Title
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Keywords

Air Infiltration, Air Leakage, Insulation, Pressurization, Retrofits, Residential Buildings.

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Introduction

In early 1979, Bonneville Power Administration began conducting an experiment on residential energy conservation, using 18 occupied houses the administration owns at the Midway substation, near Hanford, Washington. The Midway community provides an excellent site for an intercomparative study of different energy-efficient retrofit measures. The climate in central Washington requires both heating and cooling. The homes are situated on either side of two perpendicular streets, and have a good mix of orientation. All are of similar style and construction---wood-framed, one story, single-family detached--- three with full basements, nine with partial basements, and six with crawl-spaces only. The houses were built during three different periods---seven in 1943, eight in 1951, and three from 1965-1968---and have similar floor areas, ranging from 1110 to 1329 ft^2 (excluding basements).

All of the homes are equipped with electric baseboard heaters and window-mounted air conditioners. The houses built before 1965 had 2 inches of mineral wool insulation in the ceilings and exterior walls; those built after 1965 had 6 inches of fiberglass insulation in the ceiling and 1.5 inches of fiberglass insulation in the walls. Most of the exterior doorways have old, leaky, brass weatherstripping. The pre-1965 houses have double-hung, wooden windows without weatherstripping; the newer homes have horizontal aluminum sliders, again without weatherstripping.

For the study, the 18 houses have been divided into three groups (or cells). The five houses in the control group (cell 1) received no retrofits. The six houses comprising cell 2 received the following retrofits: increased attic insulation (to R-30) with additional blown-in fiberglass insulation, R-19 batts of fiberglass insulation secured to the interior perimeter foundation wall of the crawl-space, and increased attic ventilation from additional soffit and ridge vents. The seven houses comprising cell 3 received storm doors and windows in addition to the retrofits of cell 2. One house in cell 3 was also retrofitted with a solar space heating system, with a forced air distribution system (with the ductwork in the basement), and electric backup.

Submeters for water heaters, space heating equipment, and other electric appliances (including window air conditioners) were also installed with the retrofits, and consumption is currently being monitored every 15 minutes. Weather measurements at the site include wind speed and direction, outdoor dry bulb temperature, and solar radiation.

In addition to being arranged in a matrix of three groups with different weatherization retrofit stategies, the houses are also set up in a separate matrix of four groups with different types of water heating systems: solar, electric heat pump, point-of-use electric heaters, and the existing electric resistance heaters. The effects of the weatherization and water heating retrofits are being monitored independently. The water heating retrofits are not dealt with in this paper unless they seem to affect air leakage.

Pressurization Measurement

In September 1979, a two-person team from the Energy Performance of Buildings group at Lawrence Berkeley Laboratory measured air leakage in all 18 houses at Midway before the retrofits were installed, using the fan pressurization technique (described by Grimsrud et al., 1978). The houses were measured again in May 1980, after the retrofits were completed, under conditions as similar as possible to those of the tests in September, to determine if the retrofits significantly affected infiltration rates. In conjunction with the pressurization tests, specific air leakage sites (e.g., at windows, electrical outlets, and plumbing penetrations) were identified using "smoke sticks." (When the house is pressurized with a fan, the vapor from the smoke sticks is blown out through any cracks through which air flows.)

The results of these measurements are presented here using a new parameter for characterizing the leakage of a structure---the effective leakage area. The role of this parameter in predicting energy loss due to infiltration is analogous to the role of thermal resistance in determining conduction losses; the infiltration rate of a house is proportional to the effective leakage area. It is derived by fitting the measured data points of flow versus pressure (from both pressurization and depressurization) to the equation $Q = K(P)^n$, where Q is air flow, P is the applied pressure, and K and n are coefficients obtained by regression. The flow is then extrapolated to the pressure regime driving natural infiltration (4.0 Pa is used herein), and the effective leakage area, A, is determined from the equation $A=Q/\sqrt{2P/\rho}$, where ρ is the density of air. (For a complete description and derivation of this model, see Sherman and Grimsrud, 1980.)

The effective leakage areas of each of the 18 houses before and after retrofitting are presented in Figures 1-4 and in Table 1. We estimate a 10 percent uncertainty associated with the leakage area obtained by pressurization, due primarily to the use of an inclined manometer for measuring applied pressures and to the uncertainty in the calibration of the blower door. The monthly average infiltration rates predicted by the model are presented in Tables 2 through 4, with an associated uncertainty of 20 percent due to the leakage area uncertainty and the assumptions included in the model.

All the exhaust vents were sealed with plastic during the pressurization tests. (Each house at Midway had two of these---one in the kitchen and one in the bathroom.) The vents were sealed because they contain one-way, anti-draft dampers, which would open under the high pressures from the test (but not under ordinary pressures) and thereby create an artificially high effective leakage area. However, because the dampers are located in the ceiling and usually fit poorly, they can be significant sites of leakage. Therefore, we estimated the total leakage area of these dampers (25 cm^2 per house) and added this figure to the leakage areas calculated from the measurements.

Given the effective leakage area and some information about a house's geometry and the local weather, the infiltration rate can be calculated. We used monthly weather averages for Yakima, Washington,to obtain infiltration rates for conditions both before and after retrofitting (Table 1).

Cell 1

As expected, there was little difference between the two sets of measurements for the control group of five houses (cell 1). None of these houses showed a change greater than the 10 percent uncertainty associated with the measurement. The average effective leakage area increased less than 1 percent, or 5 cm^2 (standard deviation = 31 cm^2). House #7 has the largest leakage area of all 18 homes, and is the only house with a forced-air system with ducts in the attic. This was installed when the house was built in 1943, but has not been used for at least 25 years. The pressurization tests on this house were performed with the registers closed but not sealed, and leakage through the ducts could be the source of the large effective leakage area. The oldest houses in this cell, all built in 1943, had pre-retrofit leakage areas of 610-760 cm^2; by contrast, house #11, built in 1951, has a leakage area of about 400 cm^2. In fact, on the basis of pre-retrofit measurements only, the seven houses in the study built in 1943 have an average leakage area of 680 cm^2, while those built later average 460 cm^2, about 32 percent less.

Cell 2

Like the homes in cell 1, the six homes in cell 2 (all retrofitted with additional insulation) did not show any significant changes in leakage area. The change in five of the houses was less than the associated uncertainty of 10 percent. The average decrease in effective leakage area was 1 percent, or 14 cm^2 (standard deviation = 73 cm^2). House #1 in this cell showed a decrease in leakage area of 20 percent (144 cm^2). However, this change may be misrepresentative of the actual infiltration rates. This house was also retrofitted with a roof-mounted solar water heating system. The plumbing for the system runs through the attic into the house via an access hatch in the utility room, where the storage tanks are located. No cut-out was made in the attic access hatch to accomodate the plumbing, so the hatch cover cannot be closed. If the door between the utility room and the house is closed, then the effect of the open hatch is small. However, if the door is left open (as it usually is in most of these homes), the leakage area almost doubles. The post-retrofit measurements for this house in Figure 2 and Table 1 are those obtained under the tighter condition, i.e., with the door closed and the attic access sealed with plastic sheeting.

Cell 3

The seven houses retrofitted with both insulation and storm doors and windows show a definite trend toward reduced leakage area. Three of the houses showed changes greater than the 10 percent uncertainty. The accuracy of the large decrease of 36 percent in house #17 is open to much doubt because of the low air flows at which some of the applied pressures were measured (the calibration of the pressurization equipment has a large uncertainty at flows below about 500 cfm) and so may be overestimated. Not including house #17, and including the test results of house #19 with its air registers and return air duct sealed (as explained in the next section), the average reduction in effective leakage area in cell 3 was 17 percent, or 80 cm^2 (standard deviation = 60 cm^2).

Solar House

House #19 was retrofitted with solar space heating in addition to the other retrofits of cell 3. A forced-air system was installed to distribute heat either from the phase-change storage system or directly from the collector to the house. The supply ducts run through the basement into the house via floor registers, and the only return inlet is also in the basement. A large grille was cut in a bedroom closet floor to provide the only path for the room air to reach the basement, where the return plenum is located. There are several problems with this distribution system. First, the hole in the bedroom closet floor is covered with clothes, toys, etc., which reduces considerably the return air flow from the house to basement. This will likely result in a pressurized upstairs and a depressurized basement whenever the heating system blower is on. Second, the basement did not appear to be very tightly sealed from the outside, particularly around the hopper windows and at plumbing penetrations. As a result of these two conditions, infiltration of outside air into the basement is likely to be high when the house fan is on, and cold air would be drawn into the solar collector or storage loop.

This house was retested after the retrofit in two conditions. With the floor registers and return inlet to the basement open, the leakage area was 510 cm^2; with these sealed, the leakage area dropped to 330 cm^2, a 35 percent reduction (Figure 4). Compared to the pre-retrofit condition (360 cm^2), the leakage area of the house in its present normal condition (return and registers unsealed) increased 38 percent.

Conclusions

Two major conclusions can be drawn from our leakage measurements. First, it appears that retrofitting with insulation alone does little to affect the leakage area of a structure. This seems particularly true of loose-fill fiberglass insulation, which by itself will not settle into and fill cracks around plumbing or ducts or wall-ceiling joints; a special effort must be made to pack the insulation into these openings. However, the potential for reducing the leakage area in attics in the Midway homes is limited because these houses have few ceiling penetrations. In the older Midway homes, the attic extends over the porch, which has a ceiling level lower than the rest of the house. The resulting kneewall of these homes was not insulated as part of the retrofits. This was noticeable during an infrared scan of the interior of one of the houses in cell 2; the portion of the wall adjacent to the porch proved to be cooler than the interior ceiling surfaces. This is a small area, but it could easily have been insulated with batts, which would reduce not only conductive losses but also air infiltration losses, because this type of kneewall construction provides a "chimney" for air leakage from the house to the attic. To reduce this effect, fiberglass insulation should have been stuffed into part of the kneewall cavity. This is indicative of the types of details that are often missed in retrofits.

Insulation in the crawl-spaces in homes in cells 2 and 3 was applied to the interior side of the perimeter foundation wall and about one foot of the adjacent earth floor. This strategy is an interesting one and is becoming more widely used. It is certainly easier and requires less material than the more standard practice of insulating the underside of the floor. Barring unusual soil conditions, e.g., extreme dampness, the heat loss should be about the same. The success of this strategy depends largely upon the tightness of the crawl-space during the heating season. The houses at Midway have crawl-space vents that can be closed, but several vent hatch covers were missing, and no attempt to weatherize any of the covers was made as part of the retrofits. This certainly reduces the effectiveness of the crawl-space insulation.

The second conclusion to be drawn concerns the effectiveness of storm doors and windows in reducing effective leakage area. Three houses in cell #3 had reductions greater than the associated 10 percent uncertainty. Two of these, #12 and #17, were among the tightest houses before retrofitting. (Initial inspection of these houses showed some indication that the occupants had attempted to tighten their homes by sealing cracks around the window air conditioner with foam, and covering over the air conditioner vents with plastic.) Again, we note that there is a large uncertainty in the calculated post-retrofit leakage area in house #17.

Thus the effectiveness of storm doors and windows in reducing the leakage area in these houses appears moderate. The absolute reduction is on the order of 80 cm^2. In a conventional house of typical tightness and area, this is only 8-20 percent of the leakage area.

A close look at the storm windows reveals why they are not more effective in reducing the leakage area. In the five houses in cell 3 built before 1965, the storm windows are aluminum-frame, single-hung, vertical sliders (only the bottom sash is operable). They mount onto the existing wooden window frames inside the casings, providing about a two-inch air gap between glazing surfaces. The joints between the wooden and aluminum frames are well caulked. However, smoke stick tests in one of these houses showed that the existing (interior) windows still leaked between the sash and frame, and between the upper and lower sashes. Also, because the storm windows fit inside the existing window frames, they can do nothing to reduce leakage between the rough wall frame and the window frame around the casing; smoke stick tests showed leaks at these joints as well.

The two houses built in the 1960s have aluminum window frames or casings, so that the storm windows could not be fitted into the existing frames. Therefore in these house wooden frames were added, completely surrounding the existing aluminum ones and sealed directly to the exterior siding. This may be another reason for the apparently large reduction in leakage area for house #17. The change in house #19, built in 1968, is not nearly so great, but the solar space heating system seems to have introduced new leaks that perhaps counteract the effects of the storm doors and windows in this house.

Our results indicate many places other than windows where leakage areas can be reduced. In the Midway houses, further tightening of the windows and doors with weatherstripping and caulking would improve the performance of the storm doors and windows. Plumbing penetrations through the building envelope, including the holes created by the new solar plumbing runs and the pressure relief pipes from the "point-of-use" water heaters under the kitchen sinks, typically have not been sealed in these houses. Weatherstripping and latches can be added to attic doors to tighten them. In houses where the basement is not used as living space (as is usually the case at Midway), the doors to the basement can be weatherstripped, reducing any leakage from the house to the basement. (Smoke stick tests showed these doorways to be very leaky.) In the absence of floor insulation over an unheated basement or crawl-space, any leaks in the basement walls to the outside (sole plates, band joists, windows, flue penetrations, etc.) should be sealed to keep the basement warmer, and thus reduce heat losses through the house floor (if floor insulation is installed, then any leaks in the floor should also be sealed). Special attention should be paid to tightening the hatch covers of crawl-space vents, in order to gain maximum effectiveness from the crawl-space insulation.

It has recently been decided to extend the study with the participation of the Energy Performance of Buildings and Ventilation groups from Lawrence Berkeley Laboratory. The energy consumption of the Midway houses is being extensively monitored, and after a suitable length of time, enough data will have been collected to determine the effectiveness of the retrofits already installed. Our measurements indicate that only moderate savings will accrue in the houses in cell 3 from reductions in the infiltration component of total building heat loss, and no savings at all from reduced infiltration will be seen in the other two cells. Therefore, we are interested in exploring the potential for additional energy savings from further tightening of these houses, while monitoring the effects of these retrofits on the homes' indoor air quality. This will include:

- Measuring indoor air quality in the houses before and after any further leakplugging.

- Performing limited retrofits (two man-days) on six houses.

- Performing "super-retrofits" (up to six man-days) on six houses.

- Installing air-to-air heat exchangers in the tightest houses if indoor air quality problems are found.

- Continuing to monitor energy use in each house with sub-meters for water heaters and space heating and cooling equipment.

- Careful accounting of labor and materials used for the retrofits.

This extension of the project should add much useful information about the effectiveness of different retrofits designed to reduce infiltration, changes in indoor air quality from reduced infiltration, the effectiveness of air-to-air heat exchangers, and the relative cost-effectiveness of weatherization retrofits (including insulation and storm doors and windows).

Summary

The results of our pressurization tests indicate no significant changes in the leakage areas (or infiltration rates) in the houses receiving either no retrofits or insulation only. Some reduction in leakage area was seen in the houses fitted with insulation and storm doors and windows, with an average decrease of 17 percent. However, since there appears to be many leaks and bypasses remaining, the project is being extended to perform further retrofits aimed at reducing air infiltration and analyze their effects on energy consumption and indoor air quality.

References

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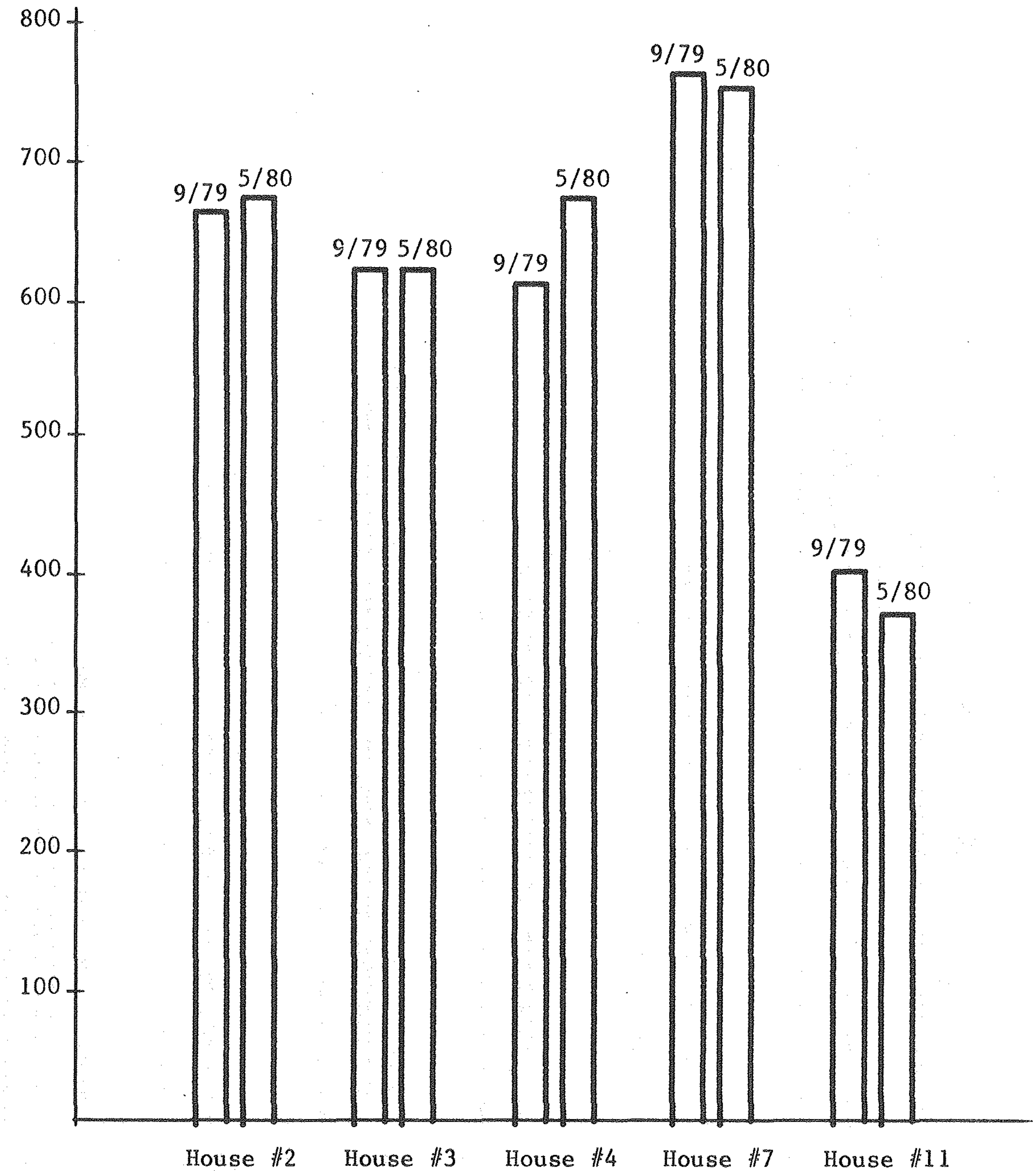

Figure 1- Cell #1 pre and post-retrofit effective leakage areas (cm^2).

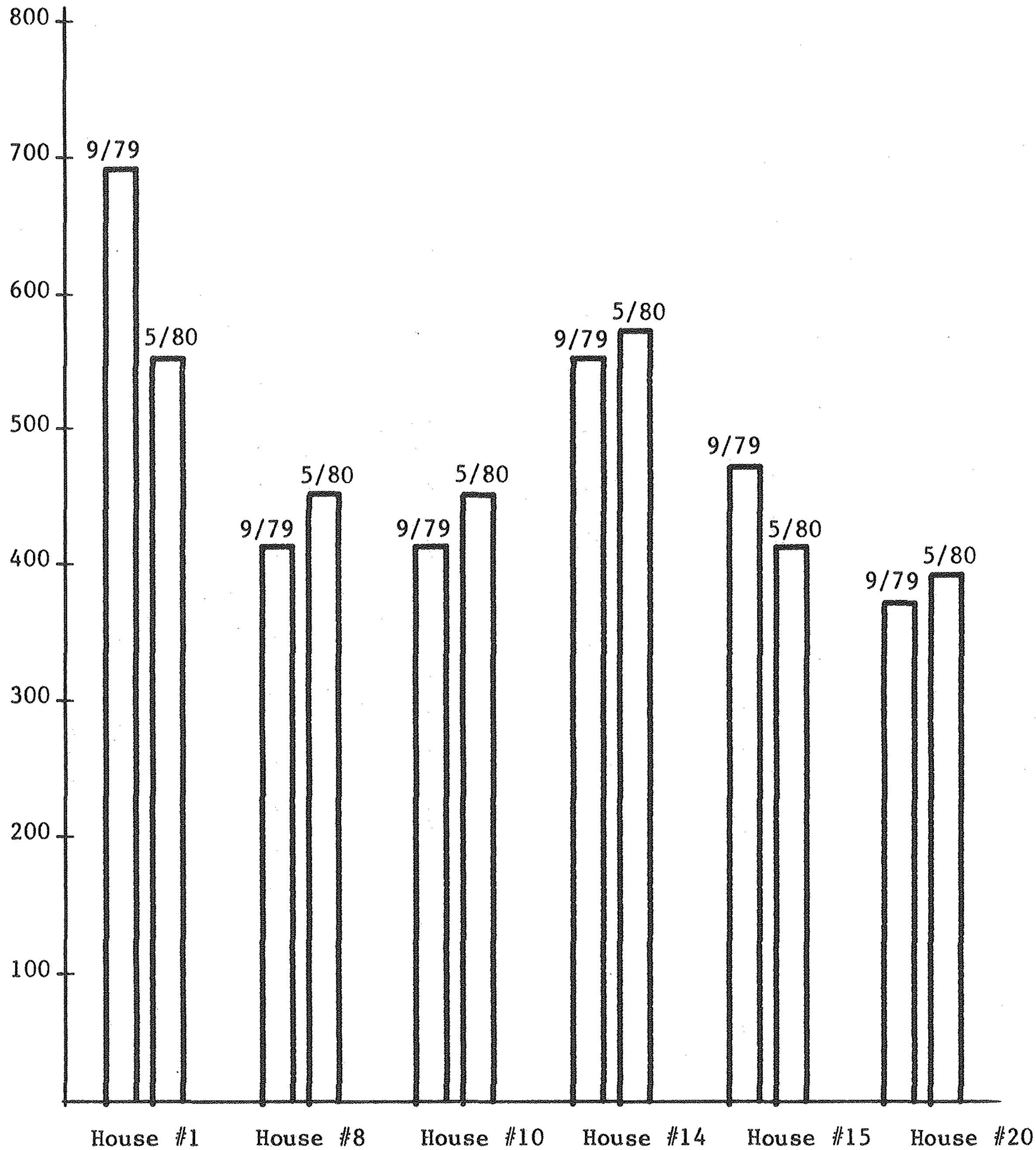

Figure 2- Cell #2 pre and post retrofit effective leakage areas (cm^2).

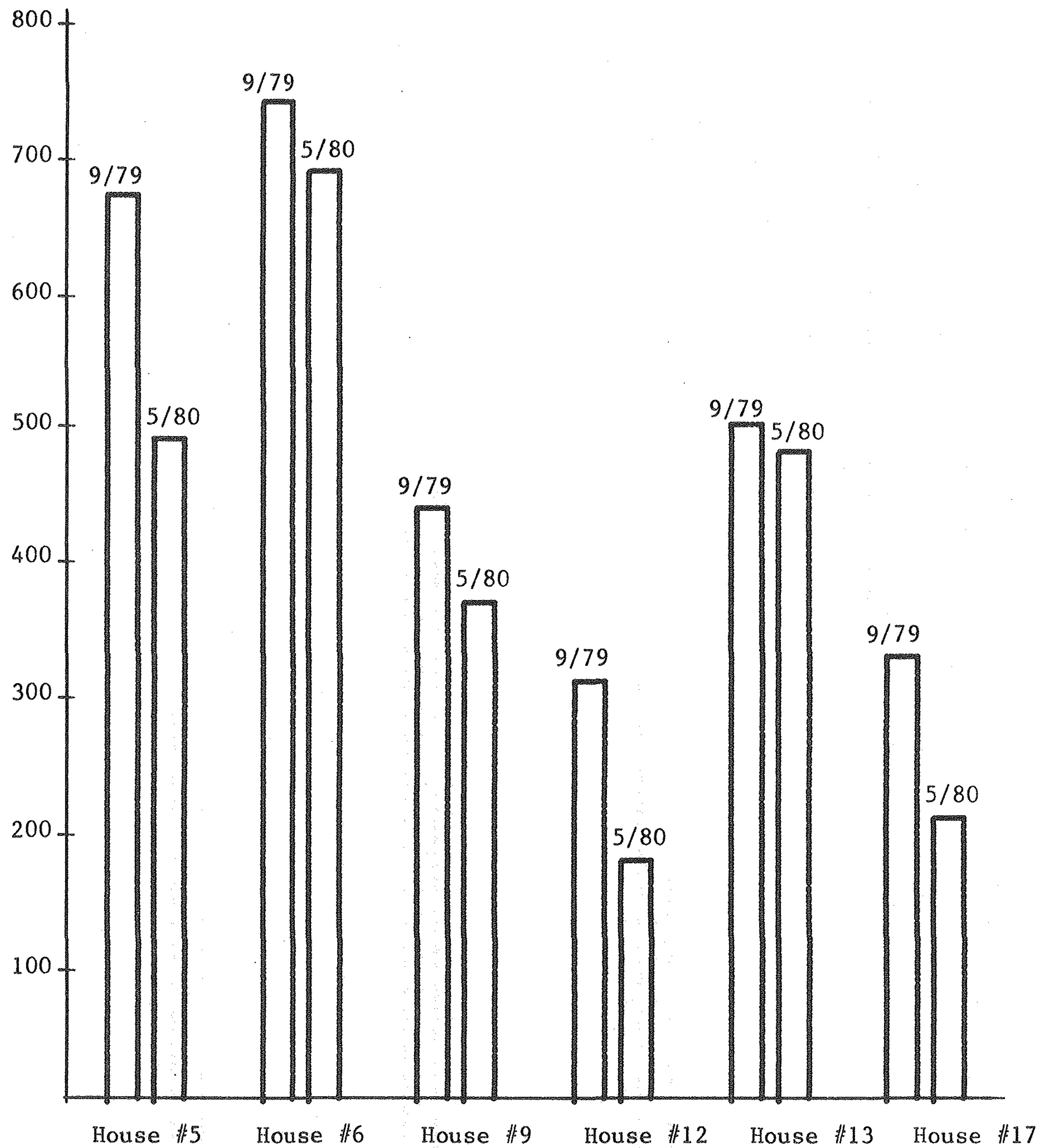

Figure 3- Cell #3 pre and post-retrofit effective leakage areas (cm^2).

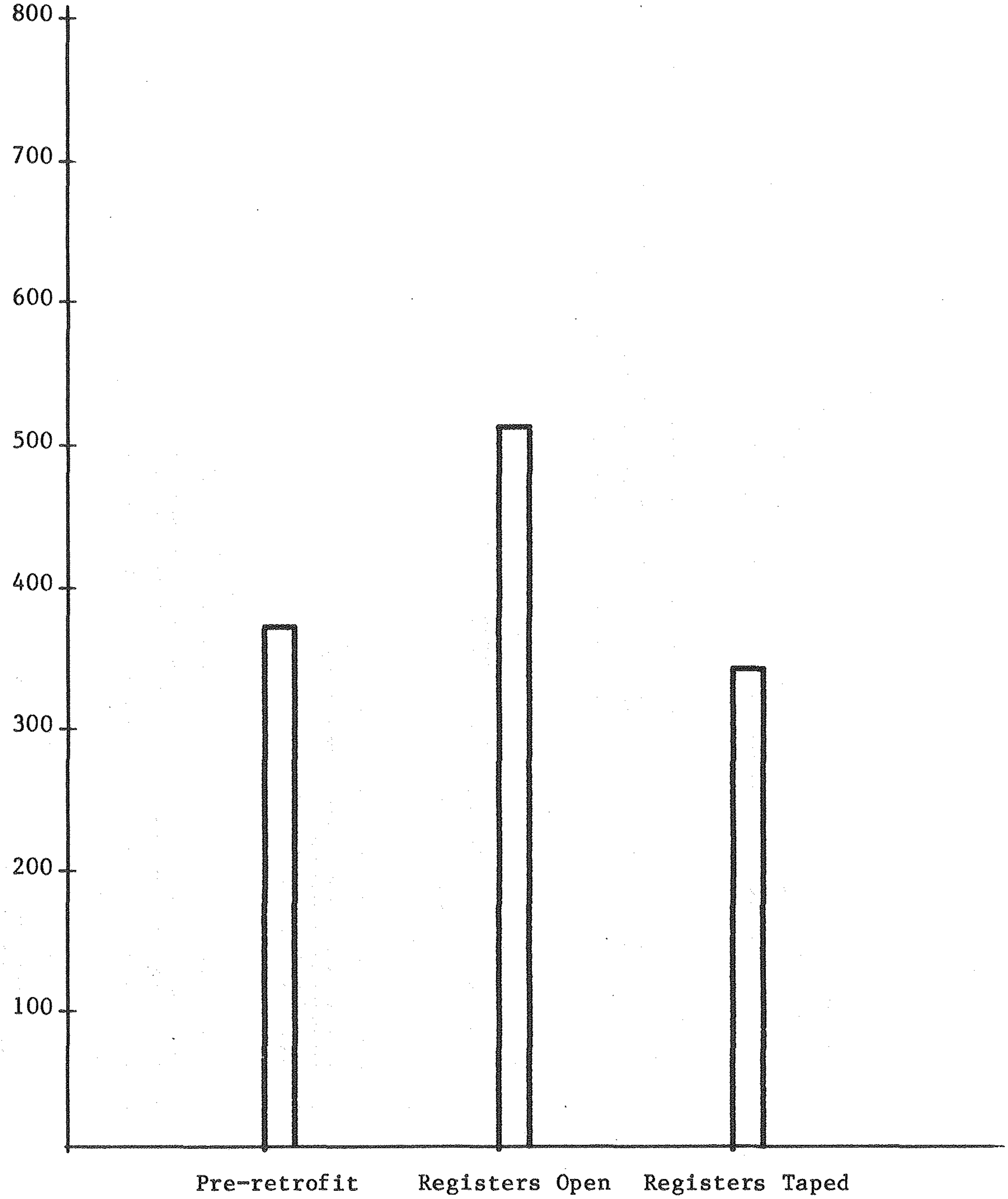

Figure 4- House #19 effective leakage areas (cm^2).

Cell	House	Area (ft^2)	Year Built	Leakage Area (cm^2)		Infiltration Rate (ACH)[1] Heating[2]		Annual	
				9/79	5/80	9/79	5/80	9/79	5/80
1	2	1161	1943	660	670	.63	.64	.53	.54
	3	1161	1943	620	620	.59	.59	.50	.50
	4	1329	1943	610	670	.51	.55	.43	.46
	7	1329	1943	760	750	.63	.61	.53	.52
	11	1319	1951	400	370	.33	.30	.28	.26
2	1	1161	1943	690	550	.66	.51	.55	.43
	8	1319	1951	410	450	.34	.37	.28	.31
	10	1319	1951	410	450	.34	.38	.29	.32
	14	1319	1951	550	570	.46	.48	.39	.40
	15	1145	1951	470	410	.45	.40	.38	.34
	20[3]	2220	1968	370	390	.18	.19	.16	.16
3	5	1161	1943	670	490	.63	.46	.53	.39
	6	1329	1943	740	690	.61	.56	.51	.48
	9	1319	1951	440	370	.37	.31	.31	.26
	12	1145	1951	310	180	.30	.17	.25	.14
	13	1319	1951	500	480	.41	.38	.35	.32
	17	1110	1965	330	210	.32	.20	.27	.17
	19	1110	1968	370	510	.36	.51	.30	.43

Table 1 Data summary for Midway pressurization tests.

1. These infiltration rates have been calculated from the effective leakage areas, as described by Grimsrud, et.al. (see References).
Average monthly wind speeds and outdoor temperatures are from NOAA data for Yakima, Washington, assuming class three local terrain.
The total effective leakage area is assumed to be equally divided among the floor, ceiling, and walls.

2. The heating season includes the months of November through March.

3. The infiltration rates for house #20 have been calculated with the full basement volume included as living space.
It has been remodeled into bedrooms and a den, and is conditioned space.
The pressurization tests were performed with the door between the kitchen and basement open.