BUILDING AIR CHANGE RATE AND INFILTRATION MEASUREMENTS

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WINTERTIME INFILTRATION RATES IN MOBILE HOMES

by

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ABSTRACT

The infiltration in mobile homes can be reduced by treatments such as caulking or adding a special sheathing board material. Present standards set limits on the infiltration rates in mobile homes. Reduction in infiltration rates are accompanied by reductions in HVAC equipment sizing and operation cost. Unfortunately, there is a general lack of actual field data to determine infiltration rates of mobile homes and the general dependence of infiltration on wind and temperature differences.

A field test setup including two unoccupied mobile homes is described. The facility permits a measure of weather, consumption, infiltration rate and surface temperatures. Data is now presented comparing the winter performance of the two mobile homes. The homes are identical on all counts except that one is treated with a special sheathing board while the other is caulked. The data indicates a general parabolic dependence of infiltration on wind (and a linear dependence on temperature difference) with consistently lower values of infiltration rate for the board-sheathed home than for the caulked home.

Key Words: Energy, Conservation, Infiltration, Mobile Homes

INTRODUCTION

Measurements of infiltration rates in mobile homes appear limited to the work by Hunt et al. [1], in a controlled environment and by Prado et al. [2], in an unoccupied older home. The work by Hunt and co-workers attempted to simulate wind effects with pedestal type fans and suggested infiltration rates in the order of 0.6 h^{-1}, with some dependence on "wind." The effects of temperature difference (between ambient and indoors) were simulated suggesting a general relationship (under no "wind" conditions) of the form

$$I = 0.362 + 0.00586 \Delta T \qquad (1)$$

Prado et al. [2] show in their measurements a strong dependence on HVAC blower operation. When the A/C blower (of a package unit) was on the infiltration rates were in the order of 2.3 to 2.7, whereas operation of the furnace blower alone gave values of around 1.2 and 1.7. With all HVAC systems off the infiltration rate was measured as in the order of 0.8. For this particular home small dependence was noted on wind, whereas a strong linear dependence was seen with temperature difference. With the furnace blower on only, this was approximated as

$$I = 1.7 + 0.0198 \Delta T \qquad (2)$$

A casual review of references [1] and [2] as well as other measurements reported for other types of buildings (see for instance references [3] through [5]), leads one to the obvious conclusion that not sufficient data has been collected to generalize the possible ranges and dependence of infiltration for mobile homes.

The work now presented is limited to wintertime data. Generalizations, based on summer data, will be published at a later date. Two objectives are noted. One, to determine the empirical dependence of infiltration rate on wind and temperature difference. Second, to compare the infiltration rate for a well-built 1975 home treated, alternatively, with sheathing board or with caulking. Obviously the removal and replacement of caulking would be destructive. Hence, instead of using one home with different treatments tested at different times, two otherwise identical homes except for different treatments are used and tested simultaneously. The homes were built on the same day along the same assembly line with identical designs, except that one was caulked and the other sheathed. Quality control on manufacturing was not quantified but every precaution was taken to assure equivalency. As a check, during the summer runs the sheathing board was removed from the home treated with it, the skin replaced and additional measurements taken. The data confirmed the probability of equivalency between the homes.

DESCRIPTION OF THE HOMES

Two mobile homes whose floor plan is shown in Figure 1 were selected for this study. The homes were identical except for the treatment used to reduce air infiltration.

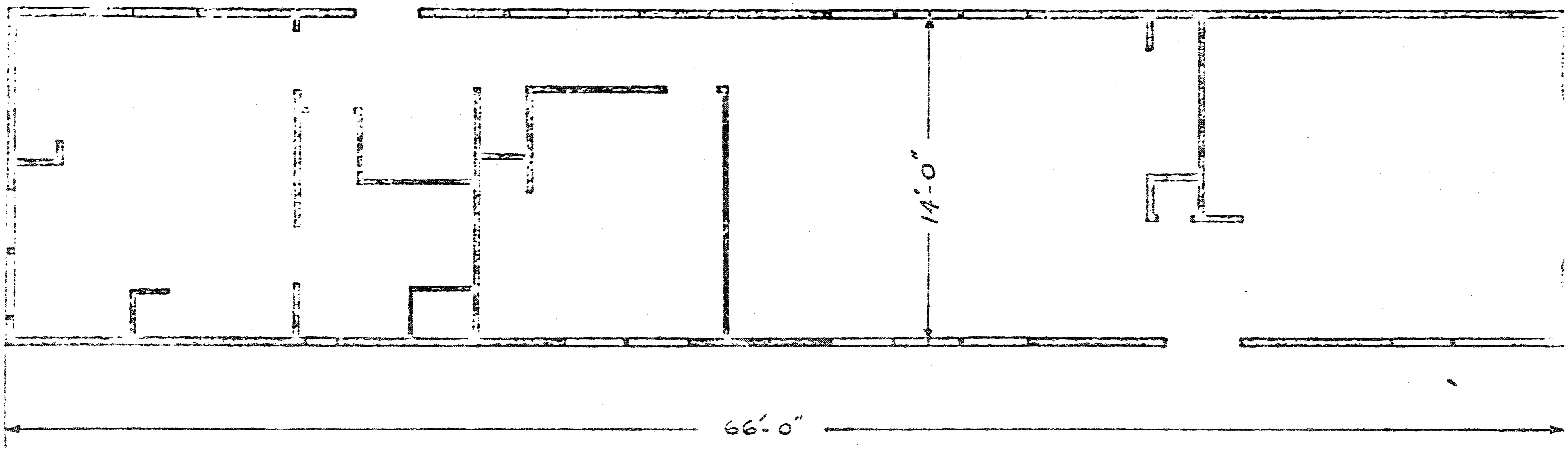


FIGURE 1 - FLOOR PLAN OF [illegible]

One of the homes used a sheathing material in the side walls and under the roof as an infiltration barrier while the other home used caulked joints at floor, wall, and roof intersections as an alternative method to reduce infiltration.

The two homes were equipped with electric furnaces and with air conditioning units to provide yearly comfort control. Thermal insulation was installed with sidewalls having R11 insulation batts, ceiling having R14, and with the floor cavity containing R7. Typical wall cross-sections are shown in Figure 2.

The test site at the Purdue University Airport provided an unobstructed exposure to the prevailing southwest wind and to solar radiation. Figure 3 shows the arrangement of the two homes and the building which housed the instrumentation and recording equipment. The measurements provided data for temperatures, winds solar radiation, energy consumption and air infiltration. Supporting weather data were also available from the weather station located at the airport.

During the test program the homes were unoccupied, thus there were no internal heat loads present. Every attempt was made to keep the test conditions inside each home identical so that the only disturbances were those caused by the weather.

MEASUREMENT PROCEDURE

The weather parameters measured were: wind speed and

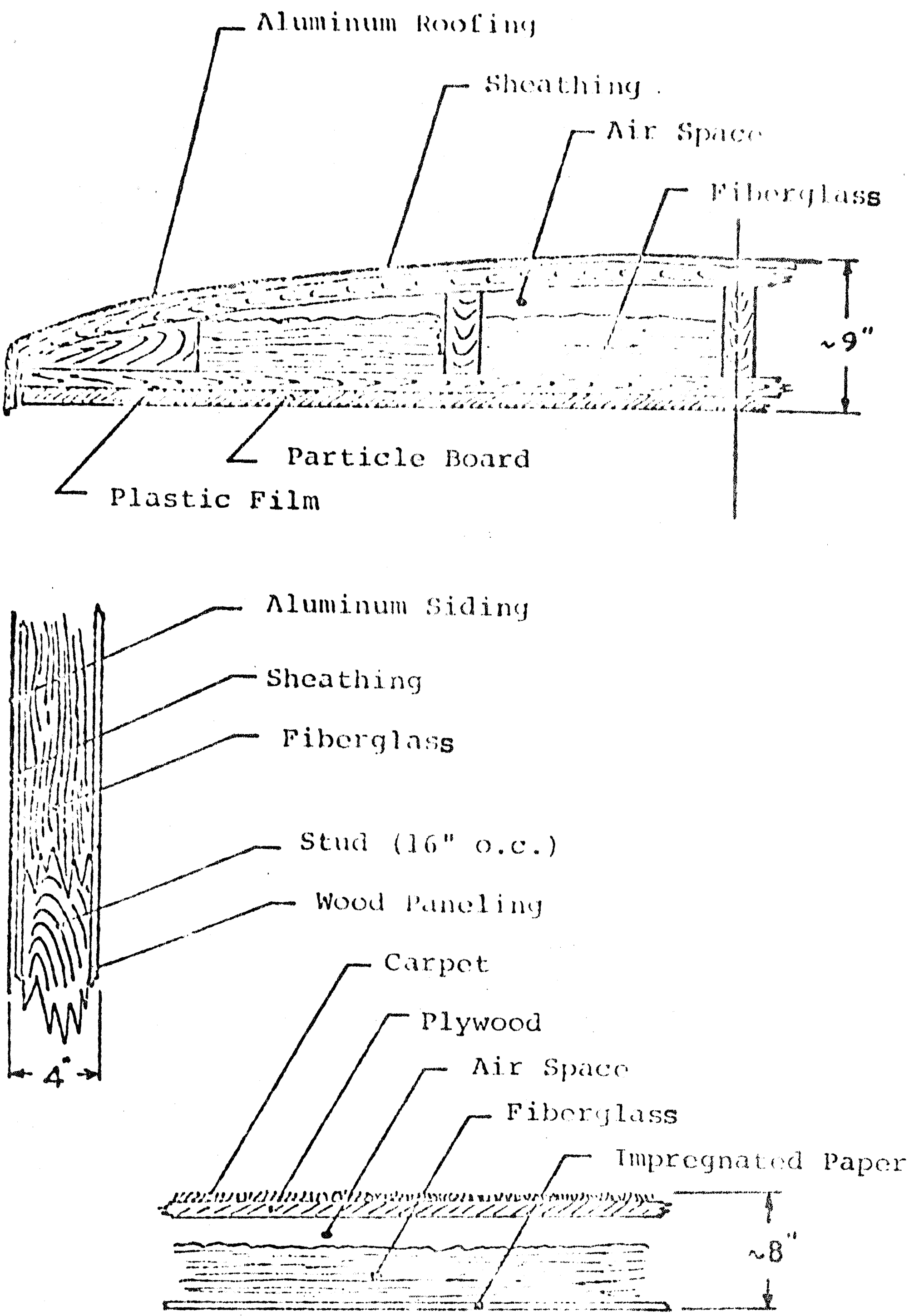


FIGURE 2 - TYPICAL SECTIONS

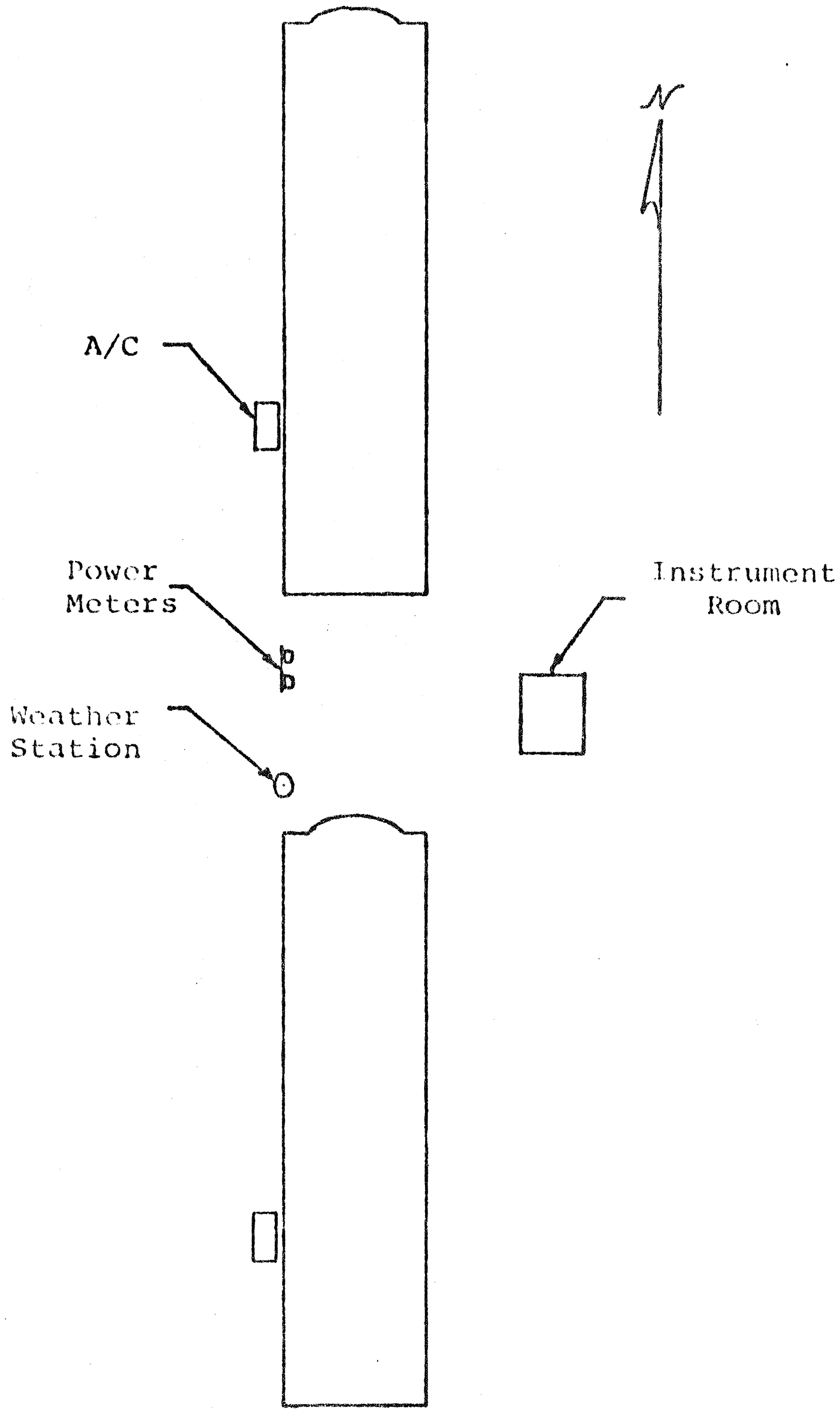


FIGURE 3 - TEST SITE

direction, solar radiation, outside and inside dry and wet bulb temperatures. The weather station included a Gill 3-cup anemometer (Model 12102), a Princeton 414 wind set and an Eppley Pyranometer (Model 8-48). All the data were sampled with an Esterline Angus recorder and tape punched for later analysis.

The quantification of air infiltration was made through a "decay-gas" method. Carbon monoxide was used as a tracer gas. The method is explained referring to Figure 4. Essentially, a slug of tracer is injected at the instrumentation shed (5) into the concentration sampling loop. Two blowers (3) and (4) in the concentration sampling loop are run continuously. The velocities within the loop are in the order of one meter per second. The total length of the sampling loop is about 80M. The tracer injected into the sampling loop is introduced at the inlet (3) of the large air distribution blower within the mobile home. The blower is also run continuously. The tracer is introduced right above the filter element. From there it is forced through the supply duct of the mobile home and through all the registers in the distribution system. The mixed tracer is then sampled through the sampling tube (1) and (2) which then takes that sample through the loop and the sampling station at the instrumentation shed itself (5). In this manner, the concentration within the loop a few seconds after the injection of a slug of tracer will be directly proportional to the concentration within the home. The rate of decay of the concentration measured within the loop then at the

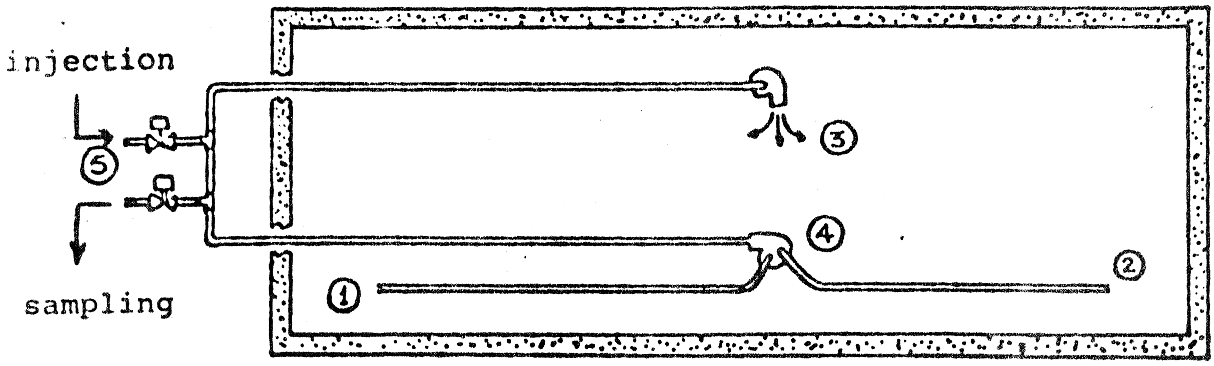


FIGURE 4. Schematic of Injection/Sampling System

sampling station will be the same as the rate of decay of the concentration of the tracer within the home itself.

From a mass balance, the change in CO level within the home (C) with a total volume V depends on the volume of air leaking in, V_{in}; volume out, V_{out}; and concentration of the mixture leaving, C_{out}; or, formally,

$$VdC = C_{in}\, d\, V_{in} - C_{out}\, d\, V_{out} \tag{3}$$

but as the air leaking in does so without any CO in it, provided there is sufficient mixing within the home, then,

$$VdC = -CdV_{out}$$

The subscript may be deleted, and defining infiltration rate as air changes per unit time, or

$$I = \frac{dV}{V}/dt \tag{4}$$

we can solve for concentration as

$$\ell n\ C = It + \text{constant.}$$

If we let the concentration be C_o at time t_o, then

$$I = \frac{\ell n \frac{C_o}{C}}{t - t_o} \tag{5}$$

Thus, by measuring C_o at some time t_o and C at a later time t the infiltration can be determined.

The sampling loop dumps the CO right over the intake of the furnace. The furnace blower is used to distribute the CO in the homes and keep it mixed during a run. A sample of the mixed air and CO is drawn uniformly from throughout the home by means of a pipe with a small hole along its length and extending essentially from one end of the home to the other. A small portion of the air/CO mixture in the sampling loop is drawn off at the instrumentation shed and the CO level is determined. The remainder of the sample is then returned to the home and recirculated. Circulation time is about 90 seconds for the North home, 105-110 seconds for the South.

The CO level is measured with two Interscan CO detectors model 1142. The instruments measure CO by means of controlled diffusion into an electrocatalytic sensing cell. The gas is electrochemically oxidized on a sensor of the proper potential. Current flows between this and a second electrode maintained at a fixed potential. The amount of current is proportional to the CO level. The instruments have an accuracy of ±2 ppm, zero drift of 1 ppm/°C and span drift of .1 ppm/°C.

All of the above values were recorded using the Esterline Angus data logger. The data logger was capable of reading at various time intervals. Most runs were taken with data sampled at 2 or 5 minute intervals. From these measurements over a given period of time the infiltration rate could be found along with the corresponding average values for weather.

RESULTS OF MEASUREMENTS

Two features of the measurement procedure lead to considerable data scatter. One, the variability in the weather, is inherent and hence unavoidable. The primary one is wind. Gustiness, sudden changes in mean velocity contribute to transients and errors in measurement. There is a surprising sensitivity of the infiltration rate on wind. As an example, Figure 5 shows an extreme case. A strong cold front, with extremely high winds followed by rain is noted. The sudden increase in infiltration is almost simultaneous with the increase in wind. Interestingly, as the rain soaks the home and "seals" the leaks, the infiltration decreases. The accuracy in the recorded wind is generally estimated to be around ±1 mph for winds above 3 mph. The second major source of scatter is based on concentration measurement procedures. The instrumentation was set up for automatic sampling. The Interscan samplers, in turn, have a zero drift dependent on instrumentation room temperature (in essence, compensated by a bias voltage). Although the shed was temperature controlled with a heat pump, some variations in temperature were unavoidable. In general, zero drifts corresponding to ±5 ppm were noted. Typical levels of concentrations measured were 100 ppm (generally between 200 and 500 ppm). In order to compute infiltration rates at least 4 data-points, or 20 minutes of run, were taken. For infiltration rates in the order of 1 h^{-1} the error in its determination would then be in the order of ±20%. The error due to zero drift would be random, rather than systematic--it is hence reflected as a scatter. (Note for I of 0.5 h^{-1}, the scatter would be closer to ±35%, whereas for I of 1.5 h^{-1}, it would decrease to ±17%.)

In order to overcome the inherent scatter a massive amount of data must be secured. Table 1 tabulates some of this data exhibiting the ranges in the parameters and the computed infiltration rates. The homes were aligned North to South. The North home is the one treated with caulking whereas the South home is sheathed. The major dependence is on wind magnitude and temperature difference between the indoor and the ambient.

The data can be grouped according to the range of temperature difference. As an example, Figures 6 and 7 show the relationship between infiltration rate and wind for ΔT's between 16C and 23C and between 30C and 37C. (For comparative purposes the expected scatter at 15 mph, the design wind, is noted. The data falls well within it.) There is an obvious dependence on temperature differences. From data such as in Figures 6 and 7 the following table can be made.

TABLE 2. Dependence on $|\Delta T|$ at 15 mph Wind

$\|\Delta T\|$ range	I_S, h^{-1}	I_N, h^{-1}
9C to 16C	0.66	1.20
16C to 23C	0.68	1.25
23C to 30C	0.78	1.43
30C to 37C	0.80	1.63
37C to 44C	0.76	1.44

TABLE 1

REPRESENTATIVE WINTER DATA

DAY NO.	START TIME	NORTH HOME INFLT HR-1	SOUTH HOME INFLT HR-1	RATIO IN/IS	WIND SPEED MPH	OUT DRY BULB (C)	SOUTH DRY BULB (C)	SOLAR RAD. WATTS/SQMT	NORTH DRY BULB (C)	WIND DIR. DEG.
363	16.17	1.280			13.80	-3.2	26.3	129	24.8	52
363	16.25		.759		14.72	-3.2	25.5	148	24.3	51
363	16.67		.760		14.42	-4.2	26.0	84	24.5	47
363	16.92		.681		13.86	-5.1	25.6	21	24.4	48
364	11.33	2.184			17.32	-10.7	26.5	251	25.9	39
364	11.75		1.129		17.19	-10.3	26.6	252	26.0	40
364	12.83		1.253		20.84	-10.0	26.4	277	25.8	43
364	15.00	1.326	.779	1.70	14.97	-9.1	26.0	151	25.4	42
364	15.50	1.475	.767	1.92	15.02	-8.6	26.2	168	25.4	38
364	15.83	1.626			16.27	-8.6	25.6	168	24.9	27
364	15.83		.869		16.23	-8.7	25.8	152	25.2	33
364	16.75		.749		13.86	-9.5	25.9	50	25.1	43
364	17.08		.549		10.45	-9.9	25.7	17	25.1	41
365	12.08	1.446	.808	1.79	12.68	-4.4	26.6	315	24.5	58
365	12.58	1.354	.734	1.85	11.80	-4.5	26.3	318	24.7	50
365	13.08	1.613	.718	2.25	12.06	-5.6	26.0	248	24.5	63
365	13.58		.825		13.44	-5.6	25.9	272	24.6	61
365	14.08		.618		12.09	-5.7	26.0	310	24.9	60
365	14.92	.804	.444	1.81	10.95	-7.0	26.0	162	24.5	74
365	15.83	1.391	.693	2.01	14.54	-9.1	25.9	105	24.4	69
365	16.25		.595		12.52	-10.6	25.4	64	24.4	69
365	16.25	1.344			12.31	-10.2	25.5	75	24.5	78
365	16.92		.724		14.80	-12.1	25.0	20	24.0	52
366	12.08	1.256	.815	1.54	11.51	-14.0	25.5	477	25.0	36
366	12.50	1.093	.688	1.59	10.91	-13.6	25.4	490	25.1	42
366	12.83	1.607	.889	1.81	12.94	-13.0	25.7	499	25.3	38
366	13.50	1.966	1.015	1.94	17.44	-12.7	25.8	494	25.6	42
366	13.92		.908		15.37	-12.1	25.7	475	25.4	44
366	14.25		1.079		15.85	-11.6	26.1	441	25.6	40
366	16.33	1.553	.816	1.90	12.83	-11.4	26.4	142	25.1	44
366	17.00		.857		13.24	-12.2	25.9	35	25.2	37
366	17.33		.591		12.06	-12.9	25.9	13	25.7	25
366	17.67		.765		13.40	-12.9	25.7	1	24.9	44
366	18.25		.668		11.14	-13.7	26.0	-0	25.7	38
3	12.67	.462	.316	1.46	5.59	-.0	26.7	198	25.0	17
3	13.00	.445	.301	1.48	5.44	.3	27.0	219	25.4	19
3	13.75	.489	.306	1.60	6.38	.5	27.3	220	25.9	17
3	14.08	.498	.339	1.47	6.62	.7	27.0	212	25.5	19
4	12.50	1.079	.613	1.76	8.84	-.2	26.1	196	24.5	138
4	13.00	.948	.517	1.83	8.16	.1	26.3	201	25.0	135
4	13.50	1.169	.561	2.09	8.38	.1	26.3	185	25.4	132
4	13.92		.483		8.41	.2	26.2	163	24.7	137
4	14.42		.417		9.04	.3	26.4	127	24.7	135
4	15.42	1.218			9.84	.3	26.5	146	24.8	136
4	15.50		.075		9.60	.3	26.3	129	24.6	137
4	16.00	1.342			10.10	.2	26.4	82	24.8	134
4	16.33		.646		10.21	.1	26.3	53	24.8	132
4	16.92		.539		10.23	.0	26.2	20	25.0	130
4	17.25		.596		11.10	0.0	25.7	7	25.1	131
5	12.33	.502	.326	1.54	7.26	-1.0	26.4	447	25.3	97
5	12.92	.489	.287	1.70	7.38	-1.0	26.3	454	25.3	89
5	14.00	.527	.291	1.81	9.07	-1.4	26.7	419	25.8	87
5	15.08	.466			7.58	-1.5	26.0	331	25.7	85

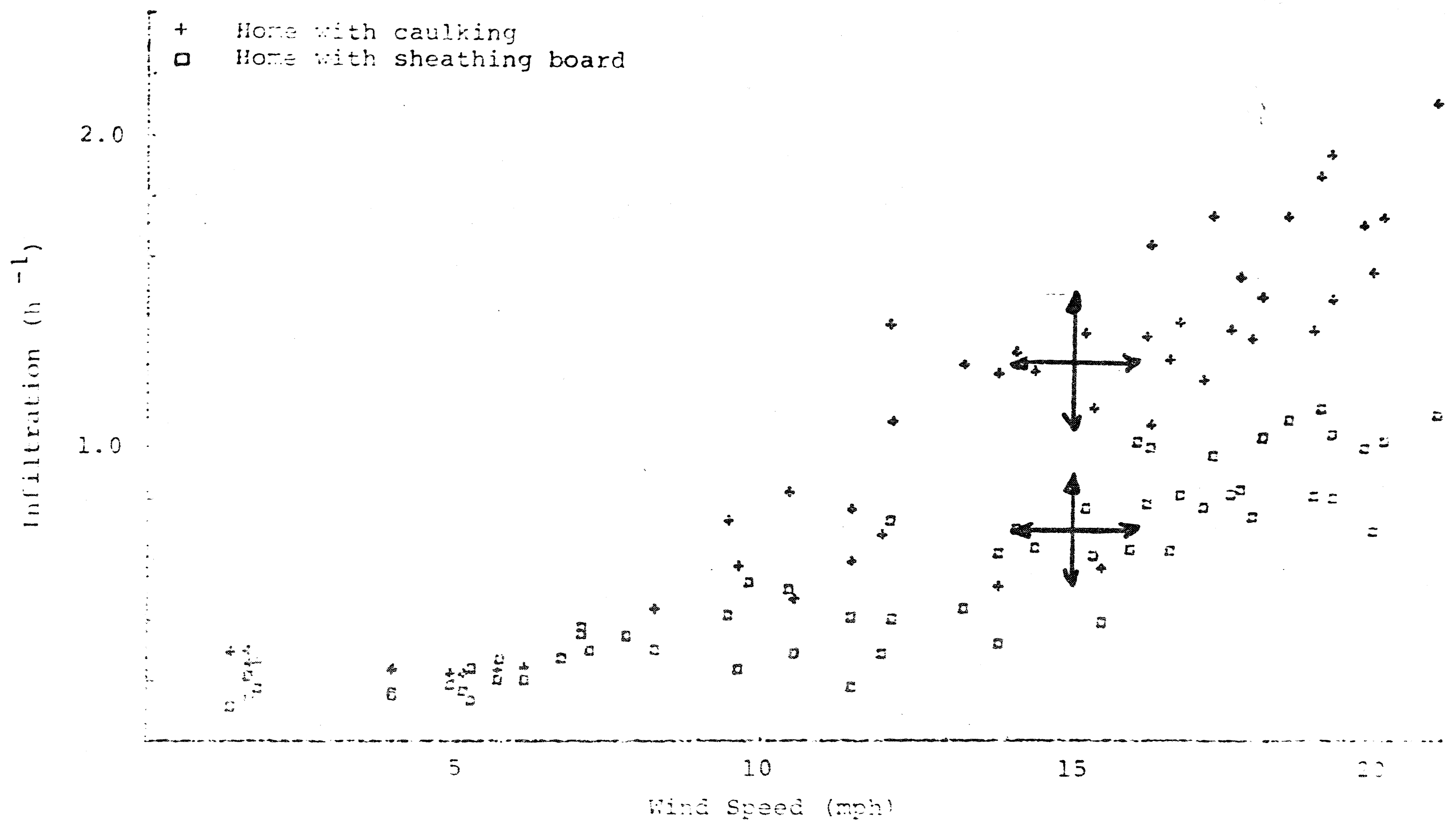
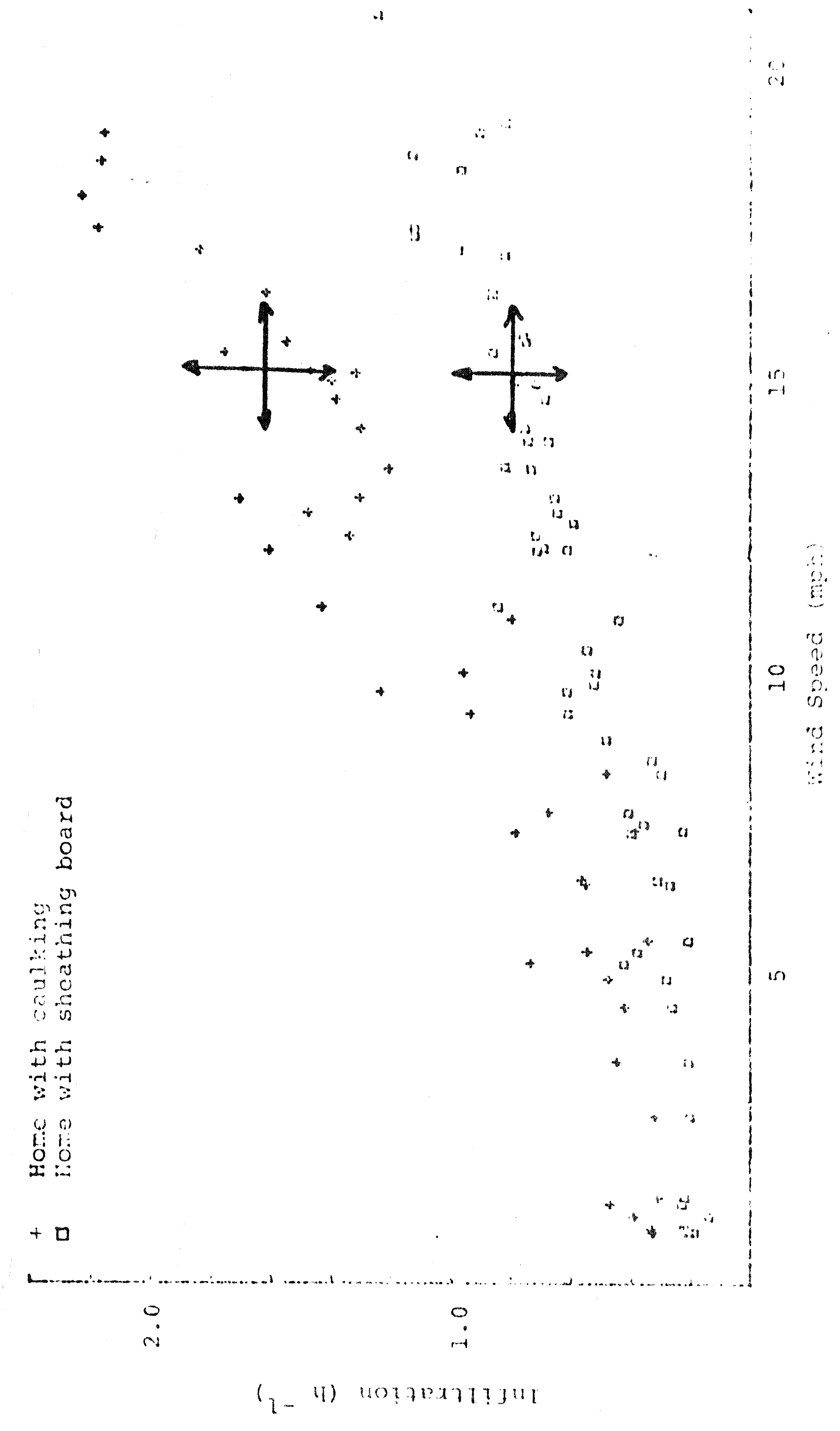


FIGURE 6. Winter Data, ΔT = 16 to 23°C.



+ Home with caulking
□ Home with sheathing board
2.0
1.0
Infiltration (h -1)
5
10
15
20
Wind Speed (mph)

The data for $\Delta T > 37°C$ is limited. The values noted were based on smoothing a curve through essentially 10 points--not quite sufficient to mask the scatter (as in Figures 6 and 7). A plot of the data in Table 2 exhibits an increase of infiltration rate with ΔT, as noted in Figure 8. (The relationships shown are approximate fits neglecting the last set of data.)

A considerable amount of data was collected with relatively calm winds. These are plotted in Figure 9 confirming the existence of an (approximately) linear relationship with ΔT. Figures 6 and 7, on the other hand, exhibit the easily justified quadratic relationship between infiltration rate and wind. That relationship could be generalized as

$$I = A(\Delta T) + B(\Delta T)\, W^2 \qquad (6)$$

with A and B functions of ΔT. Based on Figures 8 and 9 the dependence of A and B on ΔT is approximately linear, suggesting that a proper expression for (6) would be

$$I = I_o + C_1 |\Delta T| + C_2 W^2 + C_3 |\Delta T|\, W^2 \qquad (7)$$

The I_o may be a base value imposed by the furnace blower creating a small pressure difference. (The furnace blower was always on during the recorded runs.) A least square routine to all the winter data gives the following coefficients when ΔT is in °C, W is in miles per hour and I is in hours^{-1}:

	I_o	C_1	C_2	C_3
Caulked home	7.23×10^{-3}	1.35×10^{-2}	3.98×10^{-3}	1.35×10^{-5}
Sheathed home	4.66×10^{-2}	7.42×10^{-3}	2.6×10^{-3}	2.07×10^{-6}

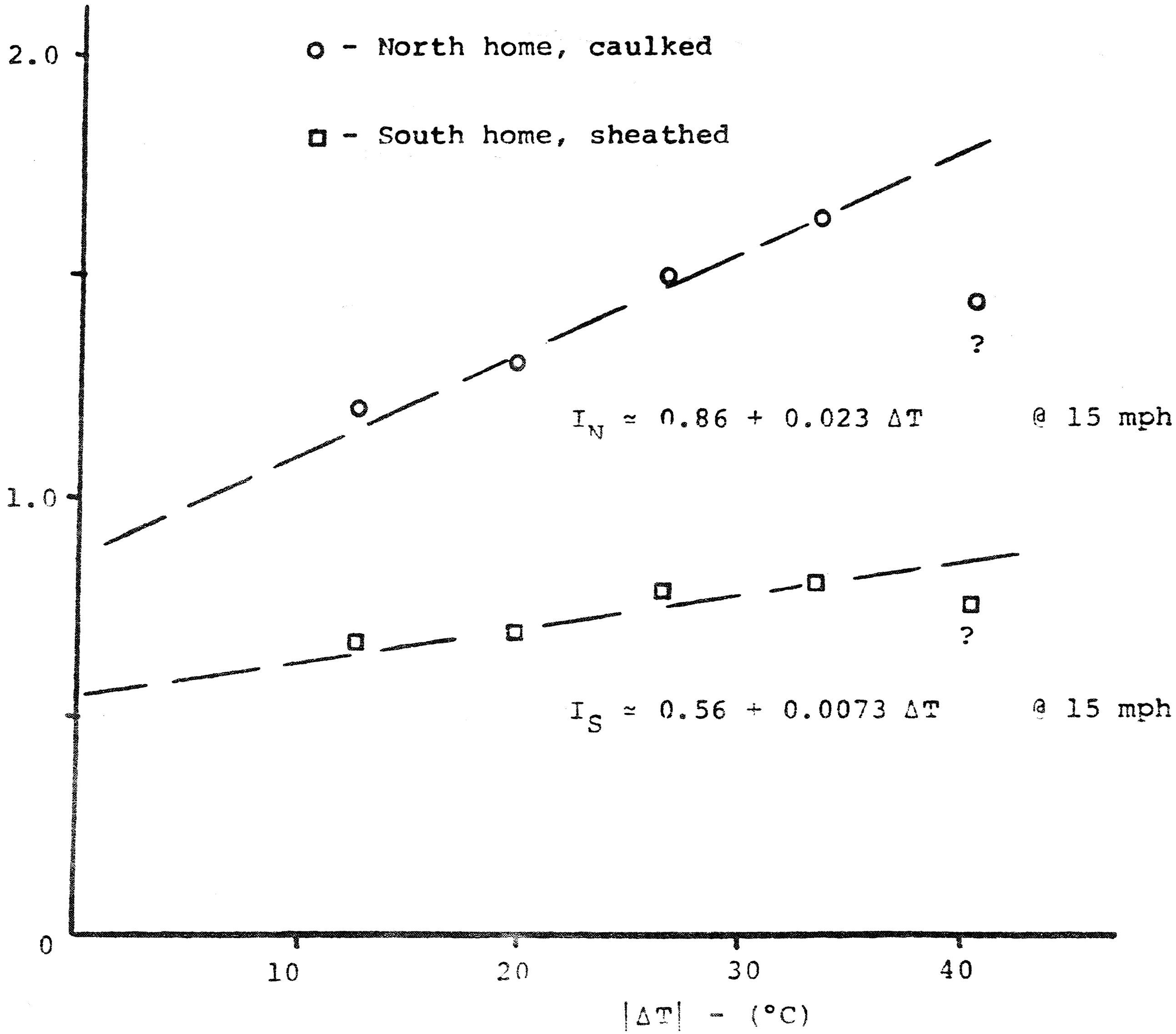


Figure 8. Average Infiltration Rate @ 15 mph vs. |ΔT|

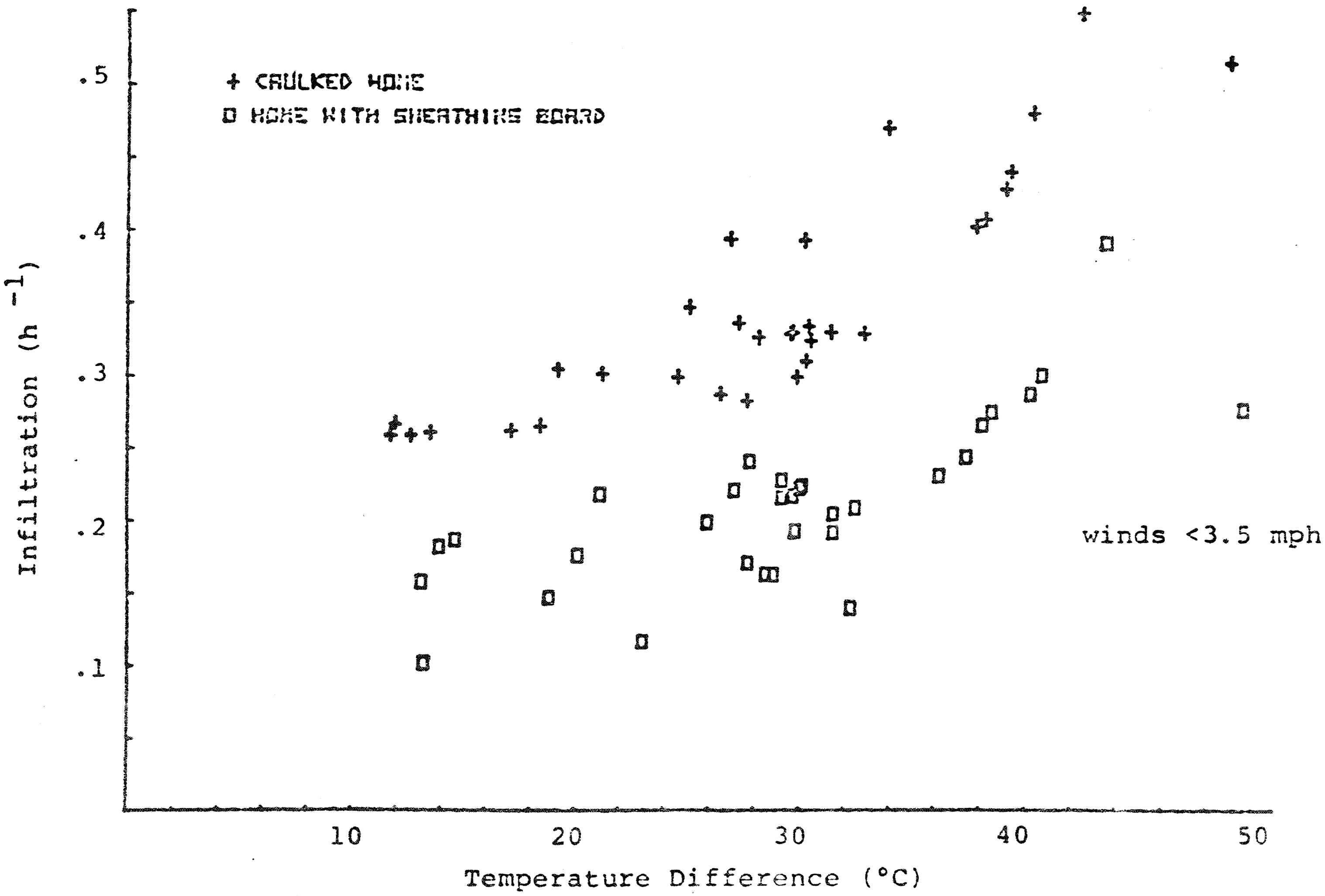


FIGURE 9. Infiltration Rate Under Calm Winds vs. $|\Delta T|$

Other parameters seemed to have little effect on the infiltration rate. The wind direction has a very small dependence for which a relationship has not been defined. Solar radiation has no detectable effect; neither does humidity (except for cases of extremely heavy precipitation).

CONCLUSIONS

Although some infiltration is required to provide fresh air for occupants, the amount naturally infiltrating through cracks and openings in the outside envelope of the homes far exceeds that value. As an example, a typical mobile home, 14 x 70 feet according to ANSI A119 may have infiltration rates in the order of 1 change per hour at design conditions (of 15 mph wind). This corresponds to 115 ft^3/min, whereas the recommended ventilation for a typical five person occupancy (according to ASHRAE Handbook of Fundamentals) would be between 1 and 50 ft^3/min.

Infiltration does indeed lead to increased energy consumption. As an example, the energy losses attributed to infiltration in a well-built 1975 mobile home (without sheathing board) for the month of February 1977 were in the order of 4800 Btu/h, or close to 36% of the total heat losses from the home for that same period. The economical advantages of reasonably-priced products capable of reducing infiltration rates are obvious.

The extensive field data taken in the two test homes exhibits an infiltration rate dependence on the velocity squared and linearly with temperature differences. The corresponding values of infiltration rate at the winter design conditions (15 mph wind, -10°F) are as follows:

for the home with sheathing board: $0.98\ h^{-1}$

for the home with caulking: $1.64\ h^{-1}$.

The above confirm that the home with sheathing board just satisfies the criteria established in ANSI A119.1 whereas the best alternative--the well-built home with caulking--far exceeds the upper bound recommended.

The summary of the winter data suggests that:

1. Further data, including summer runs, is necessary to formalize the dependence of I on ΔT.
2. A scheme for measuring a parameter descriptive of infiltration rates in mobile homes just off the assembly line is desirable. This scheme should be "calibrated" against field data and could lend itself as a quality control device.
3. There is a strong probability that the typical mobile home, unless receiving a treatment better than merely caulking, will not comply with the infiltration criteria of ANSI A119.1.

ACKNOWLEDGMENTS

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Product Company. Their support is gratefully acknowledged.

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NOMENCLATURE

A	Expressed as A(ΔT); coefficient in Eq. 6 ($hours^{-1}$)
B	Expressed as B(ΔT); coefficient in Eq. 6 ($hours^{-1}$)
C	Concentration of CO in the homes (ppm) (parts per million by volume)
C_o	Concentration of CO in the homes at time $t = t_o$ (ppm)
C_1	Coefficient in Eq. 7 (1/hours °C)
C_2	Coefficient in Eq. 7 (1/hours °C)
C_3	Coefficient in Eq. 7 (1/hours °C $(mph)^2$)
C_{in}	Concentration of CO in the outside ambient (considered to be zero)
C_{out}	Concentration of CO in mixture leaving the homes to the outside (set equal to C) (ppm)

I Infiltration rate ($hours^{-1}$)

I_N Infiltration rate, North home, with caulking ($hours^{-1}$)

I_o Infiltration rate obtained by correlation of data and extrapolated to $W = \Delta T = 0$ ($hours^{-1}$)

I_S Infiltration rate, South home, with sheathing ($hours^{-1}$)

ΔT Temperature difference between indoor and outdoor (°C)

t Time (hours)

V Volume of air-tracer mixture in the mobile home (m^3)

V_{in} Volume of air infiltrating (m^3)

V_{out} Volume of air-tracer mixture exfiltrating (m^3)

W Wind measured 16 feet above the ground (mph)

LIST OF FIGURES