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A MODEL CORRELATING AIR TIGHTNESS AND AIR INFILTRATION IN HOUSES

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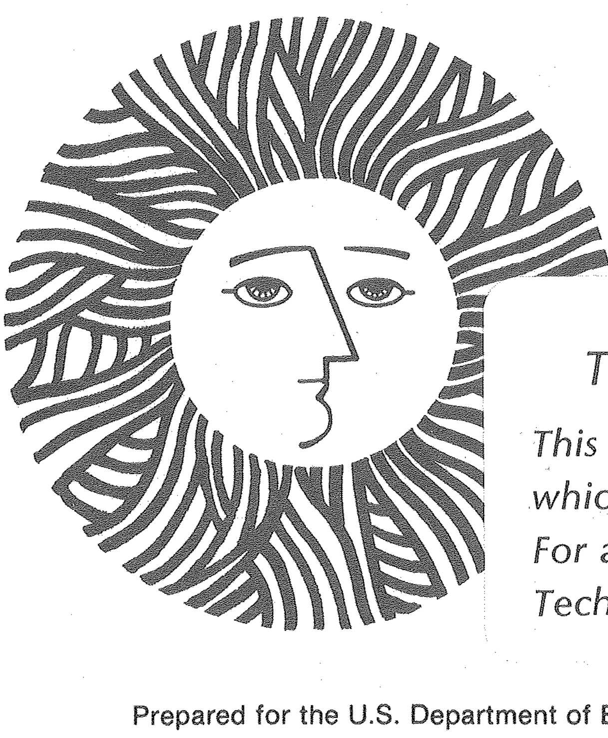

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A Model Correlating Air Tightness and Air Infiltration in Houses.

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Air infiltration, an important energy loss mechanism in buildings, has been studied in a number of houses on the east and the west coast. Two methods for measurement have been utilized: the fan pressurization technique and the tracer gas technique. The pressurization technique is used to measure the air tightness of the building envelope, while the tracer gas technique is used to measure the air infiltration. Pressurization is considered suitable for routine checking of buildings, but does not give the air infiltration as a direct result.

The model in this paper represents a technique of correlating the easily performed pressurization measurement with the more difficult tracer gas technique. The neutral pressure level is explicitly included to estimate the distribution of openings around the building envelope. The model is described in detail in this paper and is applied to a number of houses in New Jersey and California.

Keywords: Pressurization, infiltration, leakage, ventilation, neutral pressure level, modeling, correlation

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INTRODUCTION

Air leakage measurements in housing represent a promising technique to characterize housing quality. An air leakage standard for new construction exists in Sweden [1]; one is also under consideration in Canada [2]. While air leakage measurements are useful in making relative comparisons between buildings, it is commonly recognized that they currently cannot be used to predict energy use due to infiltration. Because of the importance of infiltration in the total energy loss in buildings, several projects are underway to find a relationship between air leakage measured using fan pressurization and infiltration measured using a tracer gas.

A promising approach to obtain a correlation involves constructing a model to calculate the infiltration of a building when the air leakage is known. The procedure described in this paper was introduced in a previous publication of one of the authors (A.B.) [3]; in this work the model is modified and described in greater detail. In addition, results obtained by applying the model to single family houses located in New Jersey and California are presented.

The ratio between calculated and measured infiltration for the eleven houses in this study was found to be 1.10 ± 0.30. This 27% uncertainty is compared to results obtained from a simpler model. While the results in this paper are an improvement, they still fall short of a criterion we suggest below, viz. the ability of the model to predict energy consumption.

DESCRIPTION OF THE MODEL

The model uses two primary inputs to calculate air infiltration. The first is the measurement of air leakage of the entire building envelope; the second is the pressure distribution over the building envelope caused by the wind and indoor-outdoor temperature differences.

The leakage of the entire building shell is obtained using fan pressurization. The measurement technique is described in Appendix A. An equation describing the air flow through a single opening is

$$Q = K\ (\Delta P)^{\alpha} \tag{1}$$

where

Q is the air flow (m^3/hr)

K is the air flow coefficient (m^3/hr at 1 Pa)

ΔP is the pressure difference across the opening (Pa) and

α is the flow exponent ($0.5 < \alpha < 1.0$).

Fan pressurization measurements do not yield information about flows across individual openings but rather the integrated flow characteristic for the entire envelope (see fig.1). Consequently the model uses the simplifying assumption that the leakage of the entire building shell is uniform.

The flow exponent and air flow coefficient for any house is found by fitting the measured pressure flow characteristic for the whole building to an equation having the form of eq 1. The exponents used in the calculations are listed in Table C1.

The pressures on the building envelope are obtained by summing the pressure due to the wind with the pressure due to the indoor- outdoor temperature differences at approximately 50 points on the building shell. The pressure due to the wind at location j, P_{wj}, is given by

$$P_{wj} = \frac{1}{2} C_j\ \rho\ v_j^2 \tag{2}$$

where

ρ is the density of air (kg/m^3),

v_j is the wind speed at location j (m/s) and

C_j is the shielding coefficient for that location.

The shielding coefficients are obtained from wind tunnel measurements on elementary building forms [4,5]. The values of v_j are computed from wind speeds measured at a 10m weather tower on site or at a weather station using corrections for the ground plane and terrain roughness [6].

The pressure difference due to the inside-outside temperature difference at location j, P_{tj}, is given by

$$P_{tj} = (\rho_o - \rho_i) \, g \, h_j \qquad (3)$$

Here

ρ_o is the density of the outside air (kg/m^3),

ρ_i is the density of the inside air (kg/m^3)

g is the acceleration of gravity (m/s^2) and

h_j is the height of location j above a reference level (m).

When added, the pressures from the temperature difference and wind may be positive or negative relative to the interior of the house. Summing over all sites at which the surface pressure is larger than the interior pressure gives the total air flow into the structure.

$$Q_{in} = K \sum_{j} (P_j - P_r)^{\alpha} \qquad (4)$$

where

Q_{in} is the total air flow into the structure (m^3/hr)

P_j is the weather-induced surface pressure at point j (Pa) and

P_r is the interior reference pressure (Pa).

Since we have assumed uniform leakage over the shell of the structure, K and α are independent of the location on the building envelope.

In a similar fashion the air flow out of the structure is given by

$$Q_{out} = K \sum_{j'} (P_r - P_{j'})^{\alpha} \qquad (5)$$

where the symbols have the same meaning as in eq (4). The interior pressure, P_r, will adjust until the flow into the structure and the flow out are the same.

Up to this point the model uses only measured properties of the building envelope or wind tunnel values determined independently. Results obtained using this model applied to four townhouses in Twin Rivers, NJ were previously reported [3] and are listed in Table 1. Agreement between measured values and predictions of the model is not good.

Improvements in the model are not difficult to generate; there are many areas to improve in such a simple model. The difficulty that arises with each refinement comes from the ambiguity that is associated with each change. Unless the refinement introduces a change based upon a quantity that can be measured or deduced from independent considerations, the refinement becomes merely a numerical exercise. An example of this is the assumption made that the leakage of the building envelope is uniform. While this assumption is clearly incorrect, it is an assumption that is appropriate for the level of information obtained from a whole-building leakage measurement.

A refinement in the assumption of uniform leakage distribution is possible using the location of the neutral pressure level as a measure of non-uniformity. Recent work of Tamura [7] and Sherman, et al.[8] has indicated the importance of the neutral pressure level in infiltration models. The neutral pressure level can be thought of most simply in a condition of zero wind speed but non-zero indoor-outdoor temperature difference. When this occurs the neutral pressure level is the height above the ground (assumed to be a reference plane) at which the indoor-outdoor pressure difference is zero (fig.2). If the leakage of the house is uniform, equating flow into the structure (eq 4) and flow outward (eq 5) yields the result that the neutral pressure level is at the mid-point of the structure.

Non-uniform leakage causes the location of the neutral pressure level to shift. Qualitatively, it moves toward the location of the largest openings in the structure. Its exact location can be calculated by equating flows into and out of the structure if the leakage characteristics of all the openings are known. Conversely, a measurement of the neutral pressure level gives information about the relative leakage of the surface area located above the level and that located below.

Representing the flow through an opening by equation (1) and assuming that the flow exponents for leakage above and below the neutral pressure level are the same, the air flow coefficient below the neutral level is related to that above by

$$K_b = K_t \left(\frac{H - h_o}{h_o}\right)^{\alpha + 1} \qquad (6)$$

where

K_b is the air flow coefficient below the neutral level (m^3/hr at 1 Pa)

K_t is the air flow coefficient above the neutral level (m^3/hr at 1 Pa)

h_o is the height of the neutral level above the reference plane (m).

H is the height of the house (m).

The details of this calculation are presented in Appendix B. Values of K_b and K_t are related by eq (6); in addition, they are constrained to yield the same total flow that was obtained in the fan pressurization measurement.

Unfortunately, measurements of the neutral pressure level do not exist for these houses. Estimates of the level were made based upon knowing the location of the largest openings which were identified. In addition, the leakage of the area below the neutral level was estimated using knowledge about the typical leakage for that particular kind of construction [14]. This is done for the area below, when the largest openings are located above the neutral level, otherwise it is done for the area above. The levels used are included in Table 1 which presents the results of the calculation.

Another refinement in the model, which again lacks the justification of supporting measurement detail, is the treatment of the leakage of the ceiling and roof when an attic is present. The earlier version of the model treated the roof as part of the uniform leakage of the structure and the ceiling as non-existent i.e. as if there wasn't any ceiling (see fig. 3). This choice was made to allow use of known wind-tunnel pressure measurements to calculate the wind pressures in the model. The actual leakage which is tested by fan pressurization in a house occurs through the ceiling into a well-shielded attic. This shielding of the attic space by the roof reduces the magnitude of the wind pressures seen by the top element of the building envelope. The amount of shielding due to the roof is not known; calculations show that the results are insensitive to the exact value as long as the magnitude of the pressures seen by the ceiling are smaller in magnitude than 30% of the average wind pressure experienced on the roof.

RESULTS

The results of the calculations are shown in Table 1. Specific application details are presented in Appendix C. The Table clearly shows the evolution of the model as more detail is included. This is also shown in fig. 4. This figure shows a histogram of the ratio obtained by dividing the calculated air change rate by the measured value for each house.

The average value of this ratio, $< A_c / A_m >$, for the initial version of the model is 1.91 ± 0.73. When the assumption of uniform distribution of leakage is removed and two distinct leakage values (one below and one above the neutral level) are allowed for each structure, the ratio decreases to 1.61 ± 0.59. The second modification in the model, considering the ceiling rather than the roof to be the top leakage element, reduces the ratio to 1.10 ± 0.30.

Table 1. RESULTS.

Model 1: Original Model

Model 2: Neutral Level Added

Model 3 and 3′: Shielding of Ceiling Added

House	h_o (H)	Model	A_m	$\|\Delta A\|$	A_c	A_c/A_m
SA	4.7(7.3)	1	0.38	.61	0.99	2.61
SA	6.1(7.3)	2	0.38	.30	0.58	1.53
SA	5.1(5.4)	3	0.38	.05	0.33	0.87
SA	5.1(5.4)	3′	0.38	.09	0.29	0.76
RE	4.7(7.3)	1	0.31	.37	0.68	2.19
RE	5.8(7.3)	2	0.31	.20	0.51	1.65
RE	5.0(5.4)	3	0.31	.01	0.32	1.03
RE	5.0(5.4)	3′	0.31	.02	0.29	0.94
WA	4.8(7.3)	1	0.36	.59	0.95	2.64
WA	6.1(7.3)	2	0.36	.21	0.57	1.58
WA	5.1(5.4)	3	0.36	.02	0.34	0.94
WA	5.1(5.4)	3′	0.36	.07	0.29	0.81
HE	4.6(7.3)	1	0.42	.57	0.89	2.12
HE	6.0(7.3)	2	0.42	.21	0.63	1.50
HE	5.1(5.4)	3	0.42	.08	0.34	0.81
HE	5.1(5.4)	3′	0.42	.10	0.32	0.76
SO	4.7(6.7)	1	0.50	.14	0.64	1.28
FE	4.2(7.1)	1	0.84	.36	1.20	1.43
DA1	2.7(5.0)	1	0.31	.08	0.23	0.74

DA2	2.7(5.0)	1	0.64	.07	0.57	0.89
HA1	2.6(4.9)	1	0.18	.16	0.34	1.89
HA1	1.8(2.4)	3	0.18	.06	0.24	1.33
HA1	1.8(2.4)	3′	0.18	.04	0.22	1.22
HA2	2.6(4.9)	1	0.17	.32	0.49	2.88
HA2	2.8(4.9)	2	0.17	.32	0.48	2.82
HA2	2.1(2.4)	3	0.17	.09	0.26	1.53
HA2	2.1(2.4)	3′	0.17	.06	0.23	1.35
HA3	2.6(4.9)	1	0.21	.28	0.49	2.33
HA3	1.8(2.4)	3	0.21	.11	0.32	1.52
HA3	1.8(2.4)	3′	0.21	.13	0.34	1.62

Variable	Model 1	Model 2	Model 3
$< A_c/A_m >$:	1.91 ± 0.73	1.61 ± 0.59	1.10 ± 0.30
$\Delta A = \|A_c - A_m\|$:	0.32 ± 0.20	0.21 ± 0.10	0.10 ± 0.09

Notes:

h_o is the calculated neutral pressure level (m), H is the building height, (for case 3 the height is measured to the ceiling). The ceiling shielding coefficient used in model 3 was −0.15 for the HA house and −0.28 for the townhouses. In model 3′ the coefficient used was 0.0.

DISCUSSION AND CONCLUSIONS

The purpose of a modeling exercise such as this is to attempt to find a correlation between air leakage measurements obtained with fan pressurization and the air infiltration experienced by a house. We compare the results for our model with two simpler models and with an estimate of what is needed for modeling energy use. The simplest model that can be imagined is a direct correlation between air leakage (at e.g. 50 Pa) and air infiltration. This would be expressed as

$$A_{50} = R_1 A \quad (7)$$

where

A_{50} is the number of air changes per hour at 50 Pa obtained using fan pressurization, (hr^{-1})

R_1 is a constant and

A is the measured infiltration rate (hr^{-1}).

When the value of R_1 is calculated for the houses used in this sample, a value

$$R_1 = 45 \pm 32$$

is obtained.

The large standard deviation of this result (71%) is not surprising since at the very least we can only hope to find a correlation when the air leakage is related to the infiltration at a standard weather condition. However, adjustment of an infiltration rate to a standard weather condition is an uncertain procedure. It is precisely this kind of problem that the present model addresses. The model can be used to predict the infiltration for a house experiencing any combination of wind speed and temperature difference. The ability of a model such as this to predict the measured value of the infiltration is a measure of success of the idea that a correlation between air leakage measurements using fan pressurization and infiltration of a building is possible. The ratio between calculated and measured infiltration for these eleven cases is

$$< \frac{A_c}{A_m} > = 1.10 \pm 0.30.$$

A better model than eq. 7 to use to compare the predictive quality of our model is provided if we make use of a technique of Peterson [9] to adjust infiltration rates to standard conditions. When this is done (cf. details in Appendix D) we find that the ratio between air leakage at 50 Pa, A_{50}, and air infiltration adjusted to a standard condition of $v = 3.5$ m/s and $\Delta t = 13.5$ °C, A_s, yields a value

$$\frac{A_{50}}{A_s} = 39.2 \pm 15.8$$

The wind speeds and temperature difference chosen for the adjustment to a standard condition were the average values for the measurements reported in this paper. The standard deviation of this result, 40%, is larger than the result obtained from the model described in this paper. The Peterson technique has the virtue of being extremely simple but it is unlikely that additional work on this technique will produce a correlation with a smaller uncertainty.

The uncertainties associated with both models are too large if one wants to model energy use adequately. Infiltration is commonly judged to account for one-third of the energy use in a house. Therefore a 32-35% uncertainty in predicted infiltration translates into a 10 to 12% uncertainty in energy use from that mechanism alone. Work of Sonderegger [10] has shown that the occupant's behavior causes $\approx \pm$ 15% variation in the energy use of physically identical structures. Predictive models of energy use need not attain high precision but certainly should attempt to produce results with an uncertainty less than that contributed by occupants. If the total uncertainty in energy use predicted by energy load models is to be less than 10% and if this is equally shared by (1) windows, (2) the opaque shell and (3) air infiltration, the contribution from air infiltration should not be greater than about 6%. This requires a modeling procedure which can predict infiltration with an uncertainty less than or equal to 18%. Models do not currently exist which can do this.

The specifications for an adequate predictive model given above also demand a different type of verification procedure from the technique described in this paper. The verification procedure we used related an infiltration measurement to a predicted infiltration obtained using weather conditions at the site during the measurement. A better procedure, one which we recommend be used in the future, will relate long-term infiltration measurements to average weather conditions at the site. This will reduce random error in the correlation and will produce a more reliable predictive model.

Both the simple correlation technique and the model described in this paper support the idea that a correlation between fan pressurization measurements and infiltration rates is possible to construct. Improvements are necessary and are clearly possible with our model; the improvements described in this paper are examples. Additional refinements will occur as better information about shielding conditions and the distribution of openings in buildings become available.

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Appendix A: Test Methods

In order to perform the measurements necessary for this paper two test methods were used: the pressurization technique and the tracer gas technique. The results of the first were used as a basis for the model; the results of the second were used to check the model's accuracy.

a/Pressurization/depressurization.

The pressurization technique is used for testing the air tightness of the building envelope of an entire building [3]. The procedure is the following: a fan is mounted in the building envelope. Using this fan the entire house is first pressurized and then depressurized (i.e. a differential pressure is established between inside and outside the house under test.) Once a pressure is established the fan speed is read using a tachometer. The flow is determined from previous laboratory calibrations of the flow rate as a function of the fan speed and the pressure drop across the fan. Within a short period of time a pressure-flow rate profile is established for the house.

In our case this was done with a specially designed door, with a vaneaxial fan permanently mounted in it. The height and width is adjustable to fit tightly into a wide variety of door frames. The fan is driven by a variable speed motor to achieve pressures in the range of 10-60 Pa. This blower door design was first developed at Princeton University and then further improved at Lawrence Berkeley Laboratory.

b/Tracer gas

This technique is used to measure the actual air infiltration under natural conditions in a building. Tracer gas, a gas normally not present in the structure, is injected into the test house and the concentration is measured; from that the air infiltration can be derived. Two methods were used: concentration decay following periodic injection and continuous injection.

The first method was used at Princeton [11]. A tracer gas, in this case sulphur hexaflouride (SF_6), was injected every three hours and measurements of concentration were made every five minutes using a gas chromatograph and an electron capture detector. This was done automatically for up to one week. In order to determine the air infiltration, measurements of concentration (C) from two different times (t and t + Δt) are used. The following relation is employed to find the air exchange rate:

$$A = -\frac{1}{\Delta t} \ln \frac{C_t}{C_{t+\Delta t}} \qquad (A.1)$$

At Lawrence Berkeley Laboratory both methods were used. The tracer gases used were nitrous oxide (N_2O) and ethane (C_2H_6); concentration was measured with an infrared analyzer. When the air infiltration was to be monitored continuously, (e.g. through an entire night) a controlled-flow tracer gas technique was employed [12]. Tracer gas was injected continously using a mass flow controller into the house and the concentration was measured continuously. The volumetric air infiltration rate is calculated from the equation

$$Q = \frac{F}{C} - \frac{(dC/dt)}{C} V \qquad (A.2)$$

where

Q = the volumetric air infiltration rate (m^3/hr)

F = flow of injected tracer gas (cc/hr)

C = tracer gas concentration (ppm)

dC/dt = time derivative of tracer gas concentration (averaged over at least 10 min).

V = volume of house (m^3)

Appendix B: Calculation of Neutral Level

The neutral pressure level is used, in the model, as an indicator for the vertical distribution of openings. For a given neutral pressure level an air flow coefficient below this level (K_b) and another above (K_t) is calculated so that air flow into the structure equals air flow out. This is done here for a building with a tight ceiling and floor. The calculation assumes zero wind speed but non-zero temperature difference.

$$\int_0^{h_o} K_b \ (\Delta P)^{\alpha} \ dh = - \int_{h_o}^{H} K_t \ (\Delta P)^{\alpha} \ dh \qquad \text{(B.1)}$$

$$\Delta P = \frac{\Delta P_{max}(h_o - h)}{H} \qquad \text{(B.2)}$$

where

K_b = air flow coefficient below neutral level (m^3/hr at 1 Pa)
K_t = air flow coefficient above neutral level (m^3/hr at 1 Pa)
ΔP_{max} = maximum pressure difference caused by temperature (Pa)
h_o = height of neutral level (m)
h = height above ground level (m)
H = height of house (m)

Solving this equation gives the following relation

$$K_b = K_t \ \left(\frac{H - h_o}{h_o}\right)^{\alpha + 1} \qquad \text{(B.3)}$$

This is one equation with two unknowns. The final restriction is that the total air leakage has to be equal to the result from the fan pressurization.

$$K \ (A_b + A_t) = k_b \ A_b + K_t \ A_t \qquad \text{(B.4)}$$

where

A_b = area below neutral level (perimeter x h_o)
A_t = area above neutral level (($H - h_o$) x perimeter + ceiling)

If, e.g., there are large openings above the neutral level, this is taken into account in the model by increasing the average leakiness above the neutral level. This is an approximation of the real case, which is motivated by a lack of information about the air leakage through individual openings. When no measurement of the neutral level is available in the last case, the average leakage below neutral level is assumed taking into account a typical leakage rate for that kind of structure [14].

Appendix C: House Description and Application Details.

Table Cl Test House Information

House	Sa	Re	Wa	He	So	Fe
Location	N.J.	N.J.	N.J.	N.J.	N.J.	N.J.
Type t=townhouse d=detached	t	t	t	t	d	d
Floor area (m^2)	138.3	138.3	138.3	138.3	190	152
Volume (m^3)	494.4	494.4	494.4	494.4	535	466
No. Storys	2	2	2	2	1 1/2	2
b=basement c=crawlspace s=slab on ground	b	b	b	b	c	b
Δt (°C)	17	17	17	17	17	17
Measured wind(m/s) at weather station	4	4	4	4	4	4
Calculated wind (m/s) at roof ridge	2.6	3.1	2.6	3.1	2.6	0-2.4
Air leakage at 50 Pa (ach)	13.3	9.8	12.6	11.3	9.1	16.
Flow exponent	0.68	0.67	0.67	0.63	0.61	0.55
Notes; see below	(A)	(A)	(A)	(A)	(B)	(B)

Table C1 continued

House	Da 1	Da 2	Ha 1	Ha 2	Ha 3
Location	Ca	Ca	Ca	Ca	Ca
Type t=townhouse d=detached	d	d	d	-	-
Floor area (m^2)	105	105	100	-	-
Volume (m^3)	269	269	230	-	-
No. Storys	1	1	1	-	-
b=basement c=crawlspace s=slab on ground	s	s	c	-	-
Δt (°C)	6	9	13	9	9
Measured wind (m/s) at weather station	2.1	4.5	2.8	2.8	2.0
Calculated wind(m/s) at roof ridge	1.4	3.0	1.5	1.5	1.1
Air leakage at 50 Pa (ach)	12.4	10.3	13.9	17.6	20.2
Flowexponent	0.72	0.67	0.72	0.64	0.62
Notes; see below	(C)	(C)	(D)	(D)	(D)

(A): The model was first applied on four Twin Rivers townhouses (N.J.). The first decision to be made was what flow exponent to use; the value that could be calculated from the pressure - flow rate profile was used. As a first assumption the distribution of openings was assumed to be uniform, even though there are large openings high up.

Wind pressure distributions were taken from wind tunnel measurements done on models of the townhouses [4]. It has to be mentioned that no boundary layer was included in the measurements. The windspeed was corrected for type of surrounding (for relative location of houses see fig. C1). The partition walls were assumed to be tight since they are made of masonry.

The average measured air infiltration was 0.37 air exchanges (ach) per hour. A calculation of the air infiltration for these houses gave an average of 0.88 ach (for individual numbers see table 1). This value is ≃ 2.4 times higher than the measured value.

The infiltration rate was recalculated taking into account the non-uniform distribution of openings in height. The number of openings on windward and leeward side is assumed to be the same, as the two sides have roughly the same construction with the same number of windows and doors. The townhouses have some large openings at the attic level, openings like attic door and attic bypasses * [13]. These openings will tend to move the neutral level upwards. As can be seen in fig. C2, for the He-house, the higher the neutral level the lower the air infiltration in this particular house. Assuming the level to be 7.0m would mean that at 50 Pa, when pressurizing the whole house,: $633 m^3/h$ ($4.8 m^3/m^2h$) would leak through the area below 7m and $4948\ m^3/h$ ($532\ m^3/m^2h$) would leak through the area above 7m. This is very unlikely. A more likely level would be 6.0m which would mean $17.0 m^3/m^2h$ below 6m (this value is typical for a leaky wood frame structure, see Ref. 14). This would mean a calculated value of 0.63 ach. Similar calculations for the other townhouses (see Table 1) resulted in an average calculated value of 0.58 ach, which is 1.5 times higher than the measured value.

* The bypasses are here approximated to be big leaks in the envelope.

(B): The first complication for these two houses, was to find a suitable wind pressure distribution. There are few studies made of pressure distributions on elementary building forms [4,5] and mostly they are concerned with wind loading on structures. The one used here is extensive and was made in 1951 [5]. This study was done in a wind tunnel, with no boundary layer, for houses with a rectangular or square plan form. Unfortunately none of the two houses studied have an absolutely rectangular plan form. The two houses were modified to a rectangular plan form with the same wall areas on all sides and the same height to the roof ridge as before. Then the building form in the study which had the proportions closest to the desired one was chosen. The distribution of openings was assumed to be uniform, as there were no large openings to be found.

The calculations for the So-house gave a value between 0.61-0.66 ach, depending on the wind direction. The higher value pertains to a condition for a 45-degree wind and the lower for a wind perpendicular to the long sides. These values are to be compared with the tracer gas measurements of 0.4-0.6 ach. (The exact wind direction was not known.) The Fe-house was calculated to have 1.07 ach to 1.32 ach. The first value is for a case with no wind and the second one for a case with wind (see Table C1). The Fe-house must be regarded as well protected, so a case somewhere in between should be appropriate. The measurements gave 0.84 ach. The ceiling was not incorporated in the calculations for these houses, as the So-house has a conditioned attic and the Fe-house has a relatively small attic.

(C): These two houses were identical in floor plan. The vents were taped over and no really large openings were found. The distribution of openings was assumed to be uniform. House #1 had a calculated air infiltration of 0.23 ach and a measured air infiltration of 0.31 ach, (see fig. C3). House #2 was calculated to have 0.60 ach and measured to have 0.64 ach. These houses are different in their physical make-up from most detached houses; they have high ceiling following the pitch of the roof and they have solar collectors on the roof. The major reason for the discrepancy is believed to be the fact that the two houses have projecting eaves and are surrounded by a 6′ high fence. (House #1 on all sides, while house #2 on three sides). This makes it very hard to estimate the right wind pressure distribution.

(D): Calculations were made for three detached houses in California. The last was our research house (Ha-house) in Walnut Creek. The house was modified in two steps. First the house was tested with ducts, kitchen vent and fireplace open, (the fireplace damper was closed). Then the ducts were taped over tightly. The last step was to tape over the fireplace and the kitchen vent.

When all the big openings were taped over, the distribution of openings was assumed to be uniform. The model gives the number 0.34 ach to be compared with measurements giving 0.18 ach (see Table 1). The leakiness related to the building envelope was 13 m^3/m^2h at 50 Pa. Opening the fireplace and the kitchen vent causes increased air leakage and the neutral level to move upwards; the walls should have the same air leakage as before. The predicted air infiltration is 0.48 ach. Actual measurements showed 0.17 ach *. The last case was with all vents open (i.e. floor registers, fireplace and kitchen vent). This may or may not change the neutral level compared to the first case since both big openings at low level and high level are added. If unchanged, the model gives 0.49 ach to be compared with 0.21 ach * from measurements. One complicating factor for this house is that there is a garage built as an annex, (see fig. C4). It was not possible to take this into account when assigning a wind pressure distribution to the house in the model.

* The air infiltration for the three cases was measured during different weather conditions (see Table C1).

Appendix D: A Simplified Correlation Technique

If it were possible to relate a single measurement of infiltration to the infiltration the structure would experience at a standard weather condition, we could examine the ratio A_{50}/A_s as a prediction of infiltration. A_{50} is the air exchange rate measured at 50 Pascals using fan pressurization (ach), while A_s is the infiltration of the house at standard weather condition (ach).

Recent work of Peterson [9] suggests such an approach. He uses an expression of the form:

$$A = D_1 + D_2\ (t_r - t_o) + D_3\ v_m \qquad (D.1)$$

to calculate the infiltration if the inside temperature, t_r, the outside temperature, t_o, and the wind speed, v_m are known. D_1, D_2, and D_3 are constants chosen by examining published literature describing infiltration measurements. While one can fault the physical validity of adding a term in Δt to a wind speed term [15], the procedure is simple enough to warrant such an attempt.

If the infiltration A_m, is measured at temperature t_o, and wind speed v_m, equation D.1 predicts that the standard infiltration A_s will be given by

$$A_s = A_m + D_2(\Delta t_s - \Delta t_m) + D_3(v_s - v_m) \qquad (D.2)$$

Where $\Delta t_s = t_r - t_s$, the temperature difference for the standard temperature condition, $\Delta t_m = t_r - t_o$ and v_s and v_m are the wind speeds at the standard and measured conditions, respectively. Values of D_2 and D_3 are given by Peterson for houses of loose construction to be

$$D_2 = 0.0216\ \frac{ach}{^oC}$$

$$D_3 = 0.0672\ \frac{ach}{m/s}$$

Table D1, below gives values of A_s for the eleven houses considered in this study. Standard conditions were the average values of Δt and wind speed for the measured infiltration values (Δt = 13.5 ^oC, v = 3.5 m/s).

Table D1 Simple Correlation

House	A_s	A_{50}/A_s
Sa	0.27	49.3
Re	0.20	49.0
Wa	0.25	50.4
He	0.32	35.3
So	0.39	23.3
Fe	0.73	22.7
Da 1	0.57	21.8
Da 2	0.67	15.4
Ha 1	0.24	57.9
Ha 2	0.31	56.8
Ha 3	0.41	49.3
		39.2 ± 15.8 (40%)

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FIGURE CAPTIONS

1) Figure 1 is a graph of a pressure-flow rate profile from a fan presurization. Indicated is a possible change of flow exponent, α, as suggested by laboratory studies obtained for flow through small cracks. Q is the air leakage and ΔP is the pressure difference inside-outside the house.

2) Figure 2 is a drawing of the neutral level and differential pressures induced by the stack effect in a structure. The arrows indicate the direction of the air flow.

3) Figure 3 is a drawing showing a cross section of the porous building envelope as used in the model. The walls and the ceiling are given a certain porosity, while the ground is considered to be air tight. The floor is not seen by the model. The roof is regarded as air tight except for the vents. The only effect of the roof is a shielding effect.

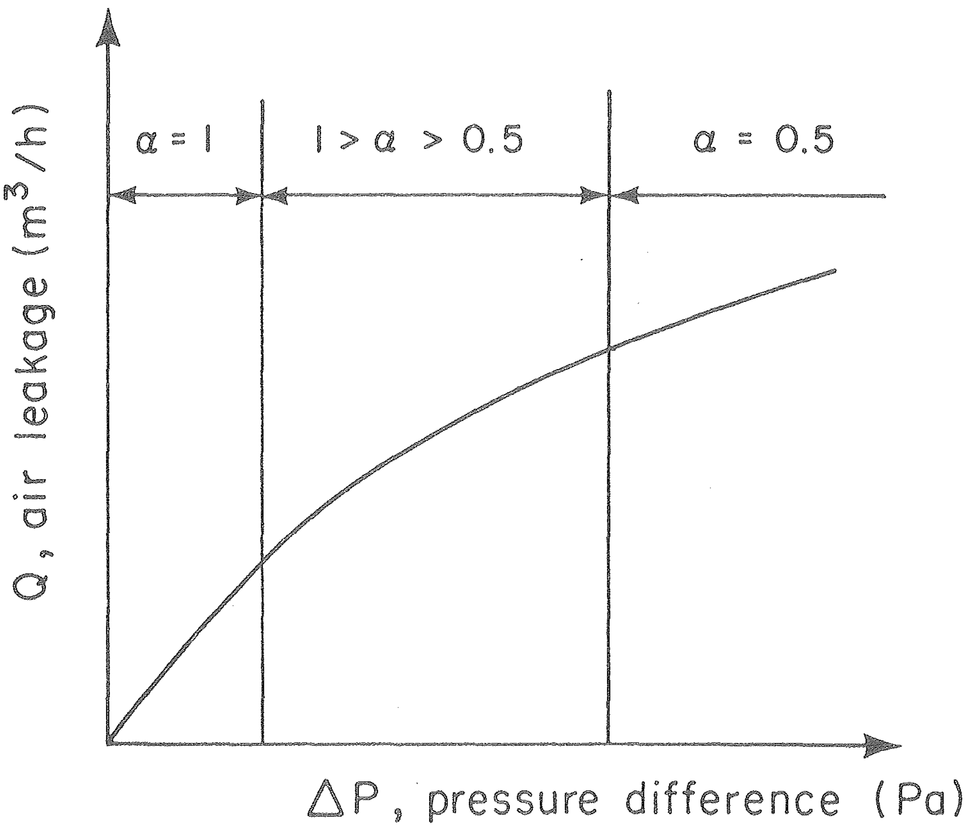
4) Figure 4 shows histograms of the ratio between calculated air infiltration (A_c) and measured air infiltration (A_m) for the different stages of the model. The variable, n, indicates number of houses.

5) Figure C1 is a drawing showing the relative location of the townhouses in New Jersey. The wind direction used in the model is indicated.

6) Figure C2 is a graph of calculated air infiltration as a function of the height of the neutral level for He-house. The air infiltration is given in air exchanges per hour (A). The height of the neutral level is given as the relative height (β) and the absolute height (h) above ground level. Indicated is also measured air infiltration with unknown height of the neutral level.

7) Figure C3 is a graph of calculated air infiltration as a function of the height of the neutral level for Da1 and Da2-house. The air infiltration is given in air exchanges per hour (A). The height of the neutral level is given as the relative height (β) and the absolute height (h) above ground level. Indicated is also measured air infiltration with unknown height of the neutral level.

8) Figure C4 is a drawing showing a site plan for Ha-house.



XBL 7911-13098

Figure 1

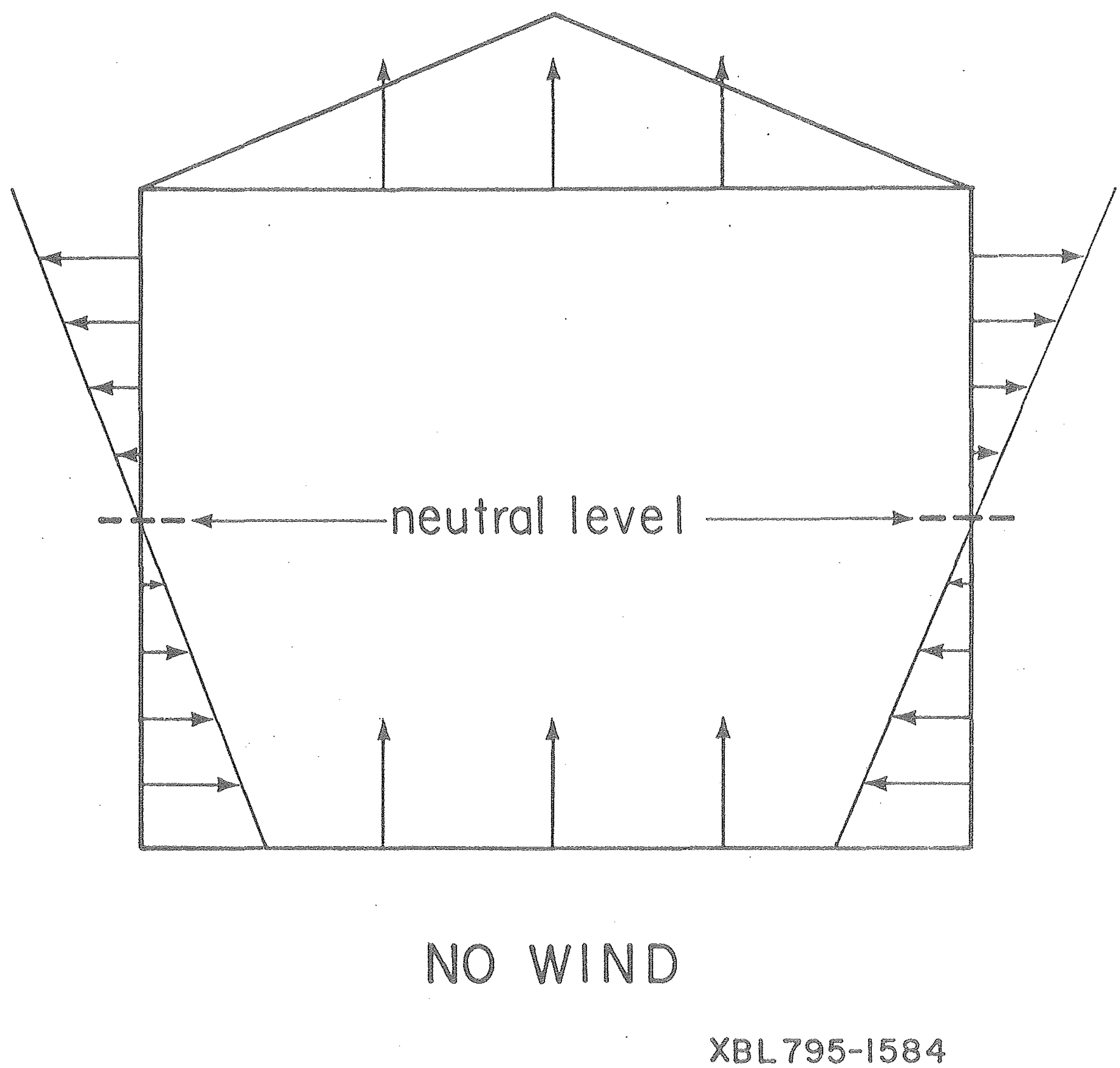


Figure 2

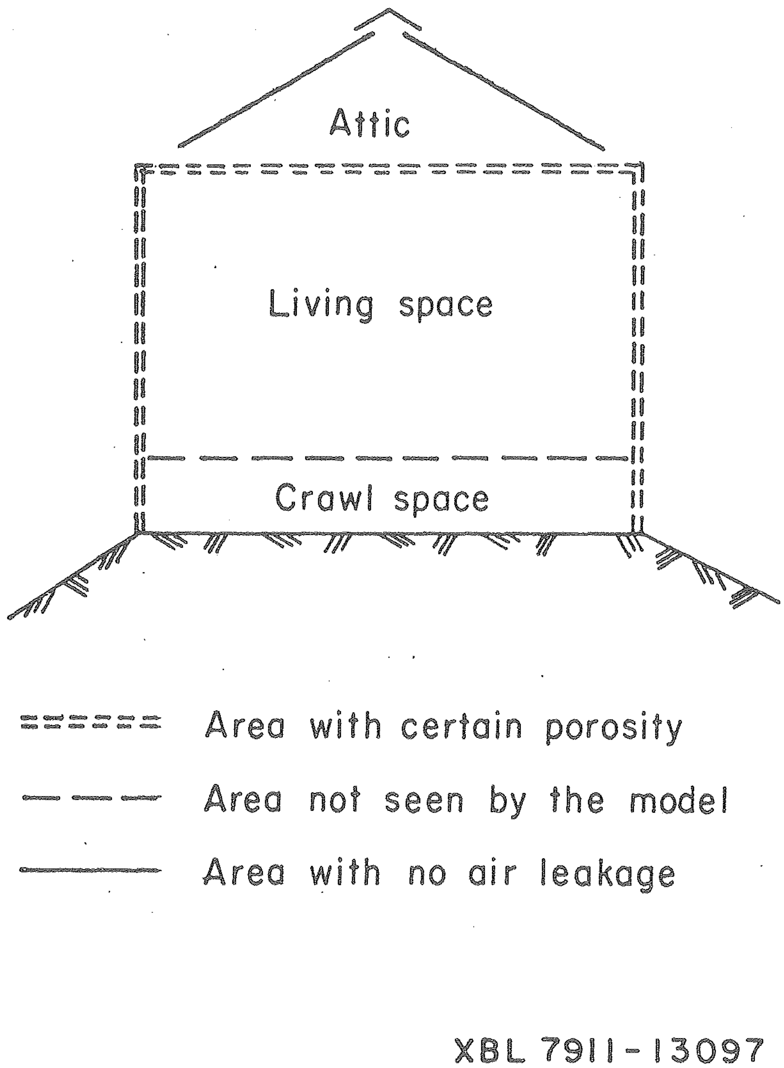
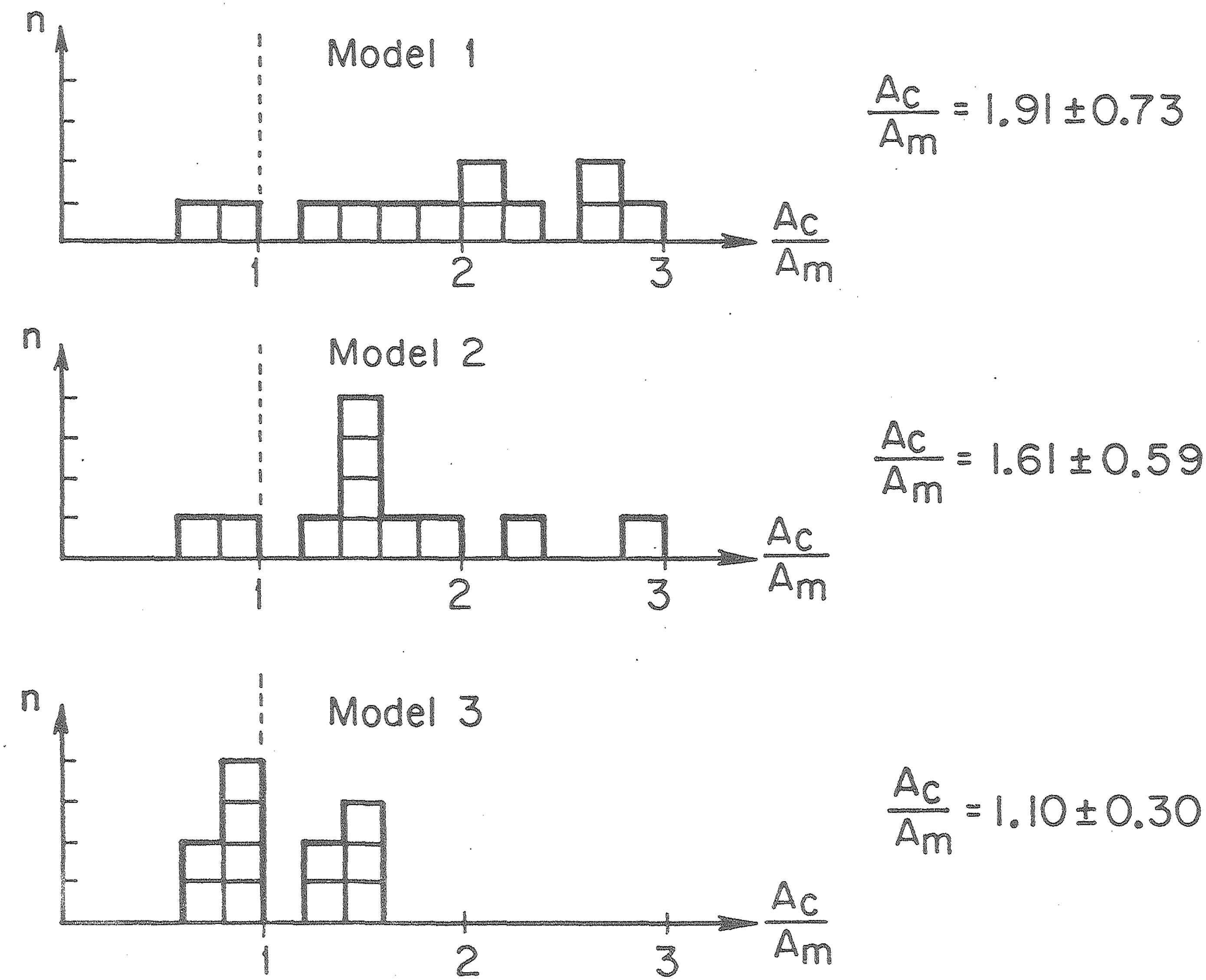
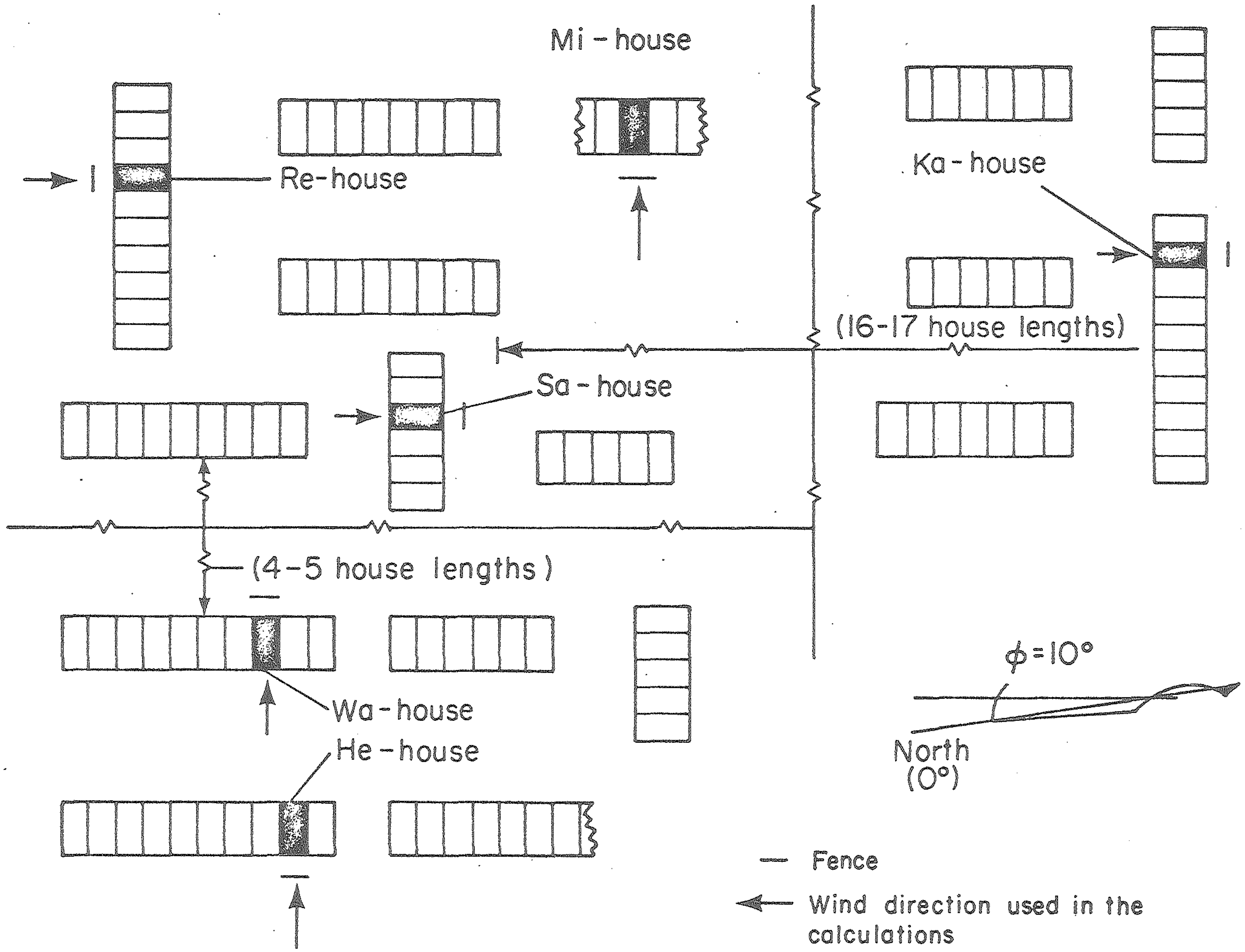

Attic
Living space
Crawl space
Area with certain porosity
Area not seen by the model
Area with no air leakage
XBL 7911-13097

Figure 3



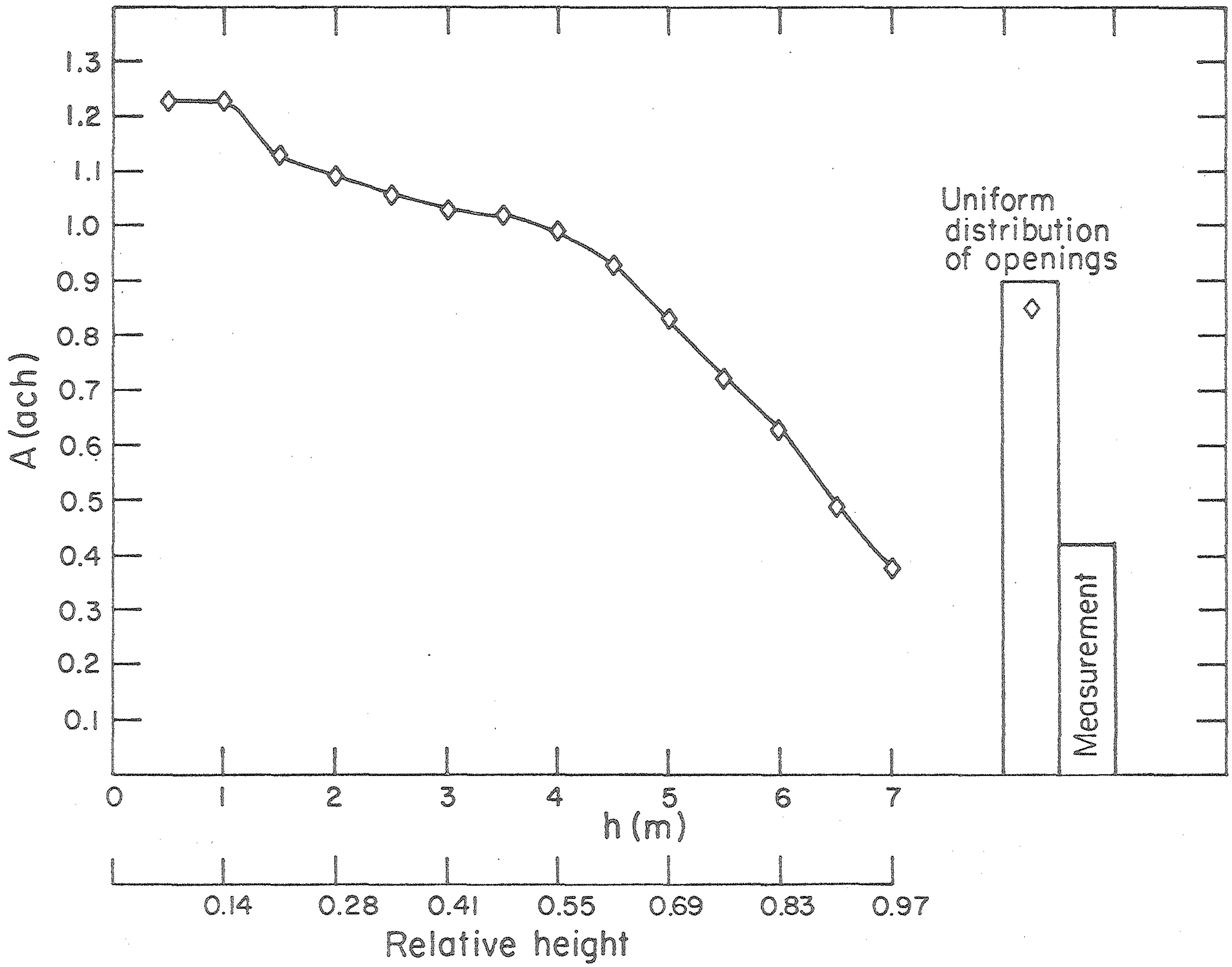
XBL7910-3879

Figure 4



XBL 7911-13099

Figure C1



XBL 7911-11571

Figure C2

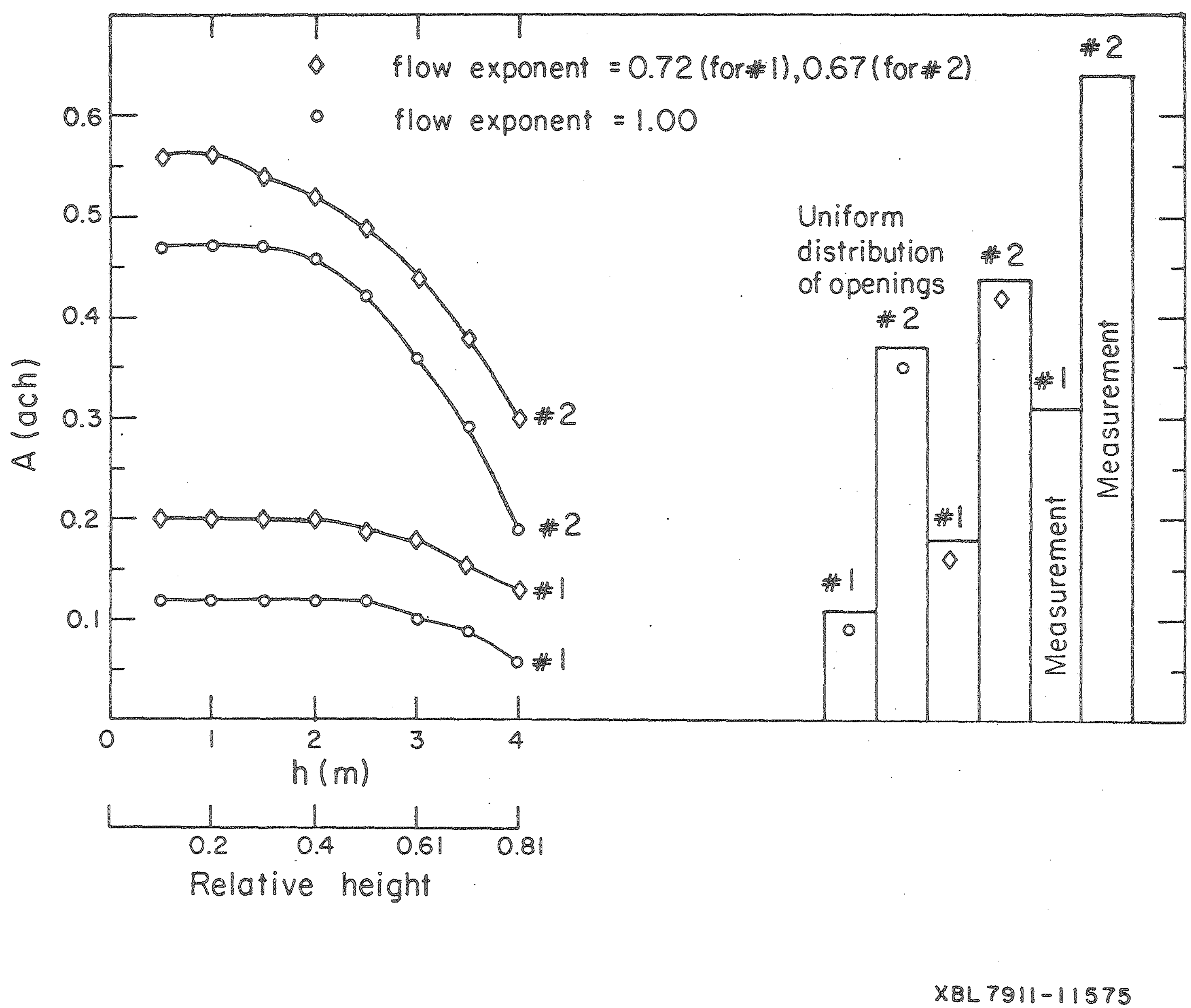

flow exponent = 0.72 (for #1), 0.67 (for #2)
flow exponent = 1.00
A (ach)
0.6
0.5
0.4
0.3
0.2
0.1
#2
#2
#1
#1
0
1
2
3
4
h (m)
0.2
0.4
0.61
0.81
Relative height
Uniform distribution of openings
#1
#2
#1
#2
#1
Measurement
#2
Measurement
XBL 7911-11575

Figure C3

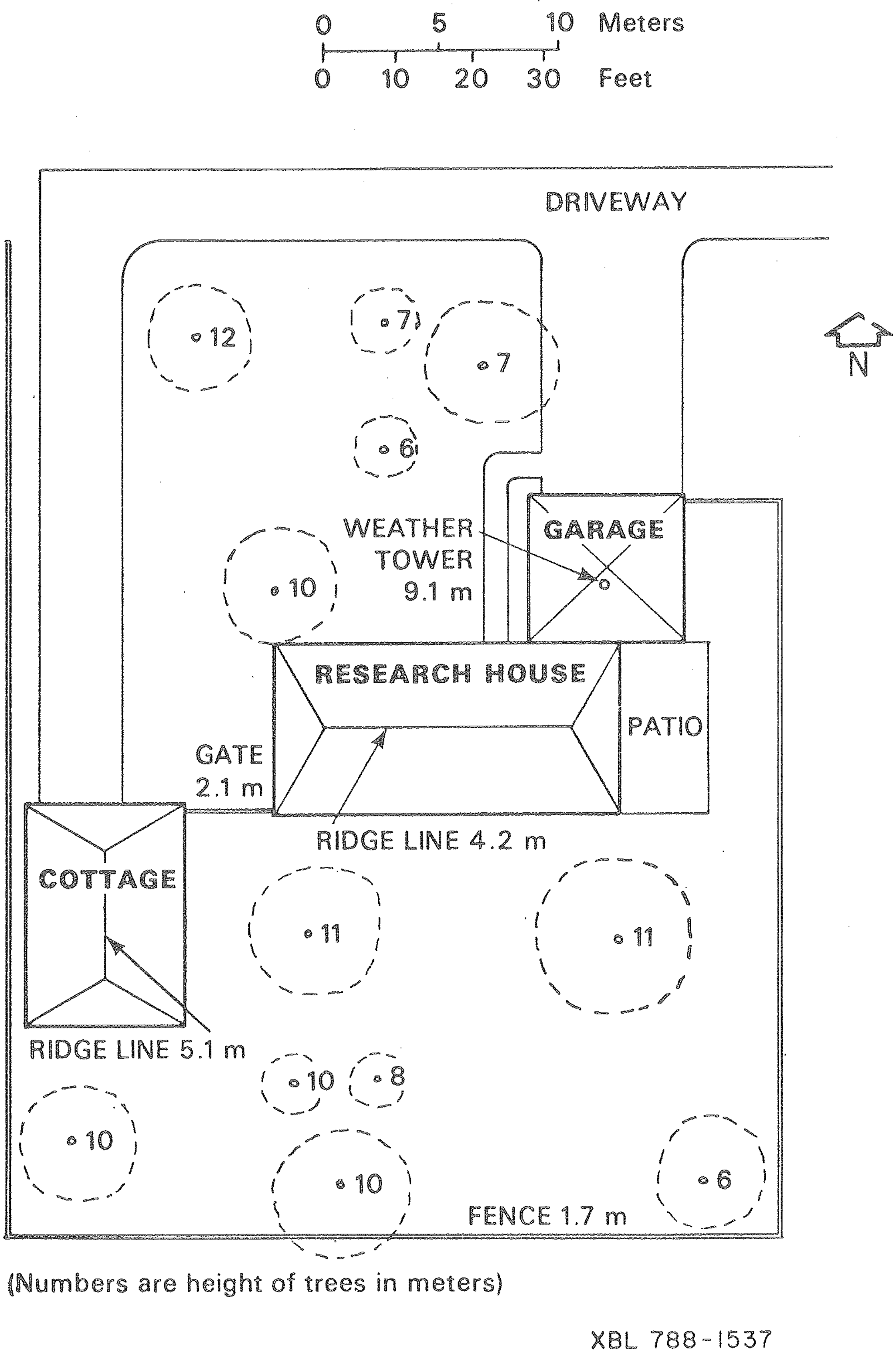

0
5
10 Meters
0
10
20
30 Feet
DRIVEWAY
N
12
7
7
6
WEATHER TOWER 9.1 m
GARAGE
10
RESEARCH HOUSE
PATIO
GATE 2.1 m
RIDGE LINE 4.2 m
COTTAGE
11
11
RIDGE LINE 5.1 m
10
8
10
10
6
FENCE 1.7 m
(Numbers are height of trees in meters)
XBL 788-1537

Figure C4

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