofit measures.
- The rate of airflow from the upstairs to the attic was lower in the experimental house than the control house, demonstrating that retrofit measures effectively reduced conditioned air losses due to the stack effect.
- Airflows from the downstairs to the upstairs were greater than in the opposite direction, particularly in the control house where air movement due to the stack effect was greater.

- Movement of air between the upstairs and downstairs of the houses was dominated by the central HVAC fan. Airflow rates during fan operation were as much as an order of magnitude higher than week-long average measurements.
- Hourly interzonal airflow rates could be estimated with the continuous multiple halocarbon tracer system. Measurement results with the system showed that hourly interzonal airflow rates could be as much as an order of magnitude higher than week-long average rates.
- SF_6 dilution, constant concentration, and constant release methods gave comparable results for the measurement of whole house air infiltration rates.
- PFT measurement results compared well with those from the constant concentration method for zone-specific infiltration rates and with multiple halocarbon tracers for long-term interzonal airflow rates.

Measurements performed in this study comprise a comprehensive data base on airflow patterns in the two research houses. The complex interaction between airflows into and between zones is demonstrated by the zone-specific infiltration rates and interzonal airflow rates. Utilities involved in air infiltration and indoor air quality studies can benefit from this study by using the results as a basis for comparing the applicability, advantages, and limitations of the various measurement methods as they relate to the specific objectives of utility-sponsored measurement programs.

RECOMMENDATIONS

The objective of this study was to develop a better understanding of interzonal airflows among the different parts of the research houses, including the unconditioned zones such as the attic.

Use of the various methods to measure air infiltration and interzonal airflow rates has provided a quantitative understanding of airflows in the two houses. The results of this study should be used for multizone modeling of indoor air quality and to provide realistic inputs to energy-use modeling. In Phase I of the EPRI project, due to a lack of data on interzonal airflows, only a single zone model was used for indoor air quality modeling. For energy-use modeling, the warranted to address problems of imperfect mixing that may occur under certain measurement conditions. The system should also be expanded to include three conditioned zones--downstairs, the upstairs living room area, and the upstairs bedroom area.

The halocarbon system was used in this study primarily during summer and winter, periods of frequent HVAC fan operation. The performance of the system also needs to be assessed more fully under conditions of limited fan operation to address imperfect mixing as a source of measurement error and to further evaluate the utility of the system to measure short-term changes in airflows due to appliance operation or occupant activity.

Now that the airflow characteristics of the houses have been measured under "baseline" conditions, periodic measurements should be performed to maintain a time-related data base. If any modifications are made to the building envelopes in response to future research needs, these changes should be accompanied by detailed multizone measurements in order to maintain an up-to-date infiltration data base.