NO. 2336

MEASUREMENT OF AIR-TIGHTNESS OF HOUSES

S. STRICKER, P.E.
Member ASHRAE

A technique for measuring the actual leakage area of houses was developed in an attempt to find causes of stubborn winter problems that had been encountered in a relatively small number of electrically heated houses in Ontario. The problems were high indoor humidity, wall-staining, cold areas, and high heating costs. This technique was used for two heating seasons as an aid in identifying the causes of these problems. A certain pattern appeared. Houses exhibiting high humidity were generally tighter than houses that had reported high heating costs (accompanied by dryness). Quite often, high humidity, attic condensation, and wall darkening (general or baseboard wall-streaking) were found to coincide, especially where smoking took place.

The method of measuring the air-tightness of a house involves operating a powerful exhaust fan temporarily installed through an open window and measuring the resulting pressure drop in the house. This measurement, combined with the fan pressure-flow characteristics, can be used to obtain the area of an opening that permits a similar air flow at the same pressure difference as that measured. The area of this opening is defined as the equivalent leakage area of the house, or ELA. The method is described in detail in Appendix A.

During the test, all exhaust fan and clothes-dryer vent dampers were allowed to operate normally. Fireplace dampers were kept closed. The furnace chimneys in the oil and gas heated houses were left open, but the operation of the burners was blocked during the test to avoid exhaust gases from backing up into the basement.

The negative pressure applied to the structure caused outdoor air to enter through openings, some of which could be felt. In three houses previously tested, the measured ELA was 2 1/2 to 3 times greater than the leakage calculated by the ASHRAE crackage method, indicating that other major leak sources must have existed. Plumbing and wiring openings and leaky headers and plates over foundation walls were common air leak problem areas.

To investigate the correlation between measured equivalent leakage area and these problems, an experiment was designed to observe the following expected correlations: (1) that relatively tight houses maintain higher indoor humidities than leaky houses, and (2) that high heating costs, cold areas, and low indoor humidities are a result of excessive leakage. Also, it was expected that in tight houses where smoking took place, pollution and wall staining levels would be high.

S. Stricker, B.A.Sc., P.Eng
Ontario Hydro, Toronto, Ontario, Canada

To investigate the effect of ELA on indoor absolute humidity, a linear regression analysis of indoor humidity versus 1/ELA was made using the March 1 data. This produced the straight line shown in Fig. 3. The correlation coefficient was 0.72 (compared to 1.0, which corresponds to a perfect fit). Note that the average outdoor humidity, 0.0028 lb water per lb air, was entered at 0 on the x-axis, corresponding to a house with an infinitely large ELA.

A similar analysis was made using the average humidity from February 5 to March 9. These results are presented graphically in Fig. 4. The correlation coefficient in this case is 0.764. Although there is a trend of high humidity levels in houses with small ELA's and vice versa, the deviations from the expected values are fairly large. No doubt many factors contribute to the deviations: different amounts of moisture generation from house to house, different effectiveness of air leaks depending on location, different house exposure, etc. Several attempts were made to find a correlation between indoor humidity and occupancy (man-hours) but the results were inconsistent, indicating a weak or non-existent relationship.

ENERGY CONSUMPTION

The energy required to heat the electrically heated houses was obtained by subtracting the estimated consumption of the water heater (100 kWH/person/month) from the gross metered energy. The energy used for lighting and cooking contributed towards heating the structure, so these components were not subtracted.

The estimated seasonal heating energy requirement was calculated from the transmission and infiltration (infiltration was assumed to be 1 ach on rooms above grade and 1/2 ach below grade) heat loss and the degree-days for the Toronto area, using a C factor of 14.5. Two new quantities were introduced:

Leakage Coefficient (LC) - defined to relate ELA to the volume of a house as $LC = ELA \times 10^4/\text{HOUSE VOLUME (cu ft)}$
Overconsumption - defined as the energy used in excess of the calculated heat loss as a percentage of the calculated heat loss.

A linear regression analysis of Overconsumption on LC (excluding points 7, 8 and 15 which were the worst behaved in the sample) gave a correlation coefficient of 0.49, Fig. 5. This rather poor correlation is caused by individual differences in solar heat gain, house exposure to wind, distribution of air leaks, and "heating habits". Although the correlation is weak, the general tendency appears to be, as expected, that houses with a high LC require relatively more heating energy.

AIR PARTICULATE LEVEL

Records of air particulate levels (or simply "pollution") were taken in living rooms only, so that the recorded levels were not necessarily the average for the entire house. The components of the particulate were not identified, but previous work indicated that cooking oils, smoke from burnt food, candle vapours, and tobacco smoke were the most frequent constituents.

The dilution and mixing of pollutants in a structure is a complex mechanism, so no attempt was made to account for it in this survey.

The indoor air pollution levels recorded in 22 houses varied widely with time and from house to house. The hourly pollution levels over 1 week periods are plotted in Figs. 6A to 6F. The estimated daily tobacco consumption and house ELA are indicated. The averages over the test periods are listed in Table 1, and they range from 0.131 to 1.34 coefficient of haze (COH, see Appendix B. Operation of exhaust fans are also presented on the same figures for Houses 8, 9, 17, 19 and 20 on a similar time-base.

MOISTURE BALANCE IN HOUSES

The two basic factors affecting indoor humidity levels are the rate of production of moisture (cooking, breathing, washing, etc) and the rate of removal of moisture by infiltration of drier outside air. The rate of moisture production is determined by occupancy and activity in the house, while the rate of removal is determined by air infiltration which is affected by wind speed and direction, area and location of structural openings, indoor-outdoor temperature difference, and building height. In Appendix C, the moisture balance equation is derived.

CONCLUSIONS

1. There is a noticeable tendency of tight houses to maintain higher humidities than others.
2. There is a slight tendency of leaky houses to require more heating energy than others.
3. Houses where smoking takes place have noticeably higher air pollution levels than others. Pollution levels above 0.70 COH can lead to wall staining.

Limitations of the ELA Measurement

Not all openings in a structure behave as sharp-edged orifices. For example, air leaks through window and door crackage can be expressed by(1):

$$Q = C\Delta p^{n} \tag{4}$$

where: C = proportionality constant

Δp = pressure difference across window

n = exponent of flow, between 1/2 and 1

Air leaks through porous materials, such as concrete blocks and insulation, can behave in a manner similar to flow through capillaries(2):

$$Q = \frac{\pi a^2}{8n} \left(\frac{dp}{dz}\right) \tag{5}$$

where: a = the radius of the capillary

n = the air viscosity

$\frac{dp}{dz}$ = the pressure gradient along the flow axis.

When air is exhausted from a house to produce a measurable pressure drop, the equivalent leakage area A calculated according to Eq (3) will be equal to the sum of the area of the individual openings only when these behave as sharp-edged orifices. Normally, some air leakage takes place through sharp-edged openings, Eq (3), some through door and window crackage, Eq (4), and some through porous materials such as concrete block or thermal insulation, Eq (5). Consequently, the equivalent leakage area A, calculated according to Eq (3), alone will generally not be equal to the sum of the area of all openings. It does, however, give an equivalent leakage at the specific test pressure. The method was used successfully to measure, within 3% to 5%, the area of a sliding window opened to 1, 1/2, 1/4 and 1/8 sq ft. The insect screen was left out for these measurements, as it reduces the measured area by a factor of about 2.

APPENDIX C

Derivation of Indoor Relative Humidity in Dwellings

In houses where there is no condensation on windows and subsequent accumulation of water or ice, the principal mechanism of moisture removal is infiltration of drier air. In a properly insulated house, moisture migration by permeating through building materials to the outside is about 0.5 lb/day on cold days. Compared to the amount of moisture released by a family of four people, about 20 lb/day, the amount that can be handled by permeation is negligible.

Suppose that initially, the moisture level in the structure is S lb water/cu ft of air, the level outside is F lb/cu ft, and that the rate of infiltration of "fresh" outside air into the structure is c cu ft/hr. By the law of conservation of mass ("whatever goes in must come out unless it stays there"), a mixture of "fresh" and "stale" (humid) air comes out of the house at the rate of c cu ft/hr. Assume that the fresh air is thoroughly mixed with the stale air as soon as it enters. Let the fraction of stale air in the structure at time t be X(t), and the fraction of fresh air be Y(t). Thus X(t) + Y(t) = 1. Initially, X(o) = 1, Y(o) = 0.

During a small interval of time (Δt):

the amount of air entering a house of volume V is cΔt cu ft;
the amount of stale air going out is X(t)cΔt cu ft;
the amount of fresh air going out is Y(t)cΔt.

The change in concentration of stale air in the interval Δt is:

$$\Delta X(t) = \frac{\text{final amount of stale air - initial amount}}{V} \qquad (6)$$

$$= \frac{(VX(t) - X(t)c\Delta t) - VX(t)}{V}$$

$$= \frac{-X(t)c\Delta t}{V}$$

therefore: $$\frac{\Delta X(t)}{\Delta t} = \frac{-X(t)c}{V}$$

In the limit, as Δt approaches zero:

$$\frac{dX(t)}{dt} = -X(t)\frac{c}{V} \qquad (7)$$

Solving:

$$\frac{dX(t)}{X(t)} = \frac{-cdt}{V}$$

$$\log X(t) = \frac{-ct}{V}$$

$$X(t) = e^{-\frac{ct}{V}}$$

Since: $$Y(t) = 1 - X(t)$$

then: $$Y(t) = 1 - e^{-\frac{ct}{V}}$$

TABLE I TABULATION OF HOUSE STATISTICS

HOUSE DESCRIPTION													APPLIANCES					OCCUPANCY					LIVING HABITS						HEATING ENERGY				LEAKAGE CHAR.		REMARKS
HOUSE NUMBER	HEATING SYSTEM (BASEBOARD, CENTRAL ELECTRIC, CABLE	FLOOR PLAN 2-STOREY, BUNGALOW, BACK SPLIT, SIDE SPLIT	CONSTRUCTION TYPE (BRICK VENEER, FRAME, SOLID MASONRY	ROOF TYPE (ATTIC, CATHEDRAL)	LIVING AREA (SQ FT) EXCL. BSMT	VOLUME (CU FT)	BASEMENT INSULATION (NORMAL, TO FLOOR, UNINSULATED)	BASEMENT FINISHED	BASEMENT WALL (BLOCK OR POURED)	BASEMENT WET OR DRY	WIND EXPOSURE (SHELTERED, MED, OR SEVERE)	NO OF FIREPLACES	CLOTHES DRYER	DRYER VENTED TO OUTSIDE	NO OF EXHAUST FANS	HUMIDIFIER	SUMP PUMP	NUMBER OF ADULTS	NUMBER OF CHILDREN	AGES OF CHILDREN	NUMBER OF DAYTIME OCCUPANTS	ESTIMATED MAN-HOUR OCCUPANCY PER DAY	ARE WINDOWS LEFT OPEN	IS HOUSE VENTILATED OCCASIONALLY	EXHAUST FANS USED (REGULAR, OCCASIONAL, OR SELDOM)	NUMBER OF SMOKERS	CIGARETTE CONSUMPTION PER DAY	AVERAGE POLLUTION LEVEL - COH	CALCULATED HEAT LOSS - KW	ESTIMATED HEATING ENERGY - KWH (C = 14.5)	TOTAL ENERGY CONSUMPTION (SEPT 1 TO APRIL 30)	HOT WATER ON FLAT RATE	EQUIVALENT LEAKAGE AREA - SQ FT	LEAKAGE COEFFICIENT	
1	B	2S	BV	A	1850	24100	F	NO	P	D	ME	1	YES	YES	3	NO	NO	2	2	4-8	3	88	NO	YES	O	2	10	0.396	19.2	27800	38100	NO	1.79	0.74	HIGH HEATING COST, COLD AREAS
2	CE	SS	BV	A	1200	15400	F	1/2	P	D	ME	1	NO	—	2	YES	NO	4	2	9-6	3	120	NO	YES	S	1	15	0.763	13.3	20200	30160	NO	1.72	1.11	
3	CA	SS	SM	A	1480	18500	F	YES	B	D	ME	2	YES	YES	2	YES	NO	3	0	—	1	56	NO	YES	R	1	6	0.462	15.5	22600	28800	NO	1.65	0.89	
4	B	SS	BV	A	1800	21300	N	YES	P	W	ME	1	YES	YES	3	YES	NO	4	1	5	1	38	NO	NO	R	1	10	0.498	17.5	25800	29300	YES	1.87	0.88	
5	OIL	B	BV	A	1630	26000	½N	NO	B	D	SE	1	NO	—	3	NO	YES	2	2	5-8	1	72	YES	NO	R	0	—	0.347	—	—	—	—	2.25	0.86	
6	B	SS	BV	A	1450	15200	N	NO	B	D	ME	1	NO	—	2	NO	NO	2	0	—	2	48	YES	NO	O	1	(P)	0.713	13.7	20200	29500	NO	1.96	1.29	SEVERE WALL-STAINING
7	CE	2S	BV	A	1440	14000	N	NO	B	D	ME	1	YES	YES	2	NO	NO	4	2	10-7	[illegible]	104	NO	YES	R	1	(P)	0.131	13.7	23100	24200	YES	1.47	1.05	
8	B	2S	SM	A	1660	21100	—	YES	P	D	ME	3	YES	YES	2	NO	NO	1	0	—	3-14	120	NO	YES	R	3	60	1.34	12.1	27300	46870	NO	2.18	1.03	WALL-STAINING, 3 CERAMIC KILNS
9	B	2S	BV	A	1750	21000	N	YES	P	D	SE	[illegible]	YES	YES	2	NO	NO	4	1	10	1	88	NO	YES	R	1	(P)	0.534	13.3	19600	24400	YES	1.33	0.63	
10	B	2S	BV	A	1850	25000	N	NO	P	D	ME	1	YES	YES	3	YES	NO	1	1	2	3	104	NO	YES	R	1	20	—	20.8	31500	44915	NO	1.96	0.78	
11	GAS	SS	SM	A	1600	18200	U	YES	B	D	ME	[illegible]	YES	YES	1	NO	NO	3	2	12-8	1	88	YES	YES	S	0	—	0.448	—	—	—	—	2.31	1.52	COLD AREAS
12	GAS	B	SM	A	1230	18700	U	YES	P	D	ME	—	YES	YES	1	NO	NO	3	1	9	2	80	NO	YES	S	1	3	0.851	—	—	—	—	1.52	0.81	
13	CA	B	F	A	780	12500	F	YES	B	D	ME	2	YES	YES	2	NO	YES	2	0	—	1	40	NO	YES	R	0	—	0.437	10.6	15600	23950	NO	1.23	0.98	
14	B	2S	SM	A	1300	15200	F	YES	B	D	ME	1	YES	YES	2	NO	NO	5	0	—	1	88	NO	NO	O	3	25	0.857	14.6	21200	24900	YES	1.45	0.95	
15	CE	2S	BV	A	1640	19700	N	NO	B	D	ME	1	YES	NO	2	YES	NO	2	3	9-7-4	2	96	—	—	R	1	10	—	17.6	25300	31700	NO	2.65	1.38	COLD AREAS
16	B	B	F	A	960	14400	F	YES	B	D	ME	—	YES	YES	3	NO	NO	3	1	12	1	72	NO	YES	R	2	20	0.996	9.7	14300	23980	NO	1.60	1.11	
17	CA	BS	BV	A	1060	14600	F	NO	B	D	ME	—	YES	YES	2	NO	NO	3	2	12-5	1	88	NO	NO	R	0	—	0.296	12.5	18900	25400	NO	1.10	0.75	HIGH HUMIDITY
18	B	B	SM	A	1460	23100	F	YES	B	D	ME	2	YES	YES	3	NO	NO	3	0	—	1	56	NO	YES	S	0	—	0.313	16.6	23300	23550	YES	1.72	0.75	
19	B	BS	BV	A	1060	14600	F	YES	B	D	ME	1	YES	YES	2	NO	NO	4	0	—	—	64	NO	YES	R	2	20	0.864	12.5	18900	24900	NO	1.52	1.04	
20	CA	2S	BV	A	1950	23400	N	YES	B	D	ME	1	YES	YES	2	YES	NO	2	5	10-3 MO	3	136	YES	YES	R	0	—	0.373	17.3	25500	41300	NO	1.90	0.81	
21	B	2S	BV	A	2073	28800	F	YES	B	W	SH	3	YES	YES	5	NO	NO	2	3	11-9-9	1	88	NO	NO	O	2	60	0.540	26.0	37700	42360	YES	2.50	0.88	
22	OIL	2S	SM	A	1100	12700	U	NO	B	D	SE	1	NO	—	0	YES	NO	2	0	—	1	40	NO	YES	—	0	—	0.823	—	—	—	—	1.60	1.26	
23	B	SS	BV	A	2320	27900	N	YES	B	D	ME	3	YES	NO	4	YES	NO	3	0	—	1	56	NO	YES	R	2	30	0.575	24.8	35700	50070	YES	3.90	1.40	HIGH HEATING COST
24	CE	BS	BV	A	1600	23300	N	NO	B	W	SE	1	YES	YES	1	NO	NO	2	1	6 MO	2	64	NO	NO	S	0	—	0.362	17.0	24600	28380	NO	1.80	0.77	HIGH HUMIDITY, WET BASEMENT

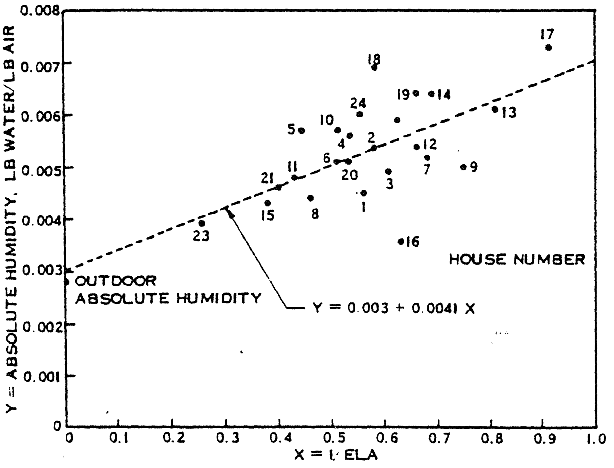


Fig. 3 Indoor humidity vs inverse of ELA March 1 data

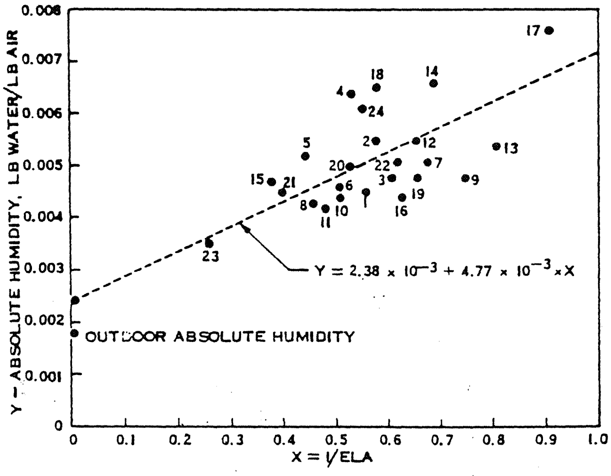


Fig. 4 Indoor humidity vs inverse of ELA Feb 5 - Mar 9 data

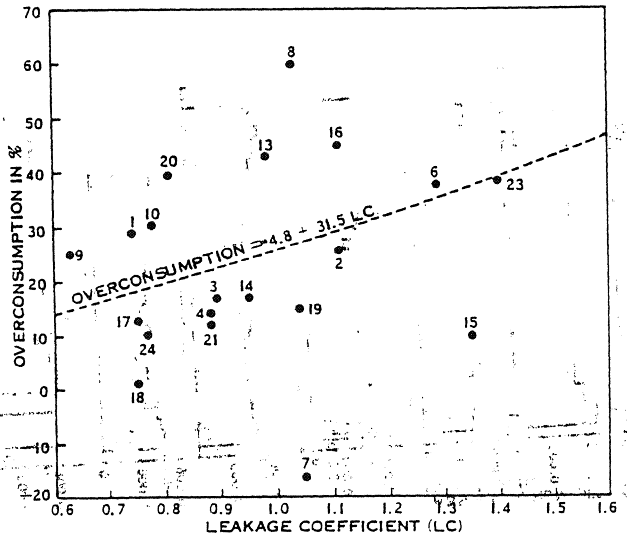


Fig. 5 Energy used in excess of estimate (%) vs leakage coefficient
$(LC=\frac{ELA \times 10^4}{House\ Vol})$

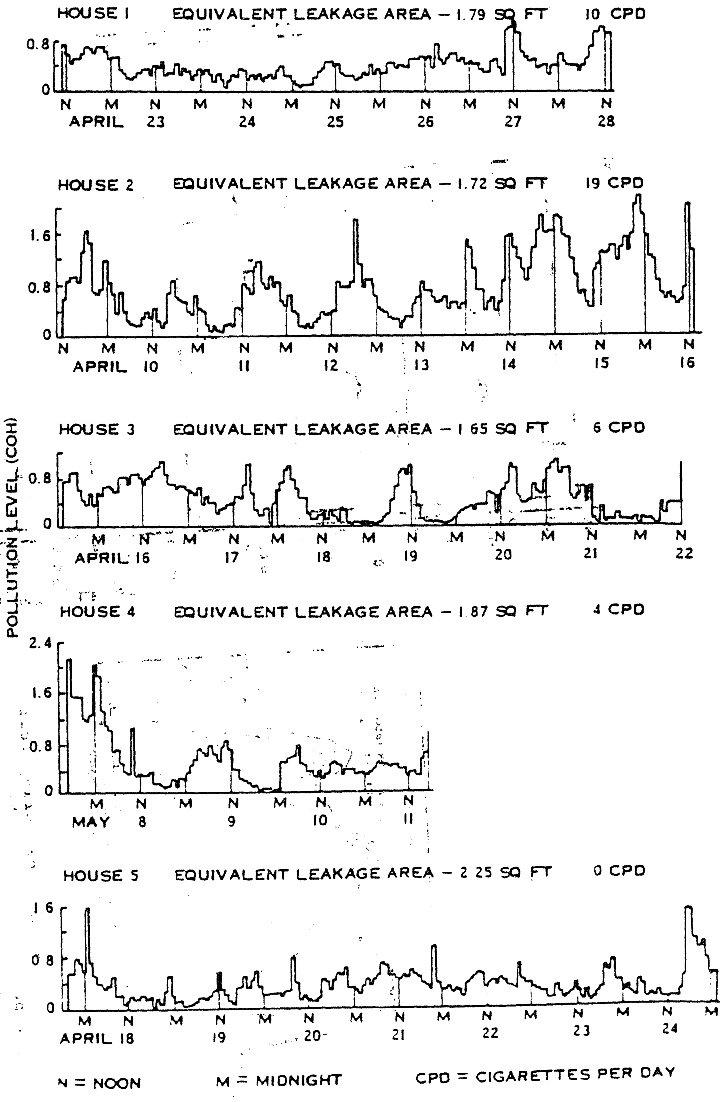


Fig. 6a Indoor pollution levels vs time

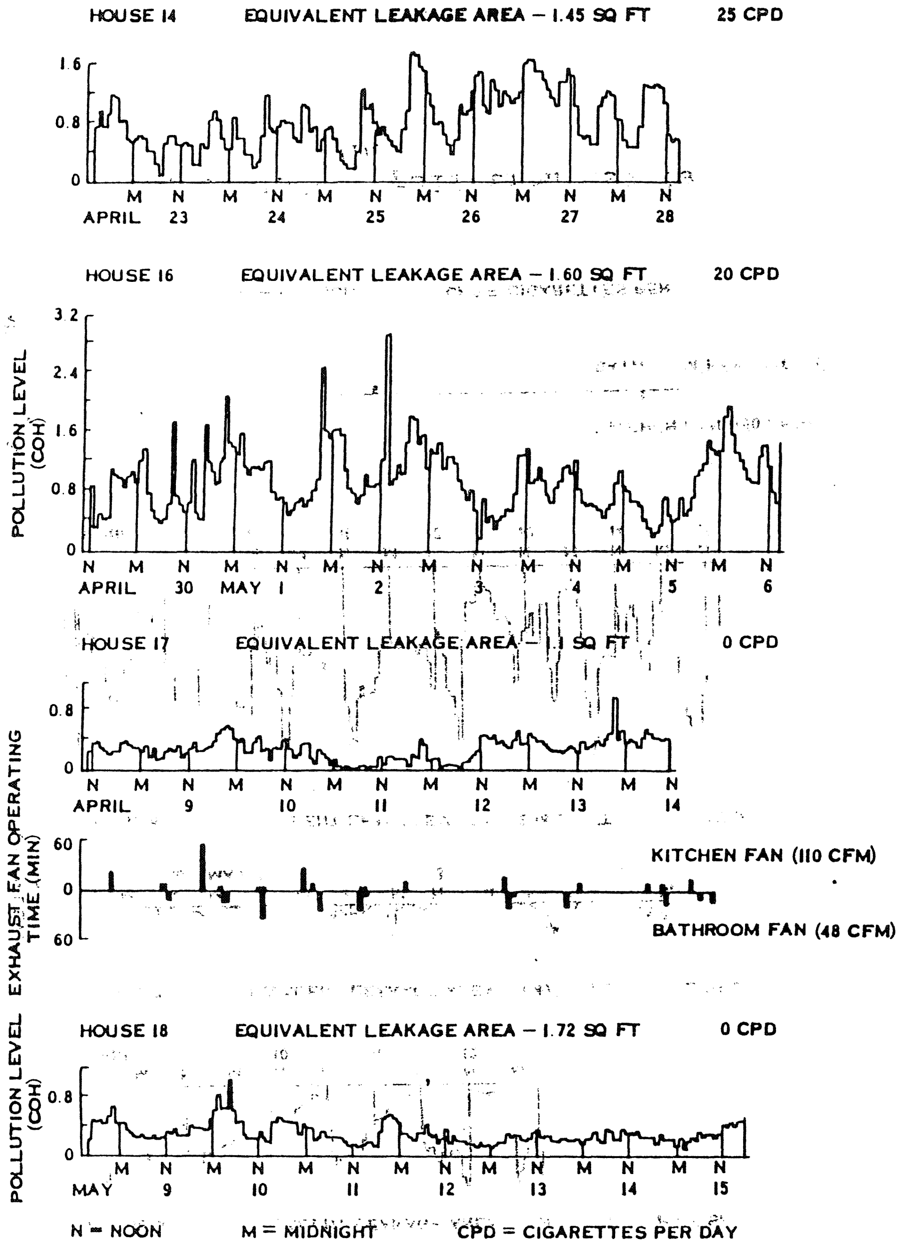


Fig. 6d Indoor pollution levels vs time

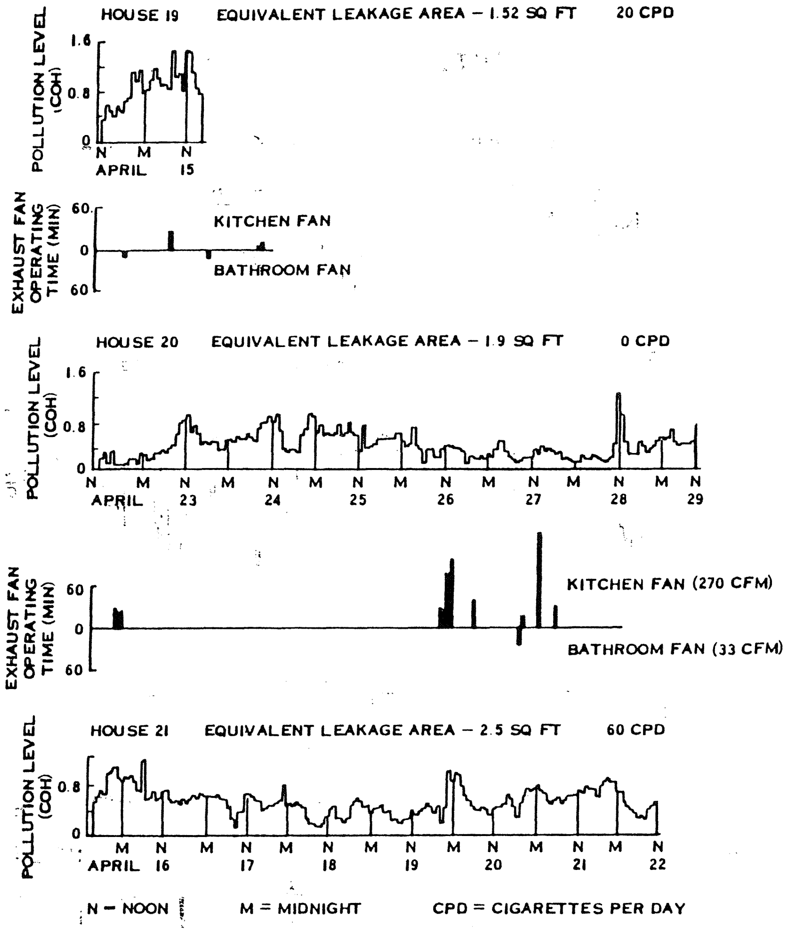


Fig. 6e Indoor pollution levels vs time

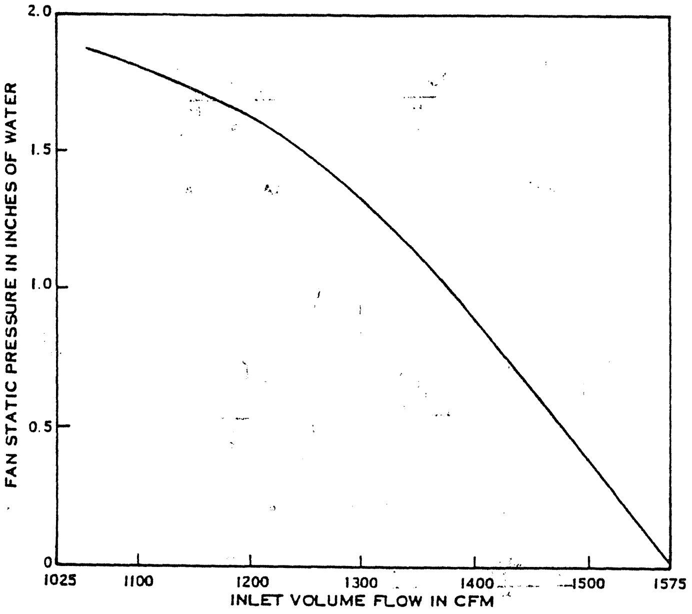


Fig. 8 Pressure-flow characteristics of exhaust fan

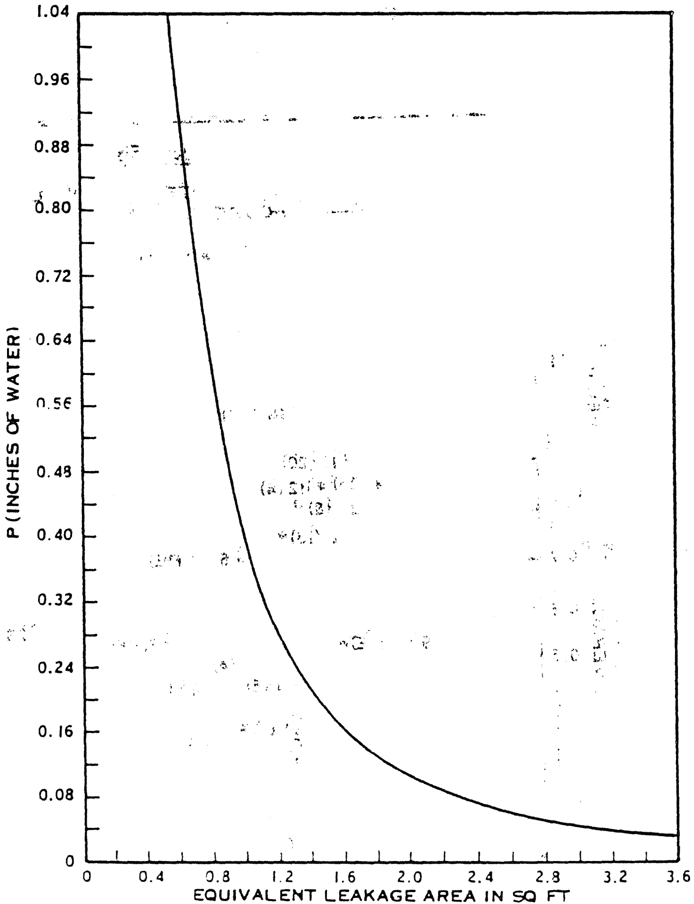
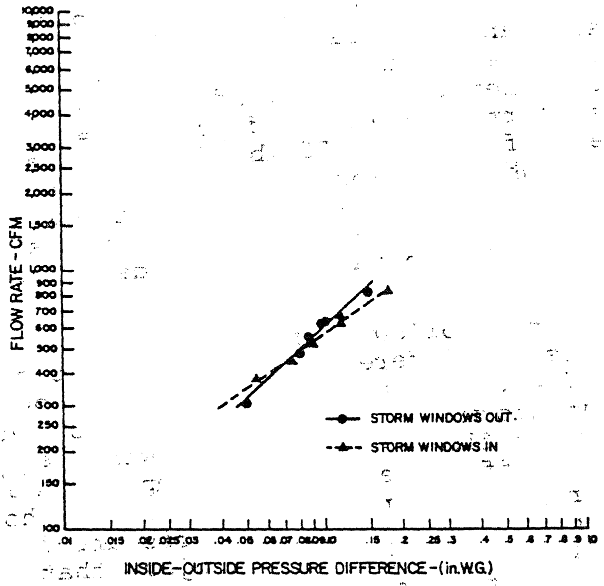


Fig. 9 Conversion graph: Measured pressure drop to ELA

While the use of p^n instead of $p^{1/2}$ eliminates the apparent change in area depending on the pressure at which the measurement is made, it also leads to an unrealistic estimate of the change in area due to installations of storm windows. As noted in Appendix A, the type of flow (ie, turbulent, laminar) may contribute the apparent area obtained from Q vs Δp data as well as the actual area itself, and the foregoing analysis would seem to bear this out.

EFFECT OF STORM WINDOWS ON MECHANICALLY INDUCED AIR LEAKAGE - - PRESSURE IN MOBILE HOME NEGATIVE



STRICKER: These comments illustrate very clearly the limitations of the ELA method: that the actual ELA calculated may vary depending on the pressure at which it is evaluated. I would question the reliability of points below 0.06 in. wg in the graph given since the likelihood of increasing infiltration (at a constant pressure difference) by adding storm windows is remote.

EDITOR's NOTE: The same question was posed to G.T. Tamura, author of Technical Paper No. 2339.

ROBERT E. PATERSON (Chevron Research Co., Richmond CA): Was any attempt made to relate infiltration factor with weather conditions, such as wind velocity or the difference in pressure inside and outside the house?

STRICKER: No attempt was made to relate infiltration factor with weather conditions. Ideally, it would be desirable to find the correlation between infiltration and ELA for a variety of weather conditions, but the correlation would be applicable only to the house tested because of the uniqueness of leak sizes, locations, and nature of air flow through these.

T.I. WETHERINGTON (Florida Power Corp., St. Petersburg FL): Does the work reported suggest that water vapor could be used as a tracer gas for infiltration measurement?

STRICKER: Water vapor could be used as a tracer gas if the amount released were accurately monitored. In an occupied house, this may be difficult to do.

WILLIAM L. HOLLADAY (Retired - Holladay Eggett & Helin, Altadena CA): In your estimates of excess energy use, you deducted the effect of water heating (100 kwh/month/occupant). Why did you not also deduct the effect of cooking and lighting?