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Comparative Ventilation Systems Tests in a Mixed Climate

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ABSTRACT

A lab house constructed in Pittsburgh has been used as a site for the comparative evaluation of several ventilation systems. The house was built to relatively high performance standards and is representative of the type of house that would be a candidate for a purposely designed ventilation system.

The systems installed and tested were (1) supply fan, (2) exhaust fan, (3) heat recovery ventilator, (4) balanced flow fan, and (5) open pipe to the RA plenum. A number of operational variations were tested with these systems: (1) central HVAC fan off/on/autocycling, (2) internal house doors open/closed, and (3) passive relief vents open/closed.

The house was set up for continuous STEM test measurements from November 19, 1997, to January 8, 1998. These tests included (1) overall house UA under each ventilation approach, which yielded a measure of the thermal impact of a system; (2) system operating power; and (3) overall house ACH measurement, yielding an indication of ventilation effectiveness.

This paper will present an evaluation of these tests with conclusions concerning the relative performance merit of the five systems in the lab house.

INTRODUCTION

For the past five years, a housing development consortium has been working to produce high quality houses at affordable costs. The intent has been to improve the energy efficiency and environmental responsiveness of the houses constructed while improving the speed of construction and reducing cost. To this end, several lab houses have been built, three in Pittsburgh, Pennsylvania, and one in Austin, Texas. Many improvements have been incorporated into these houses when compared to typical new construction in their locations. These improvements included greater insulation levels, improved air leakage sealing, better windows, high-efficiency HVAC systems, and duct leakage control (either by location or by sealing). Ventilation provisions have been incorporated in all of the lab houses.

Some comparative testing of the effectiveness of ventilation was done on the first two Pittsburgh houses, one of which employed an energy recovery ventilator while the other relied on exhaust ventilation and infiltration ventilation (Holton et al. 1997). In Austin, Texas, the focus was on the effects of ventilation in a hot, humid climate. There the lab house, with a supply ventilation system, was compared to a base house that relied solely on infiltration. Valuable insight was gained on the impact of humidity and the effectiveness of CO_2 removal.

This prior experience has supported the group's belief in the validity and necessity of providing intentional ventilation in high-performance houses. Recently a new lab house was constructed in Pittsburgh. As part of the test program, it was designed to be able to operate with any of several different types of ventilation system.

All of the previous test and evaluation (T&E) work by the group had focused on the ability of a ventilation system to provide an overall air change rate for the house and, in Austin, the humidity impacts of this ventilation. Because Pittsburgh is in a mixed climatic zone, there is a question as to the economic validity of using heat exchange ventilators rather than non-exchange ventilation systems. Heat exchange ventilators are well accepted in cold climates, and energy exchange ventilation (that also provides latent exchange) may have value in hot, humid climates, but non-exchange ventilation may be the best choice for mixed climatic conditions. The objective of the

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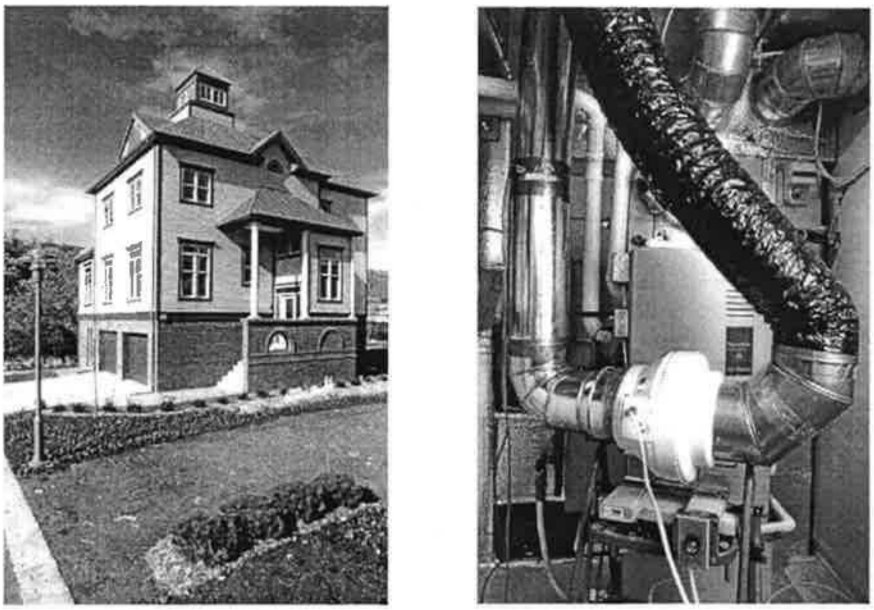

Figure 1 *(Left) the lab house, and (right) test exhaust/supply fan setup.*

research reported here was to comparatively examine the energy and cost attributes of a number of ventilation systems operating in the same house in the mixed Pittsburgh climate. The specific aspects investigated were as follows:

1. Air exchange rate
2. Heating impact of ventilation
3. Electric power impact of ventilation
4. Outdoor environmental effects on ventilation
5. Cost impact of ventilation

Other ventilation studies provide insight into a number of aspects of residential ventilation.

Parent and Fugler (1994) examined the performance of several different ventilation systems in somewhat similar houses in Quebec through a winter season. These were occupied houses. The study demonstrates the effectiveness of ventilation to control CO_2 and humidity. Further, it demonstrates that operation of a balanced fresh air supply and exhaust system can provide near uniform ventilation conditions throughout a house. Their study also concludes that natural ventilation (infiltration) is unable to maintain indoor pollutant levels below recommended limits (Canadian) during mild weather. The study principally assesses wind effects on turbine ventilators, which are omni-directional.

In a test house, CMHC studied the effectiveness of several alternative ventilation strategies based on the use of heat recovery ventilation (*Research Highlights*). The study showed that, when using the forced warm air system fan and ductwork for fresh air distribution, "there was very little difference in ventilation effectiveness obtained using a low-speed circulation system with an ECM motor or the higher, low-speed airflow rates associated with the typical furnace fan." This is most encouraging because ventilation airflow rates are significantly less than the design flow of the duct system. It is not clear whether the duct system design was for heating only or for heating and cooling (more conventional U.S. practice). A heating/cooling duct design is generally designed for the larger cooling air flow and may result in a larger duct cross section than a heating-only design. How this would affect low "ventilation" flow rates is not known.

A test program has been done with a single house and five different ventilation strategies (Reardon and Shaw 1997). This study, on an electric baseboard heated house with no central forced air system, evaluated the effectiveness of the five systems in providing ventilation to all parts of the house. Not surprisingly, the systems that utilized specific ducted exhausts to rooms in the house were superior to an exhaust system that relied on infiltration makeup air for ventilation. Likewise, a balanced system that provided ducted, tempered, fresh air to all rooms of the house gave very uniform results. These results would support the use of the central forced air heating/cooling fan and duct system for the uniform distribution of fresh air for ventilation. The study assessed stack effect influences on ventilation but not wind effects.

THE LAB HOUSE

The lab house that is the basis for the study reported here is a single-family detached house built on a redevelopment site on an island in the Allegheny River in Pittsburgh. Because of its proximity to the river, there is no basement and the lowest level is a garage and work/activity room. A two-story house is built above this with living and office spaces on the lower floor and bedrooms on the floor above (Figure 1). To demonstrate full efficiency in the use of house volume, the area under the roof was designed as a usable loft, connected to the house through the main stairway. Though a tall house by today's standards, it is not dissimilar to thousands of older houses on Pittsburgh's sloped hillsides with walkout basements and usable attic/loft spaces.

The lab house was built and tested during the early stages of the redevelopment of the island. At this point there was very little shielding from adjacent construction, from trees, or from topography. Consequently, it has full exposure to the prevailing winds, which sweep up the river valley from the southwest.

The lab house was designed to be a high-performance house. Its construction and performance characteristics are detailed in Table 1. Infiltration and duct leakage testing were done using house pressurization and duct pressurization equipment. Infiltration was also evaluated by SF_6 tracer gas methods. Overall UA was determined by short-term energy monitoring (STEM) testing (Balcomb et al. 1993).

The HVAC system in the house is a combination of air and hydronic. Because of the slab-on-grade and a market-driven commitment to a warm master bath floor, radiant hydronic coils are installed in the basement floor slab, the stair landing, and the master bath floor. These are supplied from a high-efficiency, sealed combustion, gas water heater. This system was not operated during ventilation testing.

The floor plans (Figures 2 and 3) show the layout of the air system. All ductwork is within the insulated envelope of the house and thus there is zero leakage to the outside. The high-efficiency, sealed combustion gas furnace and cooling coil are located in a mechanical closet on the second floor. The equipment is quiet, and this location allows a design with short duct runs for improved efficiency in air distribution. A zoning system is installed with automatically controlled dampers to four zones and a manual damper on the fifth zone (the basement). Zone dampers were locked open for all ventilation testing.

VENTILATION SYSTEMS

The lab house was built with provision for ventilation testing. Exhaust ducts were run from the two bathrooms on the second floor and the bathroom on the first floor to an outlet point in the ceiling of the mechanical room. An exhaust outlet was also installed from the ceiling of the mechanical room to the outside wall on the north side of the house. The test exhaust fan was installed between these two points (see Figure 1).

For the supply system, an inlet duct was installed from the outside wall on the south side of the house again to a point on the ceiling of the mechanical room. This arrangement, along with a sleeve into the HVAC return air trunk duct, put all working points for the ventilation tests at a single location, the mechanical room. This made the several ventilation configurations relatively quick to change.

TABLE 1
Lab House,
Construction Characteristics and Performance

HOUSE	
Floor area	3300 ft^2 (306 m^2)
Volume	27,450 ft^3 (777 m^3)
SHELL	
Slab insulation	R-11 (R-1.9) edge, R-5 (R-0.9) under slab
Wall insulation	R-19 (R-3.3)
Roof insulation	R-30 (R-5.3)
Floor above garage insulation	R-19 (R-3.3)
Air sealing	Spray polyurethane foam
Windows—wood, low-e, argon	R-2.8 (R-0.5), SC0.48
Doors	R-4 (R-0.7)
HVAC	
Furnace	93% AFUE, 60,000 Btu/h (17,590 W)
Air conditioning	SEER 14, 3 ton (10.5 KW)
DHW (provides under-slab radiant heat and DHW)	50 gal (190 L) High-efficiency, sealed combustion
Zoning system	4 zones auto, 1 zone manual
Air filter	6 in. (15 cm) mechanical filter
Design heating air flow	1098 cfm (520 L/s)
Design cooling air flow	1245 cfm (590 L/s)
THERMAL PERFORMANCE:	
Overall UA	455 Btu/h·°F (240 W/°C)
UA/100 ft^2 of surface	7.35
AIR LEAKAGE (WINTER TESTS)	
ACH 50 (blower door)	2.38 ACH
ACHn (blower door)	0.18 ACH
ACHn (tracer gas)	0.12 ACH
Equivalent Leakage Area	50.2 in.^{2} (325 cm^2)
DUCT LEAKAGE AT 25 PA	
Total leakage	404 cfm (190 L/s)
Leakage to outside	0 cfm (0 L/s)
Supply leakage, inside	104 cfm (50 L/s)
Return leakage, inside	300 cfm (142 L/s)

Five ventilation system variants were tested:

- Supply
- Exhaust
- Open pipe
- Heat exchange ventilator
- Balanced flow ventilator

These are diagrammed in Figures 4 and 5.

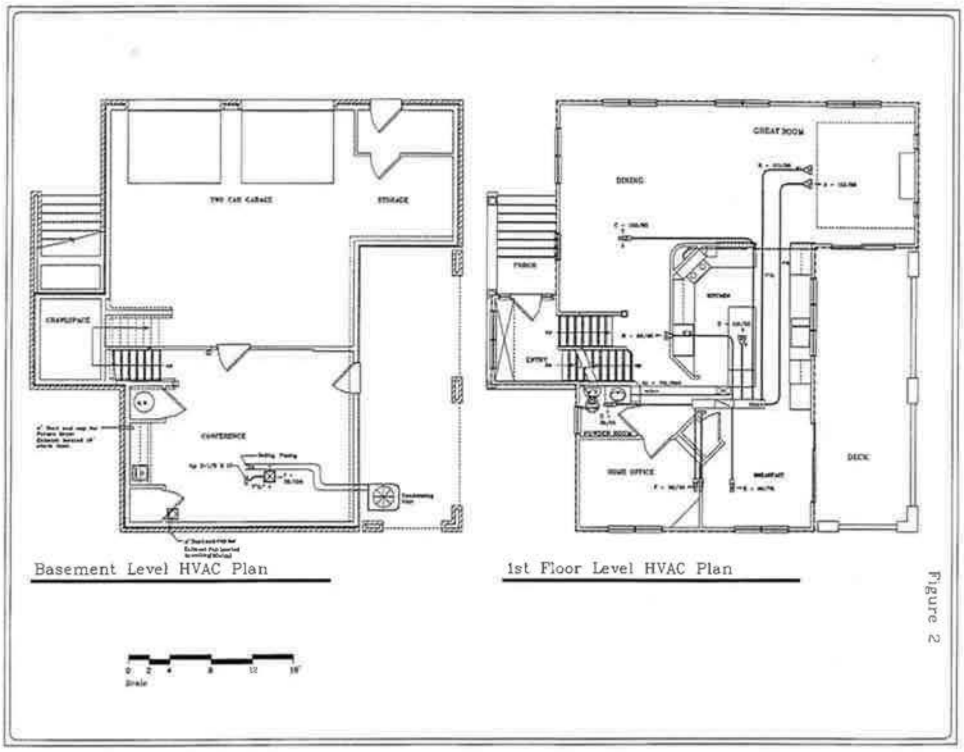

Figure 2 *(Left) basement level HVAC plan, and (right) 1st floor level HVAC plan.*

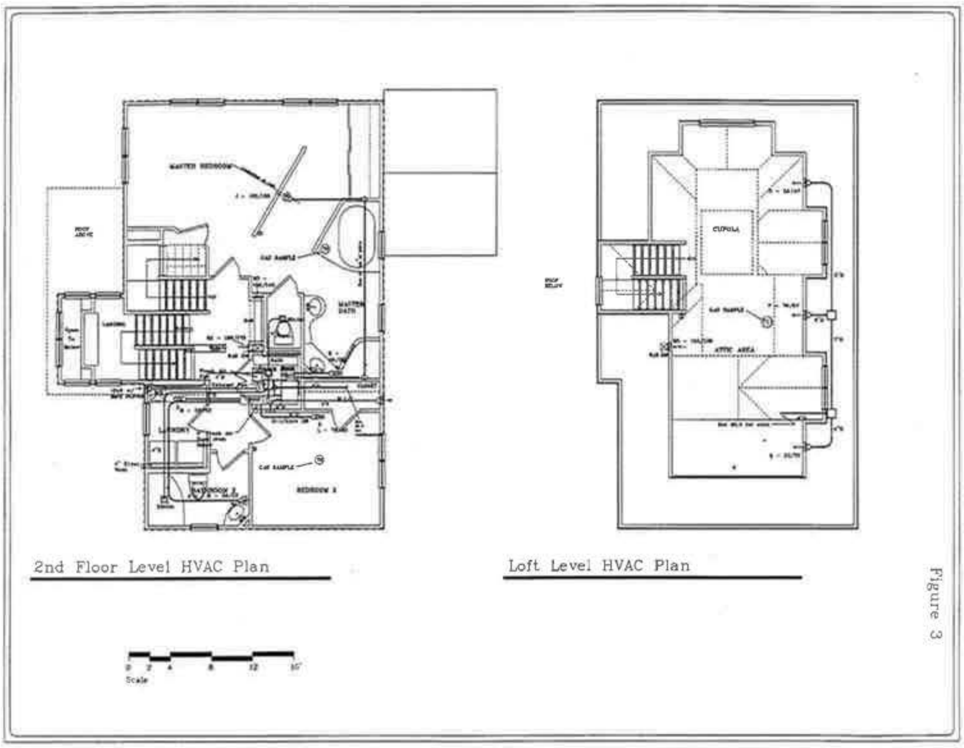

Figure 3 *(Left) 2nd level HVAC plan, and (right) loft level HVAC plan.*

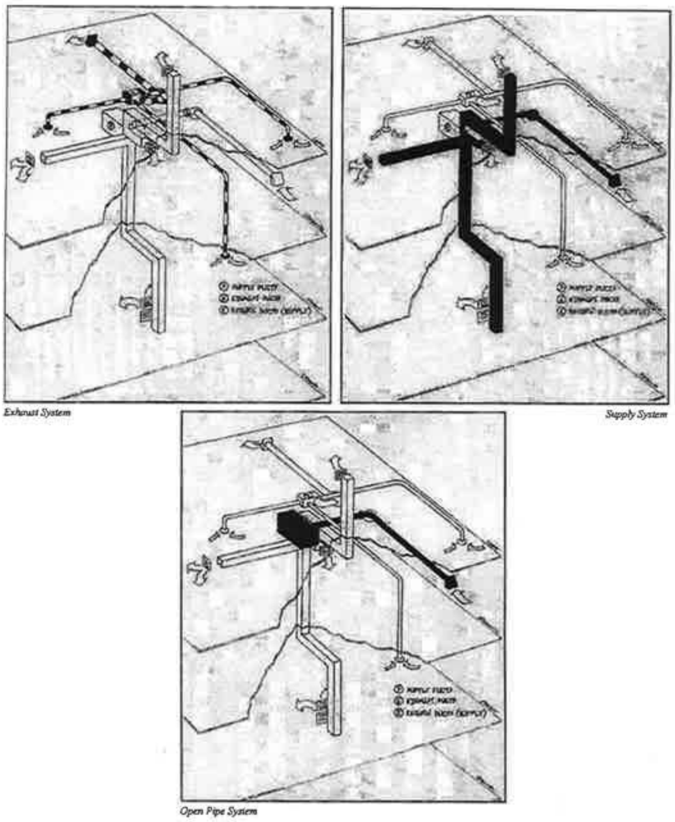

Figure 4 (Left) exhaust system, (right) supply system, and (bottom) open pipe system.

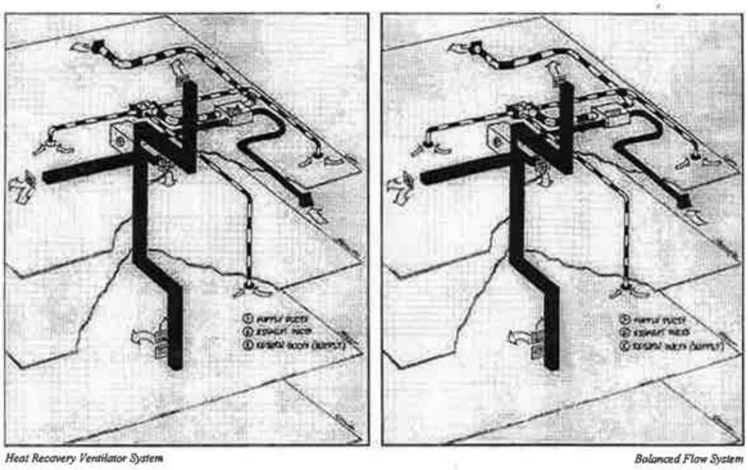

Figure 5 (Left) heat recovery ventilator system, and (right) balanced flow system.

Exhaust System

The exhaust system (Figure 4) draws from two bathrooms on the second floor and one on the first floor. Its outlet is to the north side.

Supply System

The supply intake is from the south side of the house (Figure 4). It goes through the fan and is discharged into the HVAC return air trunk duct approximately ten feet upstream of the furnace unit. Because of the flow resistance presented by the filter, blower, heat exchanger, and A/C coil, it is believed that supply airflow is in the reverse direction down the return air ducts to the return grilles at all times when the system fan is not running. Cool outdoor air could be felt coming from the second floor return air grille when the supply fan was running but the system fan was off, confirming this supposition. This path is shown in Figure 4. It results in fresh air being supplied to the loft, master bedroom, and hall on the second floor and hall on the first floor when the system fan is not running. When the system fan is operating, fresh air is supplied throughout the house by the supply duct system.

Open Pipe System

For the test of the open pipe system (Figure 4), the fresh air supply duct was connected to the sleeve in the HVAC return air trunk duct. No fan was installed in the air path and fresh air was drawn in due to suction when the HVAC system fan was running. Distribution of this fresh air was from the supply ducts throughout the house.

Heat Exchange Ventilation

To test heat exchange ventilation (Figure 5), a residential heat exchange ventilator was connected across the two exhaust duct openings and the two supply duct openings. It exhausted just as the exhaust system did and supplied fresh air via the same path as the supply system.

Balanced Flow Ventilation

The balanced flow ventilation (Figure 5) utilized the same duct connections and the ventilation unit of the heat exchange ventilator. The heat exchange core was removed and the two sides of the flow path were separated by an insulated divider that was inserted into the air chamber in place of the heat exchange core. The result was a unit with supply and exhaust blowers operated by a single motor.

TEST SETUP

Ventilation Flow Measurement

The flow station used to measure supply fan and exhaust fan airflow quantities was a 7 in. (18 cm) balancing grid. Two pressure tubes in a crosshair configuration in the airstream provide external pressure taps to measure a resultant station pressure. Previously, the resultant station pressure had been calibrated against a series of full pitot tube traverses at various flow rates. A very good correlation was found between 65 cfm (30 L/s) and 180 cfm (85 L/s); the 160 cfm (75 L/s) target flow falls within this correlated range. Use of the flow correlation table alleviated the need for extensive pitot tube traverses during the daily test setup. The station pressure was measured with a digital pressure gauge. It was used in the low range, where it has a resolution of 0.1 Pa and an accuracy of ±1% or ±0.2 Pa, whichever is greater. The flow station was typically mounted in a four-foot straight section of duct (Figure 1).

House Ventilation Rate

Overnight hours were selected for testing, primarily in an attempt to minimize wind effects. Ventilation effectiveness was measured using a tracer-gas test system, with CP grade sulfur hexaflouride (SF_6) as the tracer. The concentration-decay tracer-gas methodology was used. A multi-gas analyzer with a six-channel multiplexer was used to measure zone gas concentrations.

With the multiplexer as part of the gas analyzer system, six sampling ports were available. The locations selected for sampling included the outdoors and five interior zones:

1. Basement conference room
2. First floor kitchen
3. Second floor master bedroom
4. Second floor bedroom number 2
5. Third floor loft

Continuous SF_6 injection and concentration measurement was used so that it was possible to assess air exchange in the house for any time period during the testing program.

Heat Loss

The lab house was set up to conduct short-term energy monitoring (STEM) testing (Balcomb et al. 1993). The STEM test is an accepted method for determining the overall heat loss of a house and is well suited to comparison testing of the type done in this project.

The STEM test determines a building load coefficient (BLC) that is expressed in Btu/h·°F (W/°C). This is sometimes referred to as simple UA, as the measurement terms for both BLC and UA are the same. The BLC, as determined in the STEM test, includes infiltration as well as shell losses. For the purposes of this comparative ventilation study, the use of the STEM test-determined BLC, or as termed in this report, UA, seems an excellent measure of the overall effect of a given ventilation system in operation in the house. Again, for comparative purposes, it does not seem unreasonable to use it, along with degree-days, as a simple measure of annual heating energy use.

STEM test data were recorded on a data logger and transmitted to the office by computer modem. In the office it was possible to both monitor and control the testing remotely. On site, a gas analyzer measured tracer gas concentrations, and stored data was manually transferred out of the analyzer memory onto floppy disk and sent to the office via electronic mail.

The SF_6 tracer gas was injected into the house on a uniform, continuous basis so that the effect of various ventilation strategies could be derived from analysis of the SF_6 concentration in the house. This continuous data logging allowed the determination of both UA and ventilation rate throughout the test period.

Fan Power

Operating power for the HRV and the in-line fan was measured using a microprocessor-based energy measurement instrument. This measures kWh used over an elapsed period of time. The measurement sensor unit plugs into an outlet and the fan is plugged into the sensor unit.

Weather Data

Outdoor temperatures and wind velocity were recorded by the weather station installed as part of the (STEM) setup.

TEST PROGRAM

The test program was run in November and December 1997. Typically, a ventilation system was set up each afternoon and run for the next 24 hours. The ACH and UA values for a particular system were selected from the periods in the logged data that showed the lowest winds along with stable temperature. Usually this was the midnight to 6 a.m. period. The overnight hours are also the most favorable for measuring UA, as solar effects are minimized. Ventilation airflow was measured at the beginning of each test period, and ventilation fan power was measured throughout the period.

Supply and exhaust fans were set up on a stand in the mechanical room and connected to the appropriate ducts and the flow was adjusted by a speed controller to provide the desired cfm as indicated at the measurement station. The HRV and balanced flow ventilator had no speed control, other than selecting low or high flow.

The ventilation test program was conducted as an inherent part of continuous STEM testing. The house was cycled through a set of different ventilation methods, periodically pausing in the test routine to reevaluate the basic heat loss (UA) of the house as a check.

One complication affected the test and that was the need to interrupt the STEM/ventilation test sequences for other uses of the house. Because of the length of the test program, almost eight weeks, there was a conflict with previously scheduled events at the house. Thus, testing was interrupted on December 12 and on December 16-18. It is believed that these interruptions had little or no effect on the testing program.

A compilation of the data taken over the 41-day test period is presented in Figures 6-12. The figures show the key characteristics measured: UA, air changes per hour, wind speed, outdoor temperature, and indoor temperature. The time period selected for evaluation for any given system test has been outlined. Table 2 presents a summary of the test performance data for each of the test days. Note that the basic house UA during the test period was 450-480 Btu/h·°F (237-253 W/°C).

TABLE 2
Lab House, STEM/Ventilation Test Data, November-December 1997

Test Date, Conditions	Central System Fan	House UA, Btu/h·°F (W/°C)	House ACH	Outdoor Temp. °F (°C)	Wind Ave. mph (m/s)	Vent Fan Power, kW
Exhaust, 160 cfm (115 L/s)						
12/3 + vents	off	600 (316)	0.28	50 (10)	3 (1.3)	0.21
12/4	off	510 (270)	0.27	35 (2)	4 - 1 (1.8 - 5)	0.21
12/7	off	570 (300)	0.29	34 (2)	6 - 2 - 4 (2.7 - 0.9 - 1.8)	0.21
12/19	off	500 (263)	0.27	33 (1)	1 (0.5)	—
Supply, 160 cfm (115 L/s)						
11/25	off	680 (358)	0.34	47 (19)	6 - 1 - 2 (2.7 - 0.5 - 0.9)	0.20
11/26	on	560 (295)	0.27	44 (7)	3 (1.3)	—
12/2 + vents	on	590 (310)	0.29	30 (–1)	3 (1.3)	0.19
12/8	off	580 (305)	0.30	31 (–1)	4 (1.8)	0.20
12/26, doors closed	on	Furnace htg	0.28	34 (2)	1 (0.5)	—
12/27, doors open	on	Furnace htg	0.27	31 (–1)	2 (0.9)	—

TABLE 2 (Continued)
Lab House, STEM/Ventilation Test Data, November-December 1997

Test Date, Conditions	Central System Fan	House UA, Btu/h·°F (W/°C)	House ACH	Outdoor Temp. °F (°C)	Wind Ave. mph (m/s)	Vent Fan Power, kW
Heat Recovery Ventilator, lo = 60 cfm (28 L/s) (est), hi = 120 cfm (57 L/s)						
12/5, hi	off	570 (300)	no data	28 (–2)	7 - 4 - 6 (3.1 - 1.8 - 2.7)	0.12
12/6, hi	off	600 (316)	0.42	30 (–1)	7 (3.1)	0.12
12/10, hi	on	550 (290)	0.34	42 (6)	5 (2.2)	—
12/13, lo	on	510 (270)	0.24	30 (–1)	3 (1.3)	—
12/14, hi	on	550 (290)	0.35	29 (–1)	1 (0.5)	—
12/15, lo	on	Furnace htg	0.24	35 (2)	4 - 0 (1.8 - 0)	—
12/16, lo	on/auto	no data	no data	—	—	—
12/18, hi	on/auto	no data	no data	—	—	—
Balanced Flow, lo=70 cfm (33 L/s), hi = 130 cfm (61 L/s)						
12/22, lo	on	570 (300)	0.23	45 (7)	6 - 5 (2.7 - 2.2)	—
12/23, hi	on	590 (310)	0.35	38 (4)	0 - 3 (0 - 1.3)	—
12/24, hi	on	Furnace htg	0.29	46 (8)	2 (0.9)	—
12/25, hi	on	Furnace htg	0.33	40 (5)	6 - 4 - 6 (2.7 - 1.8 - 2.7)	—
Open Pipe 80 cfm (38 L/s)						
12/20	on	500 (263)	0.17	36 (3)	0	—
Base House						
11/21, co-heat	off	450 (237)	0.12	43 (6)	3 (1.3)	—
11/22, co-heat	off	470 (250)	0.15	42 (6)	1 - 4 (0.5 - 1.8)	—
11/23, co-heat	off	480 (253)	—	30 (–1)	5 (2.2)	—

TABLE 3
Lab House, Average Performance of Ventilation Strategies, November 1997-January 1998

Ventilation System	HRV	Bal. Flow	Supply	Exhaust	Open Pipe	House
Value of (date)	12/10	12/23	11/25	Projected[1]	12/20	
Air flow, cfm (L/s)	120 (57)	130 (61)	160 (75)	160 (75)	80 (38)	0
ACH	0.34	0.35	0.34	0.34	0.17	0.12
UA, Btu/h·°F (W/°C)	550 (290)	590 (310)	680 (360)	680 (360)	500 (263)	455 (240)
Fan energy, kW	0.12	0.12	0.20	0.21	0	0
Annual heating cost[2]	$530	570	650	650	630[3]	440
Annual ventilation heating cost[4]	$90	130	210	210	190	—
Fan energy cost[5]	$84	84	140	150	0	0
Total annual ventilation cost[6]	$174	$214	$350	$360	$190	—
Cost over HRV	$0	$40	176	186	—	—

Note: This analysis does not include cooling cost impacts. These would be much smaller than heating costs in the Pittsburgh climate.

Note: This analysis does not include ventilation cost impacts on central system fan operation. For good distribution, system fan on-time would be similar for all ventilation approaches.

[1] There is a UA value for the supply system at 0.34 ACH of 680 Btu/h·°F on 11/25. There is no comparable value for the exhaust system. However, comparing supply to exhaust on 12/8 and 12/7, at 0.30 ACH, we see very similar UA values at very similar ACH rates and reasonably similar outdoor conditions. Based on this similar performance between supply and exhaust, a UA of 680 Btu/h·°F at 0.34 ACH is projected for the exhaust system.

[2] Annual heating cost = UA × 24 h × 6000 (HDD base 65) ÷ 100,000 ÷ 0.90 (furn.eff) × $0.60/ccf (include vent'l tempering) (gas cost only).

[3] Estimated cost at 0.35 ACH.

[4] Annual ventilation heating cost = annual heating cost - $440 (house base heating cost including infiltration).

[5] Annual fan energy cost = kW × 8760 × $0.08/kWh.

[6] Total annual ventilation cost = htg. cost + fan en. cost.

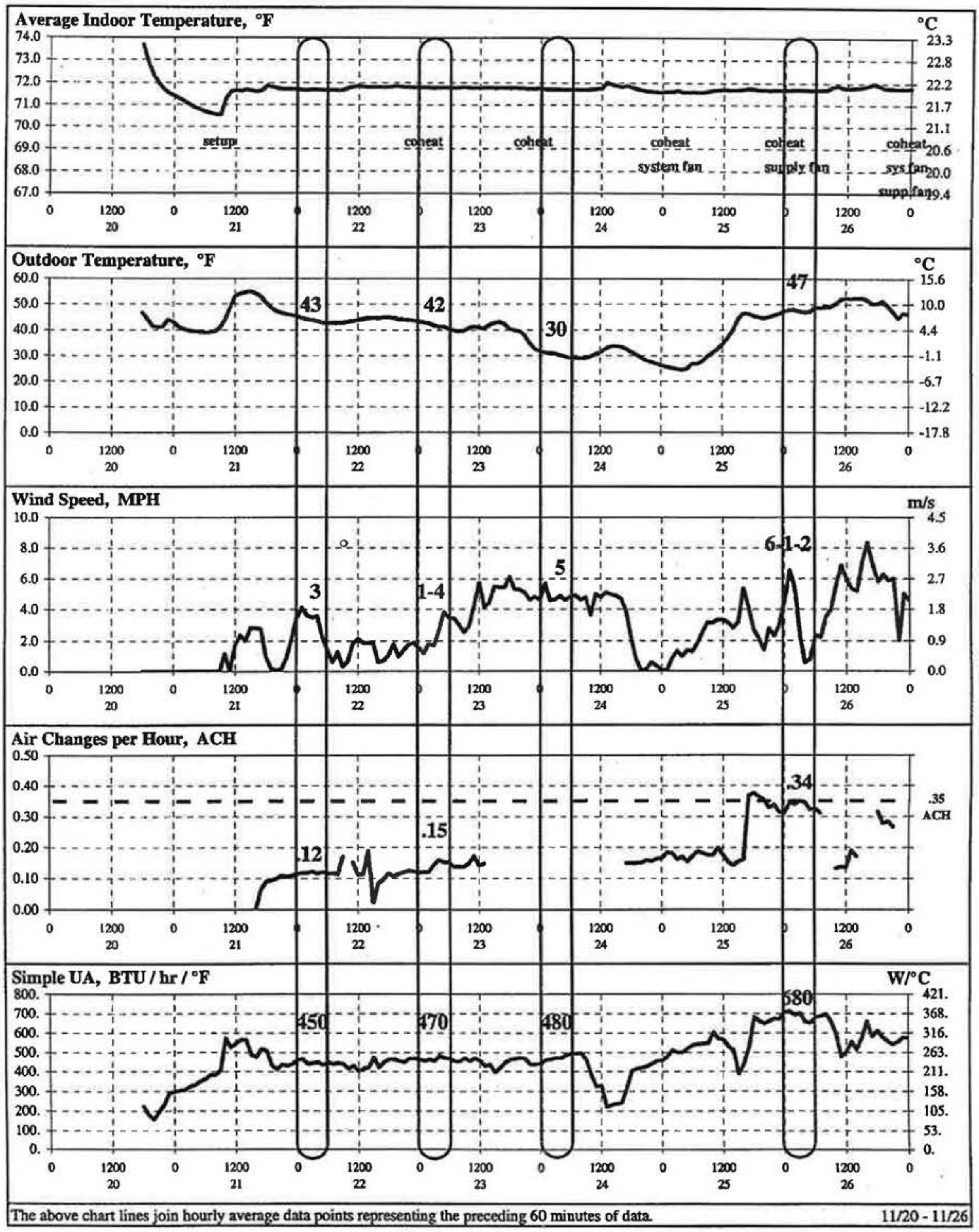

Figure 6 *Short term energy monitoring (STEM) test and ventilation test data—lab house, Pittsburgh, Pa., November 20-26, 1997.*

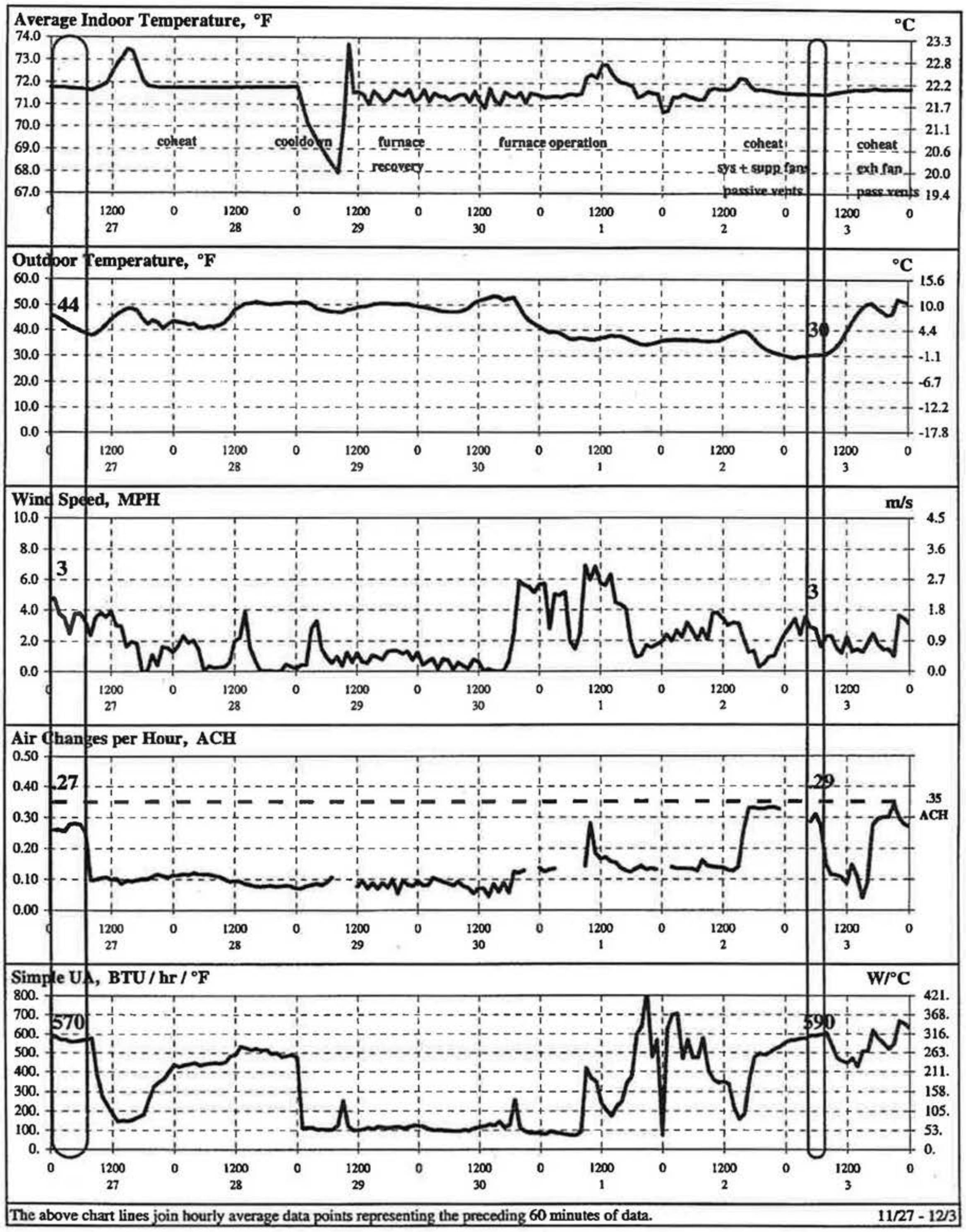

Figure 7 *Short term energy monitoring (STEM) test and ventilation test data—lab house, Pittsburgh, Pa., November 27-December 3, 1997.*

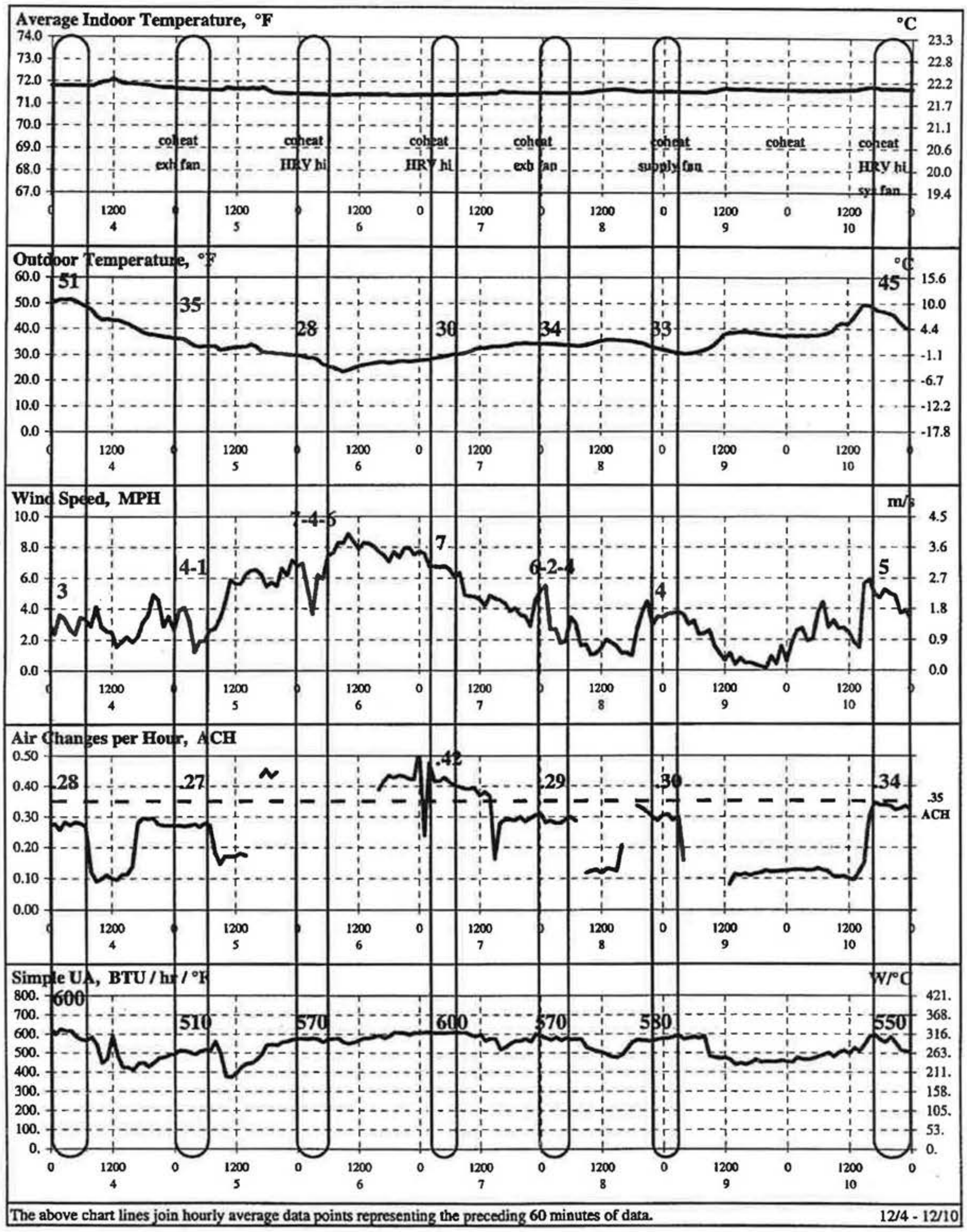

Figure 8 *Short term energy monitoring (STEM) test and ventilation test data—lab house, Pittsburgh, Pa., December 4-10, 1997.*

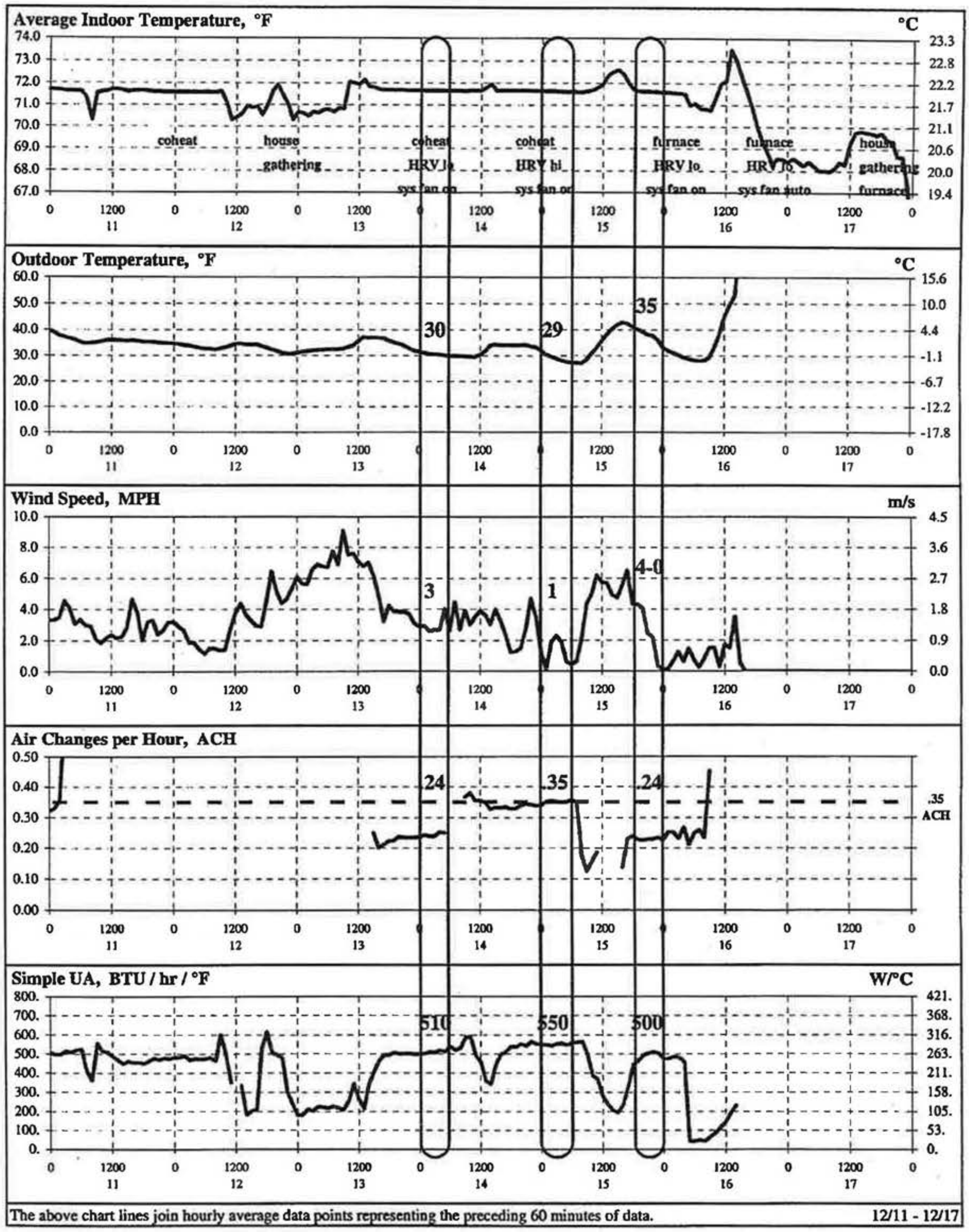

Figure 9 *Short term energy monitoring (STEM) test and ventilation test data—lab house, Pittsburgh, Pa., December 11-17, 1997.*

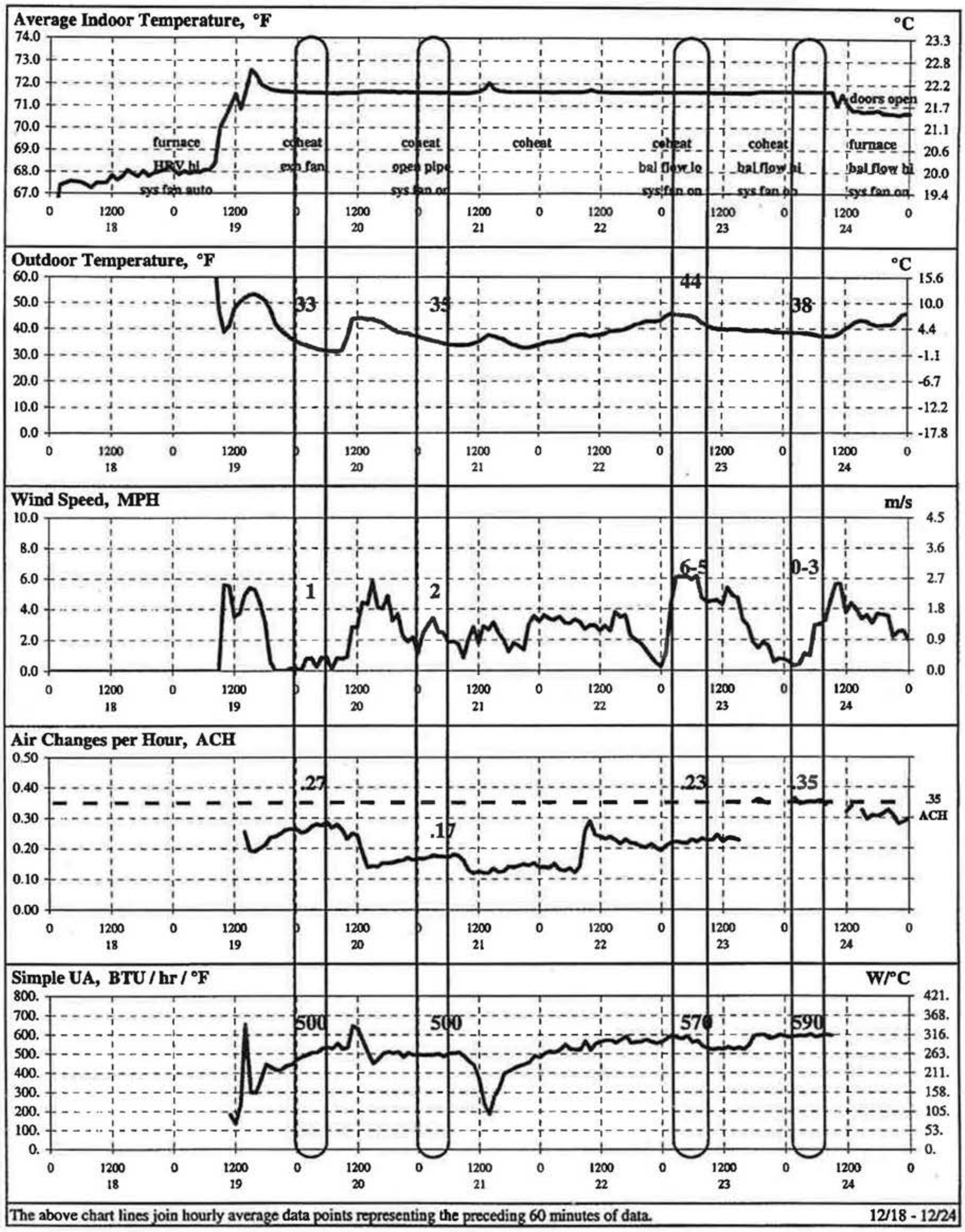

Figure 10 *Short term energy monitoring (STEM) test and ventilation test data—lab house, Pittsburgh, Pa., December 18-24, 1997.*

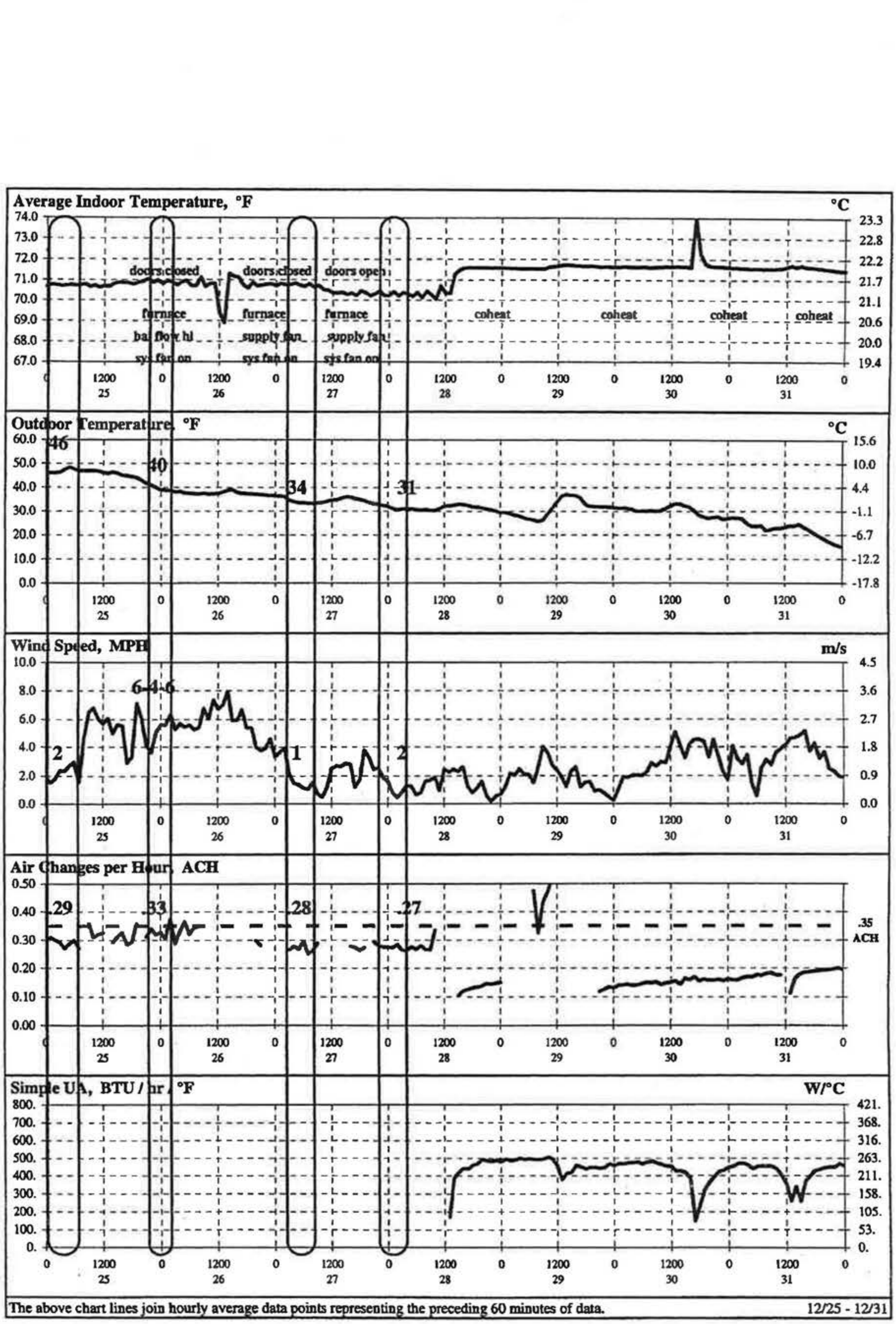

Figure 11 *Short term energy monitoring (STEM) test and ventilation test data—lab house, Pittsburgh, Pa., December 25-31, 1997.*

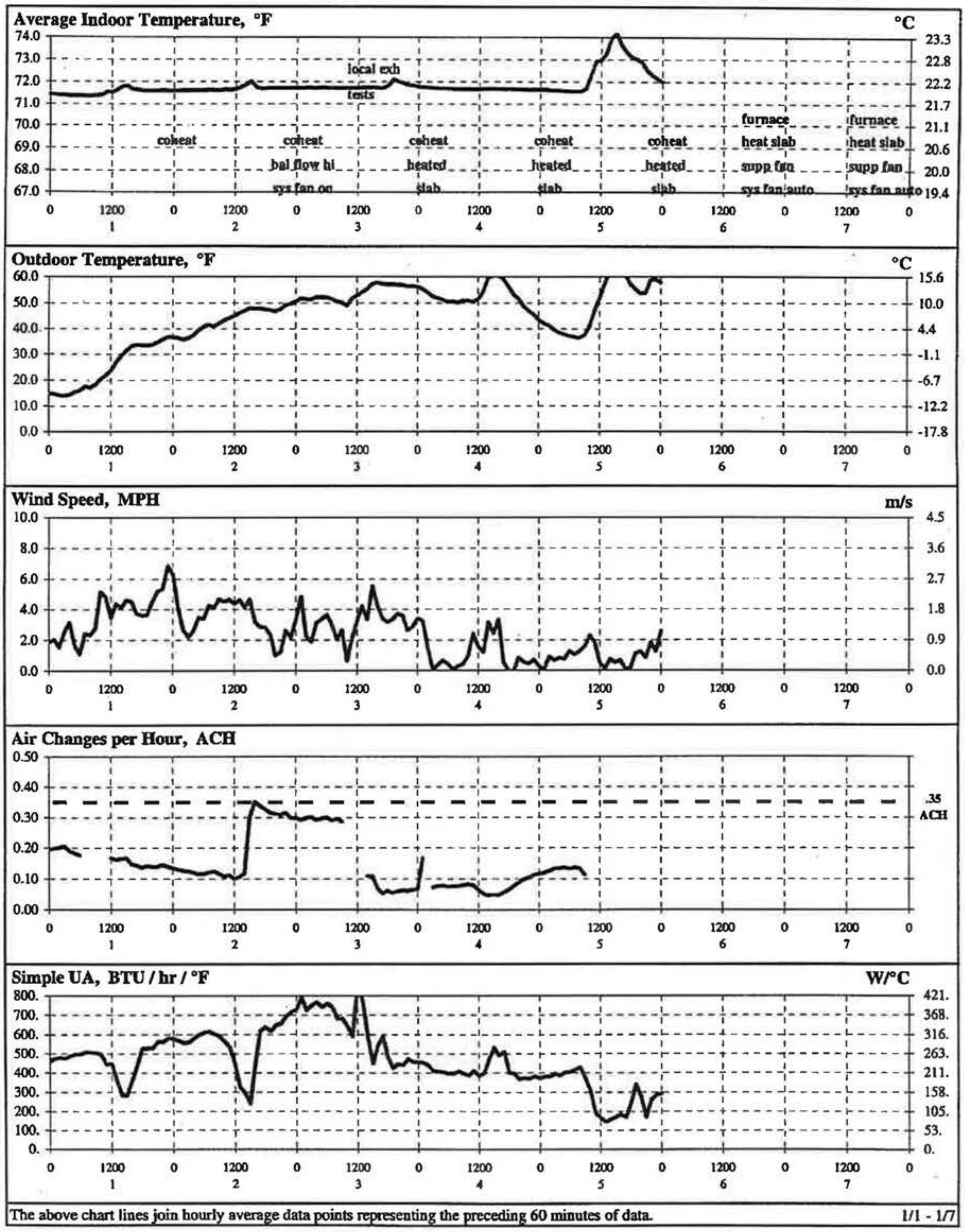

Figure 12 *Short term energy monitoring (STEM) test and ventilation test data—lab house, Pittsburgh, Pa., January 1-7, 1998.*

DISCUSSION

Exhaust Fan

The exhaust fan was set (Dec. 3, 4, 7, 19), using the flow station, to discharge 160 cfm (75 L/s), the nominal air volume required for 0.35 ACH, yet the indicated air exchange was approximately 0.28 ACH or 15% low. Because the exhaust fan slightly depressurizes the entire house, it changes the infiltration characteristics of the house. The exhaust strategy relies on infiltration for the makeup of fresh air, and depressurizing it will decrease the infiltration of the house air in the upper portions of the house and increase the infiltration of air in the lower portions of the house. The exhaust system will draw little or no air through house vents, such as the clothes dryer or kitchen exhaust, because the depressurization draws the flapper dampers closed. The average UA experienced with the exhaust fan was higher than that of the HRV, 680 Btu/h·°F (358 W/°C) (see Table 3). Operating power for the exhaust fan was 0.21 kW. The exhaust fan did not appear to be greatly affected by wind variation (see 12/7 vs. 12/19).

Supply Fan

The supply fan, like the exhaust fan, was set (Nov. 25, 26; Dec. 2, 8, 26, 27), using the flow station, at 160 cfm (75 L/s), the nominal volume required for 0.35 ACH. Its indicated air exchange rate was approximately 0.29 ACH but with wider fluctuations than for the exhaust fan. The supply fan slightly pressurized the house and altered the infiltration characteristics of the house. The supply strategy relies on exfiltration to discharge air from the house and pressurizing will increase exfiltration in the upper portions of the house and decrease infiltration in the lower portions of the house. Unlike the exhaust system, the supply system pressurization may cause some bleed off of air at local exhaust vents, such as the dryer vent or the kitchen exhaust, because the pressurization may lift the flapper dampers. This is likely to be slight, as the pressures generated are insufficient to lift most vent flap dampers open very far. The average UA experienced with the supply fan was higher than the HRV, 680 Btu/h·°F (358 W/°C) (see Table 3). Operating power for the supply fan was 0.20 kW, similar to the exhaust fan.

The supply fan may have been more influenced by wind condition than the exhaust fan, with the highest exchange rate, 0.34 ACH, experienced with variable winds on 11/25. This is 17% higher than average flow and 25% higher than the lowest flow of the supply fan.

Open Pipe

The open pipe test (Dec. 20) was to see what air exchange rate could be achieved simply by using the draw from operation of the HCVI system fan. Using the pipes installed for the supply air fan, which had several bends, the air exchange rate was 0.17 ACH with the HCVI system fan running constantly. Measured flow rate was 80 cfm. The supply pipe is far from optimum and the system fan was only operating at a reduced circulating speed. Due to STEM test requirements, the HCVI system was not heating at the time of the test, only circulating air. The indicated UA of 500 Btu/h·°F (264 W/°C) is the lowest of any of the tests, but so is the air exchange.

Heat Recovery Ventilator

Tests were conducted Dec. 5, 6, 10, 13, and 14. The calculated exhaust/supply rate to provide 0.35 ACH for the lab house is 160 cfm (75 L/s). The HRV on high only provides 0.26 ACH (120 cfm) (56 L/s), both measured, yet the air exchange measured by tracer gas indicate an exchange rate of 0.34-0.42 ACH, easily reaching the desired rate. Since the HRV does not alter pressurization conditions in the house, ventilation may have been augmented by temperature and wind-driven infiltration. At low flow, measured at 0.18 ACH and estimated at 60 cfm (28 L/s), the air exchange rate is lower than ventilation standards. The UA associated with this ventilation method roughly tracks the variation in air exchange rate, increasing during periods of greater air exchange. Operating power for the HRV, a high-efficiency model, was measured at 0.12 kW.

Balanced Flow Fan

The balanced flow fan was the HRV with the heat exchange core removed. Likely due to the lower flow resistance, it delivered 0.28 ACH (130 cfm) (61 L/s), both measured quantities, on the high setting (Dec. 23, 24, 25). This is 10 cfm (5 L/s) greater than the HRV. The balanced flow fan, like the HRV, does not alter pressurization conditions in the house. It did not appear to benefit from infiltration augmentation during the test period as did the HRV. The low flow, at an estimated 70 cfm (33 L/s), did not meet the 1/3 ACH requirement for air exchange.

As expected, the UA building load was a bit higher with the balanced flow fan than the HRV. At high flow, 12/23 vs. 12/14, the balanced flow UA was 590 Btu/h·°F (311 W/°C) vs. 550 Btu/h·°F (290 W/°C) for the HRV (see Table 3). This is 7% higher. Employing the same fan as the HRV, the operating power was the same, 0.12 kW.

Temperature and Wind Effects

On several days straight co-heating tests were done in which all the ventilation systems were sealed off, the central system fan was off, and all heating was done by the electric resistance heaters of the STEM test. In the period December 28 through January 2, a strong pattern of the dependence of infiltration rate on outdoor temperature may be seen. Considering the graphs for outdoor temperature and ACH, we see a general drop in temperature from 32°F (0°C) to 15°F (–9°C) and then back up to 45°F (8°C). In strong correspondence, the ACH graph starts the period at 0.10, generally climbs to 0.20, and again descends to 0.10. During this period, also, winds only infrequently exceeded 4 mph (2 m/s). With a well-sealed house and light winds, this rise and fall probably represents the temperature effect on stack-induced infiltration to a large extent.

Pittsburgh experienced a very mild winter so that very few deep cold test days were experienced. This made it difficult to assess comfort impacts of any of the ventilation methods.

Wind effects are not easy to isolate but are believed to be significant. During the test period, the lab house was quite exposed, with very little adjacent construction or screening foliage. The house is well sealed and probably experiences only a small infiltration change with wind variation. Wind speeds were recorded and are graphed, but their short-term variation in strength and direction is not known. The ventilation test installation was designed with the exhaust outlet on one side of the house and the fresh air inlet on the opposite side of the house to eliminate cross-contamination of the fresh air intake. These ports may be subject to positive or negative pressure of varying strength and varying duration due to wind. It is quite likely that some of the variation in measured air exchange rates was influenced, positively or negatively, by wind conditions.

UA and ACH values selected for examination were generally taken from the period with lightest winds, overnight. The correspondence of a selected UA with the concurrent ACH is probably satisfactory. This set of measurements will, however, include whatever wind effects occurred during the measurement period. Whether this is representative of the overall annual performance of the ventilation system is more questionable. Design changes on some systems may be desirable to limit the great variability of wind effect.

Operating Cost Comparison

In Table 3 some comparative costs are estimated for ventilating a house using each of the systems. These are simple calculations based on heating degree-days, base 65. In each instance, test data have been used for runs that achieved the 0.35 ACH ventilation level or an extrapolation was made to the 0.35 ACH level from the monitored data. Directly usable data thus were available for the HRV, balanced flow, and supply ventilation systems and extrapolations were made for exhaust and open pipe systems. A high-performance house such as the lab house would probably have a balance point temperature near 55°F (13°C) and thus these costs are conservative for Pittsburgh. What may be seen from the comparison is that the cost benefit of heat exchange in the HRV in quite modest, $40 a year. Much more important is the efficiency of the blower motor. For the high-efficiency HRV (and balanced flow fan), assuming constant operation, the annual electrical cost is $84. For the standard efficiency supply and exhaust fans, this cost is $140-$150. No measurements were made of cooling thermal impact and thus no cooling cost projections have been possible.

Because the open pipe system requires no fan supplement, it appears an attractive cost option. It does require operation of the system fan, but so do the others to ensure adequate fresh air mixing.

CONCLUSIONS

1. Natural infiltration is insufficient to meet the 0.35 ACH target in quality homes. Intentional ventilation is required.
2. Wind appears to cause great variability in ventilation with all systems, but in aggregate it enhances more than it suppresses ventilation. Wind effects may be experienced in all seasons.
3. The HRV and balanced flow systems appear to be more easily augmented by temperature and wind-driven infiltration than the supply or exhaust systems.
4. The fresh air inlet and exhaust should be on the same side of the house for HRV and balanced flow systems to experience the same pressure conditions. They require adequate separation, however, to preclude the reingestion of exhaust air.
5. Open pipe ventilation works, but air exchange is modest because the pressures are low. The system relies on exfiltration, which is weak at these low pressures. Cost wise, this is an attractive approach. A balanced pipe system should be explored.
6. In ventilation systems in this climate, the key to cost-effectiveness is blower motor efficiency, not heat exchange.
7. Operating power can be greatly reduced by selecting ventilation equipment with the most efficient motors. In these tests, power could be cut in half through such a selection.
8. Using the STEM test setup to measure ventilation air exchange does not appear to compromise reasonable measurement of ventilation effectiveness.

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