7735

National Research Council of Canada

Conseil national de recherches du Canada

AIR TIGHTNESS AND AIR INFILTRATION OF SCHOOL BUILDINGS

by C. Y. Shaw and L. Jones

Reprinted from
ASHRAE Transactions
Vol. 85, Part 1, 1979
p. 85 - 95

DBR Paper No. 891
Division of Building Research

Price $1.25 OTTAWA NR CC 18030

SOMMAIRE

Les écoles, en tant que groupe, constituent le troisième comsommateur d'énergie parmi les édifices du Canada. La Division des recherches en bâtiment du Conseil national de recherches du Canada a donc accepté, à l'automne de 1975, de collaborer avec le Carleton Board of Education dans le cadre d'un programme visant à réduire la consommation d'énergie dans les écoles.

Un des principaux problèmes rencontrés au départ était celui du manque de données sur les infiltrations d'air pour les édifices scolaires. Un programme de mesure des pertes d'air dans les écoles a donc été entrepris. Les résultats de ces relevés ont ensuite été appliqués à un modèle simple d'édifice scolaire, à partir duquel les infiltrations d'air et leur apport à la charge globale de chauffage ont pu être calculés.

AIR TIGHTNESS AND AIR INFILTRATION OF SCHOOL BUILDINGS

C.Y. SHAW   L. JONES

INTRODUCTION

Schools, as a group, are the third largest users of energy in buildings in Canada. The Division of Building Research, National Research Council of Canada therefore welcomed the opportunity in the autumn of 1975 to participate with the Carleton Board of Education in a program to reduce energy use in schools.

A major problem encountered initially was the lack of data on air infiltration for school buildings. A program of air leakage measurements in schools was therefore carried out. Results of the measurements were then applied to a simplified model of a school building, from which air infiltration and its contribution to total heating consumption could be calculated.

SELECTION OF TEST SCHOOLS

Eleven test buildings were selected from a total of 56 elementary schools, based on their 1975 energy consumption (1). Of the eleven schools, five were considered to have average consumption, three to have high consumption and the remaining three to have low consumption (Fig. 1). A brief description of the tested schools is given in Table I.

TEST METHOD

The air leakage characteristics of school buildings were measured by means of the pressurization method. The fan used was a vane axial type with a variable-pitch blade that can be adjusted manually to obtain flow rates between 0 and 23 m^3/s (0 to 50,000 cfm). The fan intake was connected by several lengths of 0.9 m (3 ft) diameter duct to an entrance door replaced for the tests by a plywood panel (Fig. 2).

Air flow rates were measured upstream of the fan intake using total pressure averaging tubes (2) for high air flow rates and an orifice plate for low air flow rates. The pressure differences across the exterior walls were measured at the middle of each wall near the ground. A portable pressure meter consisting of a diaphragm-type pressure transducer (static error band of 5% full scale) and a digital voltmeter were used. To minimize wind influence on the pressure measurements all tests were conducted with a meteorological wind speed lower than 15 km/h (9.3 mph) (3).

Most tests were conducted under suction conditions, partly because air infiltration occurs with buildings under this condition, but also because of the need to avoid any possible damage to furniture and discomfort to occupants. For comparison, two schools were tested under both suction and pressurization.

The buildings were tested with the air-handling system in operation and with it shut down. With the system on, an initial reading of pressure difference across the exterior walls was taken with the test fan shut down and its intake sealed. This reading, which is the amount of pressurization resulting from imbalance between outside air supply and exhaust air rates of the

---

C.Y. Shaw and L. Jones, Research Officers, Energy and Services Section, Division of Building Research, National Research Council of Canada. K1A 0R6

air-handling systems, was then subtracted algebraically from the pressure difference readings obtained with the test fan operating. All schools except School C operated under suction pressures ranging from -2 to -35 Pa (-0.008 to -0.14 in. of water).

The air leakage rates through air intake and exhaust openings, openable windows, and doors were obtained by comparing the over-all air leakage rates taken before and after they were sealed. Because of difficulties in sealing, only schools with centralized air-handling systems were tested. As well, joints between window or door frames and walls were not sealed so that any leakage there was considered as part of the air leakage through the walls.

In addition, air leakage tests were made in School J in both June and December to discover whether leakage varied with season.

EXPERIMENTAL RESULTS

The over-all air leakage rates per unit area of exterior walls and their corresponding pressure difference are shown in Fig. 3 and 4 for air-handling system either operating or shut down. The results vary from 0.0024 to 0.006 $m^3/s \cdot m^2$ at a pressure difference of 25 Pa, (0.43 to 1.2 cfm/ft^2 at 0.1 in. of water). These figures also show that, in general, the operation of the air-handling systems had little effect on over-all air leakage rate when pressure differences were lower than 50 Pa (0.2 in. of water).

Examination of the limited air leakage data (Fig. 3 and 4) indicated that there was no meaningful relation between total energy consumption (Fig. 1) and the measured air leakage rate. The variation in air leakage from school to school could not be explained by wall construction because all were similar in design (see Table I). Investigation of the construction of the school with the highest leakage value (School D) revealed, however, a large number of unsealed openings around the roof joists at the exterior wall, suggesting that poor workmanship and lack of concern for sealing can lead to high air leakage. In addition, the air leakage rate measured in June at School J was within 2% of the leakage rate measured there in December, suggesting that, for this particular school, crack width did not vary with outside temperature.

Fig. 5 indicates that with the air-handling systems shut down 15 to 43% of the over-all air leakage can be attributed to the air intake and exhaust openings and the remainder to the walls, of which openable windows and doors of two schools contributed up to 4 and 10%, respectively (the percentage areas of openable windows and doors to the total wall area are about 2 and 2.5%, respectively).

Tests were conducted on two schools to investigate the difference in air leakage rates with a building under suction and pressurization. Comparison of the over-all air leakage rate measured under the two conditions was made with the air-handling systems both in operation and shut down; in the latter case, with the air intake and exhaust openings sealed and unsealed. Fig. 6, which shows the results for School B (the more extreme of the two schools), indicates that the difference in over-all air leakage rates between suction and pressurization is minimum with the air-handling systems shut down and the duct openings sealed. If the duct openings are unsealed, the over-all air leakage rate obtained under suction, with the air-handling systems in operation, is about 10% higher than it would be under pressurization; the reverse is true with the air-handling system shut down.

GENERALIZATION OF AIR LEAKAGE DATA

The air leakage data measured in the eleven schools were used to define three classes of building construction: loose, average and tight (Fig. 7). The air leakage characteristics were defined using the following equation:

$$q = C\,(\Delta P)^n \tag{1}$$

where

q = over-all air leakage rate per unit area of exterior walls, $m^3/s \cdot m^2$ (cfm/ft^2)

C = flow coefficient, $m^3/s \cdot m^2 \cdot (Pa)^n$ ($cfm/ft^2 \cdot (in.\ of\ water)^n$)

ΔP = pressure difference across exterior wall, Pa (in. of water)

n = flow exponent

The common flow exponent for the three classes was found to be about 0.65 by curve fitting; the corresponding flow coefficients were:

	Flow Coefficient, C	
Class	$m^3/s{\cdot}m^2\ (Pa)^{0.65}$	$cfm/ft^2\ (in.\ of\ water)^{0.65}$
Tight	3.0×10^{-4}	2.1
Average	5.0×10^{-4}	3.5
Loose	7.0×10^{-4}	4.9

These flow coefficients are based on the air leakage values for schools with air-handling systems off. They can be applied to other conditions (air-handling systems on and building under pressurization) for load and energy calculations without introducing significant errors.

AIR INFILTRATION RESULTING FROM WIND AND STACK EFFECT

Using the method described in Ref. 4, air infiltration rates for a simplified model of a school building were calculated at various combinations of wind speed and ambient air temperature. The school model (1) (see Appendix A) consists of two independent parts: a single-storey classroom block and a two-storey high open hall (gymnasium) comprising 90 and 10% of the total floor area, respectively. The intake and exhaust openings of the air-handling systems were assumed to be located at the roof level.

The air leakage paths in each wall were lumped into five equally-sized openings located at equal intervals in the vertical direction. Ventilation openings were represented by a single opening located in the roof. The corresponding flow coefficients were calculated from Eq 1 assuming 70 and 30% of the total air leakage value for walls and roof, respectively. Wind was assumed to act normally to the long wall. The surface pressure coefficients were derived from the measurement of pressure distributions on a cubic model in a suburban boundary layer (5). These coefficients increase almost linearly with height from 0.46 to 0.64 for the windward wall and are approximately constant, with values of -0.25, -0.54 and -0.6 for the leeward wall, the two side walls, and the roof, respectively.

The calculated air infiltration rates are shown in Fig. 8 as a function of wind speed at the roof and inside-outside temperature difference. Wind speed at the roof level of an isolated school can be approximately related to the meteorological wind speed by the equation (6):

$$V = B\ H^{1/3}\ V_s \tag{2}$$

where

V is wind speed at roof level, km/h (mph)

H is building height, m (ft)

V_s is the wind speed at 10 m (32.8 ft) above the ground measured by the Meteorological Service, km/h (mph)

B is a constant and is equal to 0.142 and 0.211 for Imperial and S.I. units, respectively.

Using Eq 2, the relation between the roof level wind speed and the meteorological wind speed thus assumed were:

$V = 0.33\ V_s$ for classroom block

$V = 0.42\ V_s$ for hall

The contribution of stack effect to air infiltration was shown to be quite significant, even for a single-level building. This is illustrated by the results for the classroom block (see Fig. 8) where the air infiltration resulting from stack effect for an inside-outside temperature difference of 55.6°C (100°F) is approximately the same as that from a 15 km/h (9.3 mph) wind at the roof level (45 km/h or 28 mph meteorological wind speed).

EFFECTS OF AIR INFILTRATION ON ANNUAL ENERGY CONSUMPTION

The annual heat consumption for the school model was calculated both with and without air infiltration, using the Meriwether Energy Analysis Series. A brief description of the building model and the conditions used for heating load calculations is given in Appendix A. The annual heating loads were calculated for various combinations of mean annual wind speed acting normally on the long wall and ambient air temperature between -17.8°C and 23.9°C (0°F and 75°F). The values of air infiltration rates were obtained from Fig. 8, which is based on walls of average air tightness.

The calculated annual heat consumption, using 1974 Ottawa weather data for various mean annual wind speeds at roof level, is shown in Fig. 9. The contribution of air infiltration to the total annual heat consumption is illustrated in Table II, assuming a mean annual wind speed of 16 km/h (10 mph), the Ottawa average (7). It indicates that the proportion of heat consumption attributed to air infiltration is about 29%.

The use of annual average wind speeds in energy analysis will tend to underestimate heat consumption because air infiltration rate varies non-linearly with wind speed (Fig. 8), and because wind speed is generally higher in winter than in summer. A separate method of calculating the contribution to annual heating load from air infiltration, using three years of hourly weather data for Ottawa, resulted in values 4 to 7% higher than those using annual mean wind speeds; monthly loads varied from 2 to 13%.

CONCLUSION

The calculated flow coefficients for the eleven schools, assuming a flow exponent of 0.65, vary from 3.0×10^{-4} to 7.0×10^{-4} $m^3/s \cdot m^2$ $(Pa)^{0.65}$ (2.1 to 4.9 cfm/ft^2 $(in.\ of\ water)^{0.65}$). Tests on four of the buildings showed that with the air-handling system off, 15 to 45% of over-all air leakage could be attributed to flow through the intake and exhaust system openings.

Tests conducted at pressure differences below 50 Pa (0.2 in. of water) showed no significant difference in the air leakage rates when the buildings were tested under either suction or pressurization

The large variation in air leakage values could not be explained by the wall design of the schools; it was probably caused by variation in workmanship during construction and by the number of openings associated with the air-handling system.

Air infiltration rates calculated for a model school building indicated that those due to stack action are significant even for single-storey buildings. Air infiltration is also shown to be a major contributing factor to annual heat consumption.

REFERENCES

1. Jones, L., "Calculating Energy Budgets for New Schools." To be published.
2. Ma, W.Y.L., "The Averaging Pressure Tubes Flowmeter for the Measurements of the Rate of Airflow in Ventilating Ducts and for the Balancing of Airflow Circuits in Ventilating Systems," J.I.H.V.E., Feb. 1967, pp. 327-348.
3. Tamura, G.T., and Shaw, C.Y., "Studies on Exterior Wall Air Tightness and Air Infiltration of Tall Buildings," ASHRAE TRANSACTIONS, Vol. 82, I, 1976, pp. 122-134.
4. Sander, D.M., "Fortran IV Program to Calculate Air Infiltration in Buildings," DBR Computer Program No. 37, May 1974, NRCC.
5. Baines, W.D., "Effects of Velocity Distribution on Wind Loads and Flow Patterns on Buildings," Proceedings, Symposium 16, Wind Effects on Buildings and Structures, Vol. 1, June 1963, pp. 198-225.
6. Shaw, C.Y. and Tamura, G.T., "The Calculation of Air Infiltration Rates Caused by Wind and Stack Action for Tall Buildings," ASHRAE TRANSACTIONS, Vol. 83, II, 1977.
7. Hourly Data Summaries, Dept. of Transport, Meteorological Branch and later Dept. of the Environment, Atmospheric Environment Service, various dates from May 1967 to March 1974.

ACKNOWLEDGEMENT

The authors are indebted to the Carleton Board of Education for cooperation in making this study possible; and to the custodial personnel of the test schools for their assistance during the tests. They gratefully acknowledge, also, the contribution of G.T. Tamura and G.P. Mitalas in the preparation of this paper; and the assistance of R.G. Evans in the field tests and of G.L. Johnson in the computer programming.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

TABLE 1

Description of Test Schools

School		A	B	C	D
Year tested		1976	1976	1976	1976
Year constructed		1970	1971	1965	1973
Floor area, m^2 (ft^2)		2694 (29 000)	1858 (20 000)	3771 (40 600)	3493 (37 600)
Floor height, m (ft)		4.3 (14.0)	4 (13.0)	3.4 (11)	3.8 (12.5)
Volume, m^3 (ft^3)		11 495 (406 000)	7361 (260 000)	12 644 (446 600)	13 307 (470 000)
[a] Exterior wall area, m^2 (ft^2)		1175 (12 651)	1136 (12 234)	1875 (20 183)	1610 (17 330)
Window type		fixed and openable sealed double glazing	fixed and openable sealed double glazing	fixed and openable sealed double glazing	fixed and openable sealed double glazing
Window area/wall area		0.106	0.077	0.178	0.137
Openable window/wall area		0.018	0.012	0.06	0.026
Typical wall construction		15.24 cm autoclaved cellular concrete 1.6 cm drywall	10.2 cm face brick air space 5.1 cm rigid insulation 20.3 cm concrete block	10.2 cm face brick air space 5.1 cm rigid insulation 20.3 cm concrete block	10.2 cm face brick 5.1 cm foam insulation 20.3 cm concrete block
Number of exterior doors	Vestibule			2 double	
	No vestibule	5 single, 5 double	4 single, 4 double	3 single, 4 double	15 single, 4 double
[b] Ratio of adjusted door area to wall area		0.024	0.020	0.013	0.027
HVAC system		#2 oil, centralized all-air H/V systems	#2 oil, centralized all-air H/V systems	electric, localized roof exhausters and convectors	#2 oil, centralized all-air H/V systems

Notes: a. Including Windows; b. A 50% reduction in area is allowed for door with vestibule or similar arrangement.

TABLE 1 (Cont'd)

School	E	F	G	H
Year tested	1976	1976	1976	1976
Year constructed	1957	1952	1968	1965
Floor area, m^2 (ft^2)	3689 (39 711)	3093 (33 300)	5388 (58 000)	5156 (55 500)
Floor height, m (ft)	3.8 (12.5)	3.7 (12.0)	3.7 (12.0)	4 (13.0)
Volume, m^3 (ft^3)	14 054 (496 388)	11 314 (399 600)	19 706 (696 000)	20 427 (721 500)
[a] Exterior wall area, m^2 (ft^2)	2102 (22 630)	1256 (13 516)	1967 (21 179)	1613 (17 369)
Window type	fixed sealed double, openable sealed double and single glazing	fixed sealed double, openable sealed double and single glazing	fixed and openable sealed double glazing	fixed and openable sealed double glazing
Window area/wall area	0.248	0.299	0.096	0.221
Openable window/wall area	0.143	0.054	0.014	0.016
Typical wall construction	10.2 cm face brick 2.5 cm air space 2.5 cm rigid insulation 20.3 cm concrete block	10.2 cm face brick air space 2.5 cm rigid insulation 20.3 cm concrete block	10.2 cm concrete block 2.5 cm air space 2.5 cm rigid insulation 20.3 cm concrete block	10.2 cm face brick 2.5 cm air space 3.8 cm rigid insulation 15.2 cm concrete block
Number of exterior doors, Vestibule	1 single, 1 double	1 single	1 single, 4 double	1 single, 2 double
Number of exterior doors, No vestibule	7 single, 3 double	2 single, 4 double	2 single, 2 double	1 single, 5 double
[b] Ratio of adjusted door area to wall area	0.013	0.016	0.010	0.016
HVAC system	#2 oil, centralized all-air H/V systems with unit ventilator in perimeter room	#2 oil, localized exhausting systems and hot-water convectors	#2 oil, centralized all-air H/V systems and unit ventilator in perimeter room	#2 oil, localized all-air H/V systems and hot-water convector in perimeter room

Notes: a. Including Windows;

b. A 50% reduction in Area is allowed for door with vestibule or similar arrangement.

TABLE 1 (Cont'd)

School	I	J	K
Year tested	1976	1976	1976
Year constructed	1968	1972	1968
Floor area, m^2 (ft^2)	2620 (28 200)	3003 (32 331)	3219 (34 650)
Floor height, m (ft)	3.8 (12.5)	4 (13.0)	3.8 (12.5)
Volume, m^3 (ft^3)	9980 (352 500)	11 900 (420 303)	12 263 (433 125)
[a] Exterior wall area, m^2 (ft^2)	1241 (13 357)	1365 (14 695)	1815 (19 536)
Window type	fixed and openable sealed double glazing	fixed sealed domes, fixed and openable sealed double glazing	fixed sealed domes, fixed and openable sealed double glazing
Window area/wall area	0.104	0.062	0.102
Openable window/wall area	0.032	0.008	0.040
Typical wall construction	10.2 cm face brick 2.5 cm air space 2.5 cm rigid insulation 20.3 cm concrete block	10.2 cm split block face 5.1 cm air space 15.2 cm concrete block and foamed in place insulation	10.2 cm face brick 5.1 cm foamed insulation 20.3 cm concrete block
Number of exterior doors: Vestibule		3 single, 2 double	14 single, 1 double
Number of exterior doors: No vestibule	8 single, 4 double	2 single, 3 double	6 single
[b] Ratio of adjusted door area to wall area	0.024	0.016	0.014
HVAC system	#2 oil, localized exhausting systems and hot-water convectors	gas, centralized all-air H/V systems with roof-top A.H. units	#2 oil and electric centralized all-air H/V system with convector or unit ventilator in perimeter room

Notes: a. Including Windows; b. A 50% reduction in area is allowed for door with vestibule or similar arrangement.

TABLE 2

Contribution of Air Infiltration to Annual Heat Consumption in Ottawa for V_s = 16 km/h

	Wind Speed at Roof, km/h	Annual Heat Consumption, GJ/m^2/Annum	
		No Infiltration	Average Infiltration
Classroom	5.3	0.28	0.36
Hall	6.7	1.19	1.69
Total = 90% Classroom + 10% Hall		.38	0.49
% Total Heat Consumption Attributed to Infiltration = 29%			

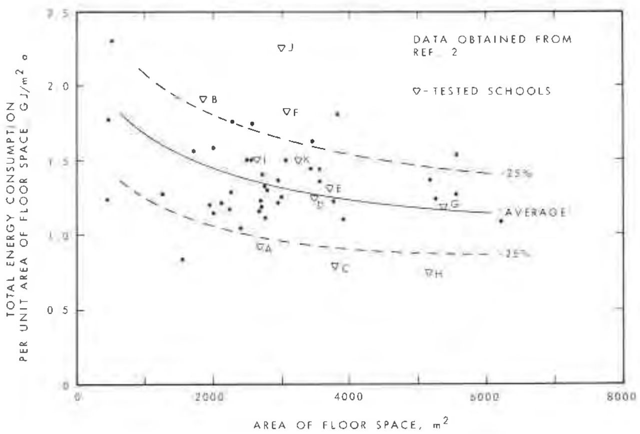

Fig. 1 1975 annual total energy consumption of the elementary schools under the Carleton Board of Education

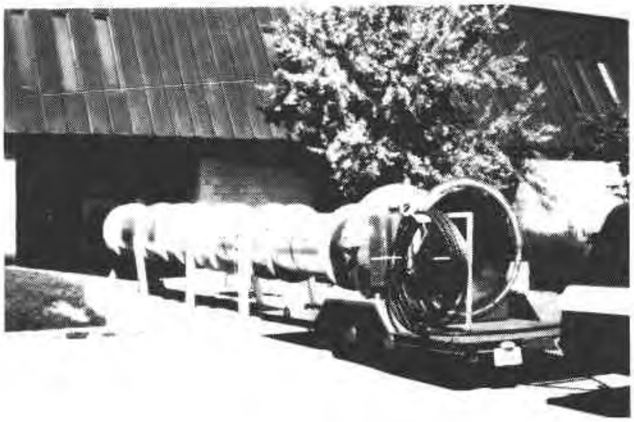

Fig. 2 Building test setup showing exhaust fan and duct connection

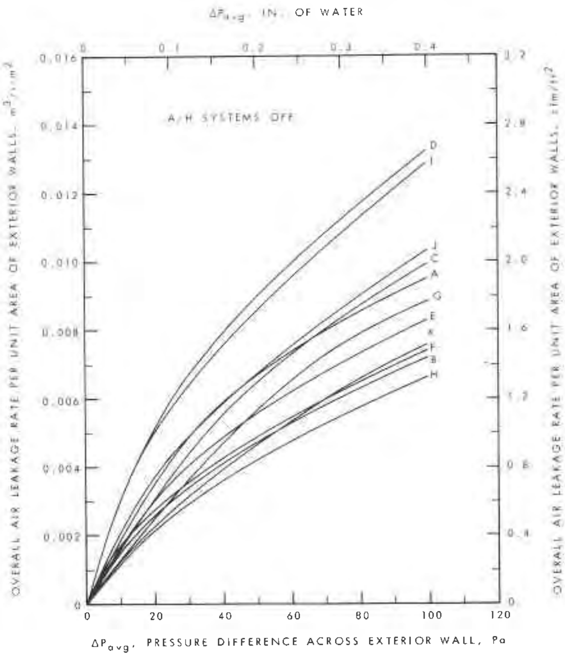

Fig. 3 The overall air leakage rates for schools with their air handling systems shut off

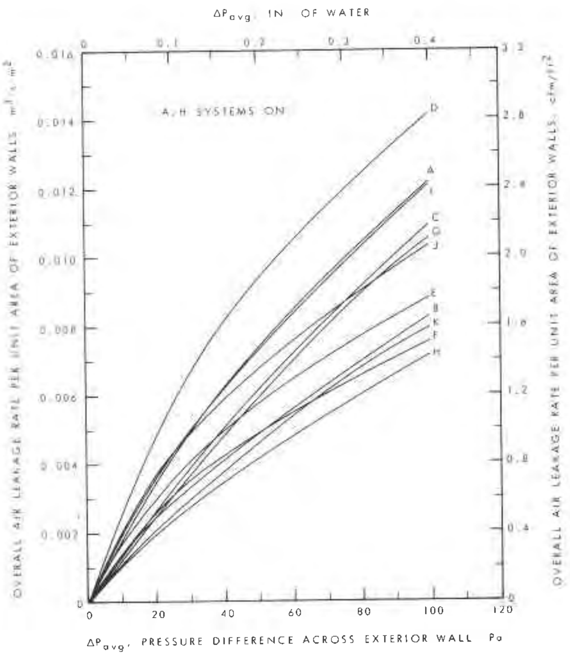

Fig. 4 The overall air leakage rates for schools with their air handling systems in operation

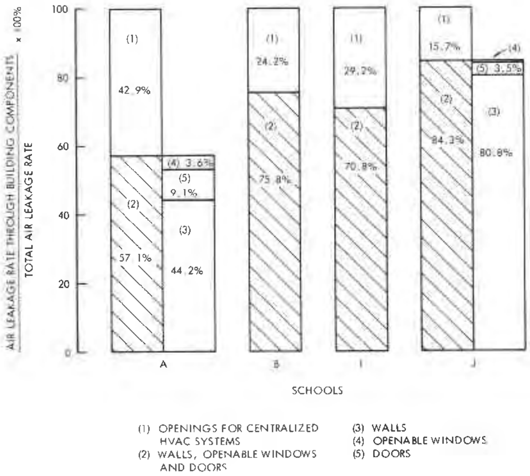

Fig. 5 The contribution of building components to the overall air leakage rate

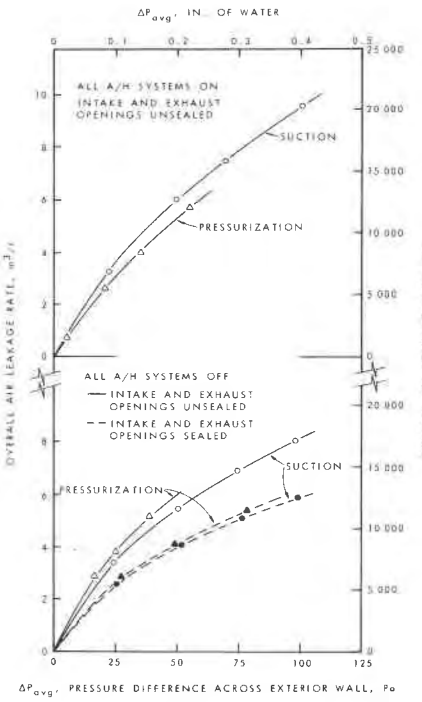

Fig. 6 The effect of pressurization or suction on the air leakage rate of School B

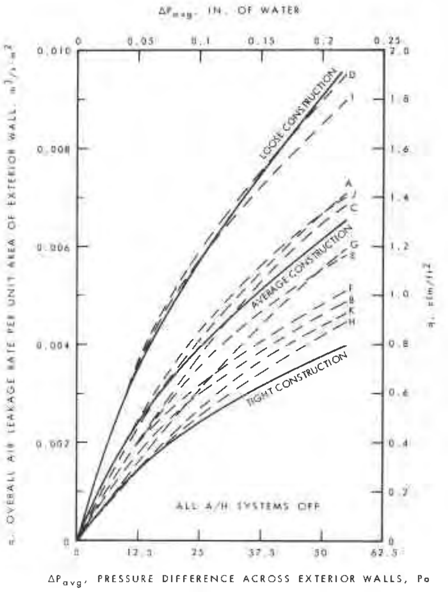

Fig. 7 The generalized overall air leakage values for school buildings

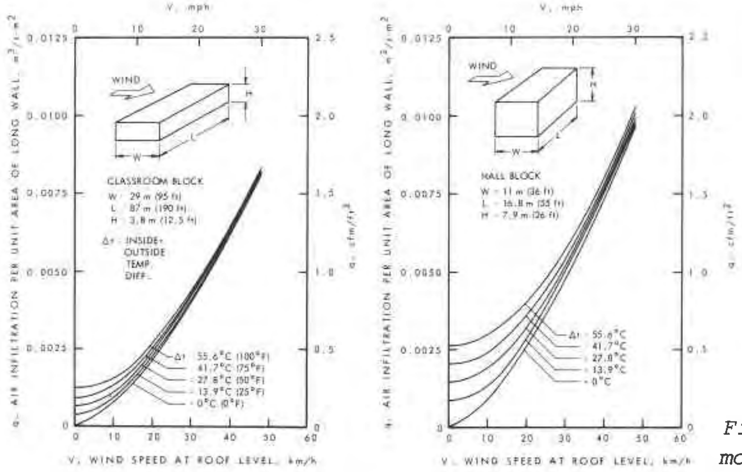

Fig. 8 Air infiltration rate of a model school of average air tightness

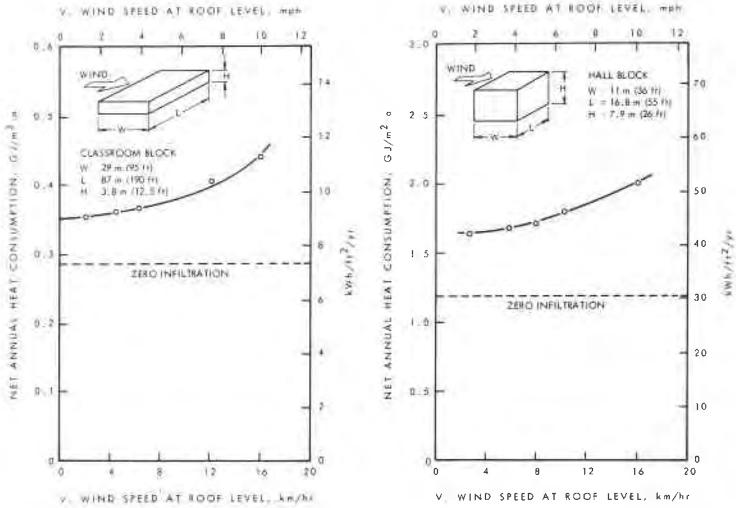

Fig. 9 Net heating load of a model school with average air tightness

School Model

Size	Over-all area 1800 m^3 (20,000 ft^2) Dimensions: Classroom Block 87 m × 29 m (190 ft × 95 ft), 2.74 m (9 ft) floor to ceiling, 3.8 m (12.5 ft) over-all height Hall 16.8 m × 11 m (55 ft × 36 ft), 6.4 m (21 ft) floor to ceiling, 7.9 m (26 ft) over-all height
Orientation	Major axis runs SW to NE
Construction	Over-all Transmittances: Wall 1.28 W/m^2 K (0.225 Btu/h ft^2 F) Roof 0.34 W/m^2 K (0.06 Btu/h ft^2 F) Glazing: Class - 25% of external wall (as viewed from inside), double-glazed with internal blind Hall - unglazed "Medium Weight Construction"
Environmental Condition	Temperature: Class - 22.2°C (72°F) Hall - 20°C (68°F) 5.5°C (10°F) set-back during unoccupied period Ventilation: 2.36 (dm)^3/s person (5 cfm) equivalent to: Class - 0.0072 (dm)^3/s m^2 (0.085 cfm/ft^2) Hall - 0.0211 (dm)^3/s m^2 (0.25 cfm/ft^2) Lighting: Electrical load: class - 12 W/m^2 (1.12 W/ft^2) hall - 19 W/m^2 (1.77 W/ft^2)
HVAC System	Class - terminal re-heat with scheduled supply air temperature Hall - constant volume variable temperature No mechanical cooling
Operation	School assumed to be used through an academic year for normal school use plus evening school. Plant operated 6 a.m. to 10 p.m. weekdays; lighting and occupancy rates reduced by ∿50% in the evenings.

DISCUSSION

JAMES E. WOODS, Assoc. Prof., Iowa State Univ., Ames, IA: You have reported that infiltration may account for about 30% of the annual energy consumption, based on your computer modelling. Have you verified these results with actual annual fuel data (energy consumption)? What was the actual fuel consumption (annual)?

L. JONES, C.Y. SHAW: No, we have not been able to verify our computer calculations with field data. We doubt very much if such verification can be made.

DAVID T. HARRJE, Sr. Resch. Engr., Princenton Univ., Princeton, NJ: Since these tests in schools covered a wide range of construction and ventilation systems, was there any attempt to use tracer gas to evaluate relative contributions?

JONES, SHAW: No. However, we hope to be able to use a tracer gas technique to measure the air infiltration rate for schools in the future.

WILLIAM RUDOY, Prof., Univ. of Pittsburgh, Dept. of Mech. Engr., Pittsburgh, PA: Would you comment on the comparable infiltration when individual unit ventilators are used in each classroom compared to a central HVAC system.

JONES, SHAW: Based on the results presented in the paper, we could find no meaningful relationship between air leakage and HVAC systems.

MARTIN ALTSCHUL, Energy Conservation Eng., University of Virginia, Charlottesville, VA: Since you found no correlation between air leakage and window area, were you able to correlate the infiltration to other factors (i.e., type of construction, building age, type of HVAC system)?

JONES, SHAW: No, we were not able to discern any definite correlations.

CLAYTON A. MORRISON, Assoc. Prof., Univ. of Florida, Mech. Eng. Dept., Gainesville, FL: Please use English units as an alternative so that practicing engineers will readily have a feel for what you wish to communicate.

JONES, SHAW: Both SI and Engineering Units were used in the paper.

G.H. GREEN, Prof. of Mech. Eng., Univ. of Saskatchewan, Saskatoon, Sask., Canada: Can you clarify how you distinguished between energy losses due to infiltration and those due to mechanical ventilation in your yearly studies of energy consumption?

JONES, SHAW: Ventilation and infiltration rates for the calculation of energy consumption are entered as separate values in the Meriwether Program--hence, by calculating energy consumption first with an infiltration rate as described and then with zero infiltration, we were able to say that infiltration was responsible for about 29% of the heating consumption for the <u>example</u> quoted.

GREEN: Where there have been reductions in the quantity of ventilation air in schools (i.e., the Carlton School Board), the reduction in energy consumption in buildings has been about 30% or more. Could you comment on this?

JONES, SHAW: Reduction in energy consumption will undoubtedly accompany lower ventilation rates, although the percentage savings will obviously vary from building to building.

Publications of the Division may be obtained by mailing the appropriate remittance (a Bank, Express, or Post Office Money Order, or a cheque, made payable to the Receiver General of Canada, credit NRC) to the National Research Council of Canada, Ottawa. K1A 0R6. Stamps are not acceptable.

A list of all publications of the Division is available and may be obtained from the Publications Section, Division of Building Research, National Research Council of Canada, Ottawa. KIA 0R6.