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A DETAILED INVESTIGATION OF THE AIR INFILTRATION CHARACTERISTICS OF TWO HOUSES

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Abstract

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A two-year study, sponsored by the Electric Power Research Institute, is investigating relationships among energy use, air infiltration, and indoor air quality. Two bi-level, detached houses, identical in design and wind exposure, are used in the study. Instruments mounted in a trailer positioned between the two houses continuously monitor parameters related to energy use, air infiltration, and indoor air quality.

Following an initial period of monitoring, one of the two houses was retrofitted to reduce its infiltration rate. An air-to-air heat exchanger was installed in the retrofitted, experimental house. The other house serves as a control. This study setting provides an excellent opportunity to compare infiltration rates under a variety of ambient and controlled conditions.

Throughout the first 12 months after the construction of the two houses, fan pressurization/depressurization measurements indicate that the air leakage rates for the control house have remained essentially unchanged. In the case of the experimental house, a 40 percent reduction was achieved by retrofitting, and this reduction has remained constant. On the contrary, during the past summer, the differences in air infiltration rates between the experimental and the control house, as measured by the tracer gas dilution method, were quite small. The paper also presents information on the impact of the heat exchanger on overall infiltration rates.

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Introduction

The rate of air infiltration into a residence affects both energy consumption and indoor air quality. As the rate of air infiltration increases, so does the energy needed for heating or cooling. To improve energy efficiency, the construction industry has tended to build increasingly "tighter" residences, i.e., those with relatively low infiltration rates. For existing residences, a concurrent building practice is to reduce the air infiltration rate through retrofitting. Although a reduced infiltration rate does improve energy efficiency, the reduction can adversely affect the quality of the indoor air.

Quantitative information on how infiltration rates affect energy use and indoor air quality, which can be used for decision-making purposes by consumers, utilities, and the Government, is not available. A study, sponsored by the Electric Power Research Institute, is aimed at providing such information. The purpose is to investigate experimentally and analytically the relationships among air exchange, energy consumption, and levels of key indoor pollutants in residential buildings. This paper describes the part of the study concerned with characterizing air infiltration. Specifically, the results of tracer gas decay and fan pressurization and depressurization tests conducted over a 12-month period are described.

Study Approach

To meet the study objectives, the following overall strategy was chosen [1]:

- Use two identical, detached houses, newly constructed in loose states, i.e., with relatively high air infiltration rates. Retrofit one residence to a relatively tight state, and equip it with an air-to-air heat exchanger to mechanically manipulate its air exchange rate.

- Monitor the two houses simultaneously for energy use, infiltration, and indoor air quality parameters over different seasons so that the impacts of different climatic conditions can be quantified.
- Conduct the study under controlled conditions with simulated occupant activities, to enable an assessment of the impact of a variety of occupancy-related factors.

The houses were built during the fall of 1982 in a suburban area near Washington, D.C. This area was chosen because its primary heating and cooling seasons are sufficiently long to permit a relatively large number of measurements. The houses are of identical bilevel/split-style design with integral garages. Both homes face north-northeast on adjacent lots and have relatively homogeneous terrains and similar wind barriers on all sides. Fig. 1 shows the floor plans. The upper level of each house has a volume of 7,600 ft^3, and the lower level, excluding garage, has a volume of 4,000 ft^3.

The builder (Ryan Homes, Inc.) was instructed to omit a number of items routinely included to reduce infiltration. These omissions were intended to yield a higher-than-customary rate of air infiltration and thereby to maximize potential pre- and post-retrofit differences. The principal omissions were as follows:

- Sill plate sealer and caulking between masonry and frame wall
- Vapor barrier in upper level floor overhang

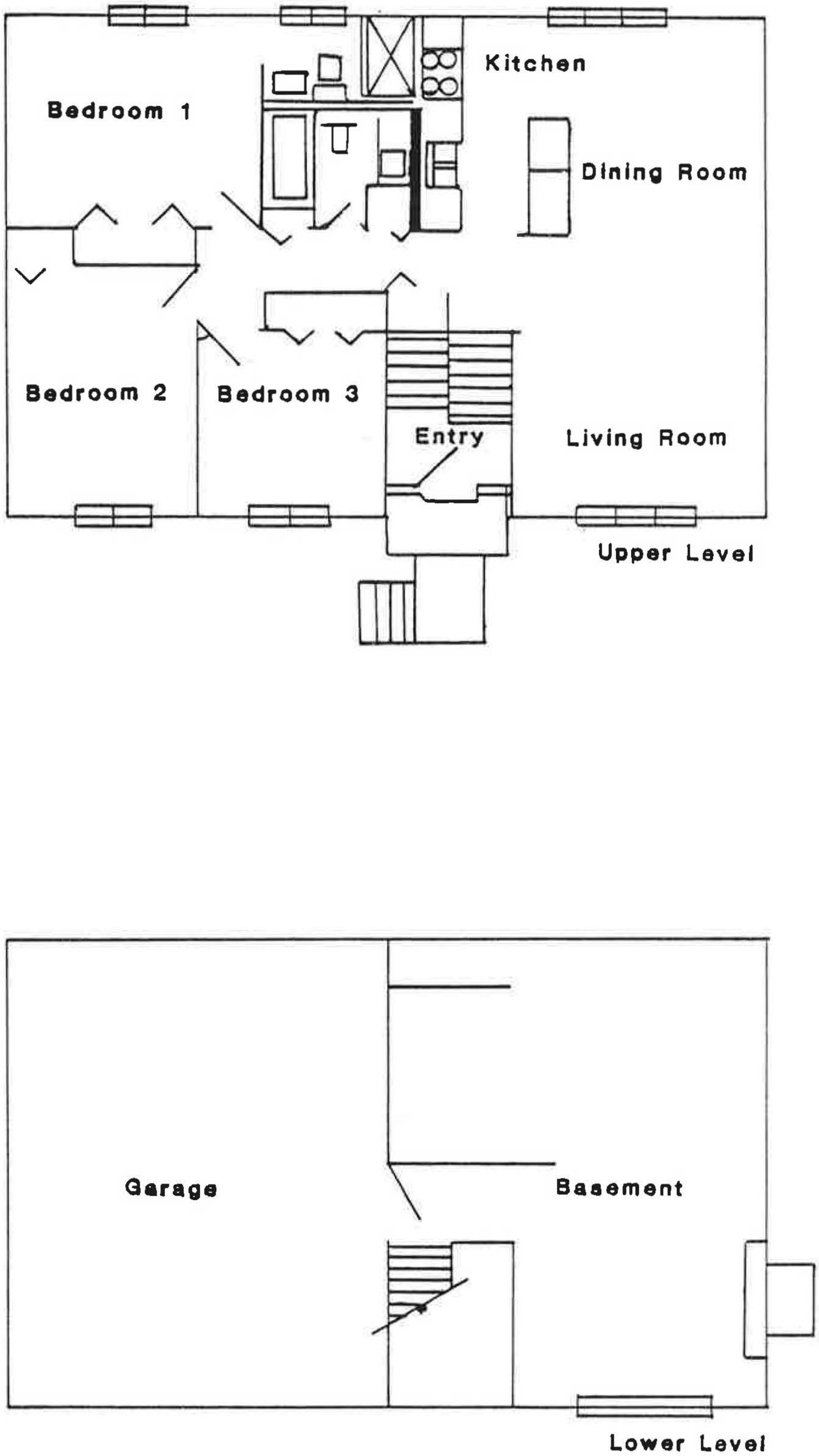


FIG. 1--Floor plans of the test houses.

- o Vapor barrier on inside foundation/knee wall
- o Sealing of electrical outlet and switch boxes
- o Sealing of pipe and cable penetrations through wall top plates
- o Caulking of windows
- o Exterior door adjustments
- o Weatherstripping of attic access panel
- o Garage door adjustments
- o Sealing of wood stove insert plate and mouldings
- o Adjustment of exhaust fan dampers.

GEOMET's mobile laboratory, located between the two houses, contains instrumentation to measure air exchange, environmental parameters, air pollutants, and energy consumption. The variables measured by the system can be grouped as follows:

<u>Air Pollutants</u>

a. Carbon monoxide
b. Nitrogen dioxide
c. Radon
d. Radon progeny
e. Formaldehyde
f. Inhalable particulates

<u>Tracer Gas</u>

a. Sulfur hexafluoride

<u>Environmental Parameters</u>

a. Barometric pressure
b. Relative humidity
c. Temperature
d. Wind speed and direction
e. Solar radiation

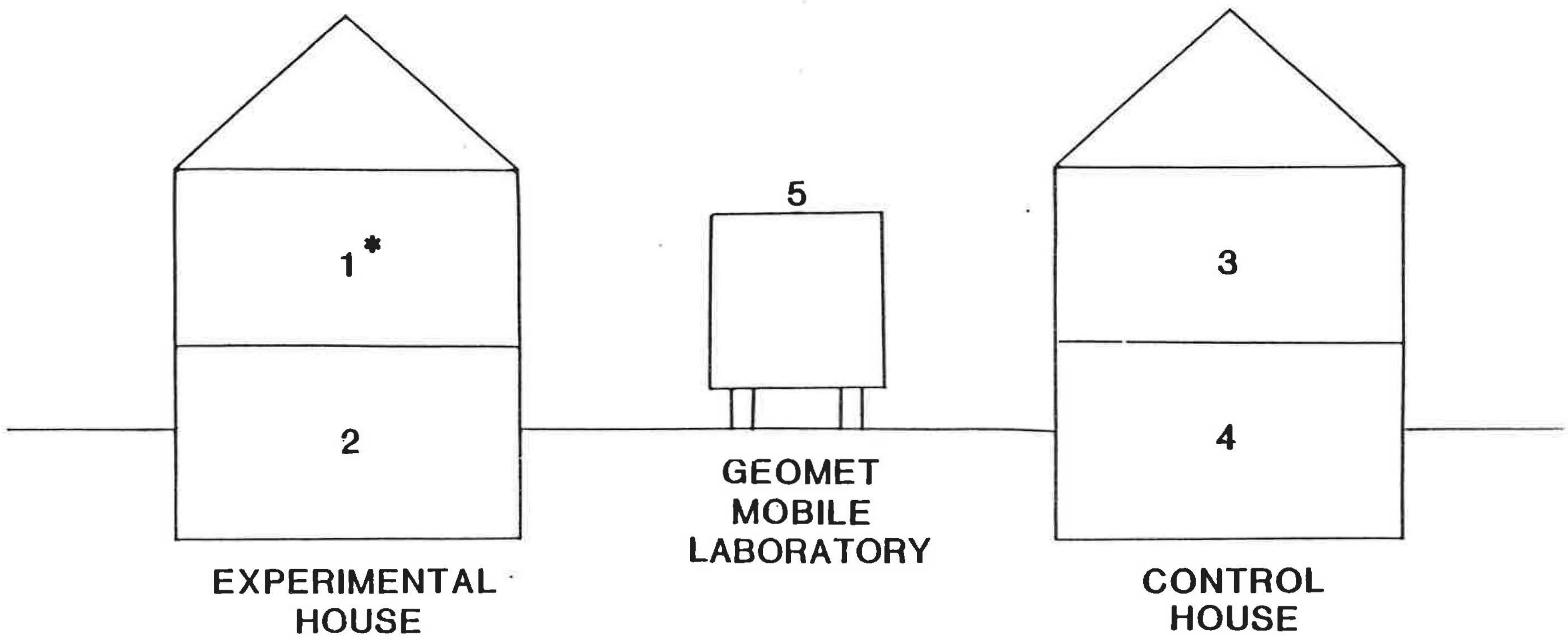
<u>Energy Consumption</u>

a. Total house
b. Heating and air conditioning: circulation fan, compressor, and heating coil
c. Electric dryer
d. Water heater
e. Refrigerator
f. Clothes washer
g. Dishwasher
h. Heat exchanger
i. Kitchen exhaust
j. Bath exhaust

Both blower door tests and baseline tracer gas studies (as described later in this paper) showed that one of the houses consistently had a slightly lower rate of air exchange. To maximize potential differences between the houses, the tighter house was chosen for retrofit. This retrofitted house is referred to as the experimental house. A whole-house air-to-air heat exchanger with a rated capacity of 200 CFM at pressure drop of 0.1 inch of water was added to the experimental house. The other house, left in its original state of construction, serves as the control house for the study.

Five zones--two per house and one outdoors--are used for measuring air exchange and most pollutants and environmental factors (Fig. 2). Representative sampling locations within each zone were determined as the measurement system was being completed and tested during the spring of 1983.

Sulfur hexafluoride (SF_6) is the tracer gas used for measuring air exchange. An electron-capture gas chromatograph manufactured by S-Cubed, Inc., is used to measure tracer gas concentrations. The sampling strategy for SF_6 was dictated by the 3-minute analytical time required by the instrument for each sample. Beginning on the hour, and every 3 minutes thereafter, an instantaneous sample is taken through a polypropylene sampling line from a fixed location in one of the zones. A valve sequencer controls the order of sampling; consequently, each instantaneous sample for a particular zone is separated in time by exactly 15 minutes. This strategy enables the calculation of air change rates over 15-minute periods or multiples thereof. A purge time included in the sampling procedure eliminates the possibility of carryover between successive samples. The integrity of the entire process has been verified by inputting standard concentrations from each sampling



* **1. MAIN FLOOR, EXPERIMENTAL HOUSE; 2. LOWER LEVEL, EXPERIMENTAL HOUSE; 3. MAIN FLOOR, CONTROL HOUSE; 4. LOWER LEVEL, CONTROL HOUSE; 5. OUTDOORS.**

FIG. 2--Measurement zones.

location. To accommodate changing environmental conditions, an automated injection system was installed so that either the frequency or volume of an SF_6 injection could easily be varied. The tracer gas is injected directly into the air circulation system, which is programmed to operate coutinuously for about 30 minutes when an injection occurs.

In analyzing the effects of weather on air infiltration, and the subsequent influence on indoor air quality, it is necessary to be certain of the building envelope tightness over all seasons. Variations due to weather and moisture effects have been shown in past studies [2,3] to directly influence the building tightness by 20 percent or more. To provide these data, the pressurization approach is used in a series of visits, usually at 4- to 6-week intervals, that extended across more than a year of testing. These tests consist of pressurizing and depressurizing each house through prescribed pressure steps. Based upon international convention [4], the pressure difference between the house interior and exterior at 50 Pa (0.2 in. of water) is used to compare building tightness expressed as air changes per hour (ACH) at 50 Pa. A blower door, consisting of a flow-calibrated variable-speed fan mounted in an adjustable door, is used for tightness measurements. The data consist of flow rates for a variety of pressures to produce an air leakage profile. Measured in terms of ACH (50 Pa) or ELA (equivalent leakage area, a flow area in square centimeters based upon a pressure difference, inside to outside, of 4 Pa), the leakage rate could be assessed for seasonal differences as well as for variations over time.

A series of week-long experiments are conducted each season. Results of these experiments are recorded through the permanent, onsite measurement system. Throughout each weekly experiment, the HVAC circulation fan and heat exchanger settings remain undisturbed. A number of routine household activities are repeated for each experiment. On Mondays and Wednesdays during each experiment, a gas stove, a dishwasher, a washer, a dryer, and a shower are operated for prescribed lengths of time. On Wednesdays only, a bath fan and a range fan are operated concurrently with the shower and the gas stove. Vacuuming is done on Tuesdays. Thursdays are reserved for maintenance or special experiments, and all systems are calibrated on Fridays.

Fan Pressurization/Depressurization Test Results and Retrofit

The first pressurization/depressurization test of the two houses took place soon after construction was completed. Subsequent tests have been conducted at intervals of approximately 4 to 6 weeks.

The data for the control and experimental houses, as shown in Figs. 3 and 4, indicate no systematic variation in tightness on a seasonal basis. However, when the air change rate is plotted over the year, a consistent trend toward slightly greater leakage (order of 3 to 4 percent) is shown for both of these 1-year-old houses. The data scatter (expressed as percent standard deviation) in the ACH values is approximately $\pm$ 4 percent in the half-year of data collected after the retrofit in the experimental house. In terms of ELA, the data scatter is $\pm$ 5 percent for the control house, and $\pm$ 8 percent and $\pm$ 11 percent in the experimental house before and after retrofit. The least-squares fit for these experimental data are noted within brackets in Figs. 3 and 4, where I/S is the intercept/slope and AVE is the average value with the standard deviation.

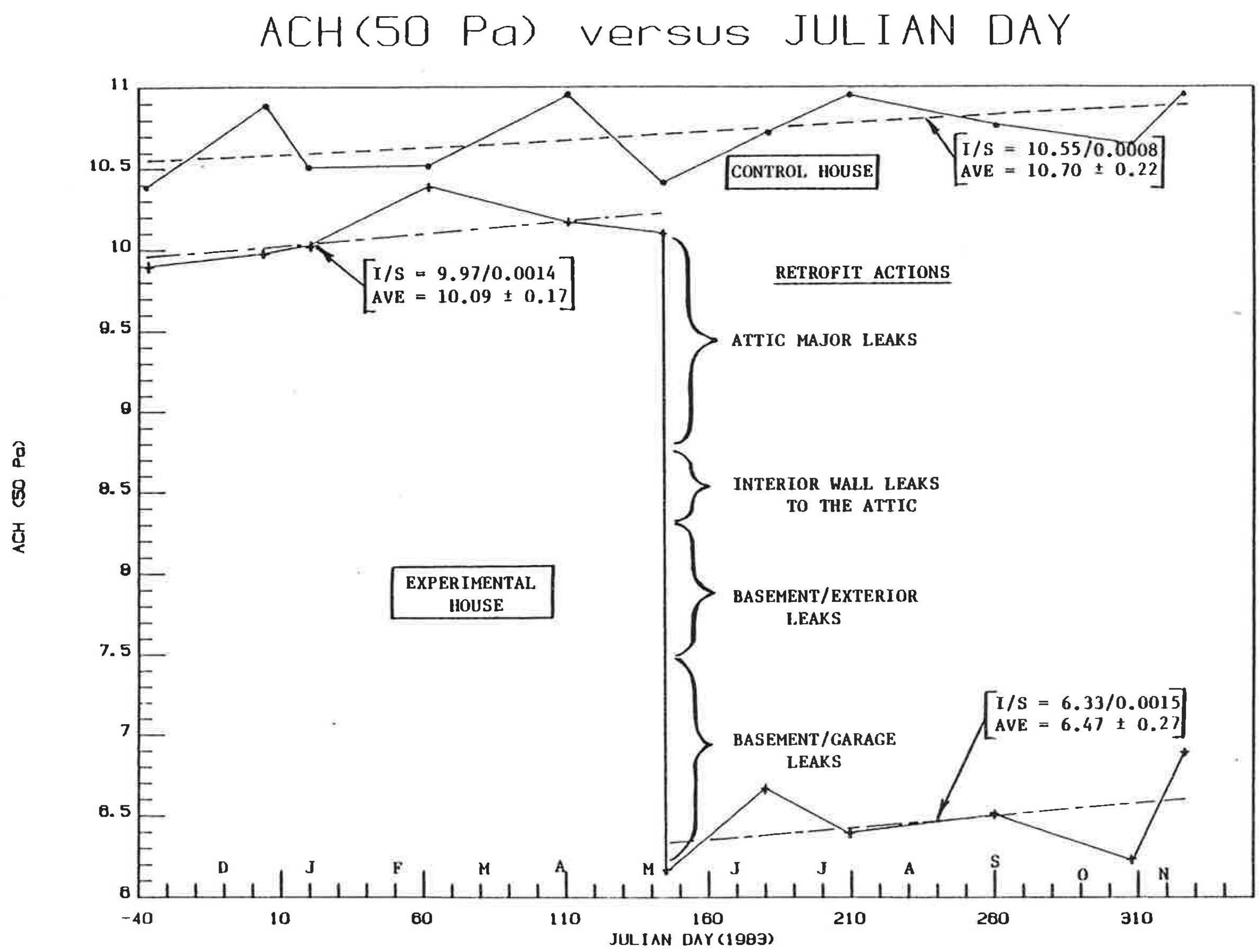


FIG. 3--ACH (50 Pa) versus Julian Day.

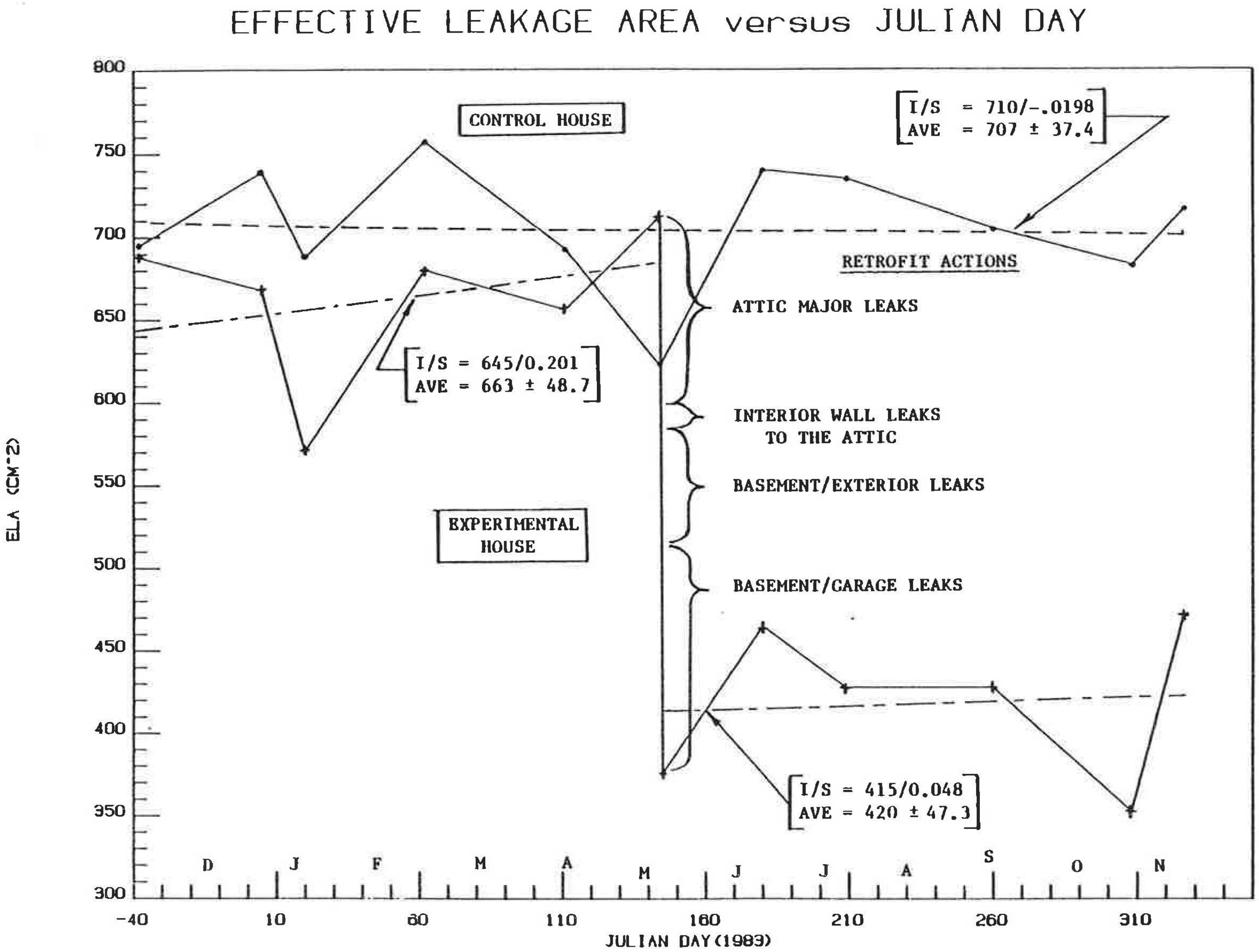


FIG. 4--Effective leakage area versus Julian Day.

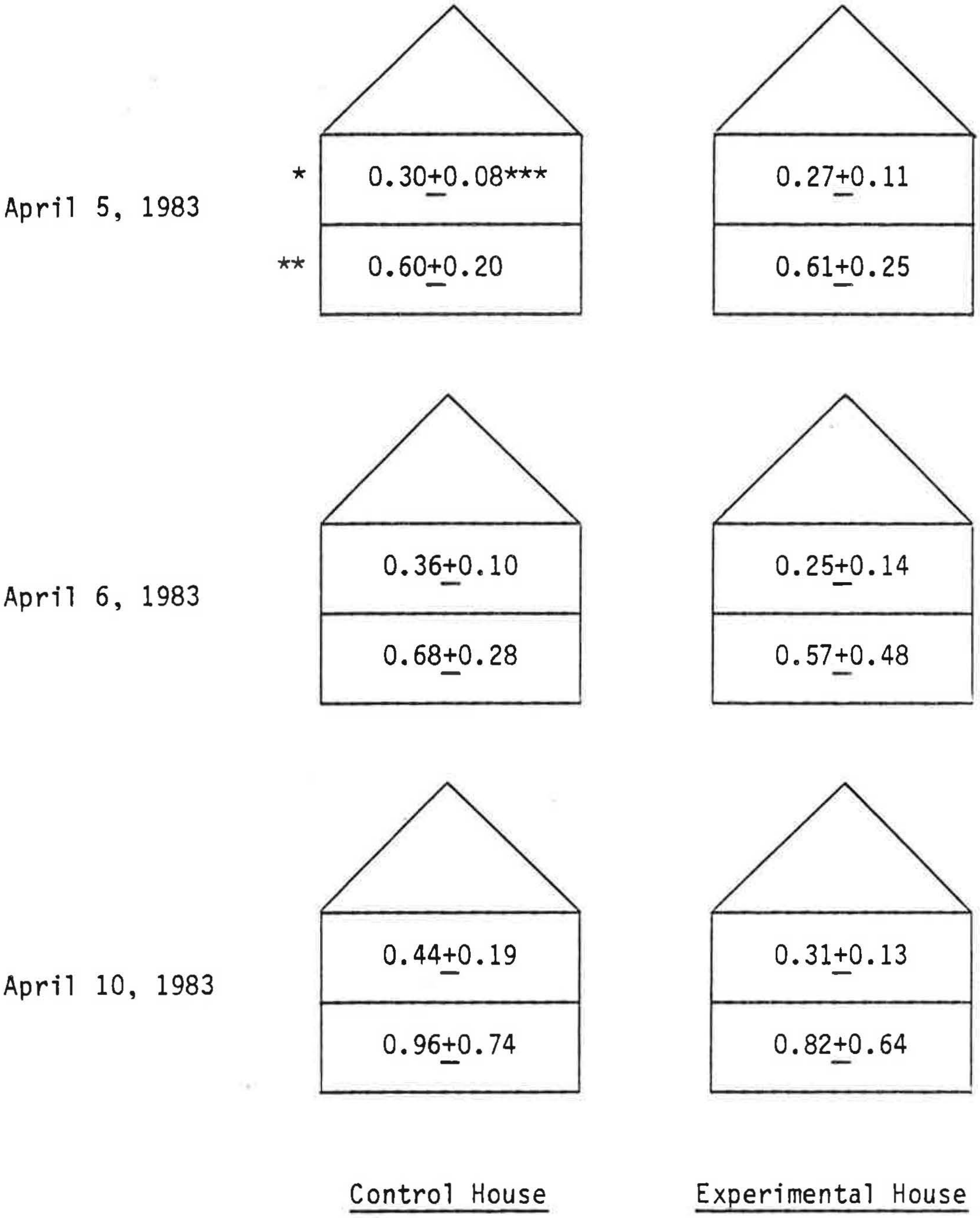
For the modified or experimental house, tightening retrofits achieved an approximately 40 percent reduction in the values of ACH at 50 Pa and in the magnitude of ELA. Retrofits were concentrated on leakage sites at the attic level and the basement or ground floor using the blower door to chart progress as the large and small openings were sealed. The progressive changes are noted in Figs. 3 and 4. Leakage reduction of this magnitude is feasible, and the reduced leakage value is holding nearly constant in the more than 6-month period of monthly testing following retrofit.

Tracer Gas Measurement Results

In April 1983 (i.e., prior to retrofit) a series of independent tests were conducted. For these tests, the air circulation system was turned off following tracer gas injection. Estimated air exchange rates for the upstairs and downstairs zones of each house, based on tracer gas decay over 3- to 4-hour periods for each test, are presented in Fig. 5.

During the first two tests, wind speed ranged from 2 to 4 mph and the indoor-minus-outdoor temperature differential, ΔT, ranged from 7 to 9°C (13 to 16°F) upstairs. In the downstairs zones, ΔT was between 3 and 4°C (5 and 7°F) for the first test and between 5 and 6°C (9 and 11°F) for the second test. During the third test, wind speed ranged from 6 to 10 mph and ΔT from 8 to 12°C (14 to 22°F) upstairs and from 5 to 10°C (9 to 18° F) downstairs.

Thus the major factors known to cause increases in air infiltration were similar during the first two tests but at higher levels during the third. As Fig. 5 shows, air change rates for all four zones varied little between the first two tests. During the third test, however, rates were



* Upstairs
** Downstairs
*** Addition and subtraction of the number following ± yields a 95 percent confidence interval for the mean.

FIG. 5--Preretrofit average hourly air change rates as measured from three independent tracer injections (in air changes per hour).

noticeably higher, particularly downstairs. For all three tests, the overall (i.e., whole-house) rate of air infiltration was lower for the experimental house.

The level of uncertainty surrounding each average rate can be assessed by constructing a 95 percent confidence interval, as noted in the footnote to Fig. 5. For the particular tests reported in this figure, the intervals are quite broad because of the small number of hourly measurements. Subsequent figures are based on considerably larger numbers of measurements and have much tighter intervals.

Average air change rates, based on two experiments of one-week duration in May 1983, prior to retrofit, are presented in Fig. 6. For the first experiment, the circulation fans were activated only when heating was demanded, whereas the fans operated constantly during the second experiment. The thermostat for heating was set at 18°C (64°F). Wind speed averaged 4 mph for both experiments, but the outdoor temperature averaged 2°C (4°F) higher during the second experiment, yielding a slightly lower ΔT. The experimental house again measured tighter in both experiments, although only marginally so.

During the week when the fans were operated constantly, the air exchange rates were virtually identical across the two zones within each house. Although the downstairs appeared slightly tighter in the control house during the fan-on-auto week, this result is an artifact of remixing that occurred whenever heating was demanded. Because the downstairs zones were leakier and had lower SF_6 concentrations than upstairs, they were in effect "reinjected"

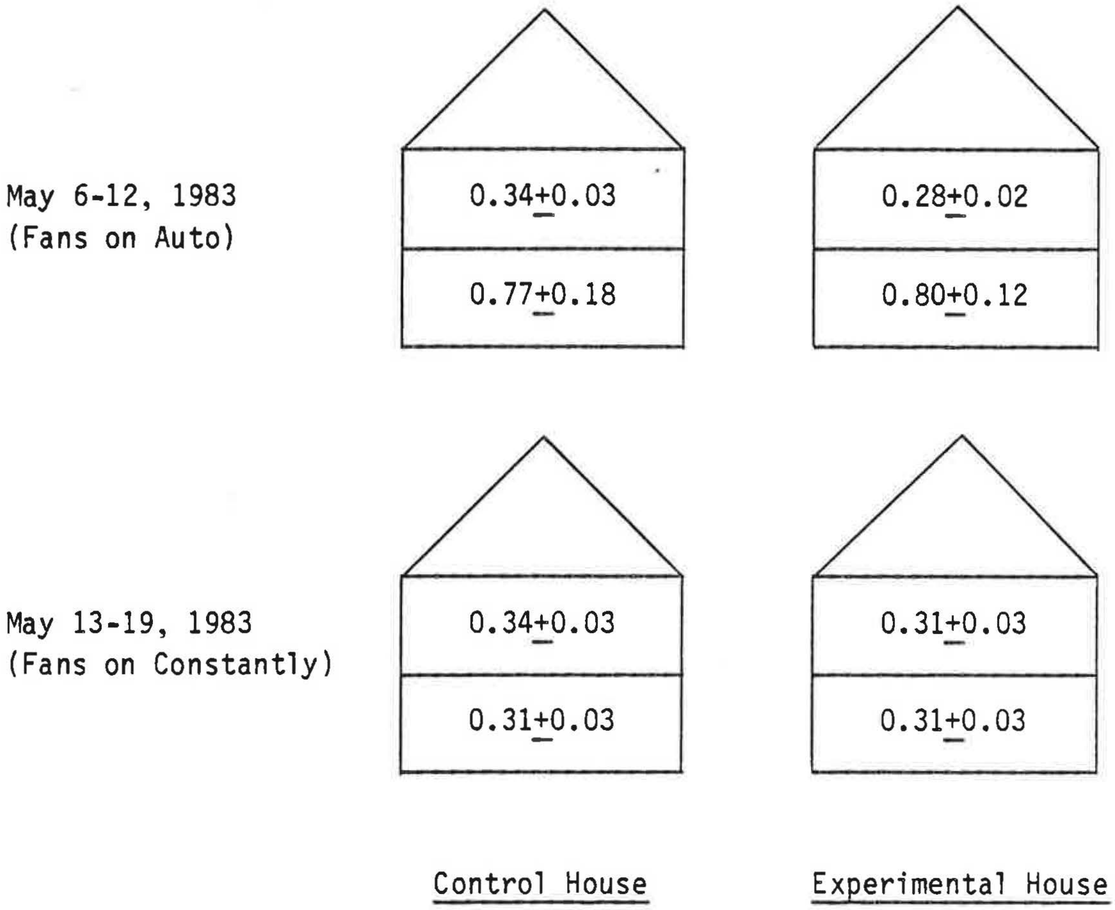


FIG. 6--Preretrofit average hourly air change rates as measured from two weekly experiments (in air changes per hour).

whenever the circulation fan was activated. The control house had a higher heating demand during the fan-on-auto experiment, resulting in more frequent remixing for that house. Estimated downstairs rates, based on periods of no fan activity, averaged 1.0 for the control house and 0.9 for the experimental house.

Changes in average air change rates between preretrofit (spring) and postretrofit (summer) are shown for the houses in Fig. 7. Changes are indicated for two different experimental settings--fans on auto and fans operating constantly. The right-hand column shows differences between the whole-house air change rates for the two houses; the whole-house rates were calculated by weighting the zone-specific rates by their respective volumes. A striking observation from this figure is that, even though only the experimental house was retrofitted, the houses experienced equivalent overall reductions in average air change rates during the transition from spring to summer weather conditions. During most summer hours, ΔT was either negative or a relatively small positive number. Apparently, the reduction in air infiltration through lower indoor-outdoor temperature gradients dampened out the potential effects of the retrofit during the summer season.

Even with the circulation fan in the auto position, there was substantial fan activity during summer daytime hours. This fact partially accounts for relatively small differences between upstairs and downstairs rates in both houses. During two of the summer experiments, the fans were kept off during the entire week, except for periodic tracer gas injections. Comparisons for the two houses at this setting are given in Fig. 8. The retrofit measures,

Experimental Setting	House	Preretrofit	Postretrofit	Change in Whole-House Rates (Postretrofit-Preretrofit)
Fans on Auto*	Control	0.34±0.03 0.77±0.18	0.15±0.02 0.19±0.02	-0.33
	Experimental	0.28±0.02 0.80±0.12	0.13±0.02 0.13±0.02	-0.33
Fans on Constantly**	Control	0.34±0.03 0.31±0.03	0.22±0.02 0.22±0.02	-0.11
	Experimental	0.31±0.03 0.31±0.03	0.20±0.01 0.20±0.02	-0.11

* Summer experiment at this setting was conducted August 26-September 1.

** Summer experiments at this setting were conducted July 15-21 and September 16-22; the rates for each zone represent averages of the two experiments.

FIG. 7--Preretrofit versus postretrofit average hourly air change rates, based on two different experimental settings.

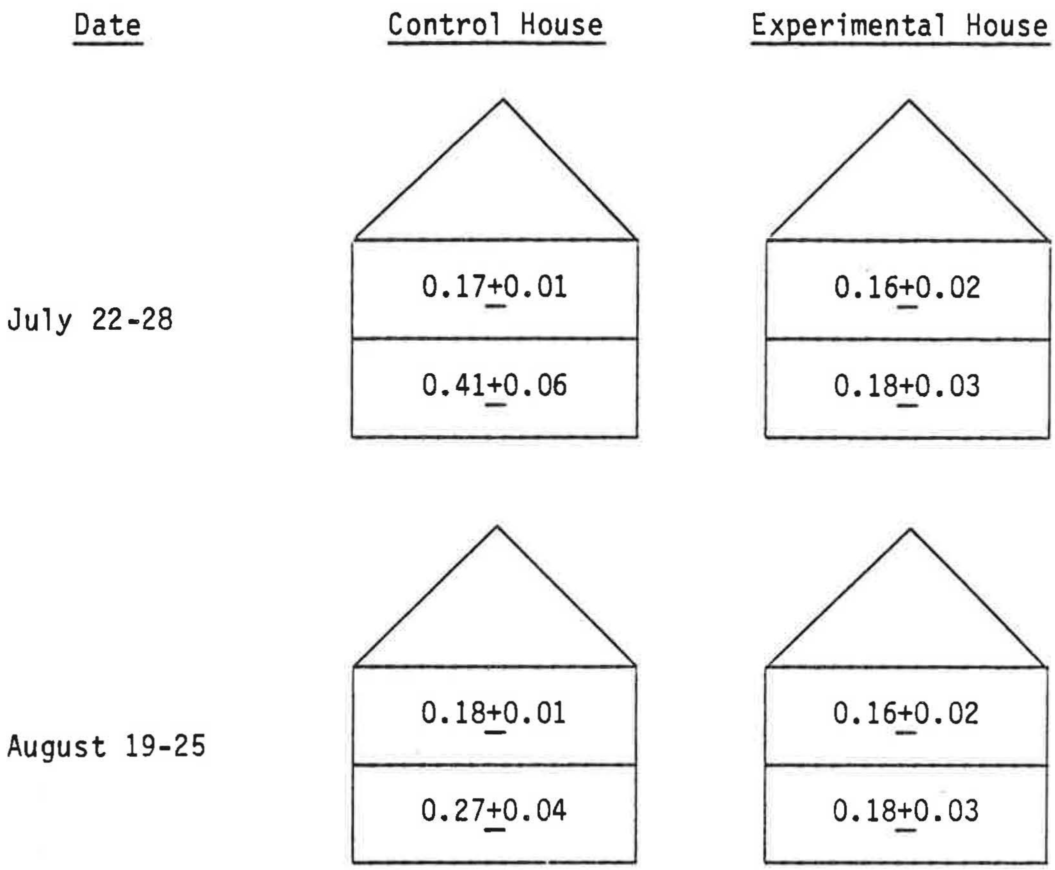


FIG. 8--Average hourly air change rates for two summer experiments with the circulation fans off.

primarily applied to the downstairs and attic of the experimental house, resulted in nearly equivalent rates for the upstairs and downstairs zones. Although the two zones for the control house had closer rates than in spring, they were not as close as rates in the experimental house. Of the four measurement zones, the downstairs zone of the control house appeared to have the most elastic response to changing environmental conditions.

The average air change rates associated with four different heat-exchanger settings for the experimental house--off, low, medium, and high--are shown in Fig. 9. As evidenced in the figure, the gradient in differences between experimental and control house rates was directly related to the heat exchanger setting. This result is further reinforced by an examination of hourly differences between the two houses. Fig. 10 shows infiltration rates for the upstairs of the two houses over a typical 24-hour period, with the heat exchanger at the medium setting. The differences between the two houses are relatively constant over time. The trends for the two houses are also generally similar but not exactly alike.

Conclusions

The study will continue through March 1984. Nevertheless, some tentative conclusions can be listed at this stage:

o Fan Pressurization/Depressurization Measurements. Through the first 12-months after construction of the two houses, the air leakage rates for the control house, as measured by the fan pressurization/depressurization technique, have remained essentially unchanged but have shown a possible

Heat Exchanger Setting* (Dates)	Control House	Experimental	Difference Between Whole-House Rates (Experimental-Control)
Off (August 26-September 1)	0.15 ± 0.02 0.19 ± 0.02	0.13 ± 0.02 0.13 ± 0.02	-0.03
Low (August 12-18)	0.19 ± 0.02 0.27 ± 0.04	0.32 ± 0.02 0.33 ± 0.03	0.10
Medium** (August 5-11) (September 9-15)	0.19 ± 0.02 0.23 ± 0.04	0.48 ± 0.02 0.49 ± 0.04	0.28
High (September 30-October 6)	0.17 ± 0.02 0.30 ± 0.04	0.58 ± 0.02 0.61 ± 0.04	0.37

* Experimental house only; the circulation fan was kept in the auto position for both houses.

** Rates for both houses represent averages of the two experiments at this setting.

FIG. 9--Average hourly air change rates associated with four different heat exchanger settings.

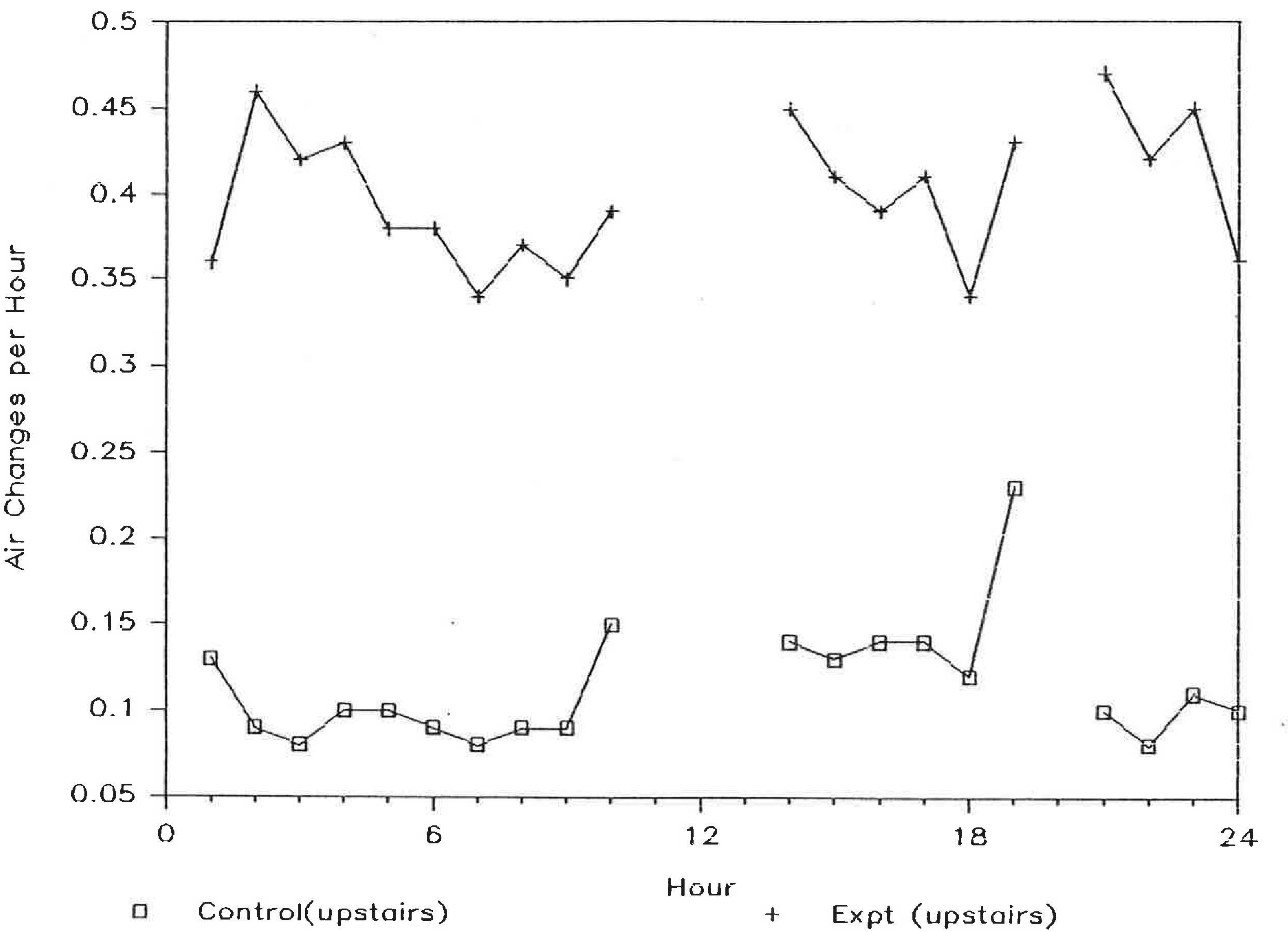


FIG. 10--Variations in hourly air exchange rates--effect of heat exchanger.

tendency toward slightly increased leakage. In the case of the experimental house, a 40 percent reduction was achieved by retrofitting for tightness. This reduction in leakage rate has remained constant for the ensuing 6 months for which data are available.

o Tracer Gas Measurements. Reduction in air infiltration rates due to retrofit, as measured by the tracer gas dilution method, seemed to have been generally overwhelmed by the reduction in infiltration rates due to the changes in ΔT and wind speeds from spring to summer. The ratios of the whole-house infiltration rates for the unretrofitted control house between spring and summer were of the order of 1.5 to 3. The spring-to-summer ratios for the retrofitted house, including the impact of retrofit, were only slightly larger (1.55 to 3.55). However, the absolute differences between the two houses were surprisingly identical.

o Air-to-Air Heat Exchanger. Operation of the air-to-air heat exchanger increased the overall infiltration rates. The increases in infiltration rates were consistent with the heat exchanger setting. The differential increase in the hourly infiltration rates due to the heat exchanger appeared to be relatively constant, at least for the summer, even though the base infiltration rate (i.e., without the heat exchanger) varied with ambient conditions.

o Single-Zone Versus Multizone Behavior. When the circulation fan is operating constantly, the upstairs and downstairs of each of the two houses behave as a well-mixed single zone and have the same infiltration rates. When the fan is switched off or when there is no heating or cooling demand, the two zones behave independently and their infiltration rates can differ by as much as a factor of 3 or more.

These findings will continue to be evaluated in light of the new data being collected. Some results from the measurements conducted in fall 1983 will also be presented at the symposium.

Acknowledgment

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