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Infiltration and Leakage Measurements in New Houses Incorporating Energy Efficient Features*

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ABSTRACT

In order to increase energy efficiency in new residential housing, building contractors are using a number of recently developed infiltration-reducing construction techniques. One of these techniques is the installation of a continuous vapor barrier. A second technique is the selective sealing of infiltration sites with polymeric foam caulk following completion of the rough framing of a house. Measurements of leakage areas and infiltration rates in houses incorporating such energy-conserving measures can provide important information about their effectiveness. Houses with energy efficient designs in Eugene, Oregon and Rochester, New York were measured for effective leakage area using blower door fan pressurization. Air exchange rates were determined by tracer gas decay analysis. Fan pressurization measurements were made on 13 new houses in the San Francisco Bay area that had been partially sealed with polymeric foam sealant. A similar group of 13 new houses that had not been sealed were measured as controls. The results of these measurements were used in conjunction with an infiltration model developed at Lawrence Berkeley Laboratory to predict average annual and heating season infiltration rates. Specific leakage areas (leakage area per unit floor area) for the Eugene houses averaged 45% of that measured in post-1975 California housing. The energy-efficient Rochester houses were found to be 50% tighter (in terms of specific leakage area) than their non-energy efficient counterparts in the same area. Excluding leakage in the heating duct system, the average specific leakage area (leakage area per unit floor area) of the houses houses sealed with polymeric foam was 3.4 cm^2/m^2 (s.d.=0.7) while the control group averaged 4.2 cm^2/m^2 (s.d.=1.1), a 19% difference. This difference was found to be statistically significant at the 95% confidence level.

Keywords: energy conservation, infiltration, leakage area, fan pressurization, tracer gas, residential housing

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INTRODUCTION

The typical house is an assembly of thousands of individual components, many of which, when brought together, match imperfectly. The installation of windows, doors, electrical wiring and plumbing requires holes of varying shapes and sizes in the building envelope that further disrupt its integrity. Heating and cooling ducts are often placed outside of the living space, allowing energy loss both by conduction and infiltration. The conventional approach to reducing energy use in new housing has been to install moderate quantities of attic and wall insulation and to caulk and weatherstrip doors and windows. These conservation measures fail to exploit the full potential of possible cost-effective energy savings.

Rising residential energy prices in recent years have increased consumer demand for energy-efficient houses, beyond what is commonly available, with buyers becoming increasingly aware of the energy-saving features they want [1]. This has encouraged energy-efficiency in the design of tract housing. Two approaches to reducing energy use in new construction can be characterized: 1) incorporation of energy-conserving construction measures as integral parts of the structure and 2) the systematic sealing of leaks and cracks in the building envelope during or upon completion of the construction process. Energy efficient tract houses generally include such features as high levels of attic and wall insulation and continuous vapor barriers, which are easily incorporated into rigorous construction schedules characteristic of tract housing. The sealing approach discussed here involves the elimination of infiltration sites with foam sealant following completion of rough framing, wiring and plumbing but before installation of the drywall.

How well do these techniques work? What features are particularly effective in reducing infiltration and increasing thermal resistance? Evaluation of the effectiveness of such conservation techniques can provide useful information to the contractor, prospective home buyer, energy policy maker or utility program manager. Such an assessment has been made as a part of several residential field measurement projects conducted in houses with energy-efficient features in Eugene, Oregon, Rochester, New York, and the San Francisco Bay area [2,3]. The first two groups of houses incorporate energy-efficient construction features, while the third group was sealed with foam caulk. Control groups were also measured in Rochester and the San Francisco area. Effective leakage areas were measured in all three sets of houses by means of blower door fan pressurization. Infiltration rates were measured in the Eugene and Rochester houses by tracer gas decay. Energy consumption data from the Eugene and Rochester houses were analyzed in order to compare savings in the energy-efficient houses with their conventional counterparts. This paper reports the results of these field measurements. Also discussed are observations and recommendations on appropriate approaches to energy-conserving residential construction.

ENERGY-EFFICIENT BUILDING DESIGN

An example of energy-efficient tract housing is the "Arkansas-style" house orginally designed by Arkansas Power and Light Company [4]. Between 1976 and 1981, some 300 of these homes were built in Eugene, Oregon by Modena Homes, Inc. The Eugene houses are one story, post-and-beam floor construction. They have ventilated crawlspaces with plastic groundcovers and include R-38 ceiling insulation, R-19 wall and floor insulation, double-pane windows (amounting to 15% of total floor area), insulated exterior doors with magnetic weatherstripping and furnace ducts located within the heated space of the building. A critical feature of these houses is the continuous vapor barrier installed on the inside of each exterior surface of the house. The floor vapor barrier is one continuous 6-mil (0.15 mm) polyethylene sheet placed on top of the tongue and groove decking and below the floor underlayment. The ceiling vapor barrier is placed underneath the ceiling joists before the gypsum board is installed. A 12-inch (25 cm.) wide polyethylene strip is stapled over the top plate of each interior wall intersecting the ceiling vapor barrier and is held in place by the weight of the ceiling insulation. The wall vapor barrier is stapled to the exterior wall framing and lapped over the floor and ceiling vapor barriers. In addition, caulking is applied where the bottom plate of the exterior wall meets the decking and around all plumbing and electrical penetrations through the vapor barrier.

Two other contractors using energy-efficient construction techniques are Ryan Homes, Inc., a large builder in the eastern United States, and Schantz Homes, Inc., a builder in the Rochester, N.Y. area. Houses built by Ryan after 1976 include R-11 fiberglass batt insulation on basement walls; R-11 cellulose insulation in exterior walls; R-30 cellulose ceiling insulation; a continuous polyethylene vapor barrier on the inside of the stud frame of exterior walls; special infiltration paper around door blocking; polyurethane foam on window blocking; use of one-piece plastic electrical boxes; and sealing of all joints such as foundation and sole plate, rim joist and deck, wall panel, door and window frames, and so on. No vapor barrier is installed in the attic or basement ceiling. In Schantz houses, a continuous polyethylene vapor barrier is installed on the inside of the wall stud frame and cellulose insulation is blown into the resulting cavity to a level of R-11. Attics are insulated with blown cellulose to R-33. No vapor barriers are present in either the attic or basement ceiling. (It should be noted that the Rochester "control" houses were built before 1976 and are insulated to R-19 in the attic and R-11 in the walls.)

In the San Francisco Bay area, several companies offer a polymeric foam sealing service designed to reduce infiltration. After completion of rough framing, wiring and plumbing, but before installation of the drywall, polymeric foam is applied to cracks and penetrations such as those between sole plate and slab, around furnace registers, and so on. The foam is applied once and timing is constrained by the tight scheduling generally characteristic of residential construction. Hence, many holes and penetrations are never filled. The advantage of polyurethane sealing is that it requires no changes in construction techniques or scheduling and is relatively inexpensive.

MEASUREMENT TECHNIQUES AND RESULTS

Fan pressurization was used to measure leakage areas in the Eugene, Rochester and San Francisco-area houses. Tracer gas decay measurements were made in the Eugene and Rochester houses. Utility data were collected for the Eugene and Rochester houses.

Fan pressurization involves the use of a large fan, or "blower door," to push air into (pressurize) or pull air out of (depressurize) a structure. Analysis of the relationship between air flow through the fan and the pressure difference between the inside and outside of the house makes it possible to calculate the "effective leakage area" of the structure. By combining this number with local wind and temperature data, general topographic features, and the distribution of leakage in the house, it is possible to estimate seasonal average air exchange rates using a predictive infiltration model developed at LBL [5].

Tracer gas decay involves injection of a gas (usually sulfur hexafluoride) into a structure. After mixing with ambient air, some of the tracer escapes through the building envelope. Measurement of the change in tracer gas concentration allows a determination of the infiltration rate of the structure during the test period [6]. Because air infiltration depends upon various changing conditions, such as wind velocity and inside and outside temperature, one cannot directly generalize from the measurements derived from a relatively short-term tracer gas decay test to infiltration rates that may occur under other conditions. It is possible, however, to compare the measured air exchange rate to that predicted by the infiltration model for known weather conditions during the period of the test. The Eugene houses were measured with single, short-term decays, while the Rochester houses were measured for longer periods in the course of an air quality monitoring project [7]. Tracer gas measurements were not made in the San Francisco Bay area houses.

Table 1 shows the results of the fan pressurization tests for the three groups of houses. Both effective leakage areas (total leakage in cm^2) and specific leakage areas (normalized to house floor area, in cm^2/m^2) are given. Also shown in the tables are predicted annual and heating season infiltration rates in air changes per hour as calculated with the LBL infiltration model. Results of the tracer gas measurements and comaprisons to the LBL infiltration model are shown in Table 2. Energy consumption and performance data are shown in Tables 3 and 4. Data for individual houses are presented in the appendix.

Leakage Area Measurements

Effective leakage areas for the energy-efficient Eugene houses with heating ducts sealed averaged 265 cm^2 ($\sigma = 91$) while specific leakage areas averaged 2.4 cm^2/m^2 ($\sigma = 0.8$). The energy-efficient Rochester homes were found to have an average effective leakage area of 576 cm^2 ($\sigma = 176$), while the pre-1976 houses (insulated, but not sealed with any special techniques) averaged 1,015 cm^2 ($\sigma = 287$). The energy-efficient Rochester houses also had an average specific leakage area of 2.9 cm^2/m^2 ($\sigma = 1.0$), while their pre-1976 counterparts averaged 5.5 cm^2/m^2 ($\sigma = 2.7$). The San Francisco Bay area houses sealed with polymeric foam had an average leakage area of 592 cm^2 ($\sigma = 198$) while the average leakage area of the control houses was 688 cm^2 ($\sigma = 185$). In both cases, measurements presented are those made with furnace registers sealed (this configuration is judged to be a better indicator of house tightness). Average specific leakage area for the foam-sealed houses was 3.4 cm^2/m^2 ($\sigma = 0.7$), while the control houses averaged 4.2 cm^2/m^2 ($\sigma = 1.1$).

In order to put these figures into perspective, Figure 1 illustrates the range of specific leakage areas measured for these groups of houses and compares them to several other sets of houses for which measurements have been made. In terms of specific leakage areas, most of the energy-efficient Eugene and Rochester houses are much tighter than either the controls or other measured houses. Interestingly, although no statistically significant difference in specific leakage area was found between the sealed and non-sealed houses in the San Francisco Bay area, both groups were significantly tighter than the California average as shown in the figure. (For comparison purposes, air change rates at 50 Pascals are shown in the tables in the Appendix.)

Tracer Gas Measurements

Table 2 show the results of the tracer gas measurements made in the Eugene and Rochester houses. Both experimental results and predictions made with the LBL infiltration model are presented in the tables. Also shown are the ratios of measured to predicted infiltration rates. Infiltration rates measured in the Eugene houses (during fairly mild weather) ranged from 0.09 to 0.27 air changes per hour. Those measured in the Rochester houses (during much colder weather) ranged from 0.22 to

Table 1: Summary of Leakage Area Measurements and Predicted Infiltration Rates

City	No. of Houses	Avg. Floor Area (m^2)	Avg. Vol. (m^3)	Eff. Leakage Area (cm^2)*	Specific Leakage Area (cm^2/m^2)*	Predicted Heating Season Infil. Rate (ACH)**
Eugene	12	111	275	265 ± 91	2.4±0.8	0.34
Rochester						
Pre-'76	12	208	506	1,015±287	5.5±2.7	0.97
Post-'76	47	206	502	576±176	2.9±1.0	0.47
San Francisco Bay						
Sealed	13	174	424	592±198	3.4±0.7	0.42
Unsealed	13	164	400	688±185	4.2±1.1	0.47

*With heating system ducts sealed off from house interior.

**Including leakage in heating system ducts.

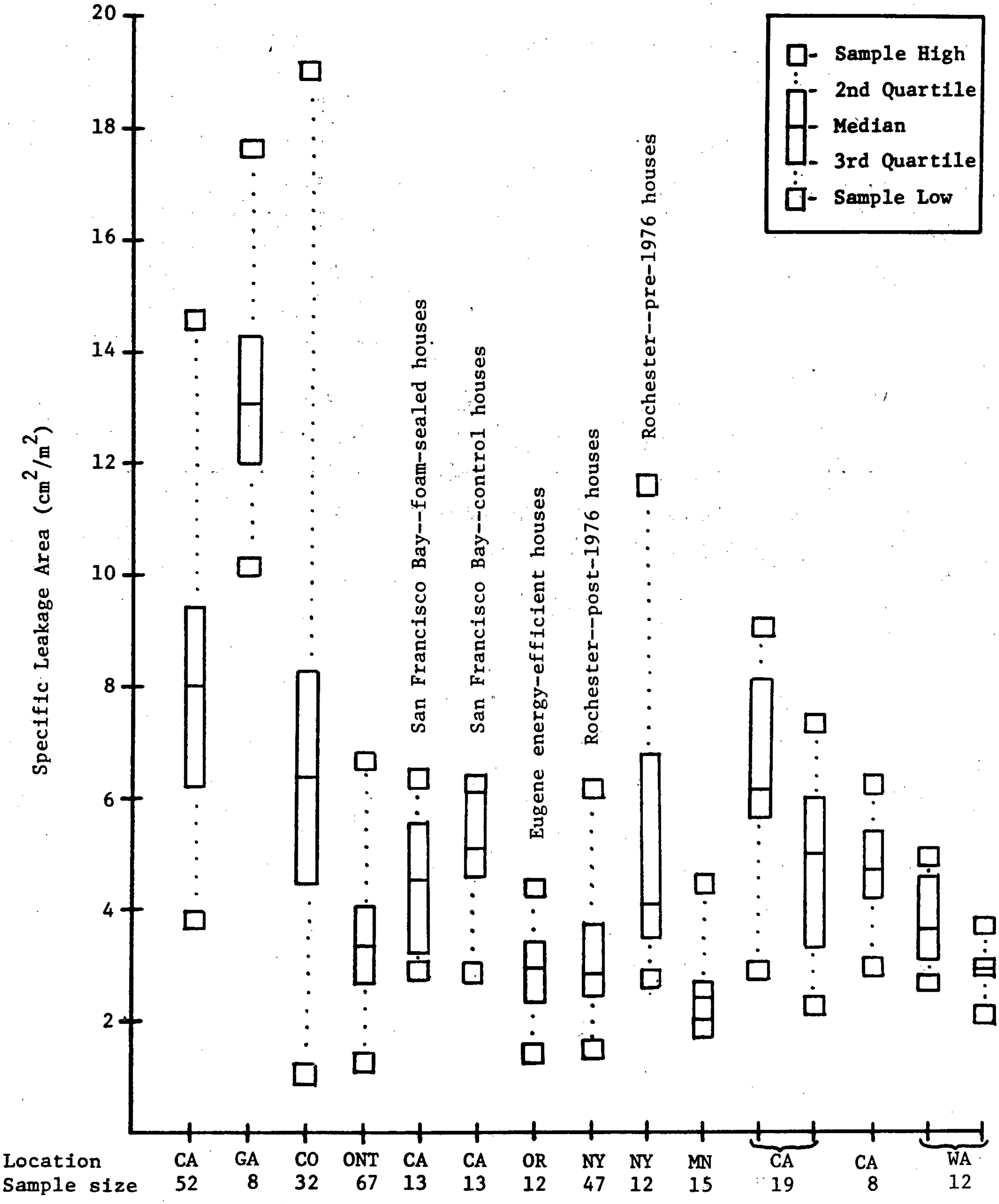

Figure 1: Specific leakage areas of new houses incorporating energy-efficient features as compared to other groups of measured houses.

1.17 air changes per hour. The Eugene measurements were made for periods of 1.5 to 8 hours, hence, the tracer gas measurements generally did not extend across major changes in weather. The Rochester measurements ranged from one to two weeks. Therefore, the Eugene measurements are compared to infiltration model predictions based upon weather conditions at the time of the test, while the Rochester data are compared to predicted heating season infiltration rates, based upon average seasonal weather conditions. For individual houses, the ratios of measured to predicted infiltration range from 0.57 to 1.50. However, for the houses as groups, the agreement between measured and predicted infiltration is quite good. For the Eugene houses, the geometric mean of the ratios of the measured to predicted rates is 0.90. For the Rochester houses, the corresponding geometric mean is 0.95.

Energy Consumption

Tables 3 and 4 present energy consumption and performance data for the Eugene and Rochester houses. Table 3 compares average energy consumption (in kWh/year) for 10 energy-efficient houses and 10 conventional houses in Eugene, broken down into space heating, domestic hot water and total minus hot water. Also presented is average energy consumption normalized to floor area (kWh/ft^2-year). Space heating energy consumption in the energy-efficient houses was 34.2% of that in the conventional houses. More efficient design of the hot water distribution system was responsible for a small part of energy savings.

Table 4 gives the results of a two-parameter energy use model applied to the Rochester houses in terms of a normalized thermal conductance parameter k (Watts/^{o}C-m^2), which is the thermal conductance (Watts/^{o}C) divided by house floor area, and the balance temperature, which is that outside temperature at which space heating becomes necessary. The pre-1976 houses have an average k value of 1.34 W/^{o}C-m^2 (σ=0.32) while the energy-efficient houses average 0.94 W/^{o}C-m^2 (σ=0.16), or 30% less. There is a large variation in individual values. The difference in balance temperatures between the two sets of houses is not statistically significant.

Table 2: Results of Tracer Gas Measurements

City	House ID #	Duration of Test (hrs.)	Infiltration Rates (ACH) Measured	Infiltration Rates (ACH) Predicted	Ratio of Measured:Predicted
Eugene	A	8	0.20	0.22	0.91
	B	2	0.27	0.25	1.08
	C	2.5	0.23	0.22	1.04
	D	2.5	0.09	0.11	0.82
	E	1.5	0.09	0.11	0.82
	F	2.5	0.08	0.08	1.00
	H	2	0.21	0.37	0.57
	I	3	0.09	0.06	1.50
	J	4	0.19	0.18	1.06
	1	2.5	0.17	0.26	0.65
	2	2	0.19	0.22	0.86
	3	1.5	0.21	0.21	1.00
		Geometric mean of all measurements			0.90
Rochester					
	1	192	0.22	0.37	0.60
	6	336	0.38	0.42	0.90
	10	168	0.30	0.23	1.30
	33	168	0.38	0.42	0.90
	37*	168	1.17	0.92	1.27
	45	168	0.37	0.38	0.97
	49*	336	0.42	0.42	1.00
	52	144	0.28	0.22	1.29
	56	168	0.50	0.56	0.89
	59	264	0.33	0.47	0.70
		Geometric mean of all measurements			0.95

*House built before 1976.

Table 3: Energy Consumption Data for Eugene Energy-Efficient and Conventional Houses (for average year)

Avg. Floor Area (m^2)	Space Heating Energy (kWh/yr.)	Space Heating Energy (kWh/m^2-yr.)	Domestic Hot Water Energy (kWh/yr.)	Total Energy, excluding Domestic Hot Water (kWh/yr.)	Total Energy, excluding Domestic Hot Water (kWh/m^2-yr.)
Energy Efficient Houses (10 houses)					
104	3,273±1,140	31.3±6.9	5,476±2,343	10,749±2,885	103.0±24.3
Conventional Houses (10 houses)					
123	10,992±3,953	91.5±34.7	7,449±1,823	21,183±4,671	173.7±33.6

Table 4: Rochester Energy Modelling Data

Avg. Floor Area (m^2)	k ($W/^{o}C-m^2$)	Balance Temp. (^{o}C)
Pre-1976 (11 houses)		
222	1.33± 0.32	16.1± 0.9
Post-1976 (28 houses)		
198	0.94± 0.16	16.3± 1.6

OBSERVATIONS AND CONCLUSIONS

Data from the Eugene and Rochester houses indicate that energy-efficient construction techniques are very effective in reducing both infiltration and energy consumption. Leakage areas in the newer Rochester houses were almost 50% less than those measured in the older ones. In the Eugene houses, the reduction was 55% when compared to post-1975 California housing (because no conventional houses in Eugene were measured for leakage). In those Eugene houses where large penetrations in the vapor barrier were present (e.g., thermal storage area in a passive solar house), larger leakage areas were measured, suggesting the continuous vapor barrier to be of major importance in reducing infiltration. Inclusion of the heating ductwork within the building envelope in the Eugene houses was also judged to be effective in reducing air leakage through the envelope. As a group, the average floor area of the Rochester houses (208 m^2) was significantly greater than that of the Eugene houses (111 m^2). The Rochester houses were all 2 to 4 stories (including basement). The major difference between the two groups of houses was the absence of the continuous vapor barrier in the attic of the Rochester group. In spite of the fact that the Eugene houses had a higher surface to volume ratio, the average specific leakage areas of both groups of houses were almost the same (with a similar standard deviation).

Overall, the thermal performance of the energy-efficient houses was better than that of the conventional houses. The Eugene houses used 34% of the space heating energy and about 68% of the total energy used by the conventional houses. Since we have no comparative leakage areas for conventional houses in the Eugene area, we cannot estimate what fraction of the reduction in energy use might be attributable to reduced infiltration. The energy-efficient Rochester houses showed a 30% reduction in the thermal conductance parameter as compared to the control houses. About one-third of this change in heat loss can be attributed to reduced infiltration.

What are the costs of these improvements? The cost of the conservation measures in the Eugene houses was $1.75 per square foot (in 1980 dollars). Annual savings are approximately 6 kWh/ft^2-year. At a current electricity cost of 2.5 cents/kWh in the Pacific Northwest (low by national standards), savings for a standard 1,100 square foot home are $165 per year, with a simple payback of about 12 years. However, the cost of conserved energy [8] is approximately $5.50/MBtu compared to a current electrical energy cost of $7.30/MBtu. Hence, the improvements can be considered cost-effective. (Table 5 lists the economic parameters used for this calculation.)

The incremental cost of the improvements in the Rochester houses is $500. Under all reasonable economic assumptions, these improvements are cost-effective. The cost of conserved energy for the Rochester houses is $1.08/MBtu as compared to the retail price of $7.14/MBtu for natural gas (somewhat higher than the current national average, and assuming a 70% furnace efficiency).

The effectiveness of polymeric foam sealing as practiced in the houses tested by LBL is questionable. A t-test applied to the data showed that for measurements made with furnace registers sealed, the specific leakage areas of the two groups of houses were statistically different at the 95% confidence level. However, with registers unsealed, the two sets of measurements are different only at the 90% confidence level. We believe there are three reasons for the small difference. First, there is the problem of quality control. As we made pressurization measurements in the sealed houses, we also inspected for leaks using air current tracers ("smokesticks"). We found the application of the foam to be erratic and often incomplete. Second, the foam is applied once and, subsequently, other holes are made in the building envelope. This results in many leakage sites being missed. Finally, there are major areas of the house where the foam is not applied, for example, in the attic and crawlspace. Consequently, while the foam undoubtedly blocks off some leakage paths through the envelope, alternate flow paths are untouched. We believe that the foam could be more effective if it were applied in several stages. Indeed, a house sealed according to our recommendations was tested and found to have a specific

Table 5: Economic Analyses of Eugene and Rochester Houses

City	Amortization Period (yrs)	Real Disc. Rate (%)	Energy Esc. Rate (%/yr)	Cost of Conserved Energy ($/MBtu)	Present Cost of Energy ($/MBtu)
Eugene	30	5	3	$5.54	$7.30
Rochester	30	5	3	$1.08	$7.14

leakage area of 2.8 cm^2/m^2 with registers sealed, comparable to the energy-efficient houses in Eugene and Rochester. Unfortunately, construction is such a tightly scheduled process that there is often no time available for multiple applications of foam. Other conservation activities must be scheduled, too, but they generally do not require return trips to the building site by specialized teams.

To summarize, the data collected in Eugene and Rochester indicate that it is easy and fairly inexpensive to realize major energy savings in new houses with minimal expenditures of time and money if the conservation measures are installed as an integral part of building construction. These sets of houses do not exploit the full potential of possible cost-effective conservation measures, as demonstrated by the low-energy houses being built in Canada [9]. Nonetheless, they represent major advances as far as residential conservation is concerned. The application of polymeric foam sealant during construction will be effective only if greater care is taken during the application process.

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APPENDIX

Table A1: Effective Leakage Areas (Registers Unsealed) and Predicted Infiltration Rates for Eugene Houses [a]

House ID	Floor Area (m^2)	House Volume (m^3)	Effective Leakage Area (cm^2) [b]	Specific Leakage Area (cm^2/m^2)	Predicted Infiltration Rates (ACH) [c]	
					Heating Season	Annual
A	107	260	410	3.8	0.46	0.41
B	107	262	342	3.2	0.39	0.34
C	102	249	256	2.5	0.32	0.27
D	102	249	230	2.2	0.28	0.25
E	108	264	220	2.0	0.24	0.21
F	102	249	130	1.3	0.17	0.14
H	81	197	350	4.3	0.49	0.42
I	81	197	284	3.5	0.40	0.34
J	134	326	314	2.3	0.29	0.26
Solar 1	140	390	482	3.4	0.37	0.32
Solar 2	116	293	337	2.9	0.35	0.30
Solar 3	147	368	345	2.4	0.34	0.29
Average	11	275	308 ± 93	2.8 ± 0.8	0.34	0.30

[a] Each house measured with furnace registers sealed and unsealed (see Table 4) for comparisons. House C tested with fireplace covered with plastic and uncovered. Solar 3 tested in six leakage configurations involving opening and closing of various ventilation systems and a solar greenhouse. Only the two Solar 3 measurements corresponding to the sealed and unsealed register configurations are reported in this paper.

[b] Estimated error in leakage area assumed to be 10%.

[c] Infiltration rates include design ventilation area (bathroom, dryer vents), 10 cm^2 per opening.

Table A2 : Effective Leakage Areas of Ductwork in Eugene Houses

House ID	Effective Leakage Area		Duct Leakage Area	
	Ducts Unsealed (cm^2)	Ducts Sealed (cm^2)	(cm^2)	% of total
A	410	344	66	16%
B	342	300	42	12%
C*	256	230	--	--
D	230	160	70	31%
E	220	166	54	25%
F	130	128	2	2%
H	350	307	42	12%
I	284	257	27	10%
J	314	272	41	13%
Solar 1	482	468	14	3%
Solar 2	337	288	49	15%
Solar 3	345	258	36	25%
Average			40	15%

*Represents change in effective leakage area when fireplace is covered with plastic. There is no ductwork in this house (radiant ceiling heat).

Table A3: Effective Leakage Areas and Predicted Infiltration Rates for Rochester Houses

House #	Builder[a]	Year Built	Const. Type[b]	Total Floor Area (ft^2)	Effective Leakage Area (cm^2)	Specific Leakage Area (cm^2/m^2)	Predicted Infiltration Rates: Heating Season (ach)	Predicted Infiltration Rates: Annual (ach)
1	B	1977	2	2200	499	2.4	.37	.28
2	B	1977	2	2000	393	2.1	.30	.23
3	B	1976	2	2000	450	2.4	.36	.28
4	B	1976	3	2230	466	2.2	.42	.33
5	B	1977	4, S	2200	525	2.6	.44	.35
6	B	1977	4, S	1900	494	2.8	.42	.33
7	B	1976	2, S	1880	602	3.4	.58	.46
8	B	1977	2, S	2030	480	2.5	.41	.31
9	B	1977	3	3000	684	2.5	.44	.33
10	B	1976	2, S	1700	221	1.4	.23	.19
11	B	1977	2, S	2000	519	2.8	.43	.33
12	B	1976	3	2700	740	3.0	.56	.44
13	B	1976	3, S	2000	352	1.9	.29	.23
14	B	1977	3	2750	443	1.7	.33	.26
15	B	1975	3	2020	251	1.3	.22	.18
16	C	1978	3	2760	653	2.5	.43	.33
17	C	1979	3	3220	700	2.3	.41	.31
18	C	1979	2	2600	696	2.9	.42	.32
19	C	1980	3	2550	861	3.6	.61	.46
20	C	1979	3	2340	645	3.0	.45	.34
21	C	1978	3	3100	843	2.9	.50	.39
22	B	1979	3	2880	737	2.8	.53	.42
23	B	1979	2	2320	370	1.7	.26	.21
24	B	1980	4, S	1840	626	3.7	.65	.52
25	B	1980	3, S	2075	768	4.0	.70	.55
26	B	1980	3, S	2075	545	2.8	.49	.38
27	C	1978	2, NB	2800	1000	3.8	.57	.43
28	C	1979	3	2200	606	3.0	.55	.41
29	B	1980	3, S	2045	673	3.5	.61	.49
30	B	1980	4, S	2200	528	2.6	.45	.36
31	B	1980	2	2000	514	2.8	.47	.37
32	B	1980	2	2000	450	2.4	.42	.33
33	C	1979	3	2330	551	2.5	.42	.32
34	C	1978	4, S	1800	414	2.5	.46	.36
35[c]	B	1980	4, S	1900	1113	6.3	1.21	.94
36	B	1980	2	1500	760	5.5	1.00	.78
37	A	1974	2	1930	976	5.4	.92	.73
38	A	1973	3	2700	1010	4.0	.71	.54
39	A	1973	3	3050	733	2.6	.47	.35
40	B	1980	3, S	1890	593	3.4	.61	.48
41	B	1979	2, S	2080	527	2.7	.42	.33
42	A	1973	3, S	3700	1028	3.0	.51	.39
43	A	1974	3	1920	1604	9.0	1.70	1.33
44	B	1978	3	3000	637	2.3	.41	.31
45	B	1979	3	3260	606	2.0	.38	.29
46	B	1979	3, S	2075	541	2.8	.45	.35
47	B	1980	3, S	1630	576	3.8	.60	.46
48	A	1973	2, S	2850	951	3.6	.63	.48
49	A	1973	3	2000	653	3.5	.42	.32
50	A	1973	3	2700	1028	4.1	.71	.54
51	A	1973	3	1400	1538	11.8	2.18	1.71
52	B	1980	2	1680	225	1.4	.22	.18
53	B	1977	2	2200	593	2.9	.47	.38
54	A	1973	3	1550	978	6.8	1.16	.92
55	B	1980	2	1100	508	5.0	.87	.69
56	B	1980	2	1700	502	3.2	.56	.44
57	A	1974	2	1600	911	6.1	1.14	.89
58	A	1974	3	1400	775	6.0	1.04	.82
59	C	1978	3	2315	581	2.7	.47	.37

[a]A = pre-1976 Ryan Homes, B = Post-1976 Ryan Homes, C = Schantz Homes,

[b]Number of floor levels, S = split level, NB = no basement.

[c]House construction was not finished when measurement was taken.

Table A4: Leakage Area Measurements and Predicted Infiltration Rates in San Francisco Bay Area Houses

House ID	Effective Leakage Area (cm^2)		Specific Leakage Area (cm^2/m^2)		Infiltration Rate (ACH)
	Ducts Open	Ducts Sealed	Ducts Open	Ducts Sealed	Ducts Open
Houses Not Sealed with Foam (13 houses)					
1	793	777	5.4	5.3	0.44
2	861	671	5.9	4.6	0.48
3	935	717	6.4	4.9	0.52
4	558	510	4.6	4.2	0.38
5	896	817	6.1	5.6	0.50
6	774	706	6.4	5.8	0.52
7	770	698	5.2	4.8	0.43
8	395	286	2.7	1.9	0.22
9	568	401	3.7	2.6	0.35
10	1,551	944	6.1	3.7	0.62
11	1,293	841	5.5	3.6	0.60
12	1,011	757	5.1	3.8	0.57
13	1,032	818	4.9	3.9	0.51
Houses Sealed with Foam (13 houses)					
14	824	707	5.0	4.5	0.41
15	572	387	4.4	3.3	0.36
16	850	625	5.4	4.0	0.44
17	435	354	2.8	2.3	0.23
18	701	529	4.5	3.4	0.36
19	551	453	3.5	2.9	0.29
20	503	398	3.2	2.5	0.26
21	444	377	2.8	2.4	0.23
22	759	656	4.3	3.7	0.40
23	1,009	589	6.5	3.8	0.62
24	1,033	930	4.3	3.9	0.59
25	1,288	819	5.5	3.5	0.57
26	1,212	876	5.9	4.3	0.65

* Estimate

Table A5 : Energy Use Data for Eugene Energy-Efficient and Conventional Houses (for average heating year)

Avg. Floor Area (m^2)	Space Heating Energy (kWh/yr.)	Space Heating Energy (kWh/m^2-yr.)	Domestic Hot Water Energy (kWh/yr.)	Total Energy, excluding Domestic Hot Water (kWh/yr.)	Total Energy, excluding Domestic Hot Water (kWh/m^2-yr.)
Energy Efficient Houses					
107	3,743	34.7	3,172	12,750	119.2
107	3,489	32.4	7,423	12,946	120.4
102	2,600	25.5	11,045	13,264	129.7
102	2,241	22.0	4,776	8,388	82.2
108	2,854	26.6	4,564	9,347	86.8
102	2,299	22.0	4,003	9,518	92.6
114	5,161	45.2	6,682	16,368	143.6
84	2,484	30.1	4,656	7,498	89.2
84	2,561	30.1	4,726	8,400	100.7
134	5,296	39.4	3,716	9,012	67.2
Conventional Houses					
94	4,910	52.1	6,952	11,246	120.4
112	10,052	90.3	7,683	18,890	169.0
112	14,635	130.8	6,451	21,394	192.2
112	11,669	104.2	8,742	20,296	181.8
112	14,269	127.4	10,552	26,824	240.8
112	14,413	129.7	6,152	21,818	195.6
112	6,932	61.4	8,434	17,492	156.3
144	6,875	47.5	3,678	23,069	159.8
149	16,580	111.2	7,934	27,209	182.9
171	9,590	55.6	7,914	23,589	137.8

Table A6: Rochester Energy Modelling Results

Post-1976 Rochester homes energy performance results

House #	Floor Area (m^2)	K (Slope) ($W/^oC-m^2$)	T_{bal} (Intercept) (°C)	R^2 [a]	Heating System [b]
1	185	1.22	14.6	.94	EFA
2	185	0.91	18.6	.98	EFA
3	186	1.12	13.9	.94	EFA
4	207	0.89	16.0	.90	HP
5	203	0.89	15.1	.97	HP
7	175	0.94	15.7	.90	HP
8	189	1.08	16.7	.99	EFA
9	279	0.74	16.3	.96	EFA
10	168	1.02	15.3	.98	EFA
11	186	0.79	18.9	.88	HP
12	251	0.95	17.2	.99	EFA
13	186	0.99	13.0	.99	EFA
14	256	0.84	16.3	.96	EB
15	188	0.99	13.9	.93	EFA
22	258	0.69	18.6	.95	GFA
23	216	0.75	14.8	.99	GFA
24	171	0.91	16.4	.94	GFA
25	193	0.86	18.9	.98	GFA
26	193	1.30	16.6	.95	GFA
29	190	0.89	15.7	.87	GFA
30	204	0.92	16.7	.97	GFA
32	186	0.79	19.1	.98	GFA
35	177	0.92	17.6	.95	GFA
40	175	1.18	17.8	.99	GFA
47	151	1.20	16.5	.85	GFA
52	164	0.81	15.1	.85	EB
53	204	1.08	16.0	.97	HP
55	204	0.79	14.8	1.00	GFA

Pre-1976 Rochester homes energy performance results

House #	Floor Area (m^2)	K (Slope) ($W/^oC-m^2$)	T_{bal} (Intercept) (°C)	R^2 [a]	Heating System
37	186	1.31	15.5	.98	GFA
38	251	0.94	16.6	.98	GFA
39	283	1.16	16.9	.97	GFA
42	344	0.85	16.3	.97	GFA
43	178	1.43	17.5	.96	GFA
48	265	1.42	15.9	.92	GFA
50	251	1.12	15.3	.96	GFA
51	195	1.84	17.1	.96	GFA
54	181	1.58	16.0	.98	GFA
57	177	1.77	16.1	.93	GFA
58	130	1.26	14.2	.87	GFA

[a] Correlation coefficient
[b] EFA:electric forced air; GFA:gas forced air; HP:heat pump; EB:electric baseboard.

Table A7: Air Change Rates at 50 Pascals

Eugene Houses

HOUSE ID	ACH @ 50 Pa	House ID	ACH @ 50 Pa
A	8.6	H	9.1
B	7.1	I	8.8
C	6.8	J	5.8
D	6.0	Solar 1	6.6
E	5.4	Solar 2	6.7
F	4.4	Solar 3	5.8
		Avg 6.8 ± 1.4	

San Francisco Houses

Controls		Foam Sealed	
House ID	ACH @ 50 Pa	House ID	ACH @ 50 Pa
1	8.0	14	7.6
2	8.8	15	7.7
3	8.8	16	7.8
4	7.0	17	4.9
5	8.8	18	5.8
6	10.6	19	5.4
7	7.9	20	4.9
8	4.6	21	4.9
9	5.2	22	8.0
10	11.7*	23	9.3
11	8.7*	24	7.2*
12	9.7*	25	9.0*
13	8.1	26	9.5
Avg	8.3 ± 1.9	Avg	7.1 ± 1.7

*Estimate

Table A7: Continued

Rochester Houses (Pre-1976)

House ID	ACH @ 50 Pa	House ID	ACH @ 50 Pa
37	10.7	49	5.4
38	7.3	50	7.9
39	6.6	51	20.0
42	6.2	54	11.4
43	14.9	57	12.8
48	7.5	58	10.8

Avg. 10.1 ± 4.3

Rochester Houses (Post-1976)

House ID	ACH @ 50 Pa	House ID	ACH @ 50 Pa
1	6.5	25	6.7
2	4.0	26	6.3
3	4.6	27	6.5
4	6.1	28	6.3
5	6.9	29	6.2
6	6.0	30	5.4
7	8.0	31	5.7
8	7.0	32	5.1
9	6.4	33	4.7
10	5.6	34	5.8
11	6.8	35	12.4
12	7.4	36	10.5
13	6.6	40	6.5
14	5.5	41	6.2
15	6.8	44	4.7
16	6.6	45	4.6
17	7.1	46	5.7
18	9.7	47	8.0
19	5.9	52	6.4
20	4.6	53	6.8
21	4.9	55	11.4
22	5.4	56	8.4
23	4.0	60	5.9
24	6.5		

Avg 6.5 ± 1.7

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