Measurement of Air Leakage of Houses

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In connection with a study of heat losses from electrically heated houses, a novel method of measuring the air leakage area of houses was developed. Field measurements indicate that doors and windows account for only a fraction of the total air leakage. A survey is described where some correlations were found between the leakage area and indoor environmental conditions such as relative humidity, air-particulate levels and heating-energy consumption. Leakage areas that give rise to acceptable indoor conditions are given.

A TECHNIQUE for measuring the leakage area of houses is described, which was developed in an attempt to find causes of stubborn wintertime problems suspected of being related to too much or too little ventilation. The problems were: high indoor humidity, wall-staining, cold areas and high heating-energy consumption. Measurement of the rate of natural infiltration is difficult and time consuming since it involves tracer techniques and long-term recording, and the observed infiltration is very sensitive to weather conditions.

The measurement of leakage areas as described herein, offers a quick alternative for obtaining a measure of the air-tightness of houses, which controls natural infiltration. A survey involving 24 houses is also described, which attempted to correlate leakage measurements with the environmental variables dependent on ventilation. Although the correlations are not strong, useful guidelines were obtained. Leakage-area measurements can be used to classify houses according to their air-tightness, and can often indicate ways of avoiding heating problems and in some cases ways of reducing energy consumption.

Measurement of Leakage Area

The leakage measurement is carried out by exhausting air from the house with a powerful fan, measuring the drop in pressure, and calculating the equivalent area of an opening that would permit a similar airflow rate at the same pressure drop. This value is called the "equivalent leakage area" (ELA) of the house.

Referring to Figure 1, a vane-type axial-flow fan capable of delivering 1500 cubic feet per minute at 0.4-inch water column is mounted through a flexible plastic film and placed on an adjustable stand in front of an open window. The plastic sheet is folded back and fastened neatly to the window frame with masking tape to form an airtight temporary seal. A rubber hose installed through the plastic film is used to provide an inclined

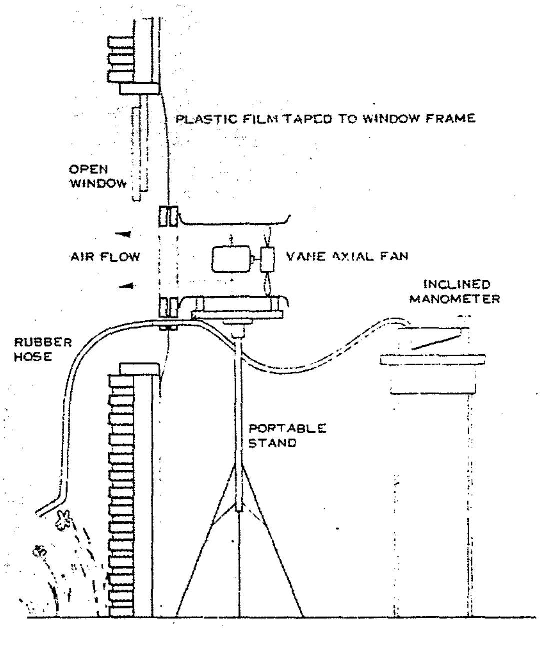

FIGURE 1 — Arrangement of equipment and instrumentation for measurement of equivalent leakag area of houses

manometer with a pressure tap to the outside.

After all exterior doors and windows are closed (with the exception of the window through which the temporary exhaust is mounted), and interior doors are opened, the exhaust fan is energized. The manometer stabilizes after several seconds and the drop in static pressure in the house is noted. The pressure reading can be converted to an equivalent leakage area by use of Figure 2. This figure is derived from the pressure–flow characteristics of the fan and the formula given in the Appendix for pressure drop across a sharp-edged orifice.

The accuracy of the ELA measurement was tested by deliberately opening a window a measured amount ranging from $\frac{1}{8}$ to 1 square foot. The new ELA's obtained agreed with the measured increases within 5 per cent for the $\frac{1}{8}$-square-foot opening, and even better for the larger areas. The effect of insect screening on the partly opened window was a reduction of measured area by a factor of about 2. Air paths through porous materials (such as concrete blocks and fibrous insulation) can give rise to inaccuracies in the ELA evaluation as explained in the Appendix.

Applications

Leakage-Area Measurement

The ELA measurement can be used as a measure of the leakage area available for infiltration in a building. The typical range of ELA in single-family houses is between 0.7 and 3.0 square feet. The calculated window and door leakage area using the method recommended by ASHRAE* typically is $\frac{1}{3}$ to $\frac{1}{2}$ as large as the measured ELA, indicating that other major structural leaks exist in houses.

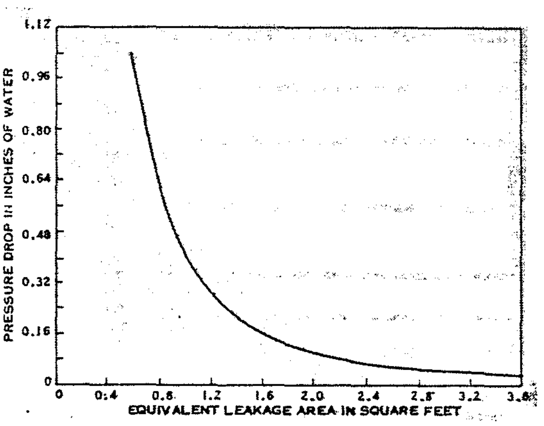

FIGURE 2 — Relation between measured pressure drop and equivalent leakage area

Measure of Quality of Workmanship

To obtain a figure of merit of leakage independent of house size, a new quantity is introduced, "leakage coefficient" (LC), which is defined as ELA divided by house volume (in cubic feet) including basement. A factor of 10^4 is applied to the numerator to bring LC close to 1.0. Typical values range between 0.6 and 1.5. The lower values are obtained in well-built houses, and the larger in relatively leaky houses.

Measurement of Contributions to Air Leakage

The ELA measurement can be used to find the contribution of certain parts of a structure to the total air leakage. For example, after measuring the ELA, doors and windows can be covered with plastic film using masking tape and the measurement repeated. Their contribution to the total leakage area can be obtained by subtracting the second ELA measurement from the first.

Location of Air Leaks

While the fan is operating, an observer can search for openings in the structure that allow entry of outside air. During cold weather, outside air being drawn into the house can be detected by feel or smell, revealing sources of air leakage that would otherwise not be obvious.

Survey of Leakage of Houses

To investigate the correlation between ELA (or LC) of houses and environmental variables controlled by ventilation, 24 occupied houses were surveyed. Data were obtained to assess the influence of ELA on indoor humidity levels, air-particulate levels, heavy energy con-

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* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

sumption and comfort conditions.

The sample of houses selected was representative of the three types of construction found in the Toronto area. Fifteen were of brick-veneer construction, seven were solid masonry and two were frame. All had habitable basements. Nine of these were split-level, ten were two-storey, and five were bungalows. Houses on slab are uncommon in Ontario; hence, none were included in this study. Of the 24 houses surveyed, 20 were electrically heated—twelve by baseboard heaters, four by central forced-air furances and four by ceiling heating cable. Two houses were oil-heated and two were gas-heated, these being central forced-air systems. The living areas, excluding basements, ranged in size from 780 to 2320 square feet, and in total interior volume between 12,500 and 28,500 cubic feet.

The survey involved recording or noting the following:

- indoor relative humidity
- indoor air-particulate levels
- operation of exhaust fans
- equivalent leakage area
- meteorological data
- electricity consumption
- occupancy
- tobacco consumption
- living habits
- heating problems.

Data on the first three items were collected by standard instrumentation. ELA was determined by the method described in the Appendix. Meteorological data were obtained from a nearby airport weather station. The remaining information was collected from detailed questionnaires. Table 1 and the following paragraphs summarize the more significant findings.

Observations

Indoor Humidity

All humidifiers and vapourizers were kept off for the duration of the study. Indoor relative humidities were recorded simultaneously for four weeks in mid-winter, averaged on a daily basis and converted to absolute humidities.

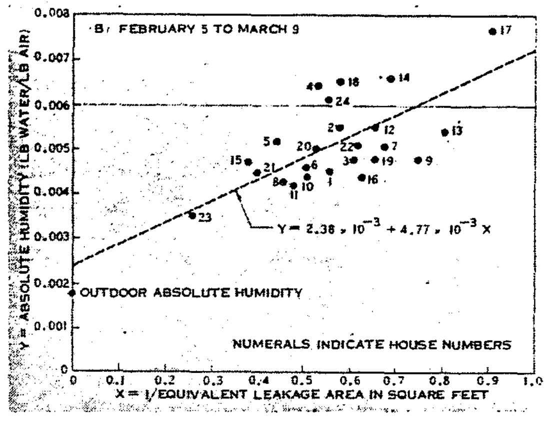

FIGURE 3 — Relation between indoor humidity and inverse of equivalent leakage area (4-week average)

Visual observations of the plotted data revealed that maxima and minima do not occur on the same days in all houses, nor do they necessarily coincide with the maxima and minima of the outdoor humidity. Comparison of indoor humidity levels with wind speed over the test period shows no obvious correlation, even though a drop in indoor humidity would be expected on cold, windy days because of increased infiltration.

To investigate the correlation between ELA and indoor humidity, a linear regression analysis of indoor absolute humidity (4-week average) on the inverse of ELA was performed (since an inverse relation is expected). The results are presented graphically in Figure 3. The correlation coefficient was 0.76 compared with 1.00 (which corresponds to a perfect fit). Although there is a trend to high humidity levels in houses with small ELA's, the deviations from the expected values are fairly large. No doubt many factors contribute to the deviations, such as: different amounts of moisture generation from house to house; different effectiveness of air leaks, depending on location; and different house exposures. Correlation between indoor humidity and occupancy (man-hours) was also attempted, but the results were inconsistent, indicating either a weak relation or that other variables obscure the influence of occupancy.

Air-Particulate Levels

As air-particulate levels were measured in living rooms only, the recorded levels are not necessarily the average for the entire house. The components of the particulate were not

Table 1 — TABULATION OF HOUSE STATISTICS

House No.	Type of Heating System *	Floor Plan †	Type of Con-struction ‡	Living Area§ (sq ft)	Total Interior Volume (cu ft)	Estimated Occupancy (man-hours per day)	Cigarette Con-sumption (per day)	Average Pollution Level (COH)	Equivalent Leakage Area (sq ft)	Leakage Coefficient (LC)	Remarks
1	BA	2S	BV	1850	24,100	88	10	0.396	1.79	0.74	High heating cost, cold areas
2	CE	SS	BV	1200	15,400	120	15	0.763	1.72	1.11	
3	CA	SS	SM	1480	18,500	56	6	0.462	1.65	0.89	
4	BA	SS	BV	1800	21,300	88	10	0.498	1.87	0.88	
5	Oil	BU	BV	1630	26,000	72	0	0.347	2.25	0.86	
6	BA	SS	BV	1450	15,200	48	**	0.713	1.96	1.29	Severe wall staining
7	CE	2S	BV	1440	14,000	104	**	0.131	1.47	1.05	
8	BA	2S	SM	1660	21,100	120	60	1.340	2.18	1.03	Severe wall staining
9	BA	2S	BV	1750	21,000	88	**	0.534	1.33	0.63	
10	BA	2S	BV	1850	25,000	104	20	—	1.96	0.78	
11	Gas	SS	SM	1600	15,200	88	0	0.488	2.31	1.52	Cold areas
12	Gas	BU	SM	1230	18,700	80	3	0.851	1.52	0.81	
13	CA	BU	FR	780	12,500	40	0	0.437	1.23	0.98	
14	BA	2S	SM	1300	15,200	88	25	0.857	1.45	0.95	
15	CE	2S	BV	1640	19,700	96	10	—	2.65	1.35	Cold areas
16	BA	BU	FR	960	14,400	72	20	0.996	1.60	1.11	
17	CA	BS	BV	1060	14,600	88	0	0.296	1.10	0.75	High humidity
18	BA	BU	SM	1460	23,100	56	0	0.313	1.72	0.75	
19	BA	BS	BV	1060	14,600	64	20	0.864	1.52	1.04	
20	CA	2S	BV	1950	23,400	136	0	0.373	1.90	0.81	
21	BA	2S	BV	2073	28,500	88	60	0.540	2.50	0.88	
22	Oil	2S	SM	1100	12,700	40	0	0.823	1.60	1.26	
23	BA	SS	BV	2320	27,900	56	30	0.575	3.90	1.40	High heating cost
24	CE	BS	BV	1600	23,300	64	0	0.362	1.80	0.77	High humidity, wet basement

* BA—baseboard, electric; CA—cable, electric; CE—central, electric

† 2S — 2-storey; BU—bungalow; BS—back split; SS—side split

‡ BV— brick veneer; FR—frame; SM—solid masonry

§ Excluding basement area

** Pipe smoker

identified, but previous work indicates that cooking oils, smoke from burnt food, candle vapours and tobacco smoke are the most frequent constituents. The dilution and mixing of pollutants in a structure is a complex mechanism, and no attempt was made to account for it in this survey.

The indoor air-particulate levels recorded in 22 houses varied widely with time and from house to house. The hourly levels for four typical houses over 1-week periods are plotted in Figure 4. The estimated daily tobacco consumption and ELA are indicated also. Each 1-hour sample consisted of a darkened spot on a filter-paper strip. The measured transmittance was used to calculate the coefficient of haze (COH), which is defined as the loss in light transmittance of a 1000-foot column of air. The average COH for the 22 houses surveyed ranged from 0.131 to 1.340.

In Figure 5, average particulate levels are plotted against ELA, with house number and tobacco consumption indicated. All seven houses with non-smokers had a COH below 0.45. Of the remaining 15 houses, only two had a COH below 0.45, five were about 0.50, seven about 0.85, and only one (house 8) was above 1.30. House 8 is unusual in that pottery classes were held in the basement. For these classes three firing kilns were used, and tobacco consumption was estimated to be 60 cigarettes per day. Referring to Table 2, four of the five baseboard-heated houses having a COH above 0.70 experienced noticeable degrees of wall staining.

No noticeable wall staining occurred in houses with central forced-air furnaces or in any of the remaining baseboard-heated or cable-heated houses, with the exception of house 18. In this case, slight darkening was noted over the baseboard in the basement recreation room, which may have resulted from occasional smoky operation of the fireplace in that room.

The air-particulate levels in houses 5 (oil heat) and 11 (gas heat) in which no smoking

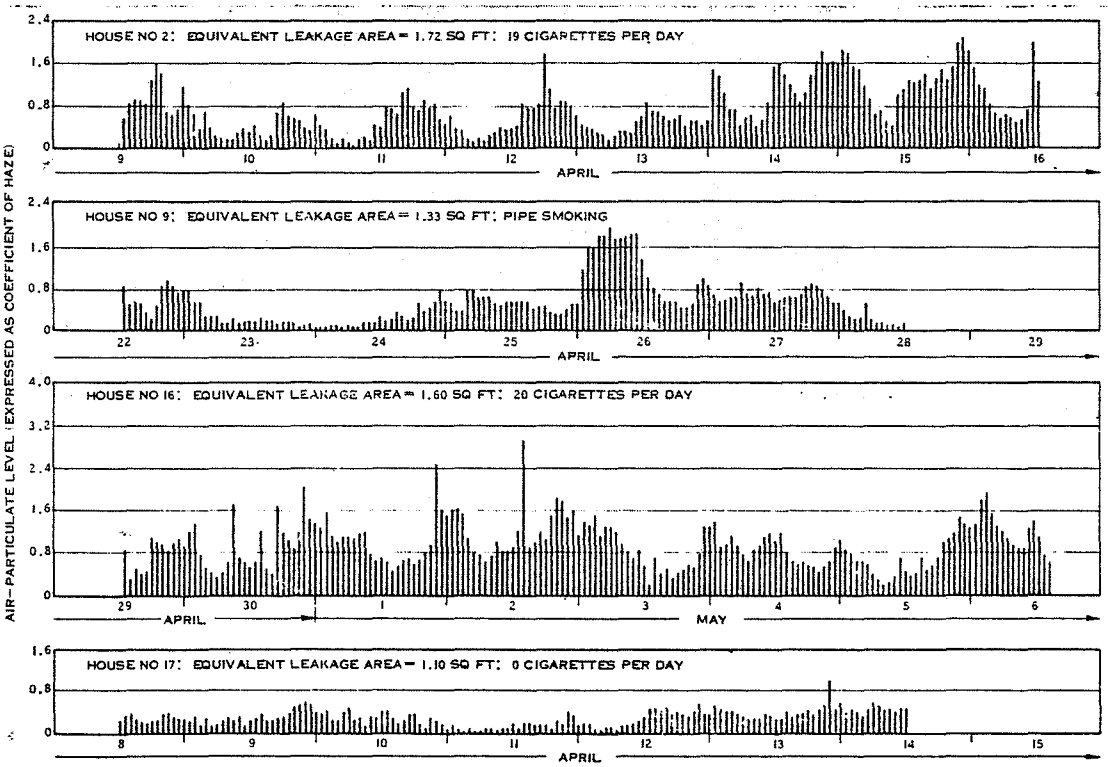

FIGURE 4 — Hourly air-particulate levels recorded in four electrically heated houses during periods indicated

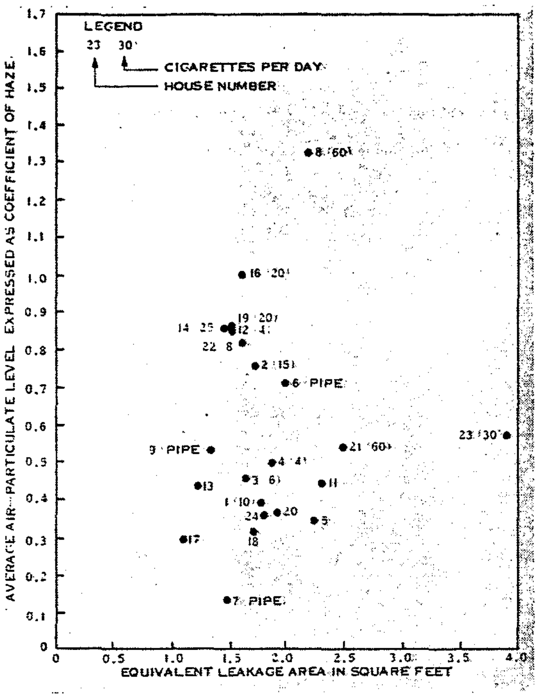

FIGURE 5 — Relation between average air-particulate levels and equivalent leakage area for 22 houses indicated

takes place are similar to those in electrically-heated houses 13, 17, 18, 20 and 24 in the group of non-smokers (see Figure 3). Houses 12 (gas heat) and 22 (oil heat) in which some smoking takes place have particulate levels similar to those in electrically heated houses 2, 6, 8, 14, 16 and 19 where smoking takes place.

Energy Consumption

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

2 — RELATIVE DEGREES OF WALL STAINING IN ELECTRIC-BASEBOARD-HEATED HOMES

e	Average Pollution Level (COH)	Degree of Wall Staining	Tobacco Consumption
	0.71	Severe	Pipe smoker
	1.34	Very severe	60 cigarettes per day
	0.86	Severe	25 cigarettes per day
	1.00	Noticeable	20 cigarettes per day
	0.86	Slight	20 cigarettes per day

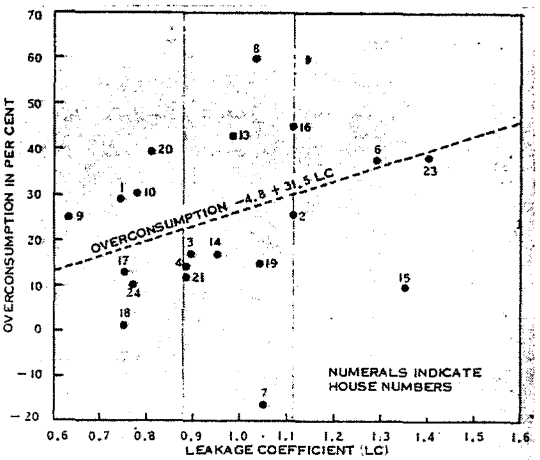

FIGURE 6 — Relation between energy overconsumption and leakage coefficient of 20 electrically heated houses. Analysis excludes houses 7, 8, and 15

The estimated seasonal heating-energy requirement was calculated from the transmission and infiltration* heat loss and the degree-days for the Toronto area, using a *C* factor† of 14.5. A new quantity is introduced, namely, "overconsumption", which is the energy used in excess of the calculated heat loss, expressed as a percentage of the calculated heat loss.

A linear regression analysis of overconsumption in relation to leakage coefficient (excluding houses 7, 8 and 15, the worst behaved in the sample) gave a correlation coefficient of 0.49 (see Figure 6). This rather poor correlation results from 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 leakage coefficient require relatively more heating energy.

Acceptable Range of ELA's

Relative humidities higher than about 35 per

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* Infiltration was assumed to be 1 air change per hour for rooms above grade and ½ change below grade.

† The *C* factor used in calculating seasonal electric energy consumption is an experience factor, usually ranging between 14 and 19 and depending on house size, location, insulation, fenestration, occupancy and living habits.

cent during sub-zero weather lead to such problems as severe window condensation, attic condensation with consequent freezing and accumulation of large quantities of ice, and wall condensation accompanied by staining and mould growth. At 72°F dry-bulb temperature, the corresponding absolute humidity level is approximately 0.006 pound of water per pound of dry air. With reference to Figure 3, it can be seen that five houses have indoor humidity levels above this "safe" value. Homeowners of houses 17 and 24 in this group complained of unacceptably high indoor humidity leading to severe condensation on windows and walls. These five houses had ELA's ranging between 1.10 and 1.87 square feet. There are ten others within the same range of ELA with indoor humidity levels well within the "safe" level, probably because of a lower rate of moisture production or because the distribution of air leaks provides more effective ventilation in this group.

From the Standpoint of Humidity Control

In houses not equipped with automatic humidification equipment, the indoor humidity level is determined by the rate of production of moisture (from cooking, breathing, washing and so forth) and the rate of removal of moisture by infiltration of drier outside air. The rate of moisture production is determined by occupancy and activities 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.

From the Standpoint of Air-Particulate Levels

The acceptable ELA of a house depends strongly on the rate of generation of air particulates, as illustrated by Figure 5. In houses where smoking does not take place, ELA's as low as 1.10 square feet are acceptable. In houses where smoking takes place, ELA's larger than 2 square feet tend to keep particulate levels below the critical COH of 0.70.

From the Standpoint of Energy Consumption

From Figure 6, the deviation of individual house overconsumption from the mean is very high, making it difficult to draw meaningful conclusions. However, since the sample contained some houses that were too tight and others that were too leaky, one can postulate that the central band of the data represents "no-problem" houses. The band of LC's from 0.88 to 1.11 contains ten houses that displayed no problems (with the exception of house 8, the pottery school). The ELA of these houses ranged between 1.47 and 1.72.

Conclusions

Some correlations exist between ELA and environmental variables such as indoor humidity and air-particulate levels. Houses having a measured ELA between about 1.5 and 2.0 square feet have no environmental problems, unless occupancy level or cigarette consumption is high. The ELA measurement technique can be used to evaluate the quality of workmanship in house construction, as it affects air-tightness, and can indicate the remedy to be applied in avoiding indoor environmental problems during the heating season.

APPENDIX

Determination of ELA of a House

Houses of normal workmanship have numerous openings that permit outside air to penetrate the structure under the influence of wind, stack-effect, and pressure differences caused by forced-air furnaces. A measure of the total area of openings can be obtained by deliberately applying a pressure difference between the house exterior and interior and noting the air flow. Using the formula for air flow through a sharp-edged orifice, the ELA can be evaluated as described below.

The relation between wind speed and volume flow through a sharp-edged orifice is [1]

$$Q = VAE \, , \tag{1}$$

where

Q = air flow through orifice, in cubic feet per minute,
V = wind speed, in feet per minute,
A = free area of orifice, in square feet, and
E = effectiveness of opening (assumed to be 0.6 for winds normal to surface).

A wind speed of V in a direction normal to a large wall produces a surface pressure, in inches of water, expressed as

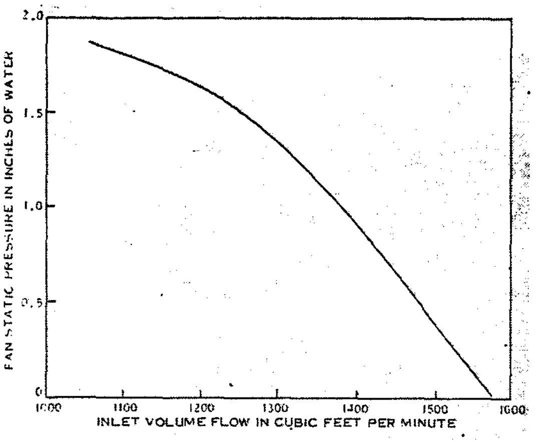

FIGURE 7 — Pressure–flow characteristics of exhaust fan used in study

$$P = \frac{0.000482\,V^2}{88^2} = 6.22 \times 10^{-8}\,V^2. \tag{2}$$

This equation is based on an air density of 0.075 pound per cubic foot.

By substituting equation (2) in equation (1) to eliminate V,

$$Q = \sqrt{\frac{P}{6.22 \times 10^{-8}}}\,AE = 0.401 \times 10^4 \sqrt{P}\,AE\ . \tag{3}$$

This equation describes air flow through a sharp-edged orifice as a function of pressure difference across the orifice. To determine the orifice area, P and Q must be known. If an exhaust fan of a known pressure-flow characteristics is used, either P or Q will determine the corresponding Q or P. For field use, it is more convenient to measure pressure difference than volume flow.

The fan used had the pressure–flow characteristics shown in Figure 7. Several combined values of P and Q were substituted into equation (3) to obtain the pressure-orifice-area graph shown in Figure 2. In this manner, a single pressure-difference measurement can be related to an orifice area, that is, the ELA. *Limitations of 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 an equation of the form [1]

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

where

C = proportionality constant,
Δp = pressure difference across window, and
n = exponent of flow (between $\frac{1}{2}$ and 1).

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

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

where

a = radius of capillary,
η = air viscosity, and
$\frac{dp}{dz}$ = pressure gradient along flow axis.

Where air is exhausted from a house to produce a measurable pressure drop, the ELA calculated according to equation (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 (equation (3) applies), some through door and window crackage (equation (4) applies), and some through porous materials such as concrete block or thermal insulation (equation (5) may apply). Consequently, the ELA calculated according to equation (3) alone will generally not be equal to the sum of the area of all openings, but does give an equivalent leakage at the specific test pressure.

REFERENCES

1. *ASHRAE Guide and Data Book—Fundamentals*, 1972, Ch 19, pp 333–44.
2. *Encyclopaedic Dictionary of Physics*. Vol 7, Pergamon Press, pp 649–50.

CORRECTION — Volume 26, Number 3

Source and Nature of Radioactivity in Nuclear Reactor Systems: B. C. J. Neil.

On page 5, the 13th line from the top of the right-hand column should read "reactor core; therefore, its presence cannot".