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INFILTRATION AND AIR LEAKAGE COMPARISONS: CONVENTIONAL AND ENERGY-EFFICIENT HOUSING DESIGNS

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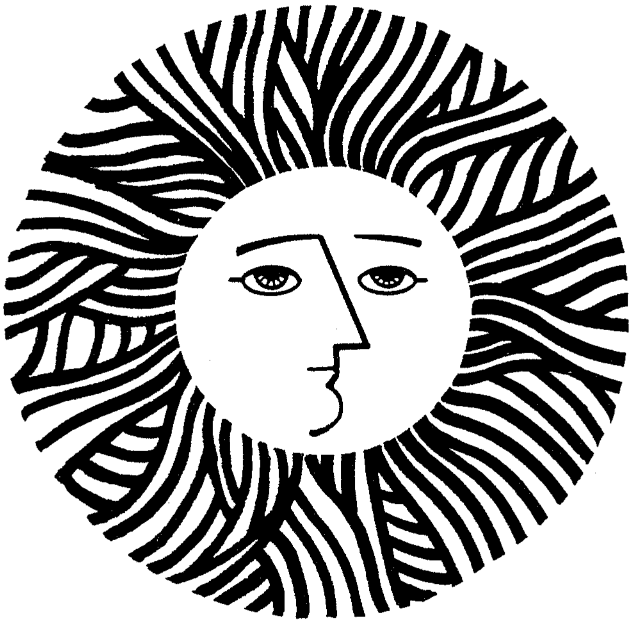

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Infiltration and Air Leakage Comparisons: Conventional and Energy-Efficient Housing Designs

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ABSTRACT

Generalized modeling of air infiltration rates in structures is complicated by insufficient information about the construction quality of the structure and the local terrain in the vicinity of the building. Air leakage measurements using fan pressurization give information about construction quality while surface pressure measurements together with weather data can be used to deduce information about the influence of local terrain on infiltration rates.

This paper describes results of measurements of air leakage, surface pressures and air infiltration for several conventional and energy efficient houses located throughout the United States. The measurements are compared with predicted infiltration obtained from a simple model combining measured air leakage values and average surface pressures. It was found that within limits there was reasonable agreement between

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measurements and predictions. Particular features of the energy efficient houses which reduce air leakage, and therefore air infiltration, are described.

Keywords: infiltration, ventilation, leakage, pressurization

INTRODUCTION

While the importance of reducing air infiltration in buildings is widely recognized as an important goal for energy conservation, many problems remain to be solved before infiltration values can be incorporated into building standards. An important related problem is to ensure adequate indoor air quality in structures as designs and construction techniques improve, making buildings tighter. Another is to develop a measurement procedure that can be used to verify that new buildings are meeting a prescribed limit for air leakage. An essential part of the latter problem is understanding the relationship between air infiltration and air leakage measured with fan pressurization. In an attempt to find a simplified method for measuring air infiltration, this paper examines a model which predicts infiltration of a building based upon (i)the air leakage and (ii)the average surface pressure experienced by the building.

INFILTRATION MODEL

The model used to describe these results has been discussed previously(1,2) and will be summarized only briefly here. A model similar to this has also been used in wind tunnel studies by Mattingly and Peters(3) and by Kelnhofer(4)

Measurement of the air leakage of a house using fan pressurization yields an average leakage function for the house. Measurements of the mean surface pressures (the driving mechanism for the air infiltration process), combined with the leakage function predict the air flow through the structure (the response):

$$Q = L < P > \qquad (1)$$

where Q is the air flow (volume/time) into or out of the structure,

L is the leakage function of the structure computed from the pressurization measurements (volume/time/pressure) and

$< P >$ is the mean surface pressure (i.e. the pressure difference across the building envelope) averaged over the entire structure.

This calculated air flow divided by the volume of the house yields the air infiltration which we compare to air infiltration measured with a tracer gas.

The model contains many assumptions. Some assumptions result from an inherent inability to obtain more information about the process (e.g. the leakage values of each opening in the building envelope), while others will be modified as the model evolves in future work. We assume:

(A) That the leakage function describes a uniform distribution of cracks and openings over the building envelope. (This assumption improves as the number of large openings, such as chimneys and vents, goes to zero.)

(B) That the difference between average positive and negative surface pressures multiplied by the leakage represents flow into or out of vents. In computing the total infiltration, the larger of either the positive or negative surface pressure is used to compute the flow.

(C) That at the low surface pressures seen, the flow through the structure is linearly proportional to the average positive (or negative) surface pressure. This, in turn, assumes that the major portion of the air flow comes through cracks. Honma's work(5) shows that for the pressure range similar to the surface pressures observed in this study, the flow through a crack is linearly proportional to the pressure difference across the crack.

These assumptions and their implications are discussed more completely in the work of Sherman, Grimsrud et al.(6)

TEST PROCEDURES

Infiltration was measured using a standard tracer gas technique. Ethane was injected into the return duct of a forced air heating system until its concentration in the house reached 80 ppm. If the house did not contain a forced air heating system the tracer was distributed and mixed until the 80 ppm concentration was achieved. At this time the injection stopped and the concentration was monitored as a function of time. If the air infiltration is constant and if good mixing occurs between the inside and infiltrating air, the concentration decreases exponentially in time with a time constant given by the reciprocal of the air exchange rate.

Air leakage values with fan pressurization were obtained by temporarily sealing a tubeaxial fan driven by a variable speed motor into a doorway of the house (cf. Figure 1). The fan speed was adjusted to give predetermined pressure differences between the inside and outside of the structure; flow through the fan was measured using a fixed pitot tube array combined with a flow straightener. At the pressures used, the flow through the fan is equal to the leakage through the shell of the house.

Measurements of air leakage using both pressurization and depressurization were made. In addition, measurements with the houses in their normal operating condition, were followed by measurements with major vent openings covered by plastic and taped. Figure 2 shows a typical leakage curve.

Surface pressures were measured using a capacitance differential pressure sensor attached to a manifold (cf. Figure 3). Seven pressure taps were connected to the manifold using 6 mm i.d. plastic tubing. Each tap was sampled in sequence for ten seconds at 40 Hz by opening and closing solenoid valves on the manifold under the control of a microprocessor. The microprocessor averaged the pressure data, and stored the results on a floppy disk.

Local weather conditions (wind speed and direction, dry bulb temperature) were measured at each site using equipment mounted on a 10 meter weather tower. Indoor temperature and relative humidity were measured using a hygrothermograph located in the living room of each house. As with surface pressures, weather data was averaged and logged by the microprocessor.

HOUSE DESCRIPTIONS

The particular specifications of the houses are given in Table 1 below. The degree days are average values taken from standard references; the other data were measured on site. Appendix A contains additional parameters for each house describing the type of house, its surrounding terrain and its heating system.

TABLE 1. Summary of Survey House Descriptions

ENERGY EFFICIENT HOUSES

HOUSE SPECIFICATIONS			^{o}C DEGREE DAYS		SIZE		LEAKAGE
ID	STATE	YR	HEATING (18.3 base)	COOLING (26.6 base)	AREA (m^2)	VOLUME (m^3)	at 50 Pa. (hr^{-1})
Elendil	CA	1978	1440	560	98	570	5.5
Ivanhoe	MN	1977	4380	275	174	490	1.8
Nogal	CA	1977	1440	560	107	292	6.5
Telemark	MN	1978	4380	275	197	480	2.6
Torey Pines	IA	1978	3580	410	220	480	3.0
Valencia-1	CA	1978	1440	560	104	270	11.2
Valencia-2	CA	1978	1440	560	104	270	9.4
Valencia-3	CA	1978	1440	560	119	334	4.6
Valencia-4	CA	1978	1440	560	119	334	7.3

CONVENTIONAL HOUSES

HOUSE SPECIFICATIONS ID	 STATE	 YR	^{o}C DEGREE DAYS HEATING (18.3 base)	 COOLING (26.6 base)	SIZE AREA (m^2)	 VOLUME (m^3)	LEAKAGE at 50 Pa. (hr^{-1})
Haven	CA	1965	1760	560	100	230	13.6
Neilson	CA	1924	1780	50	96	249	14.9
Pamplona-1	CA	1978	1440	560	123	411	8.2
Pamplona-2	CA	1978	1440	560	137	491	5.8
Purdue	CA	1949	1780	50	93	240	8.2
San Carlos	CA	1940	1780	50	58	147	15.8
Southampton	CA	1929	1780	50	370	1000	11.4

The leakage values (in air changes per hour) were obtained by measuring the airflow through a fan with a pressure of 50 Pascals across the envelope. The flows for pressurization and depressurization were averaged and divided by the house volume to calculate the air change rate. The measurements reported are those made with all large openings (vents, flues, etc.) sealed; this conforms to the procedure used in the Swedish standard for air leakage. The leakage values have been corrected for an error which had been made in calibrating the air flow through the blower door. Earlier drafts of this report contained erroneous leakage values which were smaller than those reported above. Figure 4 displays the data of Table 1.

DISCUSSION

It is difficult to generalize about the distinctions between energy efficient and conventional houses. Each home is unique and requires careful inspection in order to find sources of excessive air leakage. The energy efficient homes that we sampled were all built within the last two years. All were constructed by builders who used care in caulking and sealing sill plates, window and door frames. All use vapor barriers; Elendil and Valencia 1-4 employ the kraft paper backing of the insulation while the other energy efficient houses use continuous 4 mil polyethylene. Figure 4 suggests that the difference in vapor barriers contributed to the differences seen between the houses. In discussions with their owners, care in construction was a common theme the owners used in describing the homes.

Figure 5 shows the measured infiltration (using tracer decay) plotted against the predicted infiltration (using measured leakage and surface pressures). Note that the line is the locus of points for which the measured infiltration is equal to the predicted infiltration, not a fit of the data. Table 2 lists the measured and predicted values used in Figure 5, the weather conditions and the average surface pressures during the measurements.

We used a chi-square test on the data to test the goodness of fit for our model. To do this we must estimate the error associated with each point, both the error in the measurement and the error in the value predicted by the model. The error in the measurement is given from the linear fit of the tracer data and is approximately .08 air changes per hour. The error in the prediction comes from a combination of measurement errors in the leakage and in the surface pressure determination. We estimate that these errors cause an uncertainty of approximately 20% in the predicted value of the infiltration. In addition, there is a systematic error in the determination of the surface pressures; this arises from the insensitivity of the measurement technique to pressures caused by indoor-outdoor temperature differences. If we treat this as an additional random error, the error in the predicted air exchange rate increases to a value which averages 0.16 ± 0.09 air changes per hour. The range depends primarily on the temperature difference which existed during the measurement.

Once these uncertainties have been assigned we can apply a chi-square test to the data. Using 63 points and ignoring errors introduced by the stack effect we obtain a chi-square of 72. This gives a confidence level of 19%. If we include the errors due to the stack effect the chi-square and confidence level become 51 and 85%.

TABLE 2
Measured and Predicted Infiltration Values for the Test Houses

House	A (Measured) ach	v m/s	Δt °C	$< \Delta p >$ Pascals	A (predicted) ach
Ivanhoe	0.12	4	22	4.6	0.18
	0.12	8	22	9.5	0.38
	0.10	6	22	6.2	0.25
Telemark	0.13	5	26	3.0	0.20
	0.10	4	25	2.4	0.16
	0.08	3	25	2.4	0.16
Torey Pines	0.35	7	18	2.8	0.36
	0.31	6	19	2.8	0.36
	0.42	7	19	2.9	0.37
	0.42	8	19	2.6	0.33
	0.38	8	20	2.6	0.33
Valencia 3	0.82	7.6	6	3.9	0.41
	0.30	2.7	5	0.50	0.05
Nogal	0.22	1.7	3	0.20	0.08
Pamplona	0.75	8	7	3.4	1.91
	0.62	7	8	2.1	1.16
	0.32	*	*	1.3	0.74
	0.61	*	*	0.70	0.40
	0.47	*	*	1.29	0.73
Purdue	0.50	2	9	0.62	0.49
	0.52	2	9	0.72	0.57
	0.64	4	9	0.95	0.75
	0.69	5	10	1.20	0.95
Valencia 2	0.64	4.5	9	1.34	0.67
	0.29	2.1	5	0.42	0.21
Valencia 1	0.31	2.1	6	0.28	0.15
	0.33	2.2	7	0.28	0.15
Southampton	0.25	1	-1	0.55	0.20
	0.31	1	2	0.66	0.24
	0.19	1	1	0.48	0.17
Haven	0.26	5	6	0.39	0.30
	0.33	2	8	0.37	0.29
	0.23	3	10	0.31	0.24
	0.25	3	10	1.06	0.82
	0.28	2	5	0.49	0.38
	0.15	2	5	0.29	0.22
	0.61	3	9	0.68	0.53

	0.54	4	7	0.66	0.51
	0.54	4	7	0.75	0.58
	0.31	1	11	0.48	0.37
	0.29	3	12	0.36	0.28
	0.42	4	13	0.32	0.25
	0.36	4	14	0.48	0.37
	0.35	3	14	0.36	0.28
	0.47	4	15	0.34	0.26
	0.18	7	5	0.34	0.19
	0.11	3	8	0.25	0.14
	0.18	4	7	0.28	0.15
	0.13	5	3	0.25	0.14
	0.16	1	7	0.28	0.15
	0.28	1	6	0.30	0.23
	0.20	4	7	0.24	0.17
	0.23	4	6	0.27	0.19
	0.05	2	-1	0.14	0.10
	0.28	8	6	0.33	0.21
Neilson	0.70	2	5	0.39	0.45
	0.64	2	6	0.38	0.44
	0.74	1	4	0.30	0.34
	1.36	1	5	0.60	0.69
San Carlos	0.70	2.1	0	0.60	0.71
	0.80	1.1	2	0.24	0.26
	0.62	2.0	-2	0.21	0.25
	1.03	1.7	0	0.21	0.25

The predicted infiltration values reported above differ from those reported in earlier drafts of this report. As described above, a calibration error of the pitot-tube array caused us to underestimate the ow through the blower door and therefore the low pressure leakage of each house.

Another use of the model is to predict time series infiltration data. Since pressure data was collected every twenty minutes, we have an estimate of the infiltration every twenty minutes. In any real structure infiltrating air does not instantaneously mix with house air; therefore, we filter out fluctuations that occur faster than our estimate of the mixing time. An example of this is shown below in Fig. 6 for the Telemark house. This house has no central air duct and blower system to mix the infiltrating air. In this case we used a time constant of one hour to filter the surface pressures and predict the infiltration during a 48 hour period.

While this model can be useful for predicting infiltration of instrumented homes, it requires continuous monitoring of surface pressures in order to estimate the infiltration. We are currently working on models that will predict surface pressures from weather variables and structural parameters. If successful, we will be able to calculate the infiltration from measurements of the air leakage without measuring the surface pressures directly.

CONCLUSIONS

This study clearly shows that careful construction using existing US building technology can produce houses with low leakage and low infiltration. It must be emphasized that this has been seen only for new construction. The larger problem of modifying existing housing to reduce air infiltration was not addressed in this work.

The indoor air quality of the tight houses reported in this study is the subject of continuing investigation by the Ventilation Group at LBL. Results from Torey Pines and Nogal have been reported;(7) investigations are continuing in the Ivanhoe and Telemark houses. While the optimum ventilation rate for houses is not known, air-to-air heat exchangers are currently being examined as possible devices to provide adequate ventilation without the attendant energy cost of excessive infiltration.(8)

The study examines a simple model designed to predict infiltration. The model works very well for some of the houses in the sample; not well for others. When considered in terms of its goal, i.e. as a simple technique to predict infiltration based upon a small set of field measurements, the model has two serious deficiencies. The first, the need to make field measurements of surface pressures, has proven to be an excessive complication for any broad measurement program. The second is the excessive scatter in the infiltration predictions for some of the sites. The ratio of predicted to measured infiltration for all the sites is impressive (1.09), but the scatter in values is not (the standard deviation of the ratio is 0.64). In spite of these deficiencies, the agreement between the short term infiltration measurements and the simple model is quite good. We believe, for example, that some of the scatter in the results would be reduced if the predictions were compared with long-term average infiltration measurements. It is just that information which is required for energy load calculations.

Details in the model are being modified to improve our ability to predict infiltration based upon pressurization leakage measurements. Modifications include:

(a) the use of surface pressures calculated from wind tunnel measurements modified for effects of shielding in the vicinity of the site.

(b) separating wind dominated from temperature dominated pressure effects wherever possible.

(c) changing the form of the flow assumption from the current model which predicts flow proportional to the pressure difference to one predicting flow proportional to the square root of the pressure difference.

We are encouraged by this progress in the search for a technique to correlate air leakage measurements with infiltration. The simplicity of air leakage measurements is compelling reason for such an effort. We believe that the changes described will produce a more adequate approach o that correlation.

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APPENDIX A

This appendix contains a listing of various features of each house not tabulated in the text.

HOUSE ID	REMARKS
Elendil	energy efficient; 2 story; slab on grade; forced air; vapor barrier; passive solar design; little shielding.
Haven	conventional; single story; ranch style; rectangular floor plan; crawl space; forced air system; fireplace; well shielded.
Ivanhoe	energy efficient; 2 story (inc. basement); rectangular floor plan; active solar; sealed combustion wood stove; vapor barrier; passive solar; unshielded.
Neilson	conventional; single story; non-rectangular floor plan; crawl space; floor furnace; fireplace; no damper; unshielded on two sides.
Nogal	energy efficient; single story; rectangular floor plan; slab on grade; active solar and forced air; vapor barrier; well shielded.

HOUSE ID	REMARKS
Pamplona 1	conventional; single story; non-rectangular floor plan; slab on grade; forced air; little shielding.
Pamplona 2	conventional; 2 story non-rectangular floor plan; slab on grade; forced air; fireplace; little shielding.
Purdue	conventional; single story; non-rectangular floor plan; crawl space; forced air; fire place; well shielded.
San Carlos	conventional; single story; rectangular floor plan; crawl space; floor furnace; fireplace; no damper; unshielded on one side.
Southampton	conventional; 2 story; non-rectangular floor plan; basement and crawl space; forced air; fireplace; well shielded.
Telemark	energy efficient; 2 story (inc. basement); rectangular floor plan; radiant heat; passive solar; vapor barrier; sealed combustion wood stove; well shielded.
Torey Pines	energy efficient; 3 story (inc. basement); rectangular floor plan; active solar; vertical greenhouse; vapor barrier; unshielded.
Valencia 1-4	energy efficient; single story; rectangular floor plan; slab on grade; active solar; vapor barrier; passive solar; little shielding.

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FIGURE CAPTIONS

Figure 1. A sketch of the blower door assembly

Figure 2. A typical air leakage vs. pressurization curve for houses studied in this survey. The solid line connects measurements with the house in its normal operating condition; the dashed line is drawn through values measured when ducts and vents were sealed.

Figure 3. A sketch of the pressure tap and sensor configuration used in measuring surface pressures.

Figure 4. Air leakage values measured at 50 Pascals for the survey houses. The dashed line is the current Swedish standard for new construction. The shaded bars depict values obtained in energy efficient houses.

Figure 5. Infiltration predicted for each house from air leakage and surface pressure measurements vs. infiltration measured with a tracer gas. The line is the locus of points for which measured and predicted values agree. It is not a fit of the observations.

Figure 6. Calculated infiltration in the Telemark house based upon surface pressure measurements. The left vertical scale shows the twenty-minute average of the surface pressure (open circles) while the right vertical scale gives the one-hour average infiltration.

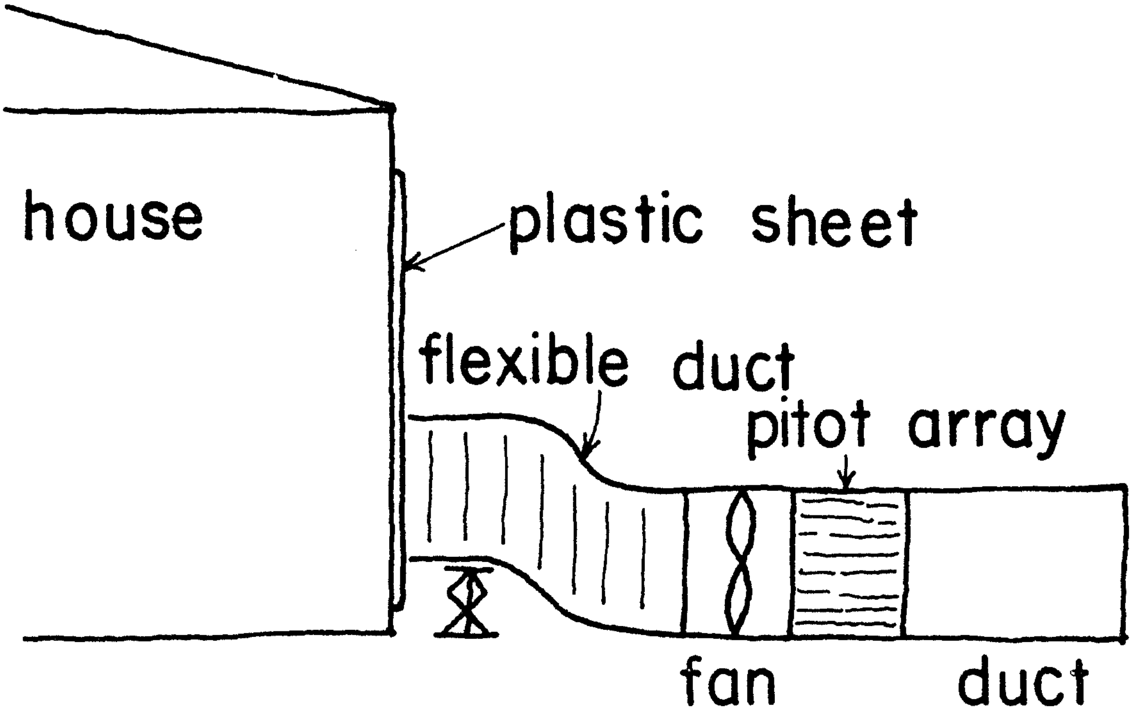

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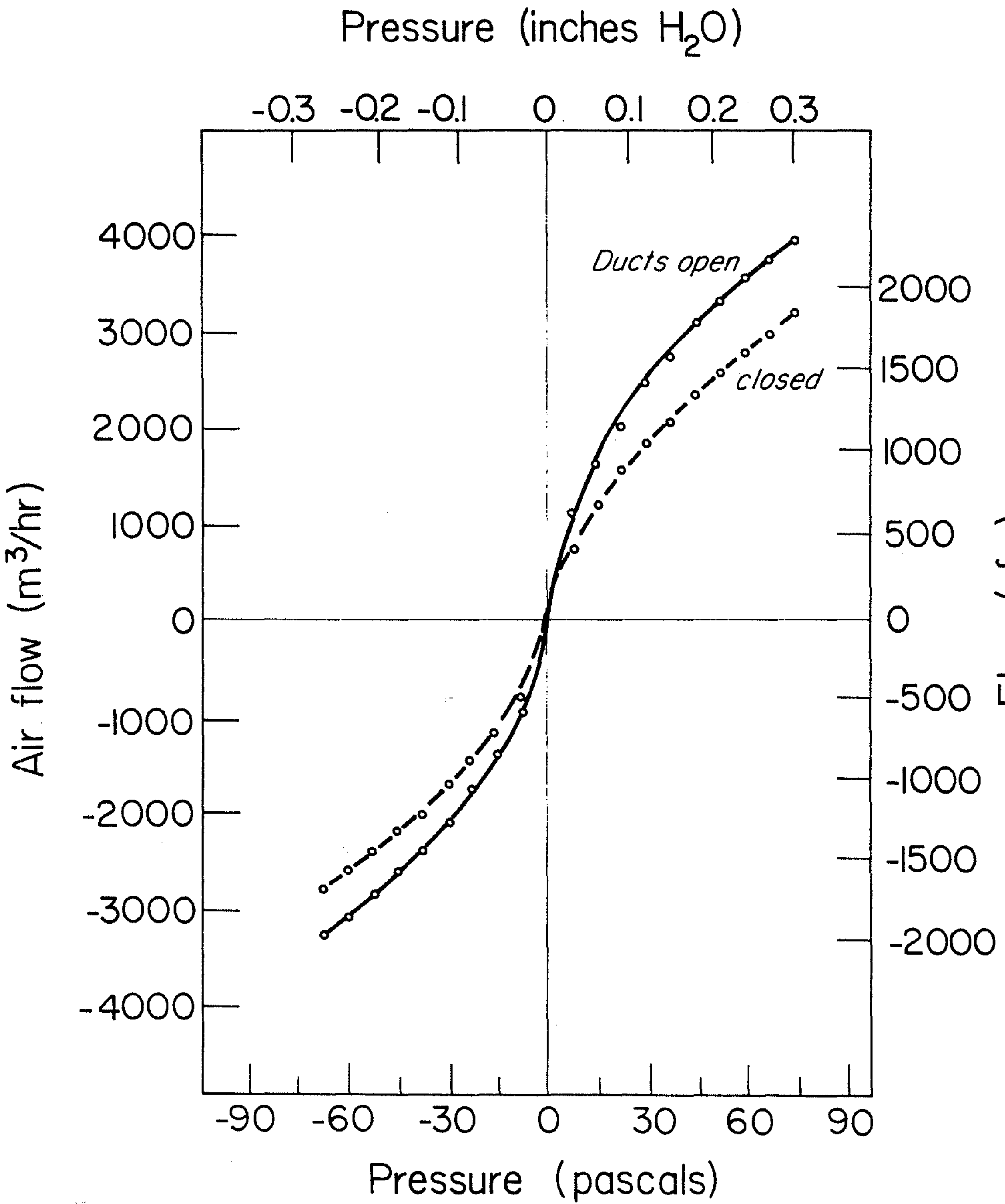
Fig. 1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0.1
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0.3
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closed
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2000
1000
0
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-2000
-3000
-4000
Air flow (m^3/hr)
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1500
1000
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0
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-1000
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Pressure (pascals)
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Fig. 2

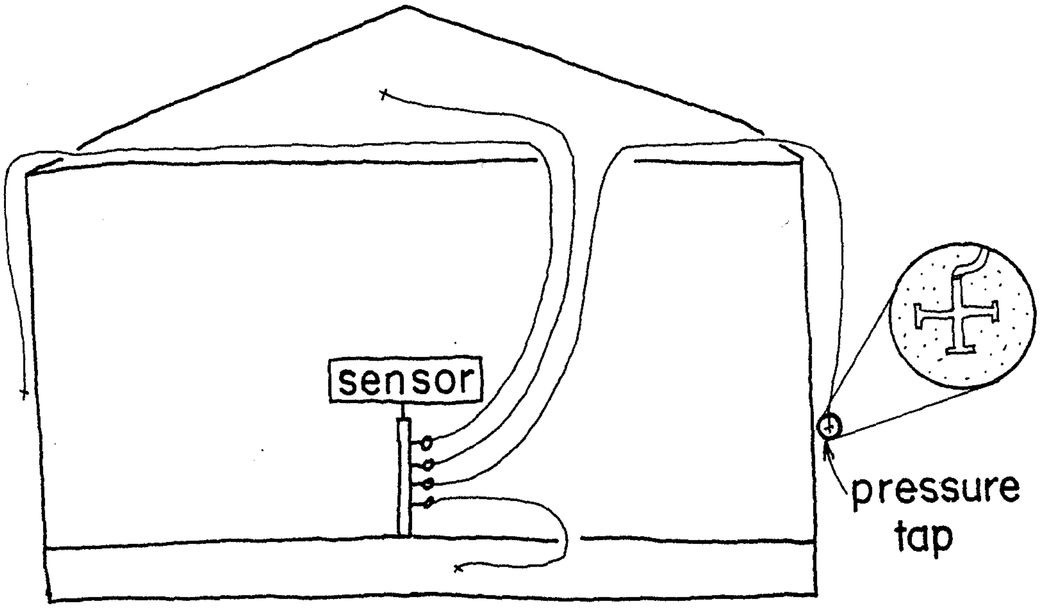

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Fig. 3

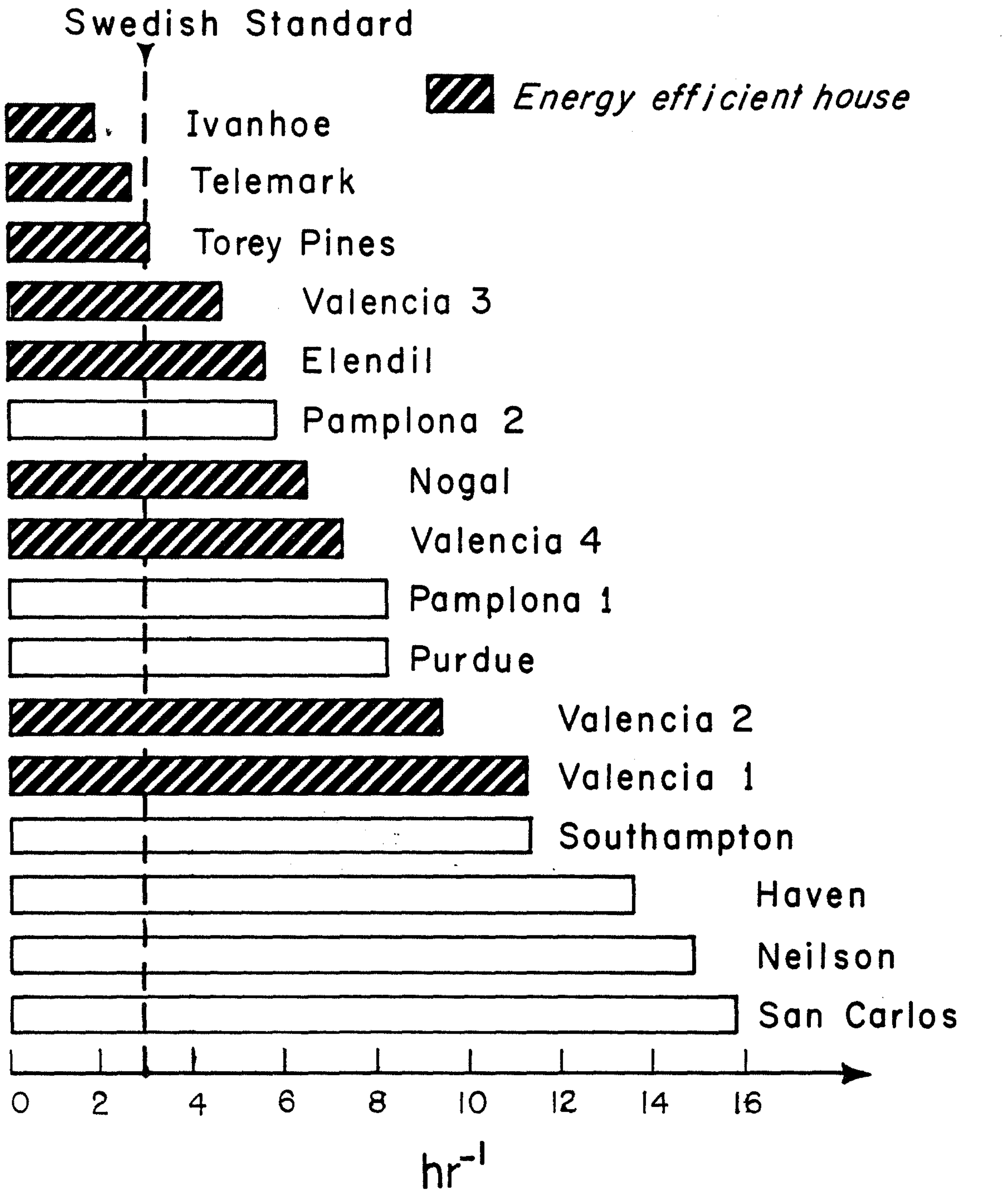

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Fig. 4

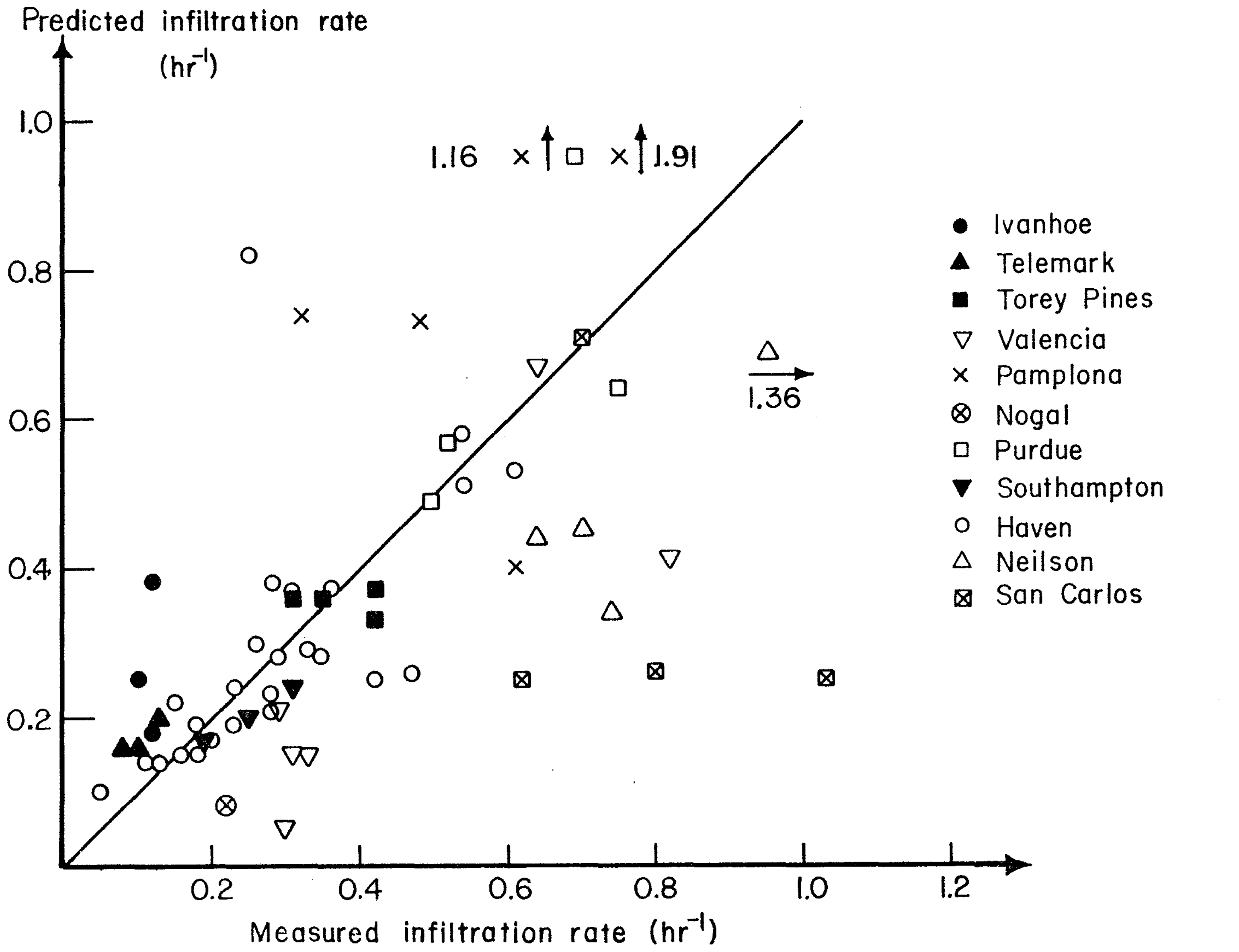

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Fig. 5

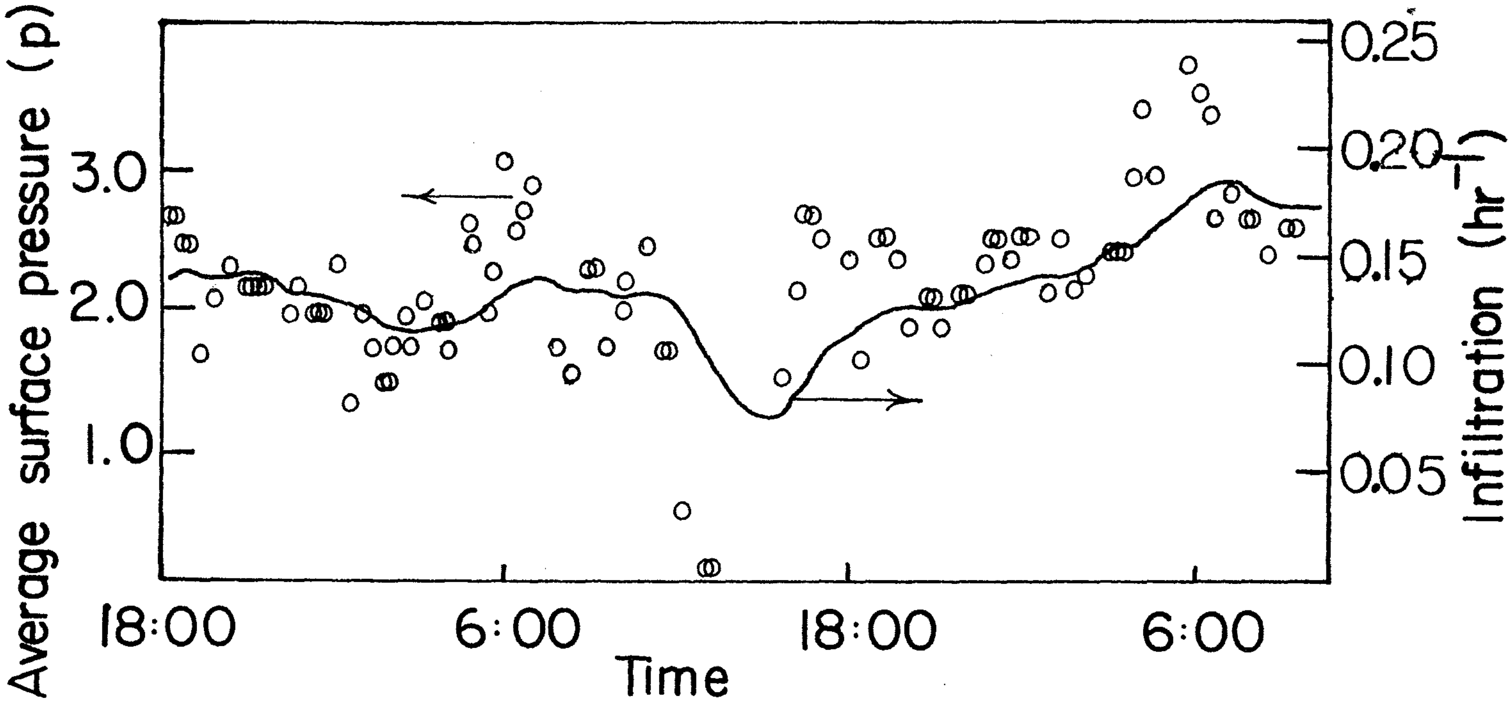

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Fig. 6