

## WIND AND TREES: AIR INFILTRATION EFFECTS ON ENERGY IN HOUSING

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### Summary

A series of wind tunnel tests have been conducted to examine the ways in which wind influences air infiltration energy losses in residential housing. A quantitative model for air infiltration has been developed that is based upon a linear relationship between air flow and pressure difference across walls and roof surfaces. With the model, a variety of wind-house orientations are tested, and the sheltering effects provided by solid fences, adjacent houses, and tall evergreen trees are assessed and compared.

### Introduction

For the past three years, Princeton University's Center for Environmental Studies has conducted a research program analyzing energy consumption patterns in residential housing. The ultimate goals of the study, which is funded through the National Science Foundation's Research Applied to National Needs program, are to devise and assess ways in which home energy consumption patterns may be improved. Of major importance has been the continued cooperation of the residents of Twin Rivers, New Jersey, which is the state's first planned community and which has served as Princeton's "laboratory".

The study has made possible a general description of home energy consumption: approximately one-third of the monthly winter fuel bill can be attributed to heat loss via conduction through walls, ceilings and floors; one-third is lost through windows; and one-third through air infiltration losses. The present research efforts are focused on the air infiltration losses.

Air infiltration occurs when external weather conditions interact with the interior conditions in a house to produce a flow of air through the house itself (see ref.1 for further details). Weather conditions which produce the pressure imbalances across the exterior walls of a house are specifically tempera-

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ture differences and wind. For instance, dense cold outside air would enter a house through cracks around windows and doors, thus displacing the less dense warmed interior air outward through the upper exterior walls or roof. This process is referred to as the "stack" or "chimney" effect. Conversely, in warm weather, cold inside air would leak out through the lower levels of the house, while warm outside air filters into the upper levels.

Air infiltration produced by wind over a house causes slight but significant "over pressures" due to stagnation effects on the windward walls, while the leeward walls experience slight but again significant "under pressures". The roof can experience either pressure effect depending upon such pertinent details as slope and angle relative to wind direction (see ref.1). Consequently, the wind affected infiltration is generally an air flow through the house from windward to leeward wall and roof surfaces. Princeton study results indicate that air infiltration is influenced to a far greater extent by wind conditions than by temperature differences (see Harrje et al. [2]).

To estimate or predict the amount of air infiltration for a particular dwelling in a specific orientation with respect to the wind, engineers have for a considerable number of years used a variety of approximate methods. One of the more widely used methods is the "crack method". With it an attempt is made to determine the area of cracks around doors and windows in the wall surfaces of the house through which air can flow. Given this area, together with temperature and wind conditions, and tables such as those presented in the ASHRAE Guide and Data Book, Ch. 19, a value for the air flow can be found. This value is expressed in air changes per hour and refers to the number of interior volumes of the dwelling replaced each hour by the infiltrating outside air. A significant limitation of the crack method is its inability to account for an open door or window — a situation not uncommon in most households.

Thus one of the major instrumentation efforts of the present study has been to develop a device which directly measures the air infiltration rate of a building regardless of window and door positions. The Princeton research team working together with the National Bureau of Standards has produced such a device — an automated unit which uses a tracer gas (sulfur hexafluoride,  $SF_6$ ) and gas chromatography to determine accurate air infiltration rates (see ref. 2).

In situations where doors are left open — even for short periods of time — or where windows are left slightly open, the air infiltration losses can range widely from their normal value of 33% of the total fuel consumption. For example, on warmer, windless winter days, air infiltration losses can comprise as low as 5—10% of the total consumption. At the other extreme, the losses have been observed to be as high as 75% of the total consumption.

These ranges and the apparent sensitivity of air infiltration rates to wind prompted a series of wind tunnel tests to examine wind/house interactions. As a result of these tests, an air infiltration model has been produced which characterizes the results of wind-produced pressure distributions on the exterior surfaces of a house. The various wind/house interactions can thus be

assessed and compared.

One of the most significant results of the present research effort concerns the relative effectiveness of fences, houses and trees as wind barriers. Although studies have certainly been made of the use of trees as crop shelters and efforts have been made to reduce the effects of wind velocity on ground level vegetation, the authors are unaware of any previous efforts to quantify the sheltering benefits of fences and trees on houses. Tall evergreen trees emerged from these studies as highly effective wind barriers — a welcomed finding given all the other advantages trees provide as put forth by Heisler in ref. 3: They also reflect noise, provide shade, enhance air quality and aesthetically beautify their surroundings. These laboratory studies are to be complemented by full-scale field studies which involve the “planting” or, more precisely, the wiring into place of 25' evergreen trees in front of Twin Rivers townhouses. The results of the field studies are now being compiled.

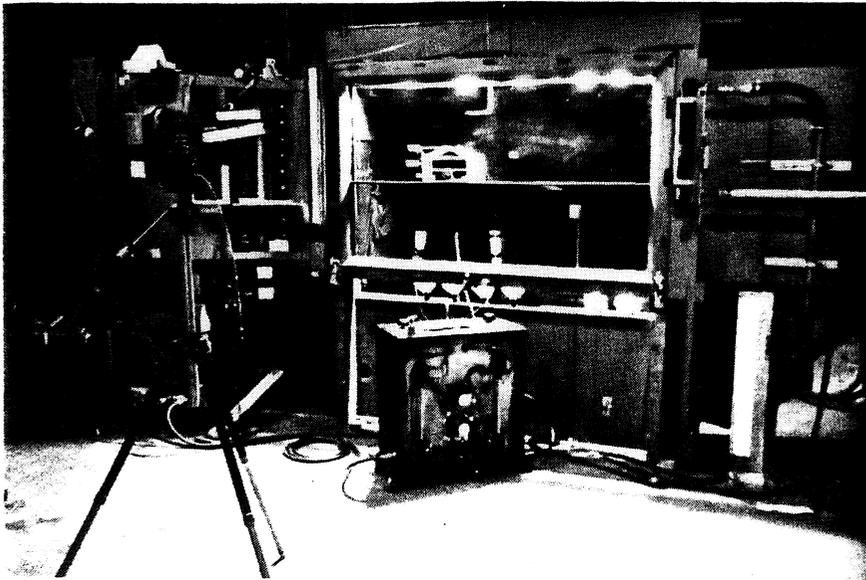


Fig.1. Smoke tunnel facility and photographic arrangement.

#### Experimental results visualization studies

Pictures of wind flows over a two-story townhouse are presented in the photographs shown in Figures 1—7. These photographs illustrate via smoke patterns the salient features of the flow when the wind blows perpendicularly to the front or back wall of the house. These patterns are produced in a wind tunnel test section which is 3 ft. (0.91 m) high, 5 ft. (1.52 m) long, and 2 in. (0.79 cm) in width. The flow patterns produced are therefore two di-

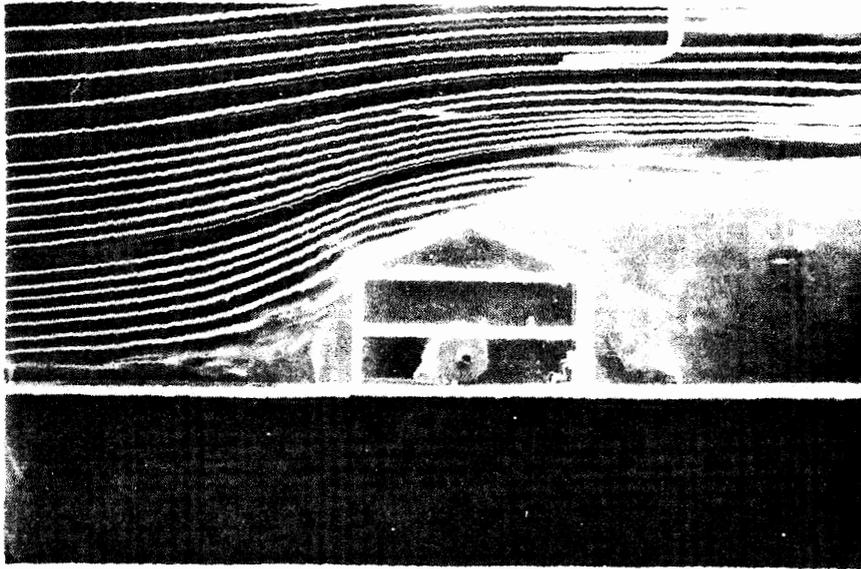


Fig. 2. Flow pattern over house shape as visualized with smoke techniques.

dimensional because of the narrow width of the test section. In these tests the flow is visualized by seeping smoke streaklines into the steady, laminar stream above the horizontal ground surface. The patterns thus produced around the 1/48th scale, two-story townhouse are considered to represent,



Fig. 3. Stagnation region on windward wall as visualized by injecting smoke through ground surface in front of house.



Fig.4. Wake flow downwind of house as visualized by injecting smoke through ground surface behind home.

qualitatively, the features of the actual turbulent wind over the full scale house. Although the Reynolds number based on house height for the flows pictured is 33,000 and that for the full scale house in a 15 mph (24.14 km/h) wind is 3,600,000, the mismatch is not considered of major significance in

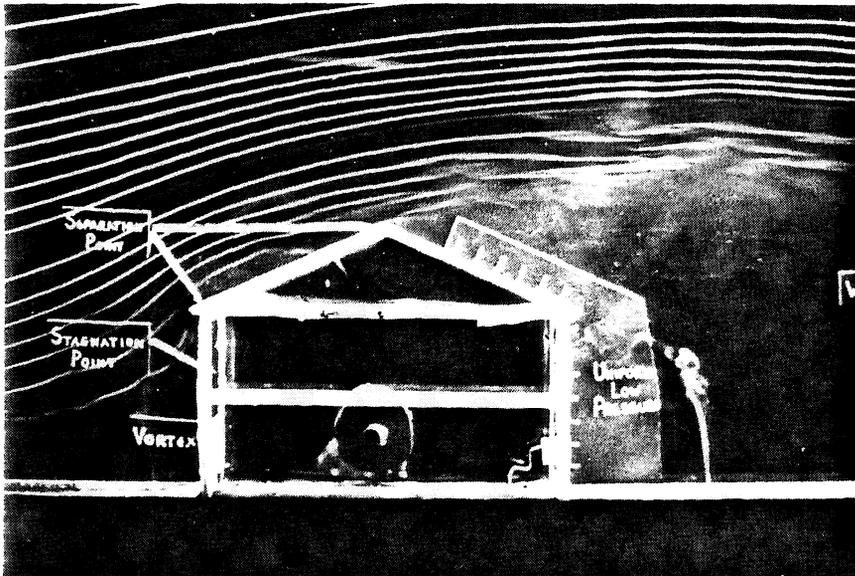


Fig.5. Salient features of the flow over the house shape.

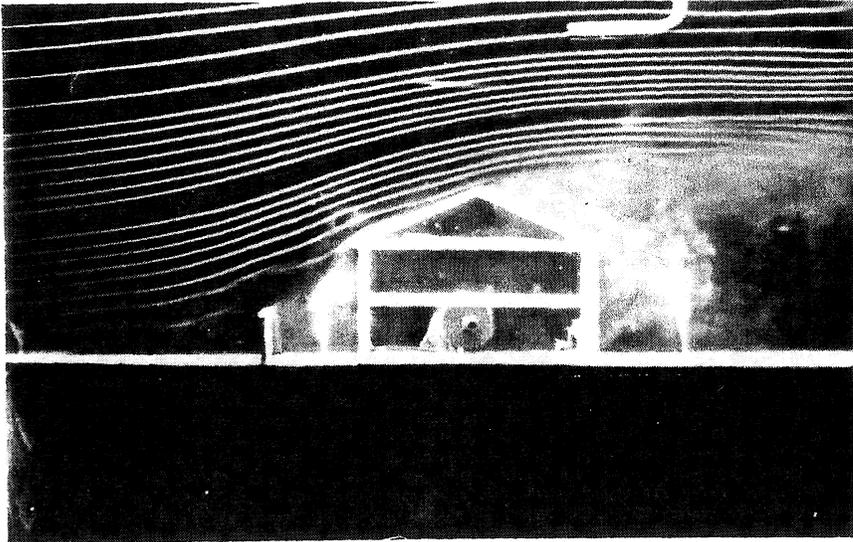


Fig.6. Flow pattern over house with a solid fence providing sheltering effects.

that the sharp corners and edges which characterize the house shape also specify the location of the important separation points in the flow field. With these points so fixed on both the model and full scale houses, the major features of the flow patterns are determined (see refs. 4 and 5).

Basically, the wind flow over the house is characterized by the oncoming stream stagnating against the windward wall of the house then flowing up and over the windward roof surface to the roof peak from which it separates.

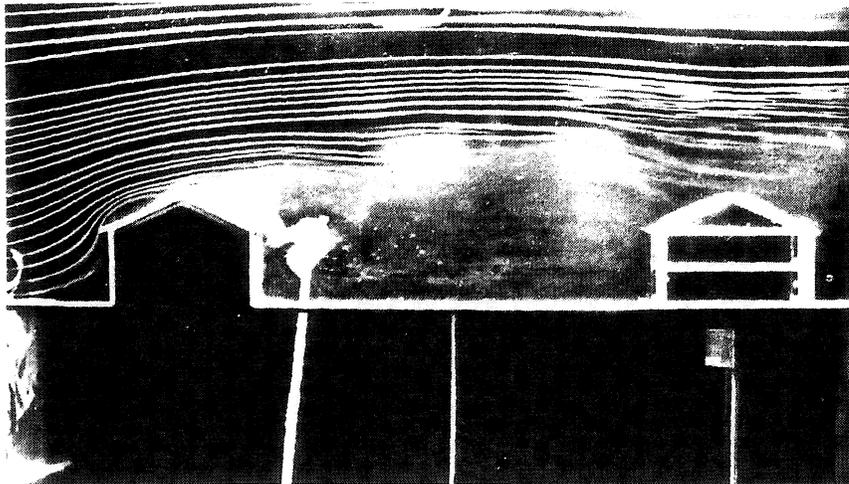


Fig.7. Flow pattern when an upwind house provides sheltering effects.

Downwind of the roof peak over the leeward roof surface and wall of the house, the pressure is that of the wake of the house which is lower than ambient. Consequently, exterior air enters the house through the windward wall and through the windward roof surface if the outer-inner pressure difference across it is positive. Over the leeward roof and wall surfaces, the outer-inner pressure difference should be negative, thus producing an outward flow of interior air. Previous investigations such as those of Dreher and Cermak [6] and Chien et al. [7] have shown that for roof slopes less than  $30^\circ$ , the wind-produced pressures are negative on the windward surface while for slopes exceeding  $30^\circ$ , the pressures are positive. As indicated by the wake visible in Figs. 2 and 4 over the leeward roof and wall surfaces of the house, the wake pressure prevails thus producing a slight vacuum pressure which tends to extract interior air from the inside of the dwelling. With this wind-produced distribution of pressure over the house, the flow of air is from the exterior into the interior where the outer-inner pressure difference is positive and where a conduit of some sort such as leaky seals around windows or cracks around doors provides a path for flow between these two regions. Where the outer-inner pressure difference is negative air flow occurs from the interior to the exterior through any available conduit. Thus, in either the heating or cooling season the inward flow of outside air and the outward flow of interior air produce the air infiltration loss for the particular dwelling.

To reduce this air infiltration energy loss, one can reduce the conduits available for air flow. Examples would be to caulk faulty seams in walls and the joints around windows and to weather strip the frames of doors and windows which are to be opened and closed. A second way to reduce these losses is to shelter the house from detrimental wind effects. For example, sheltering can be provided by fences, other houses, and trees.

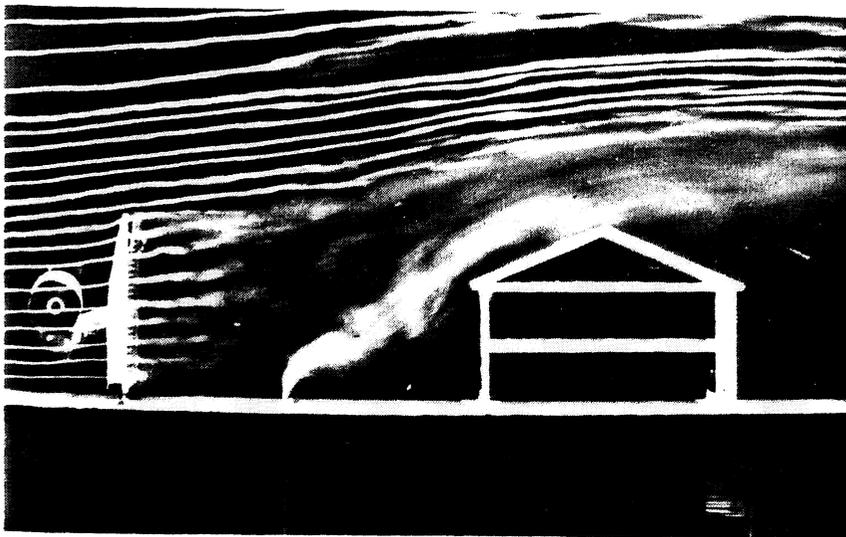


Fig.8. Flow pattern when a simulated tree provides sheltering effects.

The wind flow pattern over a fence-sheltered house is qualitatively shown in Fig.6, where the fence is about one-fifth the height of the house. When sheltering is provided by an identical house upwind of the model, the flow pattern is typically shown by that in Fig.7. It seems apparent from Fig.7 that house sheltering should be far more effective than fence sheltering. By placing the windward wall in the wake of the sheltering obstacle, a more balanced pressure distribution is produced over the house — thereby reducing the air flow through the home. Of course, the upwind house would also require sheltering of some sort and the question arises as to what kind of sheltering should be constructed on the windward sides of such communities. Trees — both deciduous and conifers — may provide one solution. The flow pattern produced by a simulated conifer such as an evergreen tree sheltering a downwind house is pictured in Fig.8. The wake of the tree is noted to be quite similar to the sheltering provided by the upwind house configuration shown in Fig.7.

#### Quantitative tests

To assess quantitatively the implications of the various wind/house interactions pictured in Fig.2 through 8, an additional series of wind tunnel tests were conducted. In these, a test house — a 1/48th scaled version of the two-story Twin Rivers townhouse, the floor plans of which are shown in ref. 1 — was built into a row of four houses. The test house is shown in Fig. 9 and 10

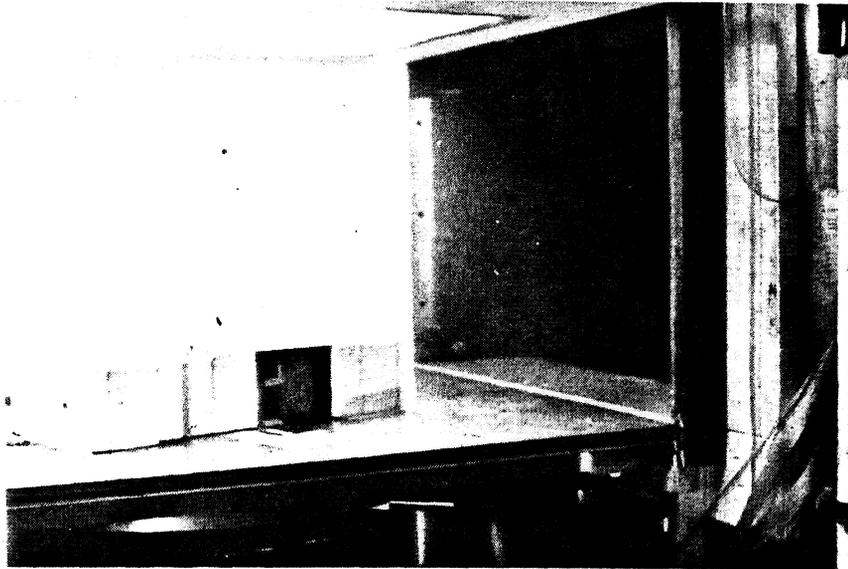


Fig.9. Four house row mounted on turntable in the tunnel test section, front view. The instrumented house is constructed of dark wood; the remaining, "dummy" houses are made from styrafoam. Wind flow is from right to left.

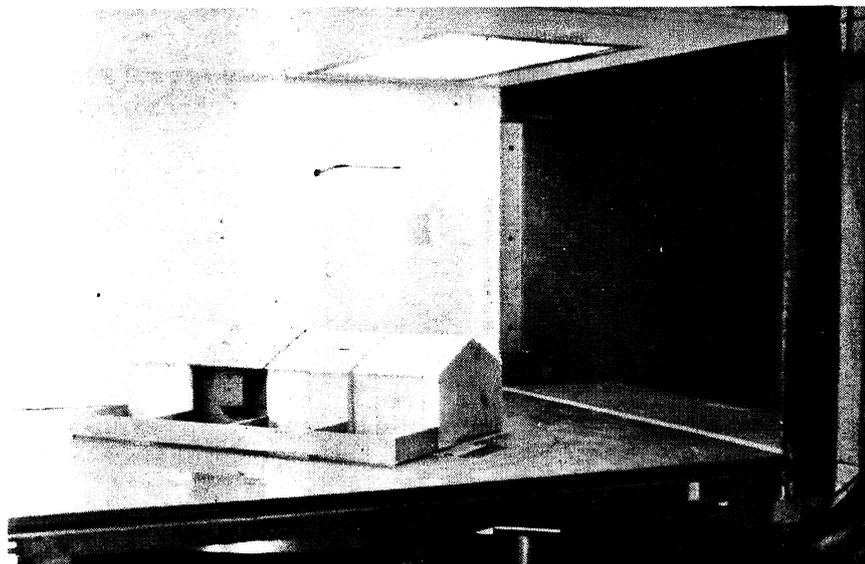


Fig.10. Four house row, rear view.

as an interior unit in which case its walls adjacent to the two neighboring units are interior walls which, theoretically, are not exposed to external weather conditions such as wind and temperature. The test house could also be moved to the end of the row of houses in which case one side wall does directly experience external weather conditions.

The test house was fitted with 71 manometer read pressure taps with which the time averaged pressure distribution over the house could be monitored. As such, the time varying turbulent pressure fluctuations were not observed. Neither was the pressure inside the test house.

With this test house, both interior and end unit house positions could be tested to determine the effects of wind-produced air infiltration for different wind speeds and directions. A model was developed through which the wind-imposed pressure distributions on the dwelling were used to assess the particular air infiltration effects. The pressure distributions obtained via these tests and used in this model can be found in ref.1.

It should be stated explicitly that atmospheric boundary simulation was not attempted in the present effort. The authors' results are intended to be comparative analyses between the various house- wind orientations and the different sheltering configurations. To attempt to predict from the present results the pressure distributions on a full-scale house in a turbulent atmospheric wind would be very difficult and at best would result only in a crude estimate. For this reason, the full-scale tree study was undertaken. The results of that study should produce a proper interrelationship between wind and air infiltration for model and full-scale conditions.

### Air infiltration model

If it is assumed that the air flow through a particular wall or roof surface occurs in a way that is proportional to the pressure difference across the surface raised to some power,  $m$ , we have, per unit area

$$q = k (\Delta p)^m$$

where  $q$  is in units of volume per time,  $k$  is a constant depending on wall porosity as well as the pertinent fluid properties,  $\Delta p$  is the inner—outer pressure difference. The ASHRAE guide notes that the exponent  $m$  is found to be between 0.5, which is for orifice flow, and 1.0, which is for Poiseuille flow (see Chapter 19). In what follows, we choose  $m = 1.0$  for the sake of convenience.

When it is assumed further that the infiltrating rate equals the exfiltrating rate we can conclude that the interior pressure coefficient for the house is

$$C_{pi} = \frac{\sum_{j=1}^N C_{pj} A_j}{\sum_{j=1}^N A_j}$$

where  $C_p$  is the conventional pressure coefficient referenced to upwind static pressure and velocity, the subscripts  $i$  and  $j$  refer, respectively, to the house interior and the  $N$  house surfaces such as walls and roofs exposed to external weather, and  $A_j$  is the surface area normalized to the front wall area of the house. The interior pressure is assumed uniform over the interior house volume, see ref. 1 for details.

Having the interior pressure coefficient, one is then able to define the infiltrating air flow rate in terms of the dimensionless parameter

$$AI = \sum_{j=1}^M < \Delta C_{pj} >^+ A_j$$

where  $< \Delta C_{pj} >^+$  is the outer—inner pressure coefficient difference which is positive and  $M$  is the number of surfaces for which this difference is positive.

### Analysis of quantitative results

With the air infiltration model described in the previous section, the time-averaged pressure data was used to determine the air infiltration rate,  $AI$ . For the end unit houses the results are presented in Table 1. Shown in the column at the left is the particular house-wind configuration tested. To the right of each configuration, for each of the three wind speeds tested are the calculated interior pressure coefficient and the averaged outer—inner pressure coefficient differences across each of the five house surfaces exposed to the wind. Fol-

TABLE 1

Tabulated results for end units

House—wind orientation		$C_{pi}$ interior	$\Delta C_p$ front	$\Delta C_p$ front roof	$\Delta C_p$ back roof	$\Delta C_p$ back	$\Delta C_p$ side	$AI$	$AI$ average
1 	1	-0.797	1.482	-0.091	-0.290	-0.303	-0.488	1.482	1.486
	2	-0.758	1.476	-0.138	-0.281	-0.328	-0.445	1.476	
	3	-0.790	1.499	-0.133	-0.279	-0.314	-0.483	1.499	
2 	1	-0.458	1.128	-0.385	-1.172	-0.796	0.746	2.351	2.358
	2	-0.432	1.147	-0.373	-1.161	-0.819	0.736	2.354	
	3	-0.434	1.150	-0.396	-1.156	-0.815	0.743	2.369	
3 	1	-0.403	-0.562	-0.528	-0.579	-0.565	1.360	2.230	2.256
	2	-0.386	-0.587	-0.532	-0.589	-0.563	1.384	2.270	
	3	-0.373	-0.591	-0.535	-0.585	-0.556	1.383	2.267	
4 	1	-0.595	-0.655	-1.065	-0.220	1.023	0.559	1.940	1.948
	2	-0.590	-0.676	-1.050	-0.219	1.031	0.558	1.945	
	3	-0.594	-0.687	-1.061	-0.219	1.037	0.562	1.959	
5 	1								1.098
	2	-0.771	-0.279	-0.309	0.125	0.970	-0.310	1.095	
	3	-0.669	-0.258	-0.336	0.069	1.032	-0.310	1.101	
6 	1	-0.794	0.806	-0.281	-0.328	-0.046	-0.094	0.806	0.785
	2	-0.751	0.767	-0.288	-0.300	-0.057	-0.075	0.767	
	3	-0.796	0.783	-0.288	-0.296	-0.052	-0.091	0.783	
7 	1	-0.278	0.007	0.031	0.021	-0.038	-0.048	0.059	0.058
	2	-0.266	-0.008	0.034	0.020	-0.021	-0.016	0.054	
	3	-0.269	-0.013	0.038	0.022	-0.027	-0.012	0.060	

lowing these is the parameter  $AI$  for the particular situation. The last column contains the  $AI$  parameter averaged over the three speeds which are: (1) 92 fps (28 m/sec), (2) 120 fps (37 m/sec), and (3) 140 fps (43 m/sec). In determining these  $AI$  values, the front and rear wall surfaces are taken to be numerically one-half the total roof area; the side wall area of the house is taken to be 64% larger than the front wall.

In the present tests, the interior pressure in the model house was not measured. To make this measurement correctly, it is necessary to produce a scaled air infiltration rate in the model house. This can be done only by constructing the model house so as to precisely scale window and door cracks and wall and roof porosity — a construction judged too difficult for the present series of tests. As a result the present results for interior house pressure cannot be compared with any of our recorded data. However, the calculated values for interior pressure can ultimately be compared to values measured within the full-scale field studies on the Twin Rivers townhouses when these become available.

Table 2 presents the results for the interior house units. The results in both Tables 1 and 2 indicate that the  $AI$  parameters are independent of wind speeds

TABLE 2

Tabulated results for interior units and tree sheltering

House—wind orientation	$C_{pi}$ interior	$\Delta C_p$ front	$\Delta C_p$ front roof	$\Delta C_p$ back roof	$\Delta C_p$ back	$AI$	$AI$ average
1 	1	-0.560	1.252	-0.459	-0.363	-0.431	1.252
	2	-0.552	1.242	-0.452	-0.373	-0.419	1.242
	3	-0.580	1.225	-0.429	-0.376	-0.419	1.225
2 	1	-0.923	1.270	-0.443	-0.716	-0.111	1.270
	2	-0.889	1.250	-0.435	-0.697	-0.119	1.250
	3	-0.899	1.258	-0.416	-0.711	-0.131	1.258
3 	1	-0.686	-0.036	-0.112	-0.018	0.166	0.166
	2	-0.633	-0.014	-0.079	-0.036	0.128	0.128
	3	-0.670	-0.008	-0.094	-0.041	0.128	0.128
4 	1	-0.684	-0.339	-0.424	-0.085	0.846	0.846
	2	-0.630	-0.349	-0.407	-0.089	0.846	0.846
	3	-0.630	-0.352	-0.425	-0.092	0.867	0.867
5 	1	-0.569	0.743	-0.124	-0.325	-0.293	0.743
	2	-0.519	0.724	-0.139	-0.311	-0.275	0.724
	3	-0.524	0.747	-0.148	-0.324	-0.277	0.747
6 	1	-0.621	0.823	-0.164	-0.419	-0.241	0.823
	2	-0.631	0.861	-0.186	-0.479	-0.196	0.861
	3	-0.632	0.866	-0.188	-0.484	-0.193	0.866
7 	1	-0.583	-0.179	-0.299	0.062	0.416	0.478
	2	-0.567	-0.201	-0.298	0.062	0.436	0.498
	3	-0.581	-0.211	-0.308	0.063	0.454	0.517

used in these tests — a consequence of the fact that the salient features of the wind flow are determined by house shape instead of Reynolds number.

From the results presented in both tables, it is found that air infiltration is greatest when wind blows toward the house at a  $45^\circ$  angle. This occurs mainly through the changes in the pressure produced by the wind angle on the roof and leeward wall surfaces. One of the reasons for the relatively high air infiltration values found in these results must be the various protuberances the architect has designed into the walls of the house. There are closet protrusions on the back walls and bay windows on the front walls of the first and second floors. The cavities produced tend to trap high pressure eddies on the windward walls, while the corners and intersections certainly have to be sources of air leakage as a result of the difficulty in maintaining air tight joints in these areas.

Mention should be made of the influential role of the roof surfaces in these

results. When outer—inner pressure differences are negative over the roof surfaces, a wind-produced “chimney” effect is set up on the house that resembles that due to negative outer—inner temperature differences. This effect is undoubtedly of extreme importance in very tall buildings, but is manifested even here for two-story townhouses with slight roof slope.

With the assumptions made in our air infiltration model, the attic is treated as a part of the interior of the house. When this is not strictly valid, an attic zone should be treated individually with the pertinent air exchanges written between attic and house interior and the external weather.

The sheltering effects resulting from an upwind fence are evident in Tables 1 and 2. In these tests, the fences used are solid wood and are scaled versions of the actual ones enclosing the patio areas behind the Twin Rivers townhouses. These full scale fences which are 1/5 the height of the houses, are 5.5 ft. (1.7 m) high with a 6 in. (15 cm) opening under the fence; they are placed approximately one house height behind the rear wall of the house. A comparison of Runs 1 and 5 or 2 and 4 in Table 1 or Runs 1 and 4 in Table 2 indicates that despite the relatively short height of these fences, the *AI* parameter is reduced in each case by the fence. In each pair of configurations, the effect of the fence is to balance the pressure distribution on the shell of the house, thereby reducing air infiltration. The most significant reduction in pressure occurs over the windward wall surfaces, but a beneficial change in the air flow occurs through the roof surfaces as well.

The effects produced by tree sheltering are presented in Table 2, where the dashes shown in Runs 5, 6 and 7 indicate the placement of simulated evergreen trees. These simulated trees are constructed by wiring three triangular patches of screening to a steel shaft. Comparing Runs 1 and 5 indicates the reduction in air infiltration produced by the tree windbreak is 40%. When the trees are placed in a staggered two-row configuration as shown in Run 6, the reduction is 31% compared with the unsheltered configuration shown in Run 1. Even in the case where an interior house is sheltered by a solid fence, the addition of a single row of trees reduces *AI* by 42% as noted through Runs 4 and 7. The combined sheltering effects produced by the fence and the tree row is predicted to be 60% (see Runs 1 and 7). Given the fact that air infiltration comprises about one-third of a winter heating bill, the fence and tree sheltering could amount to a 20% reduction in total fuel consumption depending upon the prevailing wind directions and the outside temperature.

#### Comparison of air infiltration rates

The quantitative comparison of the air infiltration results computed via the present model are shown in Table 3 where any house/wind configuration may be compared with any other.

*House location:* Table 3 permits comparison of the wind-produced air infiltration which occurs when wind blows perpendicularly to the front of both interior and end units. Looking along the top row of the matrix shown in

TABLE 3

Fractional comparison of air infiltration values for the house/wind orientations tested.  
 (The air infiltration value for the orientation of the "j" th column exceeds that of the "i" th  
 row by the fraction shown as the "ij" matrix element, i.e. orientation i exceeds j by 31%.)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	0.59	0.52	0.31	-0.26	-0.47	-0.96	-0.17	-0.15	-0.91	-0.43	-0.50	-0.43	-0.66
2	-0.37	0	-0.04	-0.17	-0.53	-0.67	-0.98	-0.47	-0.47	-0.94	-0.64	-0.69	-0.64	-0.79
3	-0.34	0.05	0	-0.14	-0.51	-0.65	-0.97	-0.45	-0.44	-0.94	-0.62	-0.67	-0.62	-0.78
4	-0.24	0.21	0.16	0	-0.44	-0.60	-0.97	-0.36	-0.35	-0.93	-0.56	-0.62	-0.56	-0.74
5	0.35	1.15	1.05	0.77	0	-0.29	-0.95	0.13	0.15	-0.87	-0.22	-0.33	-0.23	-0.55
6	0.89	2.00	1.87	1.48	0.40	0	-0.93	0.58	0.60	-0.82	0.09	-0.06	0.08	-0.37
7	24.82	39.86	37.90	32.59	17.93	12.53	0	20.38	20.71	1.43	13.71	11.72	13.66	7.59
8	0.20	0.90	0.82	0.57	-0.11	-0.37	-0.95	0	0.02	-0.89	-0.31	-0.40	-0.31	-0.60
9	0.18	0.87	0.79	0.55	-0.13	-0.38	-0.95	-0.02	0	-0.89	-0.32	-0.41	-0.32	-0.60
10	9.54	15.72	15.0	12.82	6.79	4.57	-0.59	7.79	7.93	0	5.05	4.23	5.03	2.53
11	0.74	1.76	1.64	1.28	0.29	-0.08	-0.93	0.45	0.48	-0.83	0	-0.13	0	-0.42
12	1.01	2.20	2.06	1.64	0.49	0.06	-0.92	0.68	0.71	-0.81	0.16	0	0.15	-0.33
13	0.75	1.77	1.65	1.29	0.29	-0.08	-0.93	0.46	0.48	-0.83	0	-0.13	0	-0.41
14	1.98	3.73	3.53	2.91	1.20	0.58	-0.88	1.49	1.53	-0.72	0.71	0.48	0.71	0

Table 3 for the end unit (in this case the first element) and then looking down this column for the row element that corresponds to the interior unit (the eighth), the result reads 0.20 which is to say that the end unit experiences 20% more infiltration than the interior unit. To assess this difference one may return to Tables 1 and 2 to examine in detail the corresponding pressure coefficient differences on the respective surfaces.

When the wind blows parallel to the row of test houses, the air infiltration is radically different for the windward and leeward ends of the row. The windward house sustains an air infiltration rate which is about 38 times that of the leeward unit.

The house/wind configuration that produces the maximum amount of air infiltration is that of the end unit with the wind striking both front and side walls at an angle of  $135^\circ$ . The least air infiltration is produced when the wind blows parallel to the house row and the house in consideration is the unit on the leeward end of the row.

*Fence effects:* The sheltering benefits of a small fence can be estimated by comparing the air infiltration results for cases where (1) wind impinges the front wall of the house which has no fence sheltering with (2) a similar wind flow directed at the rear wall of the house which has fence sheltering. In this way, Table 3 indicates that configuration 1 has 35% more air infiltration than configuration 5, thus showing that a fence effectively shelters an end unit when wind flows parallel to this end wall. Equivalently, it may be stated that the fence produces a 26% reduction in air infiltration as shown by the first row element in column 5. The eighth element in column 11 indicates a 31% reduction produced by the fence for the interior unit. When the wind flow makes an angle of  $45^\circ$  with the end wall of the end house, the fence produces a 17% reduction as shown by the second element in column 4.

*Tree effects:* The sheltering effects of trees can be estimated by the results presented in columns 12, 13, and 14 of Table 3. The eighth element of column 12 indicates a 40% reduction for the interior unit when the wind flows perpendicularly to the front wall. The staggered double rows of trees account for a reduction of 31% for the same wind flow. The addition of a single row of trees to augment fence sheltering is found via the eleventh element of column 14 to reduce air infiltration 42%. The most significant air infiltration reduction is obtained when the combination of a fence and trees are added to a previously unsheltered interior house. The eighth element of column 14 indicates this reduction is 60%.

### Discussion and conclusions

The present wind tunnel tests — a visualization test using smoke techniques and a quantitative test using pressure measurements over the shell of the house — indicate that the amount of air infiltration caused by wind is determined primarily by three factors: (1) the direction of the wind relative to the house, (2) the particular geometry and structural details designed into the

exterior shell of the house, and (3) the sheltering effects that may protect the house from the direct impingement of the wind.

Photographs, both movie and stills, taken during the visualization study reveal the salient features of the wind flow pattern over the scaled two-story townhouse. The important characteristics shown in these photos are the stagnation flow on the windward wall of the house, the flow over the lip of the roof to the roof peak, and the wake flow region adjacent to the leeward roof and wall surfaces.

The quantitative results of the study of the wind-produced pressure distribution on the shell of the house have been analyzed via a linear infiltration model developed in the present effort. These results permit the comparison of the effects of wind direction, house position within its row, and the assessment of such sheltering effects as fences and tree windbreaks.

The present results and the measurements made in the quantitative effort do not include the effects of turbulence in the windstream approaching the test house. Since previous investigators, including Eaton and Mayne [8], Ishizaki and Huh [9], and Baines [10], have found that turbulent fluctuations can produce significant gust effects on structures, it is suggested that future wind tunnel studies of air infiltration effects incorporate a simulated atmospheric boundary layer such as that used by Peterka and Cermak [11] and Marshall [4].

It is concluded from the present results that architectural designs which incorporate wall elements that protrude or are recessed from the wall plane should be constructed with great care. It is found that cavities and corners tend to trap high pressure eddies on windward walls and perhaps lead to excessive exterior air leakage into the house due to the difficulty of sealing such wall geometries during construction. On leeward surfaces, leaks in corner seams and other pores in the walls are outlets for heated or cooled interior air to leak into the low pressure regions adjacent to these exterior surfaces.

The quantitative comparison of air infiltration results demonstrates that significant differences occur for the variety of house/wind configurations tested. Depending upon the particular house/wind configurations, end units experienced about 20 to 30% more infiltration than interior units due to the large expanse of side wall exposed to the wind.

Besides home location in its row, the influence of wind direction relative to the house is a significant factor affecting air infiltration. It is found, for example, that when wind blows at a  $45^\circ$  angle with a windward wall, the air-infiltration produced is greater than that for the case where the wind blows perpendicularly to the wall. This result is due to the pressure changes on leeward roof and wall surfaces produced by the change in wind direction. It has been observed in the course of Princeton's study that the common walls shared by adjacent interior units are not the interior walls they are designed to be. Apparently, exterior air can leak through several paths into the cavities in these uninsulated walls. The most notable path is through the corners which are formed by the masonry portion of the common wall and the frame front

or back wall of the house. Apparently, these joints which are caulked by the builder part either through settling or expansion effects and permit air leakage to occur behind the caulked seam through siding and the building paper. Thus these common walls tend to act as end walls and thereby tend to reduce energy consumption differences between end and interior dwelling units.

Sheltering effects, such as small, solid fences and tall evergreen trees were found to significantly reduce wind-produced air infiltration losses. From Table 3, a five-foot high fence sheltering an interior unit reduced air infiltration 31%; for the end unit the fence produced a reduction of 26%. The authors tend to agree with Woodruff [12], who has suggested that landscape elements such as trees and hedges can be more effective than solid barriers such as fences because of the manner in which branches, leaves, and evergreen needles interact with the wind. He points out that the wind which filters through branches tends to break down the organized eddy patterns which prevail in the wakes of solid barriers. The sifting effects of living landscape elements thus reduce wake pressures, thereby resulting in a more balanced pressure distribution on downwind houses.

The most effective windbreak tested in the present quantitative study is that of a straight row of tall evergreen trees. This type of windbreak produced a reduction in air infiltration of 40% compared to the unsheltered interior house. The combination of trees and fences results in a reduction of 60%, compared to the case without trees. To duplicate these results, trees approximately the height of the house should be planted in a straight row across the wind path one and one-half to two and one-half house heights upwind of the house. By placing the evergreen trees about two house heights from the house, one can limit undesirable shading of sunlight on the house during the heating season. To achieve shading effects during the summer cooling season, tall deciduous trees should be placed adjacent to the house (see ref. 13). In view of the air infiltration reductions produced by wind-breaks it is concluded that such landscape elements should be included in future planning. This especially holds for communities built on open terrain where, in the past, trees generally have been cleared to facilitate excavation and construction.

In light of the quantitative results produced in the present study, it seems appropriate to make further mention of some of the implications made via the assumptions used in the present air infiltration model developed. The constant of proportionality,  $k$ , between air flow rate,  $q$ , and the pressure difference,  $\Delta p^m$ , was chosen to be unity solely because no data was available with which to estimate this quantity. In view of the importance of  $k$  in determining the air infiltration and since it is very much a result of design and construction quality, one suspects that efforts ought to be made to make field measurements of typical wall and roof values. Limits for  $k$  values can be envisioned as ultimately constituting criteria for construction quality not only in residential housing but in all types of construction.

The major conclusion of the present study is that according to our air infiltration model for analyzing wind effects, evergreen trees are significant

windbreaks. Their porosity and conical shape and the fact that they are year-round fixtures makes them an ideal barrier when placed in straight rows across the path of the wind. It now remains to be seen whether the results of these laboratory studies will be reproduced in corresponding full-scale field studies. At present, such tests are being conducted through the support and cooperation of the Pinchot Consortium and the U.S. Forest Service. The results will be the subject of a subsequent report and publication.

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