AIR INFILTRATION REDUCTION THROUGH RETROFITTING

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Abstract

This paper documents and compares the air infiltration levels experienced in five Twin Rivers townhouses before and after retrofit. The technique used to measure air infiltration rates was the tracer gas method which relied upon automated equipment. Weather data as well as 5-minute interval air infiltration measurements were used in the comparisons.

Analysis techniques included multiple regression, polar plotting, stemleaf plotting and detailed comparisons of infiltration rates as influenced by temperature differences inside-to-outside the dwelling.

The results indicate that: the retrofitted townhouses are noticably less sensitive to wind direction, showing little or no increase in infiltration when the wind directly impinges on building surfaces; the post-retrofit infiltration rates average 36% less than the pre-retrofit data, with individual houses experiencing as much as a 48% decrease; basement and attic retrofitting appear to be very influential in achieving the greatest reductions in air infiltration rates.

Keywords: Air Infiltration, Ventilation, Retrfit Air Leakage, Modeling, Residential, Air Flow Energy Losses.

Presented at the ASTM (ASHRAE) Meeting on Air Infiltration, Washington, D. C., March 1978. To be published as ASTM Special Publication on Air Infiltration.

Acknowledgement

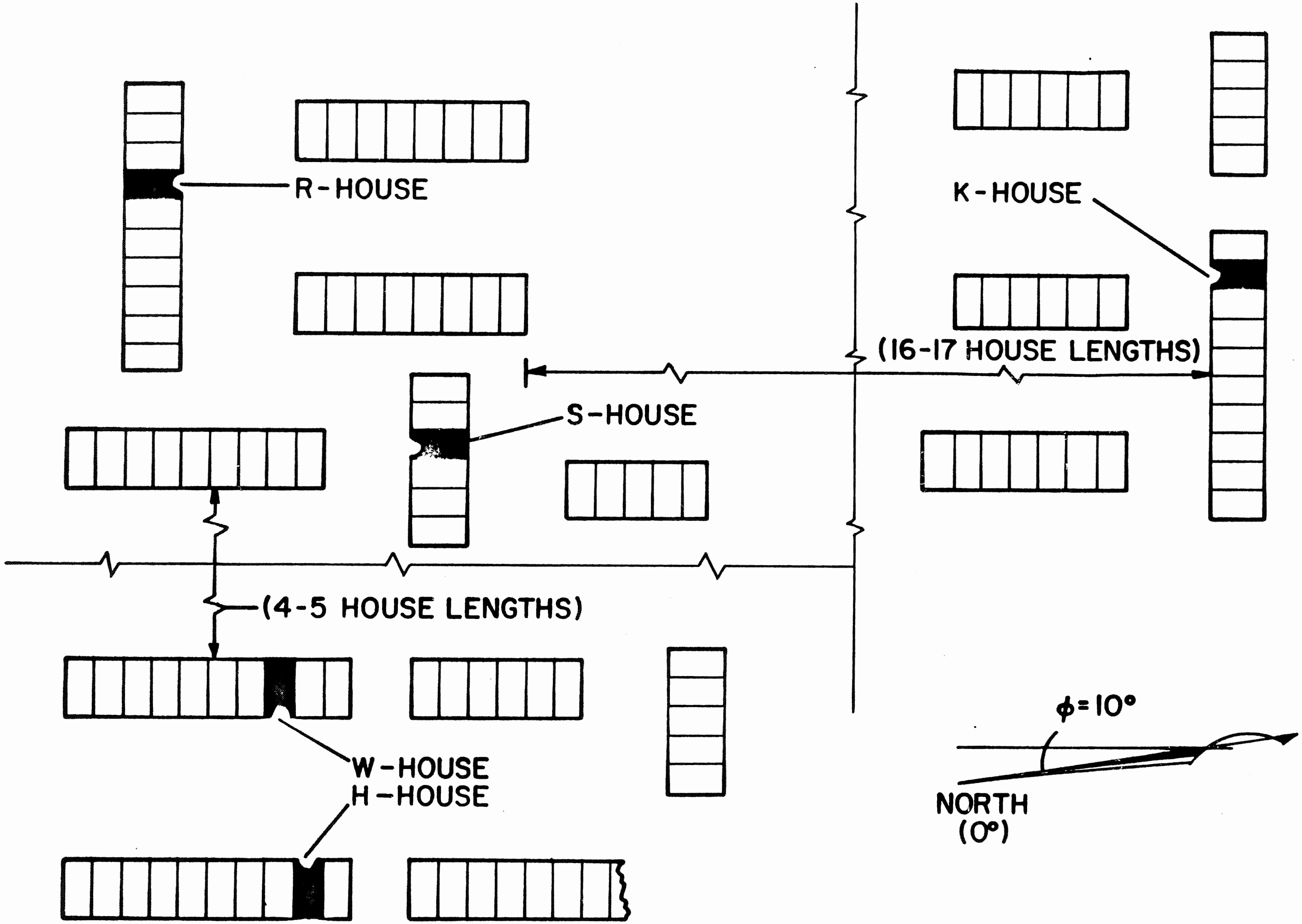
The authors wish to thank Dr. Richard Grot for the electronic advances which have allowed the automated air infiltration instrumentation to record data on magnetic tape cassette and for his advise in the data analysis. We wish to thank Ken Gadsby for his calibration and trouble-shooting of the equipment. We would also like to acknowledge the work of Nicholas Malik and of Robert Sonderegger on the tests and the data reduction.

The authors also wish to thank the U.S. Department of Energy and the Department of Commerce - National Bureau of Standards for the support of this research under contract DOE EE-77-S-02-4288 and DOC/NBS 6-35758.

1. Introduction

The effect of retrofitting on the infiltration rates of Twin Rivers, N. J., townhouses is the subject of this paper. The details of townhouses energy consumption has been part of a broader study over these past five years.[1-3] The technique of air infiltration measurement is the tracer gas method with emphasis on the use of automated sampling equipment.[4-6]

This study specifically involves regression analysis of measured air infiltration (AI) rates in townhouses before and after retrofit, attempting to correlate these rates with local weather conditions and with variables specific to the house itself. Multiple-regression equations, as previously derived by Malik[6] studying two houses during the fall and winter of 1974, are compared to the results obtained from eight additional data sets taken over the past two years. These data were taken from five test houses in all, two of them being the townhouses studied by Malik. Each is a 1400 square foot, three-bedroom, two-story townhouse with a basement and an attic (details see ref. 3 and 7) . Central heating is provided by a gas furnace. The positions of the test houses within the townhouse rows and their compass orientations vary widely, as can be seen from Figure 1. These differences are shown to be influential with regard to the effects of weather on air infiltration. Those townhouses on the west side of the development (H and W houses) see more of the winter winds which are predominantly west and northwest.



SAMPLE HOUSE SKETCH

TWIN RIVERS-AIR INFILTRATION

Figure 1

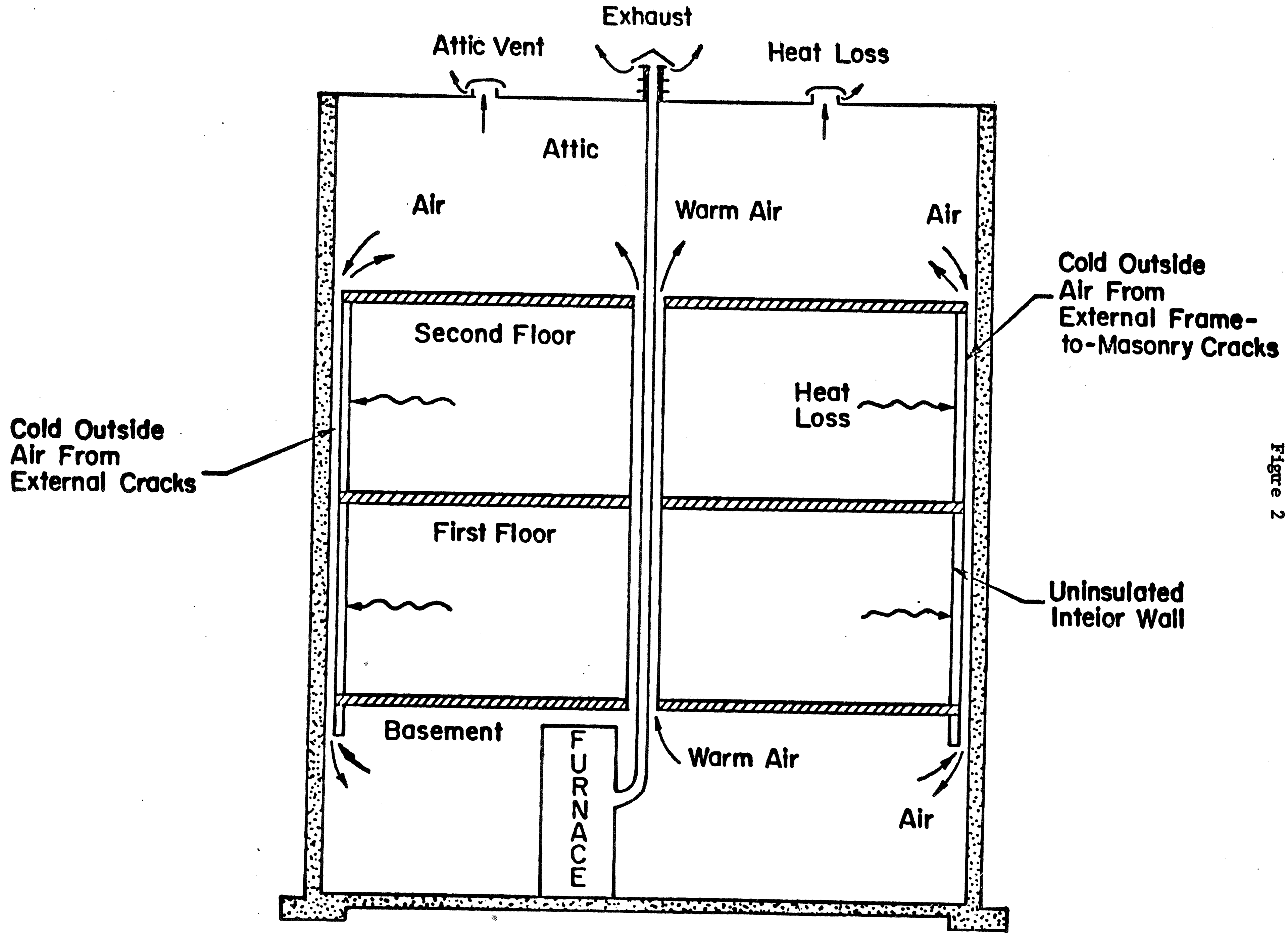
II Townhouse Retrofitting

From the standpoint of air movement as related to townhouse physical characteristics, a more detailed description of the townhouse is necessary. Figure 2 is a cross-section of a typical Twin Rivers two-story townhouse as viewed from front or rear.[8] The documented air paths shown in the figure have been the result of detailed studies[6-9] using infrared scanning, tracer gas methods and anemometer and temperature probes in the areas under investigation. Principally, air has been shown to move into the basement via the opening between attic floor joists and the firewall or through openings in or near the band joist. An overhanging building segment on the front of the townhouse proved to be a main source of such infiltration. The shaft opening around the vertical flue was a prime source of temperature driven (stack effect) air movement to the attic. The following retrofits have been designed[8] to eliminate or reduce such infiltration problems.

A: Increasing attic insulation to resistance R-30. As part of this retrofit, and more important to reducing air infiltration was the sealing of cracks along the attic floor/party wall junction and the leakage from basement to attic around the plumbing vent stack. Details on attic bypass, the movement of heat past the attic insulation, may be found in the work of Dutt and Beyea.[3,10]

B: Caulking and sealing of window frames to remove infiltration/exfiltration sites.

Figure 2



Cross-Section of Townhouse
Showing Flow Pattern

C: Wrapping of the air distribution ducts on the basement ceiling (this included the two ducts and the overhang area at the front of the house), the furnace plenum, and the hot water heater with fiberglass insulation. Cracks in the ceiling/party wall junction were blocked, as well as open cracks in the sill plate and around service wiring and dryer exhaust.

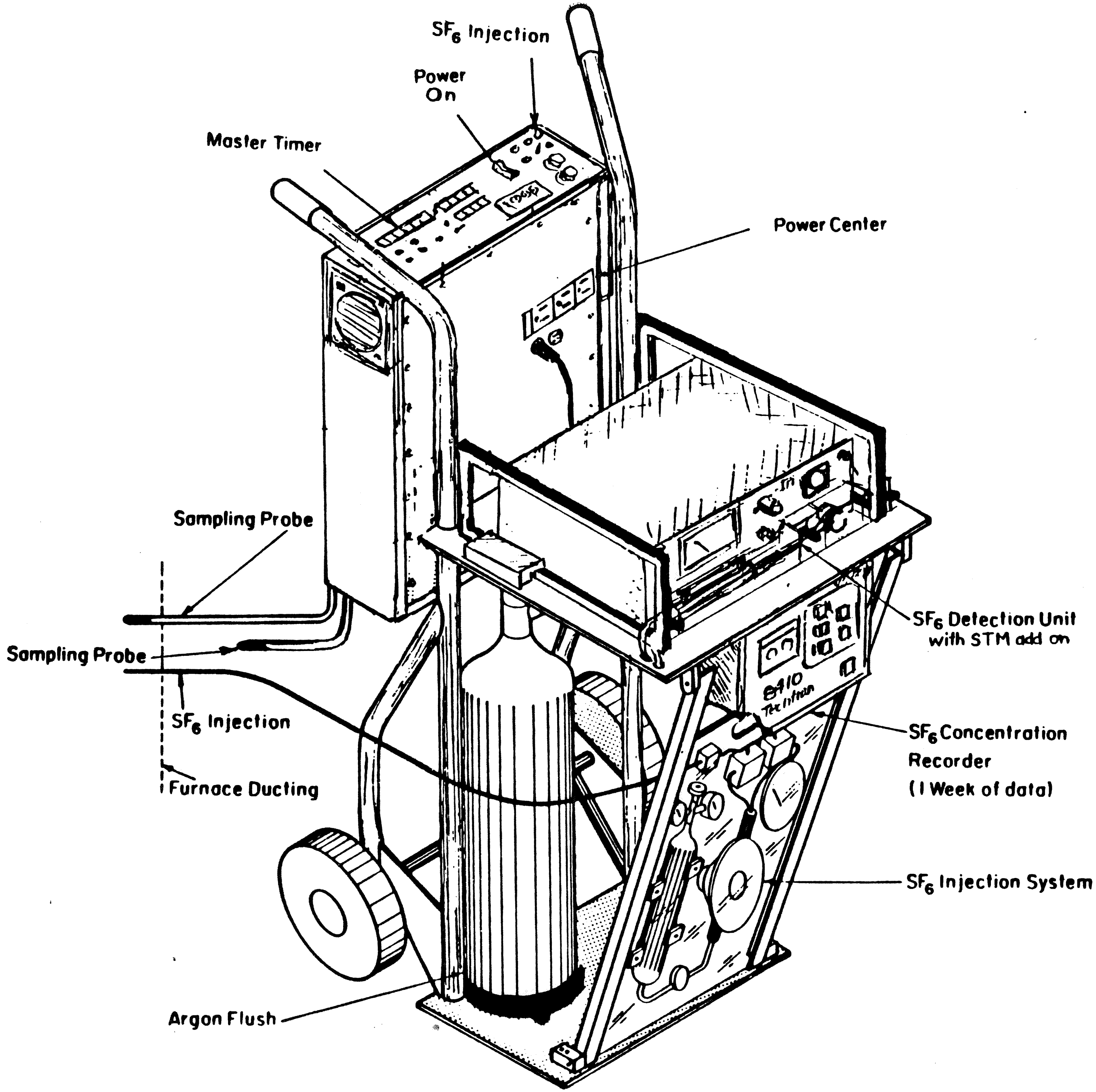
D: Sealing of the vertical shaft surrounding the furnace flue, which could act as a convective chimney for warm basement air moving to the attic in cold weather.

III Reduction of Data

The actual taking of air-infiltration data in a townhouse relied upon use of the tracer gas method using the Automated Air Infiltration Unit (AAIU), pictured in Fig. 3 (details on the equipment and method are found in ref. 4 and 5). Basically the approach consists of periodically injecting small amounts (<20cc) of sulphur hexaflouride into the heating duct system, where the furnace blower circulates and mixes the air through the house. Monitoring of the decaying SF_6 concentration was generally on a five minute basis using a electron-capture detector/gas chromatograph unit. Data on the SF_6 concentration, including time, date, sampling port and injection information, was stored on magnetic tape cassette.

Before the analysis that forms the basis of this paper could begin, the gas chromatograph data had to be converted to values of air infiltration vs. time, then integrated with weather data taken during the test period. To accomplish these tasks, a data reduction approach was developed and is outlined in ref. 11. The data in the form of tracer gas concentrations versus time as recorded on the tape cassette are read into the computer where it is compiled and checked on a natural log of tracer concentration versus time display (here any variations or errors become very evident). The data are "cleaned up" in the case of obvious errors and integrated with the appropriate weather history. In this process, one has the option to bin data as to wind direction, wind velocity, temperature differential etc, or to look at detailed infiltration rate versus time profiles, which can be "smoothed" by averaging before and after the individual five-minute infiltration rates.

Figure 3



AUTOMATED AIR INFILTRATION UNIT

IV Data Analysis

A. Goals of Analysis

The first task was to process the "raw" gas chromatograph readings to the point where air infiltration values were obtained as a profile against time. In this way a general idea of the magnitude of air infiltration could be obtained for each house, both before and after retrofitting. Following the matching of air infiltration with weather data, the next step was to display this data graphically, using variously labelled axes and, eventually, different coordinate schemes to attempt to see correlation or functionality with the several independent weather variables or with time. Finally, the available data was reduced to multi-regression equations using only these same variables. The statistical parameters of "goodness of fit" achieved from the equations were compared to those obtained from similar equations derived by Malik[6] that made use of "house" variables as well. The ultimate goal of such regression analysis would be the development of improved, generalized relations that could make use of a set of empirically obtained structural and climatic parameters to predict air infiltration levels in a variety of housing.

B Preliminary Analysis

The calculations and plots made from the first datasets were used in various ways to isolate the effects of one or two specific weather variables on air infiltration. This was accomplished by holding the other variables constant or within some tolerance interval. A "variable sensitivity analysis" was tried for 45°-wide intervals of compass wind direction (Θ) and air infiltration (AI) values were plotted against a differential temperature ("DT") measure. (At the time, the existing weather/air infiltration matching program would only provide binned weather readings, e.g. a reading at some point in time of $\Theta = 274°$, V = 2.2 mps, T = 1°C would be reported as a "weather address" of (Θ) (V) (T) - 6206.* The program was later rewritten to correct for this unnecessary loss of information). Wind velocities were indicated on the plot by different symbols, so that both temperature and wind effects could be observed. Finally, the plots generated were compared with Malik's equation[6] for the townhouse air infiltration with winds over 3 mps.

$$AI = .31 + .169 \; (T/40) \; V \cos\,(\Theta - \Theta_0) + 890G \qquad (1)$$

If we modify the equation using results from other Twin Rivers experiments, the $G \simeq 1.64 \times 10^{-5}\,(15.5 - T_o)$, where T_o is outside temperature. Assuming a year-average inside temperature of 21°C, we can rewrite the expression above as

$$AI = .23 + .169 \; (\Delta T/40) V \,|\cos\,(\Theta - \Theta_o)| + .0146 \quad T \qquad (2)$$

in which the independent variables are weather data alone. This equation can then be compared to similar equations derived from the townhouse air infiltration measurements of this study. Section IV - F discusses these comparisons.

* The binning procedure assigned numbers to the various ranges of a given parameter, 6 - 2 - 06.

C. The Polar Plots

It was realized that to be able to look at the processed readings of an entire test (dataset) simultaneously, it would be necessary to find a method of plotting AI vs. weather variables that would: 1) allow one to observe air infiltration "all the way around" the house, without it being necessary to plot only points within a given Θ interval; 2) allow isolation of certain variables to study their individual effects on AI; and 3) allow direct comparison of pre-vs. post-retrofit AI. Plotting on polar coordinate paper was chosen as a way of depicting the "dynamic" variation of AI around a given house as a result of weather variables and the surroundings of the house itself.[11] The eight data sets that were eventually used in these plots came from five sample homes, with testing done both before and after retrofitting except as noted: W-, R-, and S- houses, K-house (pre-retrofit test only), and H-house (post-retrofit only). See the "Index to Polar Plots", Table 1. Values of AI were plotted as Roman numerals, the numerals denoting wind-velocity bin number, on a "compass rose" plot with a silhouette of the test house at the center of each plot. Pre-and post-retrofit datasets were plotted separately. Generally, an attempt was made to match the temperature range of the plots "before" and "after", but in order to obtain a reasonable number of points to plot, this matching could not be perfect.* In cases where a sufficient number of points were available, the locus of air infiltration readings for a particular velocity bin was sketched atop the plot. Though

*Linear regression and further plotting will more clearly point out the role of T in air infiltration and the resultant differences among the pre-and post-retrofit datasets.

Table 1

INDEX TO POLAR PLOTS

Data Set	Test Date	#Points Plotted / Total # Points	T-Range (°C) Plotted	T-Range (°C) (Entire Test)
R Pre-Retrofit	1/24-27/77	136/187	-3 to 0	-6 to 3
R Post-Retrofit	3/25-28/77	60/224	-1 to 2	-1 to 17
S Pre-Retrofit	2/10-16/76	49/110	-4 to 4	-4 to 14
S Post-Retrofit	4/24-29/76	38/63	-3 to 9	3 to 16
W Pre-Retrofit	2/4-7/76	36/79	-4 to 4	-10 to 4
W Post-Retrofit	3/24-26/76	39/43	4 to 18	4 to 19
K Pre-Retrofit	2/10-16/76	46/73	2 to 9	-1 to 14
K Post-Retrofit	4/9-11/76	26/35	3 to 17	1 to 17

the averages differ from house-to-house, one can obtain two "average averages" using four datasets apiece for the conditions "pre-retrofit" and post-retrofit" as shown in Table 2. The pre-retrofit "average average" is .651 (exchanges/hr.) over four datasets, with a standard deviation of .221 (if we delete the W-house average, which seems anomalously high, (.982 exchanges), and average the remaining three, the pre-retrofit "average average" drops to .541 but the standard deviation is greatly reduced, to .019). The post-retrofit "average average" obtained from four datasets is .392, with standard deviation .088. The average reduction in air infiltration using all data sets is 40%, however, remember the ΔT is not the same in these comparisons.* (Deleting W-house data drops the average improvement to 28%.

Another evident phenomenon is the difference in the effects of variables θ and V on AI as we go from pre-to post-retrofit plots. <u>Air infiltration before retrofitting seems far more directionally influenced than after</u>. In general, AI seems to dip along the sides of each house (i.e., where the wind would be blowing along the long axis of the townhouse row) and rise as the wind moves to blow against either the front or the back of the house, where doors and windows may allow drafts in through cracks even while closed. This is most strikingly seen in the pre-retrofit S-house plots, Figure 4. The locus of

*The final comparison must await the regression analysis comparisons and same ΔT.

TABLE 2

Dataset	T-Range (°C)	Midpoint (°C)	Average AI
W house	-10,4	-3	.982
R house	-6,3	-1	.542
S house	-4,14	5.	.559
K house	2,14	8	.521

Dataset	T-Range (°C)	Midpoint (°C)	Average AI
R house	-1,17	8	.290
H house	1,17	8.5	.499
S house	3,16	9.5	.415
W house	4,19	12	.362

velocity bin III (4-5.4 mps) AI points* rises to about .67 as the compass heading approaches that of the front door (10°), drops to about .5 as the wind begins to blow parallel to the row, then rises again to .6 as the wind comes from the south (180°), (where 190° is the normal to the back wall). Such effects were evident in previous wind tunnel testing[12] and in the Malik study[6].

The correlation of wind velocity (V) with AI is complicated in its analysis via these plots by many factors. However, in the pre-retrofit plots there seems to be at least some evidence, in each, of the proportionality (linear or nonlinear) of AI to V,[11] evidence that was later supported by multi-regression analysis of the same datasets. In contrast AI values of the post retrofit data sets generally show very little evidence of such correlation. Although wind speeds in the post-retrofit tests averaged somewhat higher than those encountered during pre-retrofit tests, post-retrofit air infiltration values tend to "cluster" in a narrow band thus farming a circle on the polar plot. Where the average value for the pre-retrofit air exchange rate is .559 for S-house in figure 4, the post retrofit value was found to be .415 with the data points following the circle.

* Every data binning operation constitutes a sacrifice of a certain amount of information in an attempt to illustrate functionality. This "noise" must be kept in mind when viewing such plots.

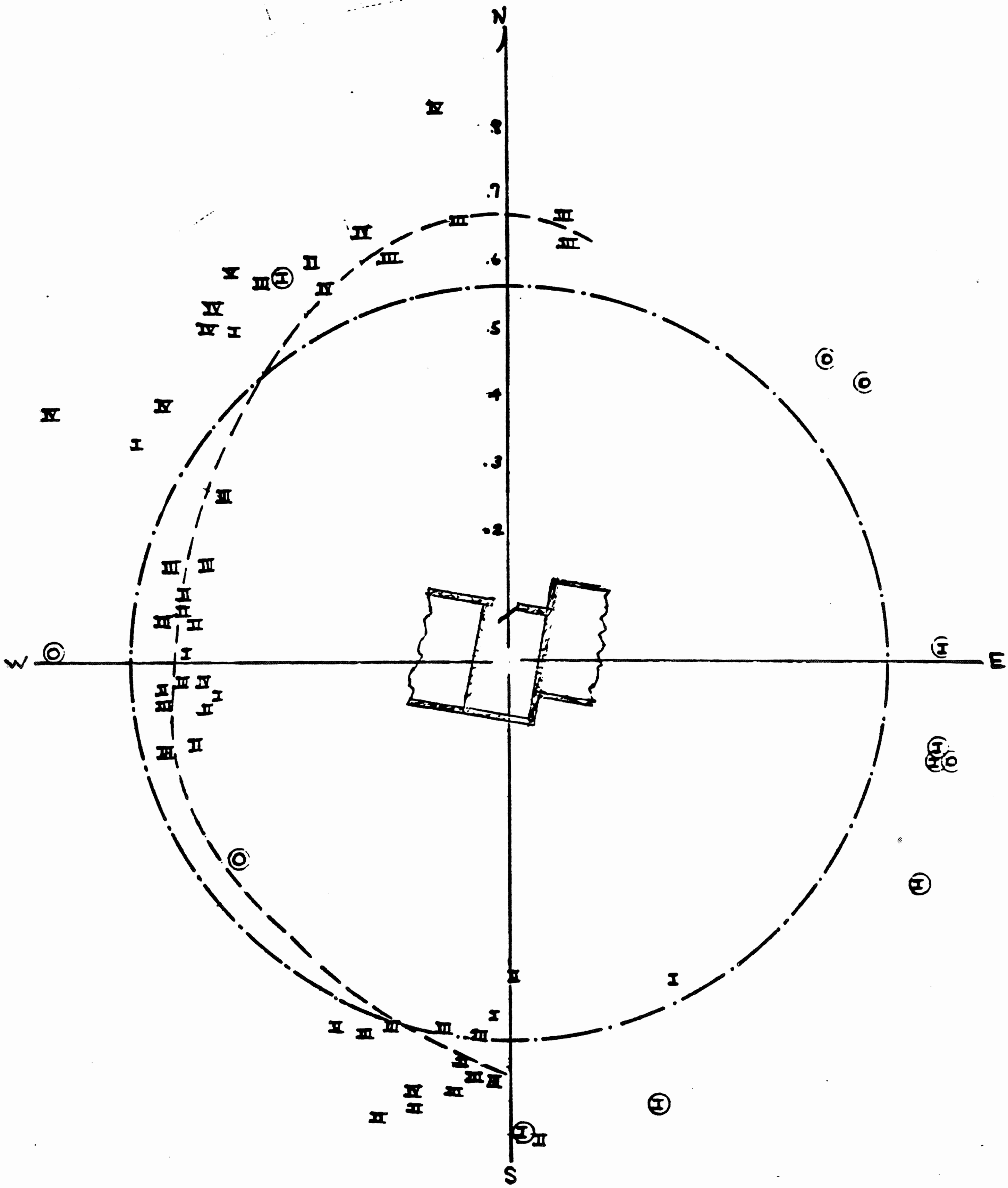


Figure 4

S-HOUSE PRE-RETROFIT

POLAR PLOT (AI vs. Θ)

Key

○ Circled points are below freezing ($0^{\circ}C$)

—·— Locus of average AI (0.559)

— — — Locus of wind velocity V=4-5 m/s

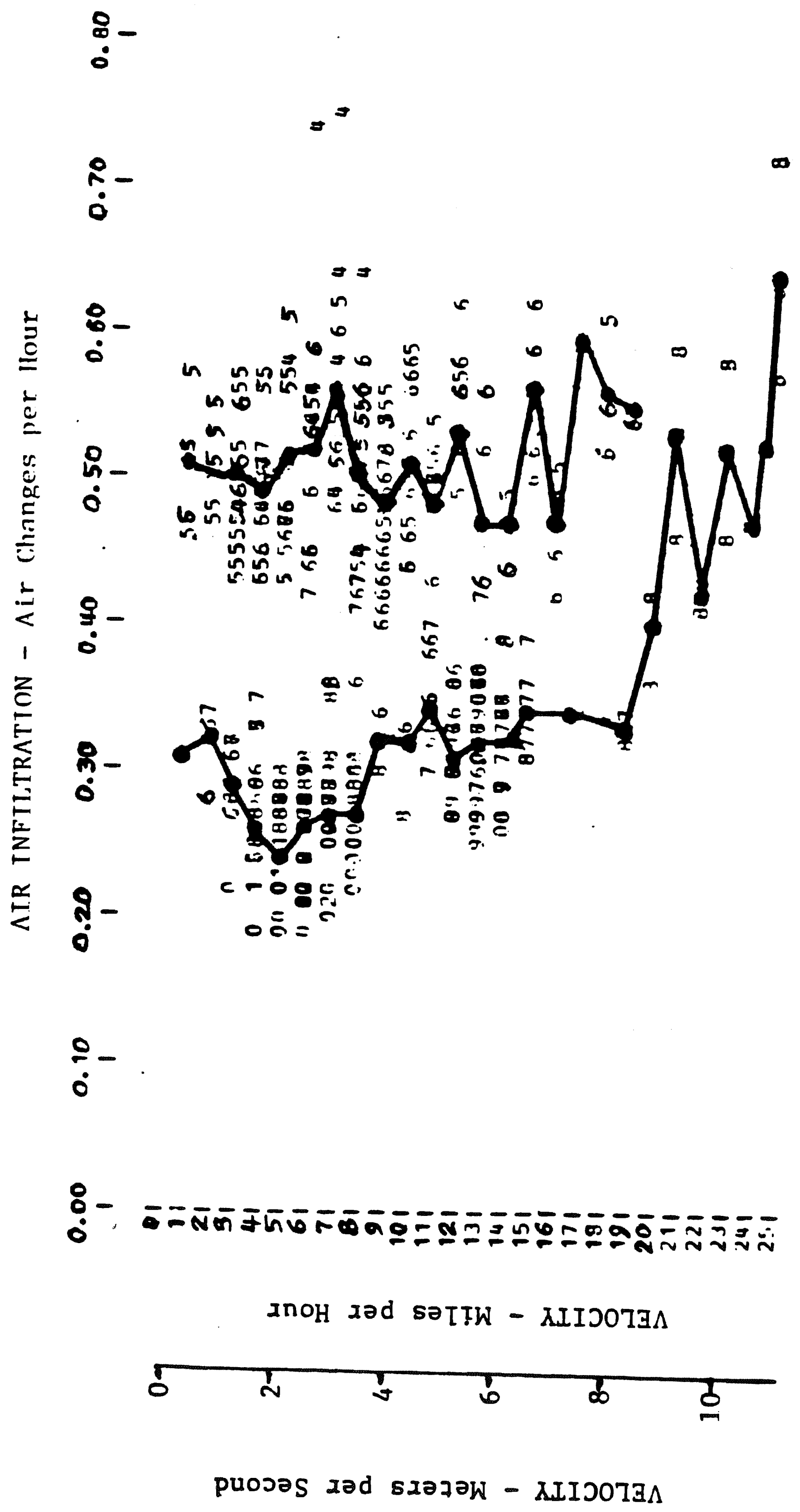
The one house that shows little variation to wind direction in the pre-retrofit tests was R-house. This townhouse was already partially retrofitted in the basement area, where efforts were being made to seal the band joist. Based on townhouse location considerations, Fig. 1, one would have expected even more wind effect for R-house than with S-house. The results obtained for the R-house are thus further confirmation of the sensitivity of the basement zone in the house to influence infiltration behavior. This follows the Malik study which treated this townhouse location as a separate air infiltration zone.

One other item that was also investigated using these plotting techniques was the possible influence of moisture to help seal openings. Ice formation in cracks with temperatures below freezing can be postulated to supply a blocking mechanism. However, no evidence of such an effect was found as temperatures moved below the freezing point. A concurrent study looking at townhouse humidification also found no evidence of such air infiltration reduction.[13]

D. "Modified Stem-and-Leaf" Plots

To investigate further the relative effects of temperature and wind velocity on air infiltration, the R-house datasets were plotted in a "modified stem-and-leaf" fashion:" AI values were plotted against T, with the V-bin numbers representing the points, and against V with T-bin numbers as points. An example of a comparison with V is shown in Figure 5. The temperature affects are treated in the next Section. One observation which has been documented before[6] is the dominant influence of T- induced (stack effect) air infiltration in these townhouses for the range of temperatures and windspeeds encountered during testing.

Figure 5



AIR INFILTRATION - Air Changes per Hour
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
VELOCITY - Miles per Hour
VELOCITY - Meters per Second
0
2
4
6
8
10

Tamura and Shaw[14] have shown in studies on taller buildings that relatively high winds are necessary to induce the same air infiltration as that brought about by a typical winter T. However, as wind velocity V exceeds 8 or 8.5 mps, AI seems suddenly to become extremely sensitive to this variable, increasing rapidly from an average of .328 at 8.5 mps to .636 at the maximum wind speed of 11 mps. Malik observes this same effect in one of his H-house (House #1) pre-retrofit data sets: "As the wind becomes westerly and as its speed starts to exceed 8 mps, the value of AI increases without scatter from 0.6 exchanges per hous to 0.9 exchanges per hour when the wind speed becomes 10 mps, indicating a slope of about 1.5 exchanges per mps". This behavior makes the derivation of a multiple-regression equation that is adequate for all values of V difficult. A similar sharp change in air flow through modeled building surfaces with both permeability and hole size variations was described by Malinowski[15] based on a series of experimental tests. The behavior was attributed to local mixing and flow phenomena.

E. Scatterplotting and Regression: AI vs. ΔT

To develop scatterplots reflecting air infiltration's response to changes in indoor-outdoor temperature difference, an indoor temperature of 21°C was used (indoor temperatures tended to be very close to this value). All outlier AI readings more than two standard deviations removed from the sample mean were first eliminated from each dataset before it was plotted. Preliminary plots of entire datasets had shown that one or two enormous AI readings could seriously bias the linear regression of AI against ΔT. It was suspected that most of these anomalous readings had their basis in any of a number of unmeasured events (likely candidates being the opening of doors, windows, etc.), and were thus not indicative of the overall performance of the house under the recorded weather conditions. If the AI values for each data set could be assumed to have a roughly normal distribution about the (sample) mean, then instituting this "2s control limit" would only remove about 5% of the total number of measurements; in fact, fewer than 4% of each dataset was removed on the average before plotting was done.

Table 3 summarizes the results of the AI vs. ΔT regression of each of the data sets that were scatter-plotted. The comparison plots themselves are shown in Figures 6-8. The H-house pre-retrofit equation was obtained from Malik's calculations[6] (using only data from times when wind velocity was below 3 mps), thus a set of points for scatterplotting is not available. From both the scatterplots and the regression equations it is evident that as the convective driving force ΔT increases, so does measured air infiltration as shown in all eight test cases. Furthermore, the regression coefficients of ΔT after retrofitting indicate a <u>definite decrease</u> in the susceptibility of the house to temperature-difference-driven air infiltration. This is observed for every house but H; in fact, the S-house coefficient shows almost an order-of-magnitude reduction after retrofitting. (Since the temperature during the S-house post-retrofit test never dipped below 14°C, this effect cannot be due to any shell-tightening caused by water freezing in cracks in the house envelope). The apparently contrasting results obtained for the H-house, where house sensitivity to ΔT seemingly increases after retrofits have been installed, are in fact probably explained by the significantly higher wind-speeds during the post-retrofit tests for this house: the effects of these higher winds, since they are not explicitly included as a term of the regression equations, must be lumped into the coefficient and

TABLE 3

BEST-FIT LINES FOR SCATTERPLOTS (AI vs ΔT) OUTLIERS REMOVED

$AI = m\,\Delta T\,(°C) + B$

Data Sets	m	B	R/f-stat
H "Pre"*	.0046	.19	-
"Post"	.0054	.20	.32/3.05
R "Pre"	.0022	.34	.25/12.9
"Post"	.0020	.19	.62/131.9
S "Pre"	.0037	.36	.58/52.9
"Post"	.0004	.35	.07/.28
W "Pre"	.0042	.57	.12/1.07
"Post"	.0006	.31	.16/1.07

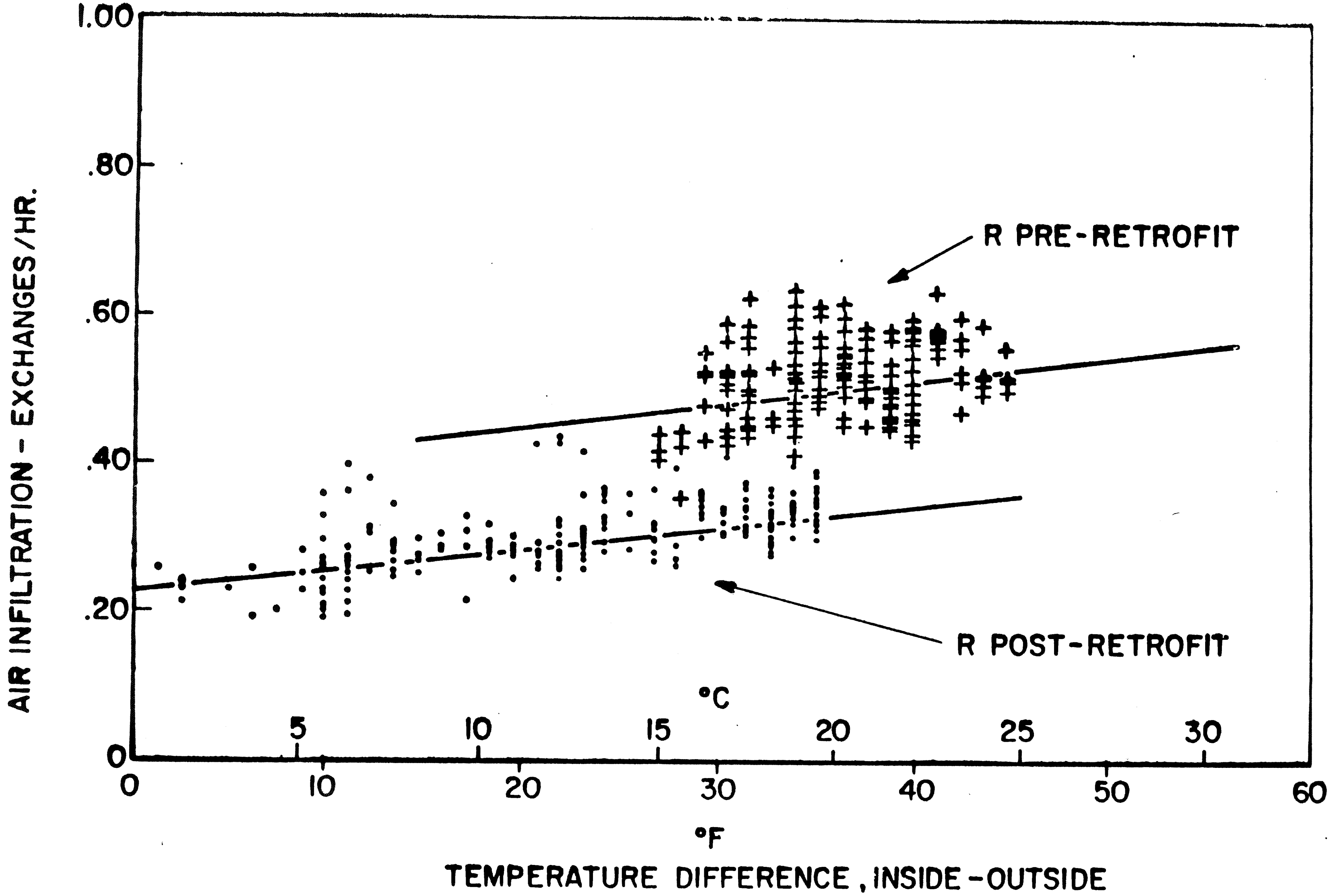
* H-house pre-retrofit expression is derived for temperature-driven effects at low wind speeds (V<3 mps), while post-retrofit data set featured higher winds (average V = 4.5 mps).

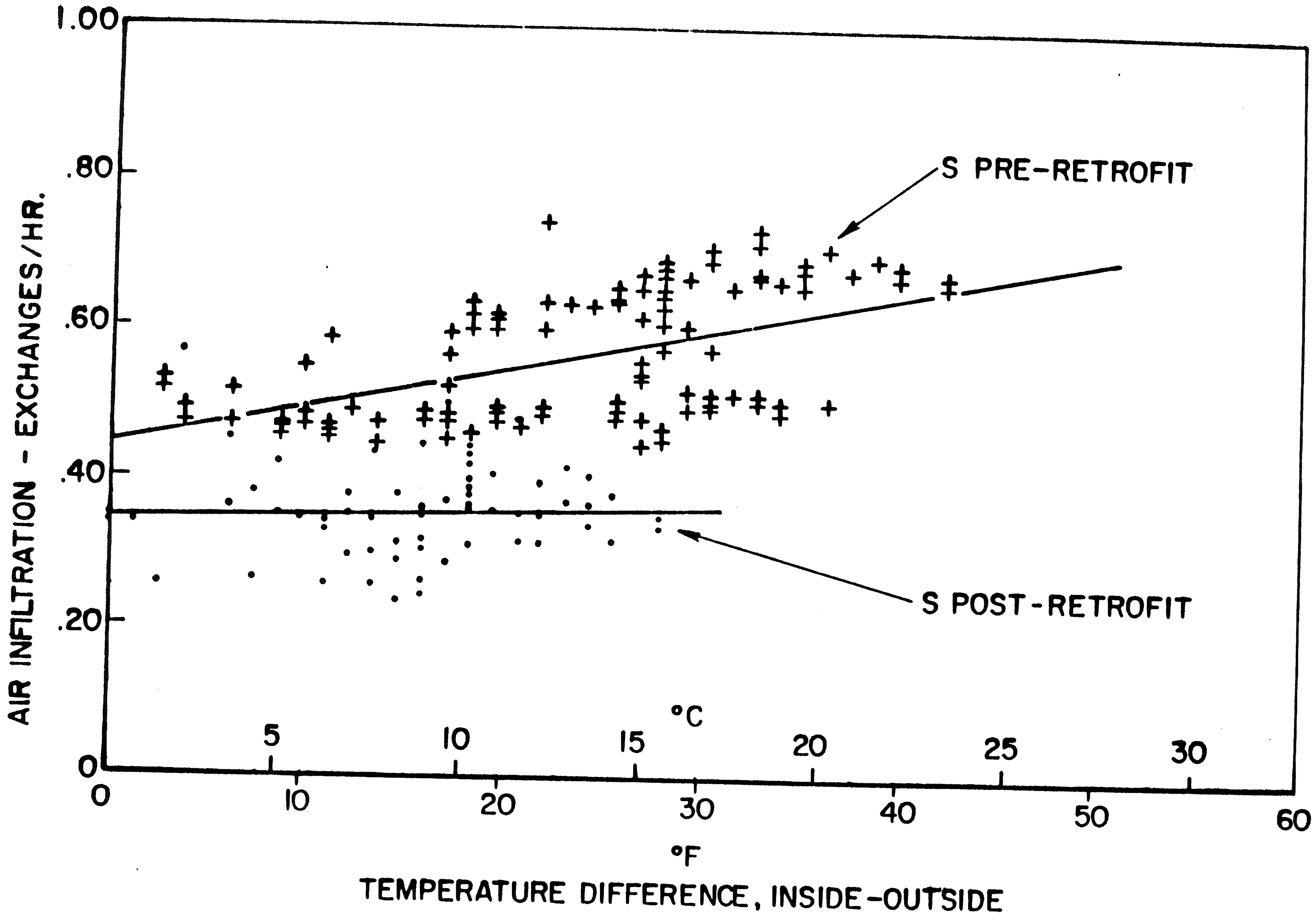
intercept during regression. (It should be noted that in every house tested, higher winds were observed during the post-retrofit tests. Considering this, the consistency of observed reduction in infiltration after retrofitting is remarkable).

In the R-, S-, and W-houses, the significant reduction to the intercept terms with retrofitting indicates a likewise reduction in "base-level" air infiltration, i.e. that which occurs without the influence of a temperature gradient ΔT across the house shell. This could mean that the retrofits have succeeded in making the house tighter against the influence of wind; this theory can be examined more closely with the results of the multiple regression analysis to follow.

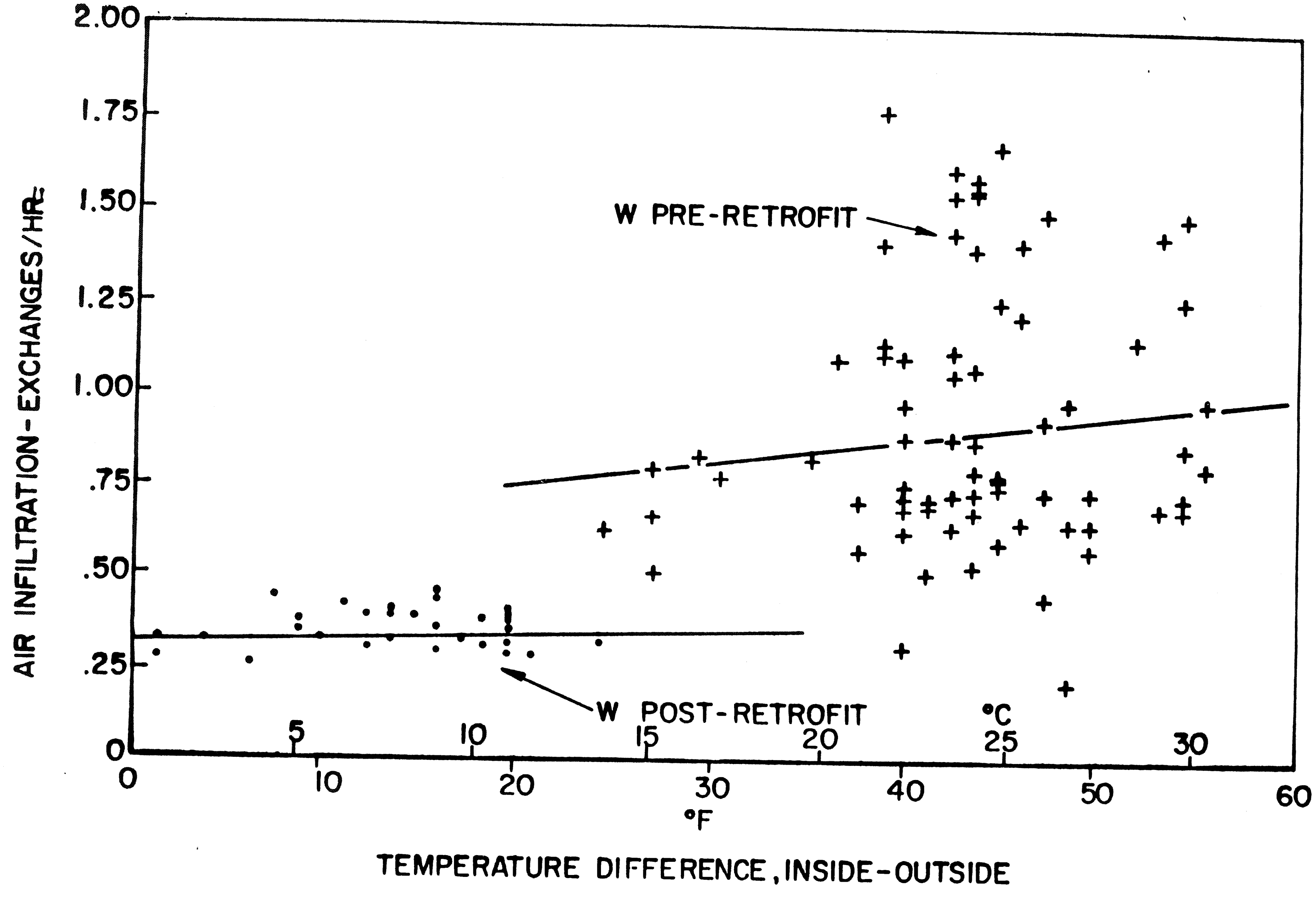
F. Multiple Regression: AI vs. Weather Variables.

Malik[6] postulated two "regimes" of air infiltration depending upon wind velocity. At low wind speeds infiltration seemed to occur mostly via the house "stack effect", driven by indoor-outdoor temperature difference ΔT; with higher speeds came enhancement of the directional effects of the wind and a coupling of temperature difference and wind effects. Malik devised a "wind-temperature interaction" regression variable (actually containing all three weather variables) to model infiltration with winds greater than 3 mps. The winds recorded during this retrofitting study were not universally high, however; though the average wind velocities recorded for each dataset with the first set of multiple-regression equations all exceed 3 mps, the standard deviations for these figures often exceed one-third the value of the averages themselves. Thus, the approach used in this study was to regress air infiltration against five models or equations and see which one best fitted the infiltration and weather data. Each of the five models contains a "ΔT" or "T" term,


R PRE-RETROFIT
R POST-RETROFIT
AIR INFILTRATION - EXCHANGES/HR.
1.00
.80
.60
.40
.20
0
°C
5
10
15
20
25
30
0
10
20
30
40
50
60
°F
TEMPERATURE DIFFERENCE, INSIDE-OUTSIDE



1.00
.80
.60
.40
.20
0
AIR INFILTRATION - EXCHANGES/HR.
S PRE-RETROFIT
S POST-RETROFIT
°C
5
10
15
20
25
30
0
10
20
30
40
50
60
°F
TEMPERATURE DIFFERENCE, INSIDE-OUTSIDE



AIR INFILTRATION - EXCHANGES/HR.
2.00
1.75
1.50
1.25
1.00
.75
.50
.25
0
W PRE-RETROFIT
W POST-RETROFIT
°C
5
10
15
20
25
30
0
10
20
30
40
50
60
°F
TEMPERATURE DIFFERENCE, INSIDE-OUTSIDE

the basic driving force of stack effect, and thus air infiltration under low wind conditions. This term is also an indicator of furnace operation, as noted previously in the modification of Malik's original equation, which contained a gas-consumption term in addition to weather-related variables; furnace operation enhances the stack effect, thus contributing to air infiltration. The wind-related terms in the models vary, from simple wind velocity V to the high-velocity wind-temperature interaction term devised by Malik.

The five models are listed in Table 4, along with the results of the robust multiple regression analysis performed for each. Model I is the modified Malik "high-wind" equation discussed earlier, derived to model the elliptical dependence of air infiltration on wind direction within the townhouse row. The constant Θ_0 is the normal to the back wall; the inclusion of both wind and temperature driving forces in the middle term reflects Malik's conclusion that these forces can interact constructively in high winds. Model II contains the same wind velocity component $V|\cos(\Theta-\Theta_0)|$ as Model I, but separates the ΔT term to reflect the fact that not all of the test data was taken under high-wind conditions. Models III and IV are more standard regression formulae. The former assumes that infiltration is linearly proportional to wind speed, while the latter dervies from a modeling of air infiltration as <u>laminar</u> flow through an crifice, where the flow Q_V due to the wind velocity head is

$$Q_V = CA\ (\Delta P)$$

and $P = \frac{\rho V^2}{2g}$ (and where C and A are the flow coefficient and orifice area, respectively). The last model tested (V) is a modification of Model IV, using the wind-component term of Models I and II.

The fits obtained for these models vary from house-to-house and between pre- and post-retrofit, as can be seen from their correlation coefficients. Three of the test houses (R, S. and W) were fitted to all five models. For all three, the best-fitting post-retrofit models involved only T and V or V^2, neglecting Θ entirely. This is clear evidence that retrofitting has transformed the house into a more uniform barrier against wind effects. Also evident is the influence on the "base-level" air infiltration constants for each of the five models. In every case except one (the H-house), retrofitting reduces the infiltration predicted with no wind or temperature driving forces. The ΔT (or T) coefficient also decreases in every case except for H in the first regression model. Here the "high V" pre-retrofit equation comes from Malik data and the post-retrofit equation is negative in the interaction term $\Delta T \cdot V|\cos(\Theta-\Theta_o)|$. However, considering all the models, the wind velocity-explicit terms show no universal decrease in coefficients following retrofitting. Even in the case of the wind-termperature interaction term (Model I), with ΔT "pulling down" the entire expression, the R-house coefficient doubles after retrofitting. There is a strong indication in these two observations that retrofitting has affected the climatic driving forces of air infiltration to different degrees.

TABLE 4

Model I $AI = \underline{a} + \underline{b}\Delta T \cdot V|\cos(\Theta - \Theta_o)| + \underline{c}\Delta T$

DATA SET		a	b	c	r	$\bar{V}$
R	Pre	.27	.00064	.0088	.46	7.6
	Post	.18	.00084	.0049	.77	9.0
S	Pre	.33	.00137	.0108	.71	8.8
	Post	.28	.00089	.0034	.31	11.4
W	Pre	.56	.00185	.0106	.24	8.0
	Post	.31	(-).00044	.0021	.19	8.5
H	Pre	.23	.0044	.0146	.92	">6"
	Post	.17	.0033	.0014	.71	9.9

TABLE 4

Model II $AI = \underline{a} + \underline{b}V|\cos(\Theta - \Theta_o)| + \underline{c}\,\Delta T$

Data Set		a	b	c	r
R	Pre	.25	.0145	.099	.46
	Post	.14	.0159	.007	.78
S	Pre	.29	.0233	.0128	.70
	Post	.25	.0112	.0058	.32
W	Pre	.43	.0470	.0157	.24
	Post	.34	.0081	.00054	.25

TABLE 4

Model III $AI = \underline{a} + \underline{b}V + \underline{c}T$

Data Set	a	b	c	r
R Pre	.68	.0081	-.0122	.41
Post	.37	.0130	-.0058	.82
S Pre	.84	.0047	-.0133	.59
Post	.40	.0219	-.0063	.68
M Pre	.88	.094	-.0198	.35
Post	.39	.0040	-.0029	.18

TABLE 4

Model IV $AI = \underline{a} + \underline{b}\,V^2 + \underline{c}\Delta T$

Data Set	a	b	c	r
R Pre	.23	.009	.012	.40
Post	.17	.0016	.0056	.85
S Pre	.34	.0003	.013	.59
Post	.22	.0021	.0060	.65
W Pre	.29	.0115	.020	.39
Post	.30	.00022	.0023	.17

TABLE 4

Model V $AI = \underline{a} + \underline{b}\, V^2 |\cos(\Theta - \Theta_o)| + \underline{c}\Delta T$

Data Set	a	b	c	r
R Pre	.24	.0025	.011	.45
Post	.17	.0024	.006	.84
S Pre	.31	.0041	.013	.70
Post	.25	.0020	.006	.38
W Pre	.42	.0095	.017	.34
Post	.34	-.0019	.00046	.25

V Summary and Conclusions

This paper documents and compares the air infiltration levels measured in five Twin Rivers townhouses before and after retrofit using automated tracer gas equipment. Post-retrofit infiltration rates range from 31 to 48% less than pre-retrofit, with an average reduction of 36%. Graphical and regression techniques were used to assess the effects of climatic variables as they influenced infiltration before and after retrofitting. The influence of wind direction on air infiltration showed a definite decrease after retrofits were installed; winds blowing directly on the front or back townhouse walls, post-retrofit, produced little more air infiltration than when the direction was parallel to the townhouse row.

The effects of retrofitting on indoor-outdoor temperature difference (ΔT)-induced infiltration are also clear from the analyses. Multiple regression of AI vs. temperature difference and other climatic variables showed reduced coefficients of ΔT in every case after retrofitting, for every house tested. Regression constants were also almost universally lowered with retrofitting, indicating a reduction in "base-level" air infiltration (i.e., that predicted under zero driving forces of V and ΔT). The effect of retrofitting in reducing wind-driven infiltration, however, is not as dramatic as that for ΔT-driven (stack effect) AI, as was first seen in the stemleaf and polar plots. Regression analysis also showed no evidence of the kind of post-retrofit damping of wind-induced infiltration that was seen for ΔT-induced cases. The latter type of infiltration may be reduced in the retrofit process by closing convective pathways within the townhouses and by controlling infiltration through the basement walls. Thus, although wind-directional effects for a given windspeed may have been quelled by the present set of retrofits, further retrofitting may be necessary to reduce the effects of wind speed, particularly winds above 8.5 mps.

The winter heating energy savings realizable from such AI reduction as previously discussed can be sizeable (on the order of 10-15%).[8,12] In addition, there are indications that even with partial retrofitting, the higher the ΔT the greater will be the reduction in air infiltration with retrofitting. Cellar and attic retrofitting emerge as particularly important in reducing infiltration: in one house, insulating the cellar and sealing up the band joist alone resulted in a predicted 23% decrease in AI. Not to be overlooked in this retrofitting program are the more uniform temperatures and absence of drafts observed after house tightening. This added comfort has additional energy conservation benefits.[3]

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