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Effect of Forced Ventilation on House Infiltration

W. P. Levins

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A03 Microfiche A01

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ORNL/CON-75

Contract No. W-7405-eng-26

Energy Division

EFFECT OF FORCED VENTILATION ON HOUSE INFILTRATION

W. P. Levins

DEPARTMENT OF ENERGY
Office of Buildings and Community Systems

Date Published: August 1981

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Oak Ridge, Tennessee 37830
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PREFACE

A recent Oak Ridge National Laboratory (ORNL) report* indicated that venting the exhaust of a clothes dryer to the outside surroundings was not as energy wasteful as it might first appear. Although all the sensible and latent heat vented outside was lost, some question existed as to how much additional infiltration air (above the normal house infiltration air) entered the house because of the operating vented dryer. All the infiltration air entering a house will eventually be either heated or cooled by the central heating and cooling system of the house, depending upon the indoor and outdoor temperatures. For this reason, a study was initiated at ORNL to determine the effect of a vented dryer on the house infiltration rate. The results of this study may also apply to vented kitchen and bathroom fans and perhaps even to combustion processes taking place in furnaces, water heaters, and fireplaces.

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*W. P. Levins, *Energy and the Laundry Process*, ORNL/CON-14 (April 1980).

EFFECT OF FORCED VENTILATION OF HOUSE INFILTRATION

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Energy Division

ABSTRACT

Tests were conducted over a period of 18 months at a house near Knoxville, Tennessee, to determine the effect of forced ventilation on the house infiltration rate. An outside-vented electric dryer was used as the power vent. The testing was carried out during a variety of weather conditions. The tracer gas technique using sulfur hexafluoride was employed to measure infiltration rates. A correlation equation was developed based on measured data that relates the change in the house infiltration rate to the dryer vent rate. The correlation equation has the form of an inverse exponential curve that shows a greater increase in the infiltration rate of a tightly constructed house than of a loosely constructed house. Calculations were made for 17 cities across the United States showing the effect of dryer location on house energy consumption.

SUMMARY

An experiment was conducted at the Tennessee Energy Conservation in Housing (TECH) Complex in Knoxville, Tennessee, to determine what effect venting a clothes dryer to the outside would have on the infiltration rate of a dwelling. The TECH Complex was an ideal location to conduct this testing because of the availability of onsite weather monitoring equipment as well as the known physical parameters of the three houses at the complex.

The tracer gas dilution method with sulfur hexafluoride (SF_6) as the tracer gas was used to measure infiltration rates. Base data for the infiltration rates of the house were gathered over an 18-month period, which encompassed a wide variety of weather conditions. Infiltration rates with the dryer not operating were correlated with the Achenbach-Coblentz equation, which has the form

$$\text{infiltration rate} = A + [B \times (\text{wind speed})] + [C \times |\text{house-to-ambient } \Delta T| ,$$

where A, B, and C are empirical constants for a given structure.

Measurements of the change in the infiltration rate with the dryer operating and venting outside showed that the increase in the infiltration rate was not simply equal to the dryer vent rate. A correlation equation was developed between the dimensionless quantities X and Y, where

$$X = I_o/V ,$$
$$Y = (I - I_o)/V .$$

The correlation equation that best fits that data is

$$Y = e^{-1.008X} ,$$

which may be rewritten as

$$I = I_o + V \times e^{-1.008(I_o/V)} .$$

Note that

I = the infiltration rate with the dryer on,
I_o = the infiltration rate with the dryer off,
V = the dryer vent rate.

Most differences between measured and predicted infiltration rates with the dryer on were within ±15%.

Calculations were made based on the results of this work showing the annual effect on the central heating, ventilating, and air conditioning (HVAC) system of a house brought about by the excess infiltration air entering the house caused by venting a dryer outside. The calculations were made assuming the house was in different locations by using weather data for 17 different cities in the United States. Calculations

were also made for the energy consumption of dryers located in three types of unconditioned spaces — breezeways, garages, and utility rooms.

The average electric clothes dryer uses about 1100 kWh/year.[1] For houses in warm climates, a savings of about 140 kWh/year is possible by locating a dryer in an unconditioned utility room relative to a location in the conditioned space of a house. However, in the more northern cities, a savings of 20 to 30 kWh/year can be obtained by locating the dryer in the house and venting it outside compared to operating the dryer in an unconditioned space. In either case the effect is relatively small, and neither significant losses nor gains are obtained by venting a dryer to the outside.

INTRODUCTION

Although venting a clothes dryer inside the living area of a house is energy efficient during the heating season, the practice has several drawbacks. If the dryer uses an internal combustion process to heat the air as gas dryers do, potentially dangerous combustion products can permeate the house air; therefore, gas dryers should never be vented inside. Lint and excess moisture in the exhaust from both gas and electric dryers can present safety and aesthetic problems if not effectively controlled. Also, venting the dryer inside during periods of warm weather can make the surroundings uncomfortably hot and humid. Thus, many clothes dryers are vented outside. Venting the dryer outside, however, can increase the house air infiltration rate.

The rate at which air enters or leaves a structure is an important factor in performing heating and cooling calculations for residences or other buildings. This air flow rate is called the air infiltration rate and usually is expressed in units of air changes per hour (ACPH). Infiltration occurs through cracks around doors, windows, walls, floors, etc., and its magnitude is determined by the quality of materials and construction and by existing weather conditions.

All infiltration is not bad, however, because it helps to replenish the oxygen supply in houses, deplete "used" air and contaminants, and furnish air for the use of fossil-fueled heating devices. In cases where infiltration does not do these jobs, ventilation must be added to the house. In cases where infiltration is too high, a penalty is paid in terms of increased space-conditioning costs and personal discomfort.

Both the measurement of and the prediction of air infiltration in residences and other buildings are receiving a great deal of attention these days because of the contribution that infiltration adds to the house heating and cooling loads and indoor air quality (see ref. 1 with respect to the laundry process). (An old rule of thumb attributes 30% of the house heating load to infiltration.)

There are many models and correlations used in infiltration modeling. Ross and Grimsrud,[2] Cole et al.,[3] Socolow et al.,[4] and Sepsy et al.[5]

have described them in research sponsored by the Department of Energy, the Gas Research Institute, and the Electric Power Research Institute. Because of the many uncertainties affecting infiltration determinations, the most common methods used today are the 30% rule-of-thumb method and those described by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). One ASHRAE method simply uses typical room air change rates based on past measurements and experience and sums them up for the entire structure. The ASHRAE crack-length method involves measuring the lengths of potential air leakage paths of the structure and multiplying them by empirical constants to obtain an average infiltration rate.

These methods are suitably accurate for calculating integrated infiltration loads over the course of a heating or cooling season. However, since the infiltration rate is constantly changing because of fluctuating ambient conditions, these average values may be far from the true value at any given time.

In those instances in which measured infiltration and weather data are available for a given structure, the Achenbach-Coblentz method has been found to give relatively good correlations. The Achenbach-Coblentz correlation uses an equation of the form:

$$\text{infiltration rate} = A + [B \times (\text{wind speed})] + [C \times |\text{house-to-ambient } \Delta T|] ,$$

where A, B, and C are empirical constants for the structure.

Many modifications of the Achenbach-Coblentz equation have been made, and refs. 2, 3, 4, and 5 summarize them well.

Quantitative measurements of air infiltration rates are presently best made using the tracer gas technique. This method involves introducing a tracer gas such as sulfur hexafluoride, ethane, nitric oxide, etc., into a structure and monitoring its concentration with a suitable instrument. Three variations of this method may be used: the dilution or decay method, the constant injection method, and the constant concentration method.[6] Each of the three variations requires its own specialized

equipment and possesses its own advantages. However, for residential use, the dilution or decay method is usually employed.

The tracer gas decay technique involves monitoring the concentration of a tracer gas (SF_6 in this case) versus time and using this data to calculate the infiltration rate. The mathematical model used in this form of the tracer gas technique is that of a first-order decay rate — that is, the rate of loss of the tracer gas from a structure is proportional to the amount of the tracer gas present at any instant in time. Expressed mathematically,

$$-\frac{\partial c}{\partial t} = kc \ ,$$

where

c = the concentration of the tracer gas in the structure at any time t,

k = the infiltration constant.

When this equation is integrated with the initial boundary conditions at $t = 0$, $c = c_o$, the solution is

$$\ln \frac{c}{c_o} = -kt \ .$$

If $\ln(c/c_o)$ is plotted versus t, there results a straight line going through the origin with a slope equal to $-k$, the infiltration rate in ACPH.

For the above equation to be valid, either perfect mixing of the tracer gas must take place, or the average concentration of the tracer gas in the structure must equal the average concentration of the tracer gas leaving the structure.

EXPERIMENTAL SETUP

To determine the effect that an outside-vented dryer has on the infiltration rate of a dwelling, an experiment was conducted at a three-house complex in Knoxville, Tennessee. The complex (Fig. 1) is made up of the annual cycle energy system (ACES) house, a solar house, in which a solar heating and hot water system are used, and the control house, in which conventional heating and cooling systems are used.

Located on the agricultural farm of the University of Tennessee, south of Knoxville on Alcoa Highway, this complex is a joint effort of the University, Oak Ridge National Laboratory, and the Tennessee Valley Authority, with the cooperation of local industries. The purpose of the TECH project, which has been in operation since August 1976, is to demonstrate energy conservation through improved thermal envelopes and through the use of innovative heating and cooling systems.

ORNL-PHOTO 1797-81

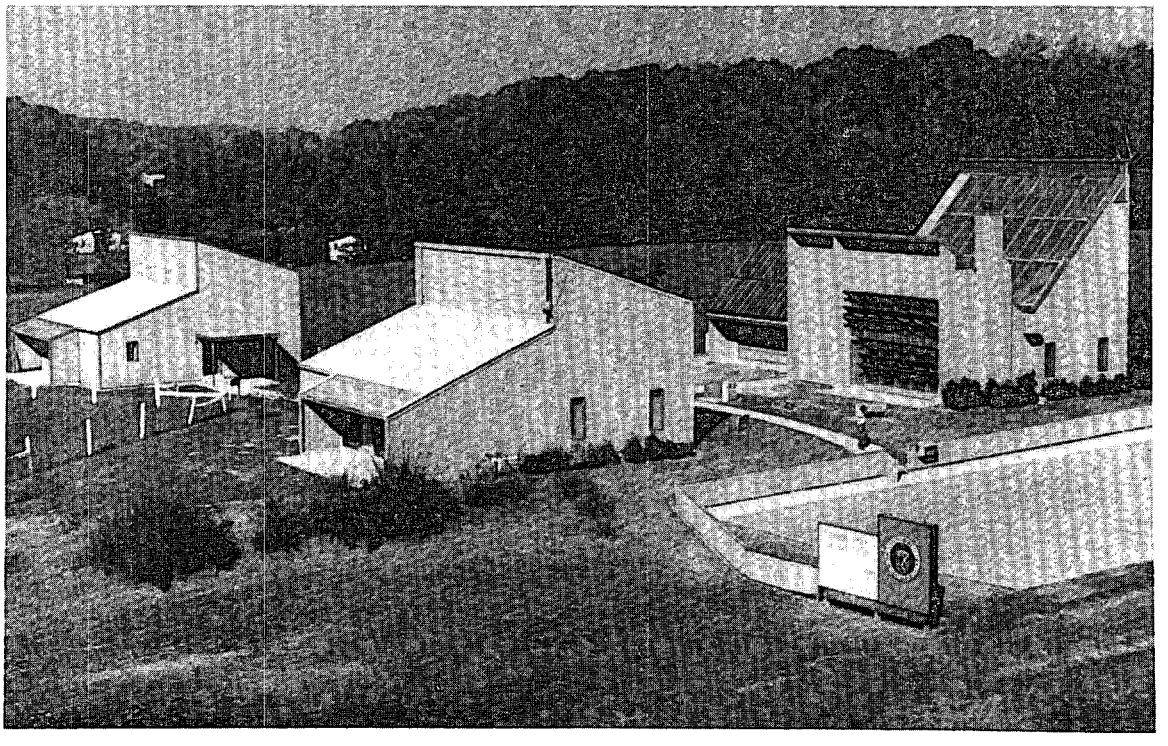

Fig. 1. The Tennessee Energy Conservation in Housing Complex.

The infiltration experiment was conducted in the control house. Figure 2 is a photograph of the control house, and Fig. 3 is a top view of the TECH Complex showing the overall layout.

All three houses in the complex have similar floor plans; their exteriors are patterned after the requirements of the solar house. The houses are 167-m^2 (1800-ft^2) single-family residences consisting of three bedrooms, two baths, a great room, a kitchen, and a mechanical equipment room. The volume of the control house is 453 m^3 (16,000 ft^3).

The houses were built with better thermal envelopes than normally found in this climate zone, to reduce heating and cooling requirements. Double-pane insulated glass was used throughout; R-38 insulation was used in ceiling areas where possible, and R-19 insulation was used in the crawl space and sidewalls, below the floor, and in the ceiling areas. Table 1 gives a detailed description of the insulation of the demonstration houses (see also ref. 7).

ORNL-PHOTO 6911-80

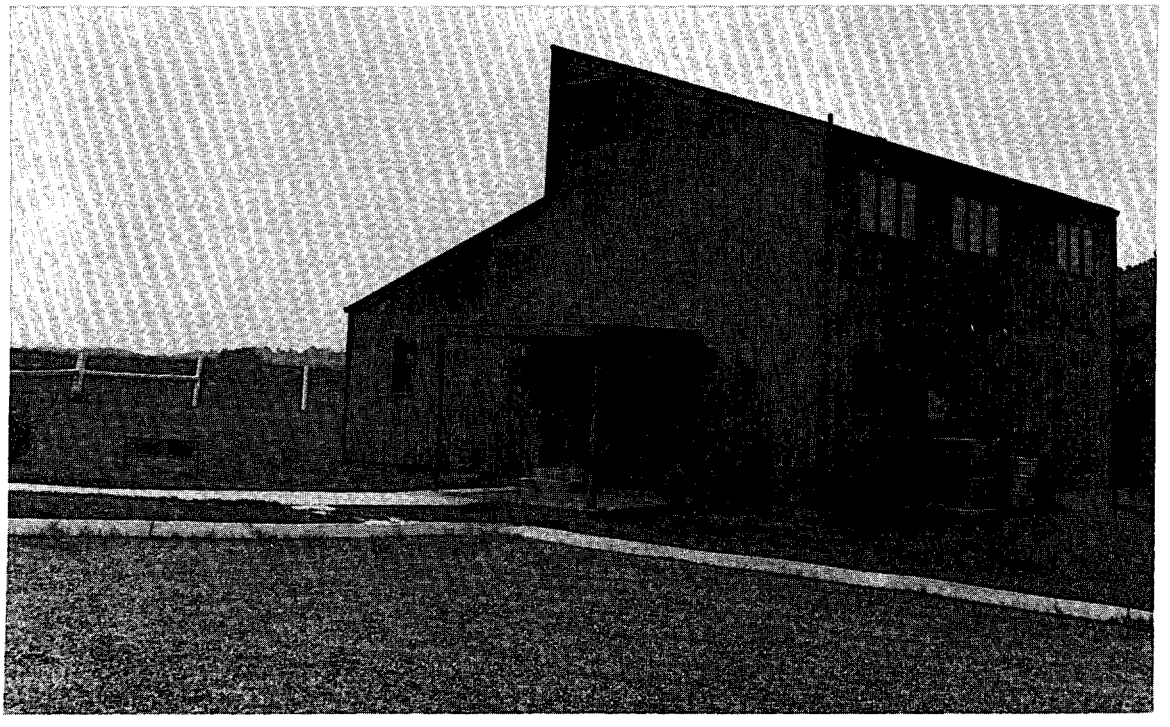

Fig. 2. TECH control house, in which the infiltration experiment was conducted.

ORNL–DWG 81–4622

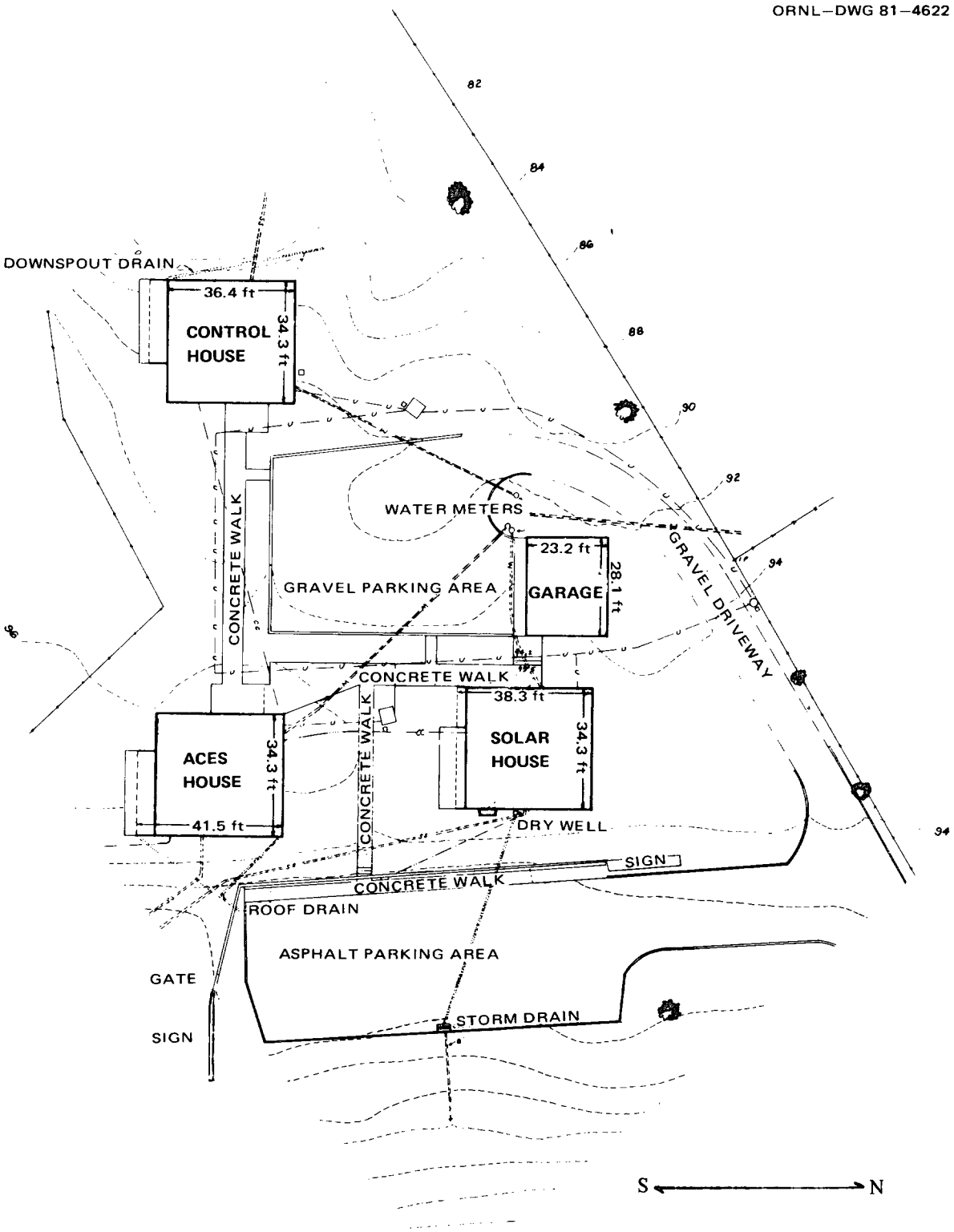

Fig. 3. Overall layout of the TECH Complex.

Table 1. Thermal insulation used in the demonstration houses

Structure part	Insulation thickness [m (in.)]	Insulation R-value	Overall U-value [W m^{-2} K^{-1} (Btu h^{-1} ft^{-2} $°F^{-1}$)]
Sidewalls	0.14 (5.5)	19	0.256 (0.045)
Ceiling, flat	0.305 (12)	38	0.136 (0.024)
Ceiling, cathedral	0.152 (6)	19	0.227 (0.040)
Floor (over crawl space)	0.152 (6)	19	0.227 (0.040)
Windows	Double-glazed wood frame		3.293 (0.58)

Source: L. A. Abbatiello and A. S. Holman, *Annual Cycle Energy System (ACES) Performance Report, November 1977 through September 1978*, ORNL/CON-42 (May 1980).

The tracer gas decay technique was used to measure the infiltration rate in the control house; SF_6 was used as the tracer gas. The instrument used to monitor the SF_6 concentration was a Systems, Science and Software model 215BGC Bench/Laboratory Tracer Gas Monitor. Figure 4 is a photograph of this instrument, and Fig. 5 is a photograph of the instrument, sampling probe, and nitrogen carrier gas bottle. The instrument contains an electron-capture gas chromatograph and can easily measure SF_6 concentrations in air from a range of 10^{-9} to 10^{-12} (one part per billion to one part per trillion). Figure 6 shows a calibration curve for the instrument.

A Sears Kenmore large-capacity electric dryer, model 69801, was used. About 2 m (7 ft) of flexible 0.1-m-diam (4-in.) plastic tubing and a standard metal through-the-wall vent kit were attached to the dryer vent.

Integrated wind speed, wind direction, and outdoor dry-bulb temperature were monitored every 15 min (weather readings were synchronized to SF_6 concentration readings) by the data acquisition system contained in the ACES house. Figure 7 is a photograph of the rear of the ACES house showing the weather monitoring instruments on the roof.

ORNL-PHOTO 6907-80

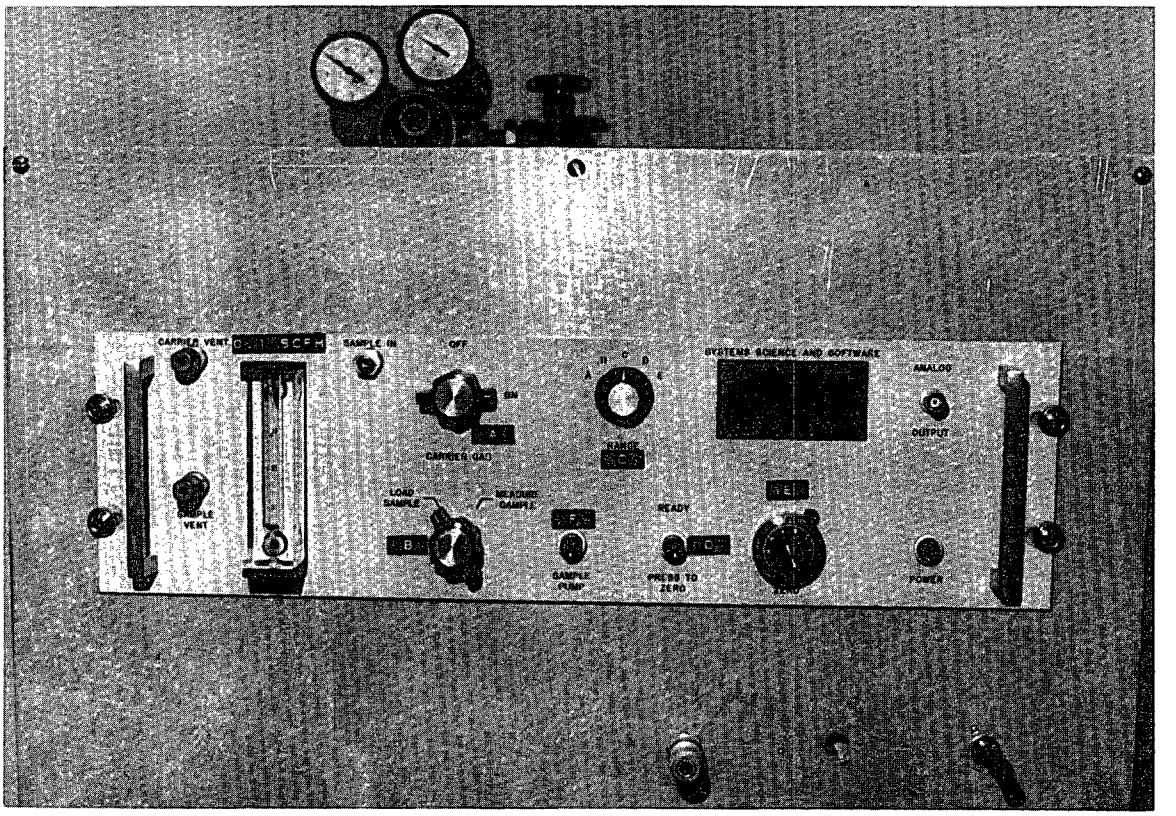

Fig. 4. Systems, Science and Software model 215BGC bench/laboratory tracer gas monitor.

Test runs* were made over the course of an 18-month period to include weather encompassing all the seasons. Most testing was done on days when the wind speed and dry-bulb temperature varied little. All infiltration measurements were made with the central blower fan of the HVAC system operating to ensure good mixing of the house air. The probe used to gather inside air samples was located at the entrance of the central return air duct.

Initial testing showed that the tracer gas monitor was able to accurately measure gas samples at 15-min intervals, so most infiltration determinations consisted of five readings taken over the course of an hour.

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*Several days were spent making preliminary infiltration measurements in order to become familiar with the equipment and also to establish a procedure for conducting the testing.

ORNL-PHOTO 6906-80

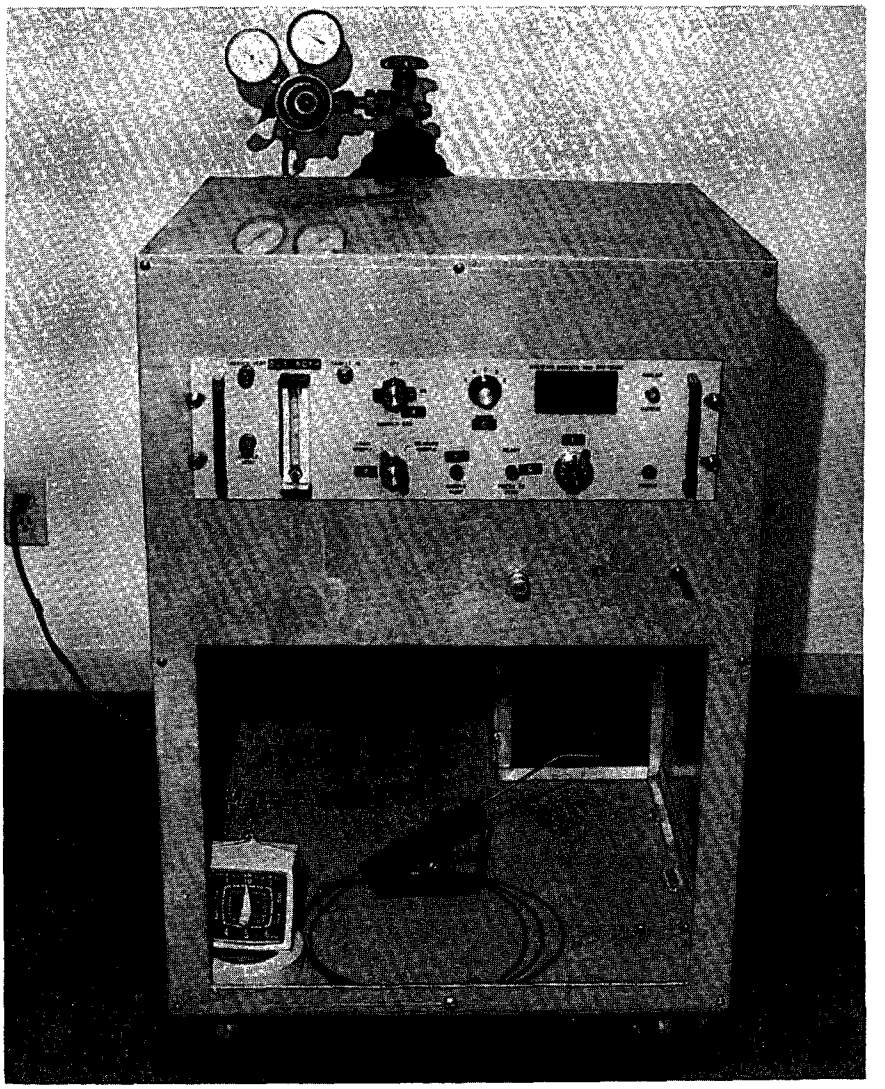

Fig. 5. Equipment used to monitor SF_6 concentration: tracer gas monitor, sampling probe, and nitrogen carrier gas bottle.

A typical test day consisted of a 1-h run with the dryer off, a 1-h run with the dryer operating, and another 1-h run with the dryer off. Two ml of SF_6 were injected into the blower inlet and allowed to equilibrate in concentration throughout the house for approximately 30 min prior to the first run each day and also for subsequent runs if the SF_6 concentration was too low to measure accurately. Concentration and weather readings were then taken at 15-min intervals during each run. A stopwatch was used for timing.

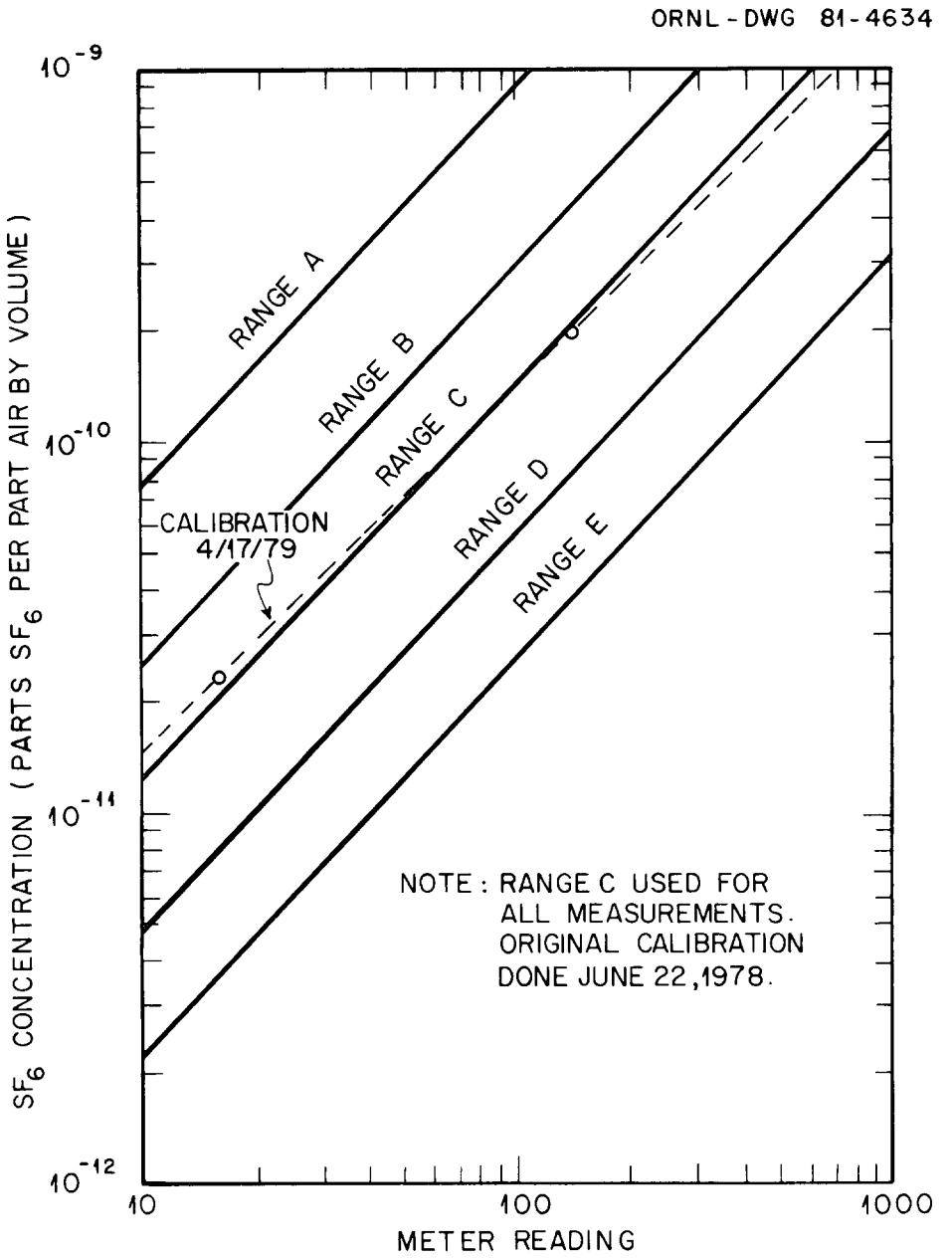

Fig. 6. Calibration curve for SF_6 meter.

The dryer was moved to two different locations in the house to determine if its location had an effect on the results. Several runs were also made with the dryer vent blocked off to determine its effect on the infiltration rate without the dryer operating.

ORNL-PHOTO 6914-80

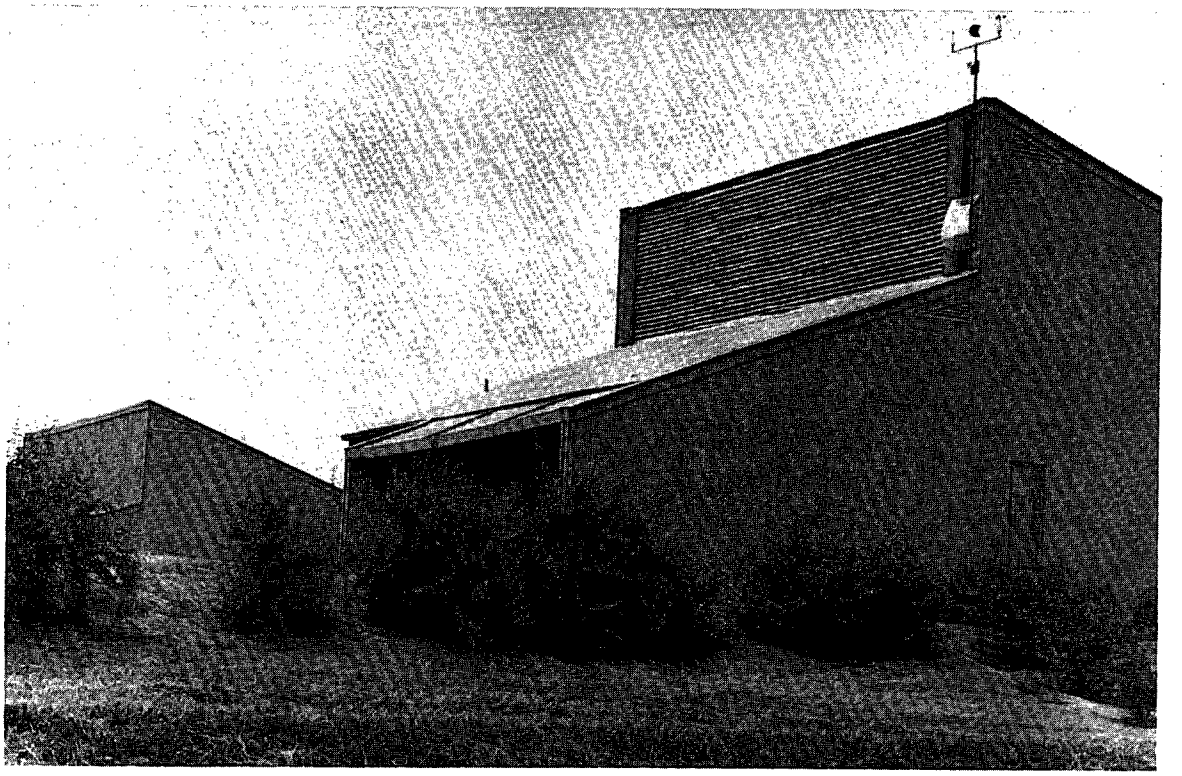

Fig. 7. Rear view of ACES house showing weather monitoring instruments on the roof.

RESULTS AND DISCUSSION

Table 2 contains a summary of the infiltration testing from November 16, 1978, to June 4, 1980. Table 3 contains a sample of the operating data for runs 37 and 38. Figure 8 shows the decay plots for the same runs. These tables and plots are typical of the experimental data obtained during the course of the testing.

Several correlations of the data were made using the Achenbach-Coblentz equation. Table A.1 in Appendix A shows how the regression equation is used to fit the data. These initial trials showed that neither dryer location, the presence of a vent (with the dryer off), nor wind direction affected the regression coefficients significantly, so these quantities were not treated as variables in this work.

Table 2. Summary of control house infiltration testing

Run No.	Date	Dryer location[a]	Dryer operating[b]	Outside temp. (°C)	Inside temp. (°C)	Temp. difference (°C)	Wind speed (km/h)	Wind direction	Measured inf. rate (per hour)
1	11/16/78	NV	×	15.6	21.1	5.6	0		0.20
2	1/03/79	NV	×	-8.3	18.3	26.6	16.1	W	1.05
3	1/05/79	NV	×	0.6	20.0	19.4	13.0	SW	0.81
4	1/05/79	UR	√	1.1	20.0	18.9	13.0	SW	0.83
5	1/10/79	UR	×	0	19.4	19.4	4.9	E	0.70
6	1/10/79	UR	√	4.4	21.1	16.7	4.9	E	0.84
7	1/12/79	UR	×	4.4	21.1	16.7	8.0	NE	0.62
8	1/12/79	UR	√	6.1	21.1	15.0	8.0	NE	0.69
9	1/12/79	UR	×	6.7	21.1	14.4	8.0	NE	0.60
10	1/17/79	UR	×	7.8	21.1	13.3	6.5	SW	0.66
11	1/17/79	UR	√	8.3	21.1	12.8	16.1	SW	0.78
12	1/17/79	UR	×	8.3	21.1	12.8	11.1	SW	0.66
13	2/06/79	K	×	0	20.0	20.0	8.0	NE	0.81
14	2/06/79	K	√	1.1	20.0	18.9	8.0	NE	0.88
15	2/06/79	K	×	1.1	20.0	18.9	8.0	NE	0.84
16	2/21/79	K	×	8.9	21.1	12.2	11.1	SW	0.74
17	2/21/79	K	√	11.7	22.2	10.6	9.6	SW	0.59
18	2/21/79	K	×	12.2	22.2	10.0	9.6	SW	0.60
19	3/01/79	K	×	14.4	21.7	7.2	25.6	SW	0.93
20	3/01/79	K	√	17.2	21.7	4.4	22.5	SW	0.85
21	3/23/79	K	×	17.2	21.7	4.4	16.1	SW	0.75
22	4/04/79	K	×	20.6	21.7	1.1	11.1	W	0.42
23	4/04/79	K	√	17.8	22.8	5.0	24.1	W	0.62
24	5/31/79	NV	×	20.0	24.4	4.4	4.9	NE	0.29
25	6/01/79	NV	×	22.8	25.0	2.2	6.5	SW	0.27
26	6/04/79	NV	×	25.0	25.6	0.6	8.0	NE	0.27
27	8/13/79	NV	×	26.1	25.6	-0.6	4.9	SW	0.32
28	8/14/79	K	×	25.6	25.6	0	6.5	SW	0.29
29	8/14/79	K	√	28.9	25.6	-3.3	8.0	W	0.61
30	8/14/79	K	×	28.9	26.1	-2.8	9.6	SW	0.33
31	9/05/79	K	×	27.8	26.7	-1.1	9.6	NW	0.37
32	9/05/79	K	√	28.9	27.8	-1.1	11.1	NW	0.62
33	9/05/79	K	×	28.9	28.3	-0.6	12.9	NW	0.46
34	10/22/79	K	×	25.6	24.4	-1.1	3.1	SW	0.27
35	10/22/79	K	√	27.8	26.1	-1.7	14.5	SW	0.67
36	10/22/79	K	×	27.2	27.2	0	19.4	SW	0.66
37	1/10/80	K	×	4.4	20.6	16.1	5.7	NE	0.39
38	1/10/80	K	√	7.2	21.1	13.9	3.1	W	0.56

Table 2 (continued)

Run No.	Date	Dryer location[a]	Dryer operating[b]	Outside temp. (°C)	Inside temp. (°C)	Temp. difference (°C)	Wind speed (km/h)	Wind direction	Measured inf. rate (per hour)
39	1/10/80	K	×	8.9	21.1	12.2	3.9	W	0.34
40	1/18/80	K	×	12.8	21.4	8.6	5.4	N	0.31
41	1/18/80	K	✓	13.3	21.7	8.3	7.3	N	0.53
42	1/24/80	K	×	7.2	20.0	12.8	28.2	SW	0.77
43	1/24/80	K	✓	10.6	20.8	10.3	40.1	SW	1.29
44	1/24/80	K	×	10.6	20.8	10.3	38.6	SW	1.06
45	1/29/80	K	×	1.1	20.0	18.9	6.5	NW	0.52
46	1/29/80	K	✓	1.1	20.0	18.9	7.3	N	0.70
47	1/29/80	K	×	1.7	20.3	18.6	8.0	N	0.51
48	2/02/80	K	×	-5.6	18.3	23.9	6.5	N	0.60
49	2/02/80	K	✓	-5.0	18.9	23.9	6.5	N	0.80
50	2/02/80	K	×	-4.4	19.4	23.9	6.5	N	0.63
51	2/15/80	K	×	11.1	21.1	10	6.5	SW	0.35
52	2/18/80	K	×	3.3	19.4	16.1	4.9	SE	0.46
53	2/18/80	K	✓	6.7	20.3	13.6	4.9	W	0.65
54	2/18/80	K	×	6.7	20.6	13.9	6.5	W	0.50
55	2/20/80	K	×	5.0	20.6	15.6	1.6	S	0.39
56	2/20/80	K	✓	6.1	21.1	15.0	3.1	SE	0.54
57	2/20/80	K	×	6.7	21.1	14.4	3.1	SW	0.40
58	2/20/80	K	✓	6.7	21.1	14.4	4.9	SW	0.61
59	2/20/80	K	×	6.7	21.1	14.4	3.1	SW	0.39
60	2/20/80	K	✓	6.7	21.1	14.4	4.9	SW	0.51
61	2/28/80	K	×	15.0	21.7	6.7	27.4	SW	0.75
62	2/28/80	K	✓	19.4	22.2	2.8	29.0	SW	0.82
63	2/28/80	K	×	20.6	22.2	1.7	32.1	SW	0.77
64	2/29/80	K	×	4.4	21.1	16.7	14.5	N	0.55
65	2/29/80	K	✓	5.0	21.1	16.1	14.5	N	0.68
66	2/29/80	K	×	5.0	21.1	16.1	14.5	NE	0.53
67	2/29/80	K	×	6.1	21.7	15.6	16.1	N	0.51
68	2/29/80	K	✓	5.6	21.7	16.1	16.1	N	0.66
69	6/04/80	NV	×	30	25.6	-4.4	8.0	E	0.33

[a] NV = no vent; UR = utility room; K = kitchen.
[b] × = no; ✓ = yes.

Table 3. Sample operating data

RUN # 37 1/10/80
DRYER IN KITCHEN DRYER OFF

TIME (MIN)	RDG	WIND KM/H	WIND DIR	TEMP (C) IN	TEMP (C) OUT	TEMP (C) DIFF	LN (C/C_0)
0	550	8.0	36	20.6	2.8	17.8	0.000
15	499	4.8	57	20.6	3.3	17.3	-0.097
30	453	4.8	91	21.1	3.9	17.2	-0.194
45	413	4.8	19	21.1	5.0	16.1	-0.286
60	371	6.4	45	21.1	5.6	15.5	-0.394
75	338	4.8	49	21.1	6.7	14.4	-0.487

THE INFILTRATION RATE IS -0.392 AIR CHANGES PER HOUR
THE CORRELATION COEFFICIENT IS -1.000

RUN # 38 1/10/80 DRYER OPERATING,
DRYER IN KITCHEN VENTING OUTSIDE

0	764	4.8	349	21.1	6.7	14.4	0.000
15	649	4.8	88	21.1	7.2	13.9	-0.163
30	561	3.2	248	21.1	7.2	13.9	-0.309
45	492	3.2	248	21.1	8.3	12.8	-0.440
60	423	3.2	217	21.1	7.8	13.3	-0.591
75	371	3.2	233	21.7	8.3	13.4	-0.722

THE INFILTRATION RATE IS -0.560 AIR CHANGES PER HOUR
THE CORRELATION COEFFICIENT IS -1.000

NOTES:
RDG=TRACER GAS METER READING
WIND DIR=WIND DIRECTION IN DEGREES
LN(C/C_0) =LN CONCENTRATION TRACER GAS RATIO

About halfway through the time period over which the infiltration data were being gathered, a new heat pump and some external (crawl space) ductwork were installed in the control house. The house displayed much tighter infiltration characteristics after the installation was completed (probably because the new ductwork was more leak free than the old). Table 4 contains the infiltration data (dryer not operating) and the corresponding equation to fit the data before the modification, and Table 5 contains the data and equation for the house after the modification, again with the dryer not operating. The sensitivity of the house infiltration rate to wind decreased by 27%

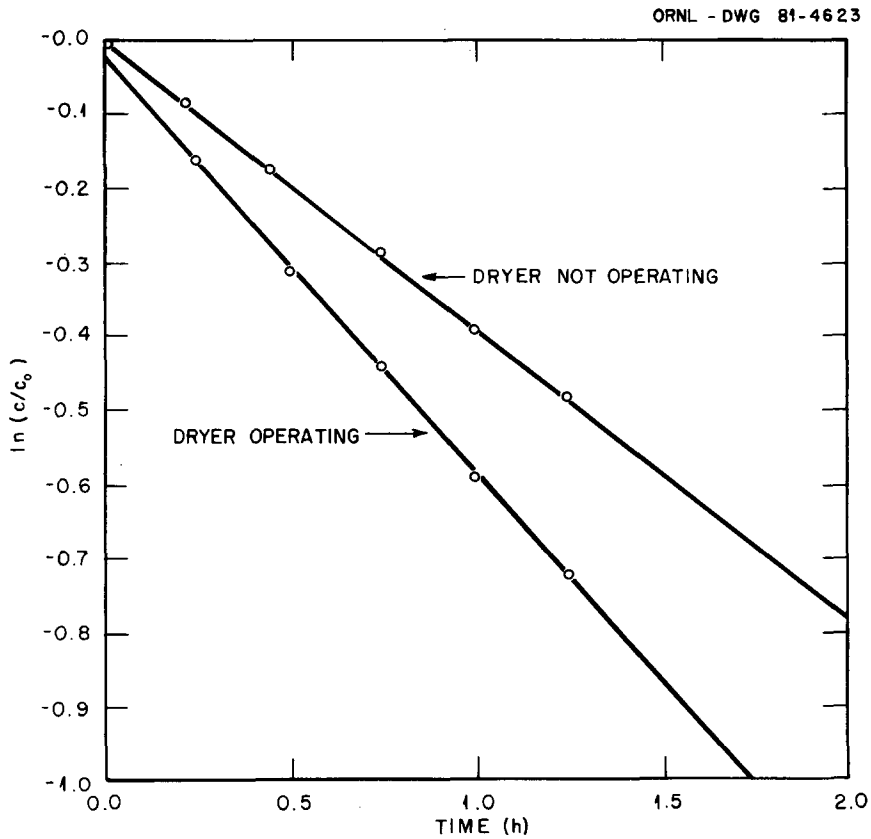

Fig. 8. Infiltration data plot, January 10, 1980.

[0.026 ACPH/(km/h) to 0.019 ACPH/(km/h)] and the sensitivity to temperature difference decreased by 36% (0.022 ACPH/C° to 0.014 ACPH/C°). The house constant for no wind or temperature differences remained essentially the same at 0.12 ACPH.

Tables 4 and 5 both show a maximum difference between measured and predicted infiltration rates of ±0.13 ACPH, with most values differing by less than ±0.06 ACPH.

To arrive at a relationship to determine the effect of the operating, outside-vented dryer on the house infiltration rate, measurements of the infiltration rates were made under similar conditions both with the dryer operating and not operating. Even though an effort was made to choose days when weather conditions were constant, these conditions did change slightly between test runs on any given day. Therefore, the infiltration rates measured with the dryer not operating were normalized to those weather conditions prevailing during the corresponding infil-

Table 4. Comparison of measured and predicted infiltration rates before house modification

The equation used is I_0(ACPH) = 0.1159 + 0.026WS (km/h) + 0.022DT (C)

TEMP DIFF (C)	WIND SPEED KM/H	WIND DIR	INFILT RATE (ACPH) MEAS	PRED	DIFF (ACPH)	%DIFF
5.6	0.0	--	0.20	0.24	0.04	19.6
26.7	16.1	W	1.05	1.12	0.07	6.8
19.4	13.0	SW	0.81	0.88	0.07	8.7
19.4	4.9	E	0.70	0.67	-0.03	-4.3
16.7	8.0	NE	0.62	0.69	0.07	11.5
14.4	8.0	NE	0.60	0.64	0.04	6.8
13.3	6.5	SW	0.66	0.58	-0.08	-12.5
12.8	11.1	SW	0.66	0.69	0.03	4.0
20.0	8.0	NE	0.81	0.76	-0.05	-5.7
18.9	8.0	NE	0.74	0.74	-0.00	-0.0
12.2	11.1	SW	0.74	0.67	-0.07	-9.1
10.0	9.6	SW	0.60	0.59	-0.01	-2.4
7.2	25.6	SW	0.93	0.94	0.01	1.1
4.4	16.1	SW	0.75	0.63	-0.12	-15.8
1.1	11.1	W	0.42	0.43	0.01	2.1
4.4	4.9	NE	0.29	0.34	0.05	17.3
2.2	6.5	SW	0.27	0.33	0.06	23.4
0.6	8.0	NE	0.27	0.34	0.07	24.9
0.6	4.9	SW	0.32	0.26	-0.06	-19.8
0.0	6.5	SW	0.29	0.28	-0.01	-1.8
2.8	9.6	SW	0.33	0.43	0.10	29.4
1.1	9.6	NW	0.37	0.39	0.02	5.3
0.6	12.9	NW	0.46	0.46	0.00	1.0
0.6	3.1	SW	0.27	0.21	-0.06	-22.3
0.0	19.4	SW	0.66	0.62	-0.04	-6.0

NOTES:
I_0 = INFILTRATION RATE
ACPH = AIR CHANGES PER HOUR
WS = WIND SPEED
DT = ABS(INSIDE-OUTSIDE TEMP DIFF)

tration measurement with the dryer operating. The slopes for the wind speed and temperature difference factors in Tables 4 and 5 were used for the normalization. Table 6 contains the normalized data for each set of corresponding runs.

Table A.2 in the appendix contains the data and results of measurements of the dryer vent rate (with the dryer hose and vent kit attached)

Table 5. Comparison of measured and predicted infiltration rates after house modification

The equation used is I_0(ACPH) = 0.1202 + 0.019WS (km/h) + 0.014DT (C)

TEMP DIFF (C)	WIND SPEED (KM/H)	WIND DIR	INFILT RATE (ACPH) MEAS	PRED	DIFF (ACPH)	%DIFF
16.1	5.7	NE	0.39	0.45	0.06	16.4
12.2	3.9	W	0.34	0.37	0.03	7.4
8.6	5.4	N	0.31	0.34	0.03	10.7
12.8	28.2	SW	0.77	0.84	0.07	8.5
10.3	38.6	SW	1.06	1.00	-0.06	-5.9
18.9	6.5	NW	0.52	0.51	-0.01	-2.3
18.6	8.0	N	0.51	0.53	0.02	4.4
23.9	6.5	N	0.60	0.58	-0.02	-3.6
23.9	6.5	N	0.63	0.58	-0.05	-8.2
10.0	6.5	SW	0.35	0.38	0.03	9.6
16.1	4.9	SE	0.46	0.44	-0.02	-4.6
13.9	6.5	W	0.50	0.44	-0.06	-12.3
15.6	1.6	S	0.39	0.37	-0.02	-5.4
14.4	3.1	SW	0.40	0.38	-0.02	-4.8
14.4	3.1	SW	0.39	0.38	-0.01	-2.4
6.7	27.4	SW	0.75	0.73	-0.02	-2.1
1.7	32.1	SW	0.77	0.75	-0.02	-2.1
16.7	14.5	N	0.55	0.63	0.08	14.5
16.1	14.5	NE	0.53	0.62	0.09	17.2
15.6	16.1	N	0.51	0.64	0.13	26.4
4.4	8.0	E	0.33	0.33	0.00	1.2

NOTES:
I_0 = INFILTRATION RATE
ACPH = AIR CHANGES PER HOUR
WS = WIND SPEED
DT = ABS(INSIDE-OUTSIDE TEMP DIFF)

made in the laboratory. The measured vent rate was 3.49 m^3/min (123 cfm). Via telecon, Sears' Engineering Laboratories in Chicago quoted a value of 3.4 m^3/min (120 cfm) for a vent rate of the dryer with hose and vent kit attached. The dryer vent rate of 3.4 m^3/min amounts to an equivalent infiltration rate of 0.45 ACPH in the control house.

Table 6 also contains tabulations for each set of runs for the house infiltration rate with the dryer off divided by the dryer vent rate (I_o/V) as well as for the change in the house infiltration rate with the dryer on divided by the dryer vent rate [$(I - I_o)/V$].

Table 6. Normalization of infiltration data for Fig. 9

Run numbers	I_o (ACPH)	Delta Temp. diff. (C)	Delta Wind speed (km/h)	I_o norm. (A C P H)	I (A C P H)	$I-I_o$ (A C P H)	I_o/V	$(I-I_o)/V$
3& 4	0.81	-0.5	0.0	0.80	0.83	0.03	1.78	0.07
5& 6	0.70	-2.7	0.0	0.64	0.84	0.20	1.42	0.44
8& 9	0.60	0.6	0.0	0.61	0.69	0.08	1.36	0.17
11& 12	0.66	0.0	5.0	0.79	0.78	-0.01	1.76	-0.02
14& 15	0.84	0.0	0.0	0.84	0.88	0.04	1.87	0.09
17& 18	0.60	0.6	0.0	0.61	0.59	-0.02	1.36	-0.05
19& 20	0.93	-2.8	-3.1	0.79	0.85	0.06	1.75	0.14
22& 23	0.42	3.9	13.0	0.84	0.62	-0.22	1.88	-0.50
29& 30	0.33	0.5	-1.6	0.30	0.61	0.31	0.67	0.69
32& 33	0.46	0.5	-1.8	0.42	0.62	0.20	0.94	0.44
35& 36	0.66	1.7	-4.9	0.57	0.67	0.10	1.27	0.22
38& 39	0.34	1.7	-0.8	0.35	0.56	0.21	0.77	0.47
40& 41	0.31	-0.3	1.9	0.34	0.53	0.19	0.76	0.42
43& 44	1.06	0.0	1.5	1.09	1.29	0.20	2.42	0.45
45& 46	0.52	0.0	0.8	0.54	0.70	0.16	1.19	0.37
49& 50	0.63	0.0	0.0	0.63	0.80	0.17	1.40	0.38
53& 54	0.50	-0.3	-1.6	0.47	0.65	0.18	1.03	0.41
55& 56	0.39	-0.6	1.5	0.41	0.54	0.13	0.91	0.29
57& 58	0.40	0.0	1.8	0.43	0.61	0.18	0.96	0.39
62& 63	0.77	1.1	-3.1	0.73	0.82	0.09	1.61	0.21
65& 66	0.53	0.0	0.0	0.53	0.68	0.15	1.18	0.33
67& 68	0.51	0.5	0.0	0.52	0.66	0.14	1.15	0.32

Notes:

I_o = infiltration rate with dryer off.
I = infiltration rate with dryer on (venting outside).
V = vent rate of dryer.
$I - I_o$ = change in infiltration rate.

Figure 9 is a plot of the two dimensionless quantities, $X = I_o/V$ versus $Y = (I - I_o)/V$. The boundary conditions for the resulting curve are that at $X = 0$, $Y = 1$ and that at $X = \infty$, $Y = 0$. These boundary conditions mean that when the infiltration rate of the house is 0 and the dryer is turned on, the house infiltration rate must be equal to the dryer vent rate; and when the house infiltration rate is infinitely large, the change in the infiltration rate caused by turning the dryer on is infinitesimal.

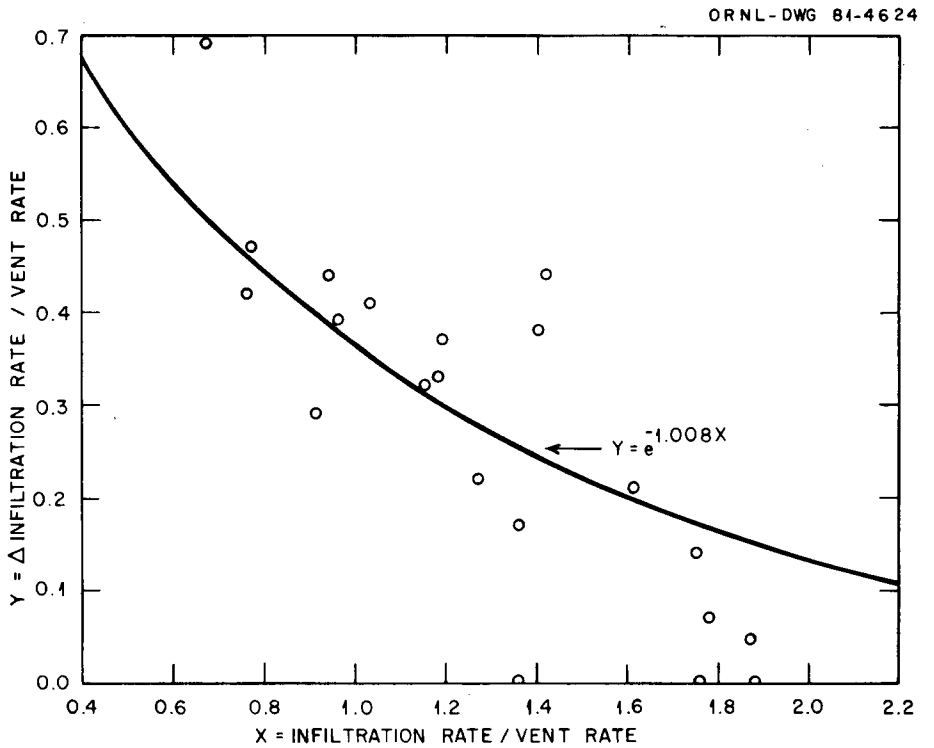

Fig. 9. Effect of vented dryer on infiltration rate.

Although other models may fit the data in the limited range covered, for the more general case, the boundary conditions dictate an exponential curve fit of the form $Y = e^{-AX}$ for the data. The value of the exponent A which minimizes the sum of the squares of the differences between the observed and predicted values of Y is -1.008. Hence, the equation best describing the data is

$$Y = e^{-1.008X} .$$

Little accuracy is lost by rounding off the exponent from -1.008X to -X. Therefore, the above equation may be written

$$Y = e^{-X} .$$

This equation may be rewritten in the more convenient form

$$I = I_o + V \times e^{-(I_o/V)} ,$$

where

I = the infiltration rate with the dryer on,

I_o = the infiltration rate with the dryer off,

V = the vent rate of the dryer.

Table 7 contains a comparison of the measured and predicted infiltration rates with the dryer operating. The predicted infiltration rates were calculated using the equations generated from Tables 4 and 5 and Fig. 9. All but two of the 23 predictions are within 17% of the

Table 7. Comparison of measured and predicted infiltration rates with dryer on

TEMP DIFF (C)	WIND SPEED (KM/H)	INFILTRATION RATE (ACPH) PREDICTED I_o	PREDICTED I	MEAS I	DIFF (ACPH)	% DIFF
18.9	12.9	0.87	0.93	0.83	-0.10	-12.2
16.7	4.9	0.61	0.73	0.84	0.11	13.7
15.0	8.0	0.65	0.76	0.69	-0.07	-9.8
12.8	16.1	0.82	0.89	0.78	-0.11	-13.9
18.9	8.0	0.74	0.83	0.88	0.05	6.2
10.6	9.6	0.60	0.72	0.59	-0.13	-21.4
4.4	22.5	0.80	0.87	0.85	-0.02	-2.7
5.0	24.0	0.85	0.92	0.62	-0.30	-47.9
3.3	8.0	0.40	0.58	0.61	0.03	4.6
1.1	11.1	0.43	0.60	0.62	0.02	3.1
1.7	14.5	0.53	0.67	0.67	0.00	0.4
13.9	3.1	0.37	0.57	0.56	-0.01	-1.5
8.3	7.3	0.38	0.57	0.53	-0.04	-7.4
10.3	40.1	1.03	1.07	1.29	0.22	16.9
18.9	7.3	0.52	0.66	0.70	0.04	5.3
23.9	6.5	0.58	0.70	0.80	0.10	12.3
13.6	4.9	0.40	0.59	0.65	0.06	9.9
15.0	3.1	0.39	0.58	0.54	-0.04	-6.9
14.4	4.9	0.41	0.59	0.61	0.02	2.9
14.4	4.9	0.41	0.59	0.51	-0.08	-16.2
2.8	29.0	0.71	0.80	0.82	0.02	2.2
16.1	14.5	0.62	0.73	0.68	-0.05	-7.8
16.1	16.1	0.65	0.76	0.66	-0.10	-14.6

Notes:

ACPH = air changes per hour
I_o = infiltration rate with dryer off.
I = infiltration rate with dryer on (venting outside).

measured values, and only three predicted values differ by more than 0.11 ACPH from the measured values.

The agreement between the measured and predicted values in Tables 4, 5, and 7 are similar to those experienced by many present-day investigators in the field.

To utilize the results of this study and put them into the proper perspective so far as venting clothes dryers is concerned, an analysis was done to determine the effect of a vented dryer on the control house's central heating and cooling system. Weather data[8,9] for 17 different cities in the United States were used to calculate monthly heating and cooling loads on the control house, assuming it were located in each of those cities. The additional house load caused by venting the dryer was calculated for each city assuming a monthly dryer usage of 34 loads per month. Table 8 contains a summary of the annual effect of the vented dryer in each of the listed cities for houses containing central heat pumps or electric resistance heat with central air

Table 8. Annual effect of vented dryer on two types of HVAC systems

CITY	DELTA HVAC LOAD (KWH/YR) ELEC RES & A/C HOUSE HTG	CLG	TOTAL	ELEC HEAT PUMP HOUSE HTG	CLG	TOTAL
ALBUQUERQUE, NM	47.8	3.7	51.5	25.3	3.7	29.0
ATLANTA, GEORGIA	32.2	5.5	37.8	16.4	5.5	22.0
BOSTON, MASS	39.5	1.2	40.6	22.9	1.2	24.1
CHICAGO, ILLINOIS	49.3	2.2	51.5	29.5	2.2	31.8
DENVER, COLORADO	55.9	1.0	56.9	32.3	1.0	33.3
FT WORTH, TEXAS	22.9	7.2	30.1	11.6	7.2	18.9
KNOXVILLE, TENN	46.0	4.8	50.8	24.0	4.8	28.7
LOS ANGELES, CAL	38.1	0.0	38.1	18.0	0.0	18.0
MINNEAPOLIS, MINN	55.5	0.8	56.3	36.8	0.8	37.6
NEWARK, NEW JERSEY	46.4	2.5	48.9	25.0	2.5	27.4
PITTSBURGH, PA	51.5	0.7	52.2	29.5	0.7	30.1
SAN FRANCISCO, CAL	47.5	0.0	47.5	22.5	0.0	22.5
SEATTLE, WASH	67.6	0.0	67.6	33.3	0.0	33.3
TAMPA, FLORIDA	11.1	10.8	21.9	5.3	10.8	16.1
WASHINGTON, DC	40.6	3.6	44.2	21.8	3.6	25.5
WESTHAMPTON, NY	43.3	1.2	44.5	23.7	1.2	24.9
WILMINGTON, DEL	49.6	2.3	51.9	26.7	2.3	29.0

NOTE:
AVERAGE MONTHLY TEMPERATURES AND WIND VELOCITIES USED

conditioners. Tables A.3 and A.4 in the appendix show samples of monthly results in three of the cities for which the calculations were made. A heat pump computer model developed by the author was used to produce Table A.4.

The additional electrical energy used by the house's HVAC system varies from a minimum of 16 kWh for a heat-pump-equipped house in Tampa to a maximum of 67.6 kWh for a resistance-heated house in Seattle. Using 5¢/kWh as the average cost of electricity, the maximum yearly cost of this energy would be $3.38 for the Seattle house. The typical electric dryer uses about 1100 kWh/year,[1] so the added energy used by the house HVAC system caused by the vented dryer is usually less than 5% of the energy used by the dryer.

Table 9 contains the results of a calculation that shows the effect of locating a dryer in various "unconditioned" spaces of a residence. The spaces modeled are an attached breezeway, an integral garage, and an unconditioned utility room. The assumptions made for the inlet dryer air temperature (before it gets heated by the dryer heating elements) are contained in Table 9. The results are expressed as the additional electrical energy used by the dryer relative to a base case of 21.1°C (70°F) inlet air to the dryer.

Table 10 combines the results in Tables 8 and 9 and shows the difference in the house energy consumption (combined HVAC + dryer kWh) for dryers located in unconditioned spaces compared to vented dryers in conditioned spaces for houses with either resistance heat and electric air conditioning or an electric heat pump.

Recalling that the average electric clothes dryer uses 1100 kWh/year and using the values from Table 10, one concludes that electric dryer energy consumption may be cut by about 14% in Los Angeles and Tampa by locating the dryer in an unconditioned utility room. However, in Boston, Chicago, and Minneapolis, locating the dryer in a conditioned space in the house and venting it outside can reduce house consumption by about 30 kWh/year.

In southern cities locating a dryer in an unconditioned space generally promotes energy savings, and in northern cities a location in a conditioned area of the house can be favorable, especially if the house is heated with a heat pump.

Table 9. Dryer energy consumption in unconditioned space relative to base case of 21.1C inlet air temperature

CITY	ADDITIONAL KWH/YR USED BY DRYER IN ATTACHED BREEZEWAY	INTEGRAL GARAGE	UNCOND UTIL RM
ALBUQUERQUE, NM	144.7	76.1	-1.4
ATLANTA, GEORGIA	102.7	34.9	-32.9
BOSTON, MASS	203.8	141.1	54.8
CHICAGO, ILLINOIS	196.5	135.5	52.7
DENVER, COLORADO	213.2	137.9	32.4
FT WORTH, TEXAS	56.0	-11.7	-79.5
KNOXVILLE, TENN	125.9	48.4	-29.0
LOS ANGELES, CAL	100.2	-16.0	-132.2
MINNEAPOLIS, MINN	206.5	155.1	89.3
NEWARK, NEW JERSEY	168.3	99.6	12.4
PITTSBURGH, PA	193.3	127.2	33.1
SAN FRANCISCO, CAL	147.3	31.1	-85.1
SEATTLE, WASH	207.5	91.3	-24.9
TAMPA, FLORIDA	-23.8	-72.2	-120.6
WASHINGTON, DC	158.5	86.9	-0.3
WESTHAMPTON, NY	200.1	130.8	34.2
WILMINGTON, DEL	169.8	100.3	13.2

NOTES: THE FOLLOWING MODELS AND ASSUMPTIONS WERE USED

ATTACHED BREEZEWAY
- INLET AIR TEMPERATURE FOLLOWS OUTSIDE AIR TEMP TO 40F
- INLET AIR TEMP NEVER FALLS BELOW 40F

INTEGRAL GARAGE
- INLET AIR TEMP FOLLOWS OUTDOOR AIR TEMP TO 70F
- AT OUTDOOR AIR TEMPS BELOW 70F, INLET AIR=OUTDOOR AIR+10F
- INLET AIR TEMP NEVER FALLS BELOW 40F
- DRYER VENTS OUTSIDE

UNCONDITIONED UTILITY ROOM
- INLET AIR TEMP FOLLOWS OUTDOOR AIR TEMP TO 70F
- AT OUTDOOR AIR TEMPS BELOW 70F, INLET AIR=OUTDOOR AIR+20F
- INLET AIR TEMP NEVER FALLS BELOW 40F
- DRYER VENTS OUTSIDE

Table 10. Difference in house energy consumption for dryers located in unconditioned spaces compared to vented dryer in conditioned space for houses with two types of HVAC systems[a]

City	Additional kWh/year used for dryer located in					
	Attached breezeway		Integral garage		Uncond. util. room	
	Res/AC	Heat pump	Res/AC	Heat pump	Res/AC	Heat pump
Albuquerque, N.Mex.	93.2	115.7	24.6	47.1	-52.9	-30.4
Atlanta, Ga.	64.9	80.7	-2.9	12.9	-70.7	-54.9
Boston, Mass.	163.2	179.7	100.5	117.0	14.2	30.7
Chicago, Ill.	145.0	164.7	84.0	103.7	1.2	20.9
Denver, Colo.	156.3	179.9	81.0	104.6	-24.5	-0.9
Ft. Worth, Tex.	25.9	37.1	-41.8	-30.6	-109.6	-98.4
Knoxville, Tenn.	75.1	97.2	-2.4	19.7	-79.8	-57.7
Los Angeles, Calif.	62.1	82.2	-54.1	-34.0	-170.3	-150.2
Minneapolis, Minn.	150.2	168.9	98.8	117.5	33.0	51.7
Newark, N.J.	119.4	140.9	50.7	72.2	-36.5	-15.0
Pittsburgh, Pa.	141.1	163.2	75.0	97.1	-19.1	3.0
San Francisco, Calif.	99.8	124.8	-16.4	8.6	-132.6	-107.6
Seattle, Wash.	139.9	174.2	23.7	58.0	-92.5	-58.2
Tampa, Fla.	-45.7	-39.9	-94.1	-88.3	-142.5	-136.7
Washington, D.C.	114.3	133.0	42.7	61.4	-44.5	-25.8
Westhampton, N.Y.	155.6	175.2	86.3	105.9	-10.3	9.3
Wilmington, Del.	117.9	140.8	48.4	71.3	-38.7	-15.8

[a]The following models and assumptions were used:

Attached breezeway
- Inlet air temperature follows outside air temperature to 40°F.
- Inlet air temperature never falls below 40°F.

Integral garage
- Inlet air temperature follows outdoor air temperature to 70°F.
- At outdoor air temperatures below 70°F, inlet air = outdoor air + 10°F.
- Inlet air temperature never falls below 40°F.
- Dryer vents outside.

Unconditioned utility room
- Inlet air temperature follows outdoor air temperature to 70°F.
- At outdoor air temperatures below 70°F, inlet air = outdoor air + 20°F.
- Inlet air temperature never falls below 40°F.
- Dryer vents outside.

House energy consumption = combined HVAC + dryer kWh.

Res/AC = Resistance heat + electric air conditioning.

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Appendix A

SAMPLE CALCULATIONS AND MEASUREMENTS

Table A.1. Derivation of the least squares fit

For an equation of the form $I_o = A + (B \times WS) + (C \times \Delta T)$, where

I_o = predicted infiltration rate (ACPH), dryer off,
I_o^* = measured infiltration rate (ACPH), dryer off,
WS = wind speed (km/h),
ΔT = temperature difference, outside to inside (C°),
A,B,C = empirical constants for a given structure,

let S = sum of the squares of the differences between the observed and the predicted infiltration rates. Then

$$S = \sum_1^N \{I_o^* - [A + (B \times WS) + (C \times \Delta T)]\}^2 .$$

To minimize S one must set the first derivatives with respect to A, B, and C equal to zero.

$$\frac{\partial S}{\partial A} = 0 = 2\sum_1^N \{I_o^* - [A + (B \times WS) + (C \times \Delta T)]\} \times (-1) ,$$

$$\frac{\partial S}{\partial B} = 0 = 2\sum_1^N \{I_o^* - [A + (B \times WS) + (C \times \Delta T)]\} \times (-WS) ,$$

$$\frac{\partial S}{\partial C} = 0 = 2\sum_1^N \{I_o^* - [A + (B \times WS) + (C \times \Delta T)]\} \times (-\Delta T) .$$

Expanding the above gives

$$(A \times N) + \sum (B \times WS) + \sum (C \times \Delta T) = \sum I_o^* ,$$

$$\sum(A \times WS) + \sum (B \times WS^2) + \sum (C \times \Delta T \times WS) = \sum I_o^* \times WS ,$$

$$\sum(A \times \Delta T) + \sum (B \times WS \times \Delta T) + \sum (C \times \Delta T^2) = \sum I_o^* \times \Delta T .$$

Using the measured data from Table 2 results in

Case 1. $I_o = 0.1159 + 0.026WS$ (km/h) $+ 0.022\Delta T$ (C°) ,

Case 2. $I_o = 0.1202 + 0.019WS$ (km/h) $+ 0.014\Delta T$ (C°) .

Table A.2. Measured vent rate of dryer (7/9/80) with vent kit attached[a]

Trial	Time (s)	Anemometer reading (m)	Inlet temp. (°C)	Exhaust temp. (°C)
1	60	532.2	33.6	71.1
2	120	1046.8	33.7	71.1
3	180	1598.4	34.0	71.1
4	60	531.8	34.1	71.1
5	120	1051.4	34.1	71.1
6	180	1596.3	34.1	71.1

[a]Average diameter of duct = 0.0991 m; area of duct = 0.00771 m^2; average linear velocity = 529.7 m/min; and average exhaust temperature = 71.1°C. Correcting vent for air entering dryer at 21.1°C,

$$V = 0.071 m^2 \times 529.7 \frac{m}{min} \times \frac{(273 + 21.1)\ K}{(273 + 71.1)\ K} ,$$

$$V = 3.49 \frac{m^3}{min} (123\ cfm) .$$

Table A.3. Effect of vented dryer on HVAC systems

MONTH	TEMP (C)	WIND (KM/H)	DTEMP (C)	INFIL (ACPH)	DINFIL (ACPH)	HVAC SYSTEM DINFIL (M3/H)	DKWH/LOAD (KWH)	DKWH/MO (KWH)
				Albuquerque, New Mexico				
JAN	1.7	12.9	19.4	0.62	0.112	50.61	0.25	8.41
FEB	4.4	14.5	16.7	0.61	0.114	51.48	0.22	7.34
MAR	7.8	16.1	13.3	0.60	0.118	53.25	0.18	6.07
APR	13.3	17.7	7.8	0.55	0.130	58.91	0.12	3.92
MAY	18.3	16.1	2.8	0.46	0.162	73.27	0.05	1.74
JUN	23.9	16.1	2.8	0.46	0.162	73.27	-0.05	-1.74
JUL	26.1	14.5	5.0	0.46	0.162	73.25	-0.09	-3.13
AUG	24.4	12.9	3.3	0.40	0.182	82.38	-0.07	-2.35
SEP	21.1	14.5	0.0	0.39	0.188	85.21	0.00	0.00
OCT	14.4	12.9	6.7	0.45	0.164	74.49	0.12	4.25
NOV	6.7	12.9	14.4	0.55	0.130	58.88	0.21	7.27
DEC	2.8	11.3	18.3	0.58	0.124	55.97	0.26	8.77
				Atlanta, Georgia				
JAN	7.2	17.7	13.9	0.64	0.108	48.97	0.17	5.81
FEB	8.3	19.3	12.8	0.65	0.105	47.36	0.15	5.17
MAR	11.1	19.3	10.0	0.61	0.114	51.51	0.13	4.40
APR	16.1	17.7	5.0	0.52	0.141	64.07	0.08	2.74
MAY	21.1	14.5	0.0	0.39	0.188	85.21	0.00	0.00
JUN	25.0	12.9	3.9	0.41	0.179	81.01	-0.08	-2.69
JUL	26.1	12.9	5.0	0.43	0.173	78.33	-0.10	-3.35
AUG	25.6	12.9	4.4	0.42	0.176	79.66	-0.09	-3.03
SEP	22.8	12.9	1.7	0.38	0.191	86.64	-0.04	-1.23
OCT	17.2	14.5	3.9	0.44	0.167	75.76	0.07	2.52
NOV	10.6	16.1	10.6	0.56	0.128	57.92	0.15	5.23
DEC	6.7	16.1	14.4	0.61	0.114	51.49	0.19	6.36
				Boston, Massachusetts				
JAN	-1.1	20.9	22.2	0.81	0.073	33.29	0.19	6.32
FEB	-1.1	22.5	22.2	0.84	0.069	31.13	0.17	5.91
MAR	3.3	22.5	17.8	0.78	0.079	35.61	0.16	5.41
APR	11.1	27.4	10.0	0.76	0.081	36.84	0.09	3.15
MAY	17.2	24.1	3.9	0.62	0.112	50.68	0.05	1.68
JUN	20.0	22.5	1.1	0.55	0.130	58.94	0.02	0.56
JUL	23.3	20.9	2.2	0.54	0.135	60.94	-0.03	-1.16
AUG	22.2	4.8	1.1	0.22	0.272	123.18	-0.03	-1.17
SEP	18.3	22.5	2.8	0.58	0.124	56.04	0.04	1.33
OCT	12.8	19.3	8.3	0.59	0.120	54.17	0.11	3.86
NOV	7.2	20.9	13.9	0.70	0.095	42.83	0.15	5.08
DEC	0.6	20.9	20.6	0.79	0.077	35.01	0.18	6.15

Note: Negative numbers indicate additional cooling system kilowatt-hours.

Table A.4. Summary of heating and cooling data for house with medium-performance heat pump

HOUSE HEATING LOAD = 27910 - 423*T BTU/HR
HOUSE COOLING LOAD = 1467.2*T - 110715 BTU/HR

HEAT PUMP CAPACITY AT 47F = 31000 BTU/HR
A/C CAPACITY AT 95F = 27500 BTU/HR

	SUMMARY		HEATING			COOLING		
MON	TOTAL BTU	TOTAL KWH	BTU DLVRD	HTG KWH	COP	BTU REMVD	CLG KWH	COP
			Albuquerque, New Mexico					
JUN	5.349E+06	790.5	2.393E+05	40.0	2.12	5.060E+06	750.6	1.98
JUL	5.695E+06	844.9	7.429E+04	10.3	2.12	5.621E+06	834.6	1.97
AUG	4.518E+06	671.2	1.161E+05	16.1	2.12	4.402E+06	655.2	1.97
SEP	2.975E+06	438.5	6.820E+05	94.2	2.12	2.293E+06	344.3	1.95
OCT	3.119E+06	440.5	2.781E+06	388.3	2.10	3.386E+05	52.2	1.90
NOV	6.759E+06	1025.8	6.759E+06	1025.8	1.93	0.000E+00	0.0	0.00
DEC	9.373E+06	1507.6	9.373E+06	1507.6	1.82	0.000E+00	0.0	0.00
JAN	9.701E+06	1608.6	9.701E+06	1608.6	1.77	0.000E+00	0.0	0.00
FEB	7.479E+06	1192.0	7.479E+06	1192.0	1.84	0.000E+00	0.0	0.00
MAR	6.485E+06	980.7	6.479E+06	979.7	1.94	6.048E+03	1.0	1.86
APR	3.603E+06	515.9	3.404E+06	485.0	2.06	1.993E+05	30.8	1.89
MAY	3.050E+06	442.2	1.536E+06	213.6	2.11	1.514E+06	228.6	1.94
TOT	6.811E+07	10458.4	4.867E+07	7561.3	1.89	1.943E+07	2897.1	1.97
			Atlanta, Georgia					
JUN	3.992E+06	595.5	8.053E+04	11.1	2.12	3.912E+06	584.4	1.96
JUL	4.600E+06	688.2	1.025E+04	1.4	2.12	4.589E+06	686.7	1.96
AUG	4.746E+06	709.2	1.880E+04	2.6	2.12	4.727E+06	706.6	1.96
SEP	2.579E+06	384.7	3.171E+05	43.8	2.12	2.262E+06	340.9	1.94
OCT	2.374E+06	337.7	1.917E+06	267.8	2.10	4.563E+05	69.9	1.91
NOV	4.654E+06	680.6	4.626E+06	676.3	2.00	2.774E+04	4.3	1.88
DEC	7.071E+06	1086.1	7.071E+06	1086.1	1.91	0.000E+00	0.0	0.00
JAN	7.086E+06	1095.7	7.086E+06	1095.7	1.89	0.000E+00	0.0	0.00
FEB	5.593E+06	848.8	5.587E+06	847.8	1.93	6.048E+03	1.0	1.86
MAR	4.783E+06	697.8	4.734E+06	690.1	2.01	4.891E+04	7.6	1.87
APR	2.540E+06	361.7	2.101E+06	294.1	2.09	4.395E+05	67.7	1.90
MAY	2.619E+06	387.3	6.209E+05	85.8	2.12	1.998E+06	301.5	1.94
TOT	5.264E+07	7873.4	3.417E+07	5102.9	1.96	1.847E+07	2770.5	1.95
			Boston, Massachusetts					
JUN	2.578E+06	373.3	1.236E+06	71.0	2.12	1.342E+06	202.3	1.94
JUL	2.629E+06	389.7	5.176E+05	71.5	2.12	2.111E+06	318.2	1.94
AUG	3.961E+06	589.0	3.334E+05	46.1	2.12	3.627E+06	542.9	1.96
SEP	2.709E+06	387.7	2.091E+06	293.9	2.08	6.172E+05	93.7	1.93
OCT	4.786E+06	698.3	4.715E+06	687.3	2.01	7.112E+04	11.0	1.89
NOV	7.515E+06	1162.2	7.515E+06	1162.2	1.89	0.000E+00	0.0	0.00
DEC	1.168E+07	2122.2	1.168E+07	2122.2	1.61	0.000E+00	0.0	0.00
JAN	1.317E+07	2578.2	1.317E+07	2578.2	1.50	0.000E+00	0.0	0.00
FEB	1.135E+07	2136.8	1.135E+07	2136.8	1.56	0.000E+00	0.0	0.00
MAR	9.847E+06	1612.9	9.847E+06	1612.9	1.79	0.000E+00	0.0	0.00
APR	6.124E+06	910.4	6.082E+06	904.1	1.97	4.165E+04	6.3	1.92
MAY	3.595E+06	509.1	3.257E+06	457.8	2.08	3.383E+05	51.3	1.93
TOT	7.994E+07	13469.8	7.179E+07	12244.0	1.72	8.149E+06	1225.8	1.95

Table A.5. Pertinent statistics for Tables 4, 5, and 6

Table 4. Model without wind direction general linear models procedure

Dependent variable: I

Source	DF	SS	MS	F value	PR > F	R^2	C.V.
Model	2	1.28551	0.64276	185.10	0.0001	0.943907	10.6598
Error	22	0.07639	0.00347		STD DEV		I Mean
Corr. total	24	1.36190			0.05892		0.55280

Source	DF	Type I SS	F value	PR > F	DF	Type IV SS	F value	PR > F
WS	1	0.57592	165.85	0.0001	1	0.49275	141.90	0.0001
DELTAT	1	0.70959	204.35	0.0001	1	0.70959	204.35	0.0001

Parameter	Estimate	T for H0: parameter = 0	PR > |T|	STD ERR EST
Intercept	0.11413	4.23	0.0003	0.02700
WS	0.02644	11.91	0.0001	0.00222
DELTAT	0.02118	14.30	0.0001	0.00148

Table 5. Model without wind direction general linear models procedure

Dependent variable: I

Source	DF	SS	MS	F value	PR > F	R^2	C.V.
Model	2	0.64445	0.32222	106.58	0.0001	0.922132	10.4401
Error	18	0.05442	0.00302		STD DEV		I Mean
Corr. total	20	0.69887			0.05498		0.52667

Source	DF	Type I SS	F value	PR > F	DF	Type IV SS	F value	PR > F
WS	1	0.55175	182.50	0.0001	1	0.63897	211.35	0.0001
DELTAT	1	0.09270	30.66	0.0001	1	0.09270	30.66	0.0001

Parameter	Estimate	T for H0: parameter = 0	PR > |T|	STD ERR EST
Intercept	0.11438	2.53	0.0209	0.04518
WS	0.01885	14.54	0.0001	0.00130
DELTAT	0.01372	5.54	0.0001	0.00248

Table A.5 (continued)

Table 6. Nonlinear model $Y = \exp(-A \times X)$
Nonlinear least squares summary statistics, dependent variable Y

Source	DF	SS	MS	R^2
Regression	1	2.12484	2.12484	0.8452
Residual	21	0.38916	0.01853	
Uncorr. total	22	2.51400		
(Corr. total)	21	0.70974		

Parameter	Estimate	Asymptotic STD ERR	Asymptotic 95% confidence interval	
			Lower	Upper
A	1.00863	0.08699	0.82773	1.18954

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