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Modeling Study of the Cooling Season Performance of Exterior Wall Insulation

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ABSTRACT

A field test was performed during the summer of 1991 in Scottsdale, Arizona, to evaluate the space-cooling electricity savings and demand reduction potential of retrofitted exterior masonry wall insulation for single-family houses. Eight houses were retrofitted and monitored in the test. The insulation—extruded polystyrene covered by stucco—was installed on the masonry wall exterior at the middle of the summer test period. Total and air-conditioning system electricity consumptions in the houses were recorded during the entire test period. Meteorological data were collected from nearby weather stations.

The air-conditioning system energy use was analyzed using the DOE-2.1D program coupled with a detailed attic performance program. The predicted data were in good agreement with the measured data for five of the houses but low for the remaining three houses. However, the predicted percent energy savings for the retrofit measure were in good agreement with the measured data for all eight houses.

In Phoenix, the retrofit resulted in about 12% annual cooling energy savings. The savings are in the neighborhood of 8% to 10% in many southern U.S. regions. They are lower in the seacoast regions, particularly in Florida, where savings of 1% to 4% were predicted. Peak hour cooling energy savings were predicted to be more uniform throughout the country. They were calculated to be generally in the range of 8% to 12%.

BACKGROUND

A field test was performed during the summer of 1991 in Scottsdale, Arizona, to evaluate the potential of reducing space-cooling electricity consumption and demand by insulating the exterior walls of masonry houses. Eight single-family houses were selected and monitored for the test. They were occupied detached, single-story homes with uninsulated exterior masonry walls and having only central electric air-conditioning systems. In the middle of the test period, the exterior walls were insulated. The total electricity consumed by the house and the electricity consumed by the air conditioner were recorded for each residence on a half-hour basis during the entire test period. Meteorological data were collected at nearby weather stations.

This paper focuses on the modeling study performed in conjunction with the field test. The objectives of this were to check the internal consistency of the recorded data, to calibrate the computer program for extrapolating the measured savings, and to use the programs to estimate the annual savings for the test houses. These programs were then used to estimate the savings for this measure applied to a prototypical house at selected locations in the southern part of the United States.

The DOE-2.1D building simulation program (LBL 1989), coupled with an attic thermal performance program (Wilkes 1991a), was used in this study. DOE-2.1D is a widely used program, and Wilkes' model allows for a more detailed calculation of the attic thermal behavior.

TEST HOUSE DESCRIPTIONS

The test houses were occupied single-family dwellings located in the same general neighborhood and constructed about 1970. The general floor plans for these one-story houses are shown in Figure 1. Overall, they are quite similar. The conditioned spaces in two houses had been expanded by finishing the garage and the utility room. Small utility rooms were added on the backs of these two houses.

General characteristics of these houses are listed in Table 1. The conditioned areas were in the range of 1,120 to 1,585 square feet. Orientations listed in this table are the angles that the front walls of the houses face relative to north. The infiltration area ratios are the averages of those derived from blower-door measurements made before and after the insulation was installed. They represent the ratio of the infiltration leakage area, as defined by Sherman and Grimsrud (1980), to the conditioned space floor area. A ratio of 0.0005 is considered to be average. The impact of the insulation measure on the listed values was very minor.

The houses were built on uninsulated concrete slabs and had uninsulated masonry exterior walls. The walls were constructed of lightweight concrete blocks measuring 8 in. thick, 4 in. high, and 16 in. long and weighing 15 pounds. The interior surfaces were finished gypsum boards that were attached to the masonry by wood furring strips. Interior walls—including those between the living space, the garage, and the utility space—were framed drywall with no insulation.

All houses had 4-ft-wide front porch roofs that extended from the garage to about the middle of the house and 8-ft-wide rear patio roofs that extended about 60% of the length of the house.

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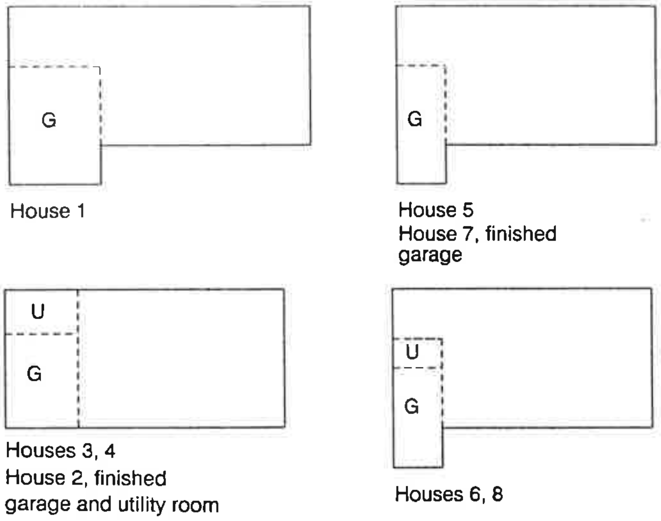

Figure 1 *General plans of the Scottsdale, Arizona, test houses.*

Available performance data for the air conditioners were limited. The nominal unit capacities, make, model number, and approximate age of the units were known. The energy-efficiency ratios (EERs), listed in Table 1, were estimated from these data and information published in the literature.

RETROFIT MEASURES

The primary retrofit measure was the insulation of the exterior wall. In addition, the interior walls between the conditioned space, the garage, and the utility room were insulated to produce a completely insulated envelope around the conditioned space.

The insulating material of the exterior wall was extruded polystyrene (XEPS) rigid boards approximately 1-in.-thick. These were installed by attaching 1.5-in.-thick wood furring strips to the walls, installing 1-in.-thick insulation boards between the strips, installing a second 1-in. insulation board layer over the furring strips and the first insulation layer, and applying stucco after a wire screen was attached. After the stucco had dried sufficiently, it was painted a light color.

A sample of the installed XEPS board was tested to determine its actual thermal resistance. At 90 days after manufacture and well within the post-retrofit test period, the tested resistance was 5.18 $h \cdot ft^2 \cdot °F/Btu \cdot in$. The thermal resistance of the insulation decreases with time as the air diffuses into the foam and the foam blowing agents diffuse outward. (It will approach a constant value as the XEPS becomes filled with air.) Using relations published in a CFC alternative technology study (Fischer et al. 1992), the average resistance of this material for the first 10 years was calculated to be 4.53 $h \cdot ft^2 \cdot °F/Btu \cdot in$. This compares to a 4.88 $h \cdot ft^2 \cdot °F/Btu \cdot in$. value using information provided by industry (Hendrickson 1992). The calculated value was used in this study, which implies slightly lower predicted energy savings. The thickness of the sample board measured was 1.04 in., and the density of the board measured was about 1.8 lb/ft^3.

The overall thermal resistance of the uninsulated test house walls (neglecting the external air films) is estimated to be 3.1 $h \cdot ft^2 \cdot °F/Btu$. Using the predicted XEPS properties, the retrofitted walls have estimated thermal resistances of 14.0 $h \cdot ft^2 \cdot °F/Btu$ during the retrofit test period and 12.8 $h \cdot ft^2 \cdot °F/Btu$ on average for the first 10 years after retrofit.*

*Values of 13.6 $h \cdot ft^2 \cdot °F/Btu$ and 12.4 $h \cdot ft^2 \cdot °F/Btu$ were used in the simulations due to an inadvertent error of using 1 in. instead of 1.04 in. XEPS board thickness. Furthermore, using the industrial predicted 10-year average value together with the 1.04 in. thickness for the XEPS board, the 10-year average wall thermal resistance would be 13.4 $h \cdot ft^2 \cdot °F/Btu$. The impact of these differences on the expected energy savings is small, altering the absolute savings less than 3%.

TABLE 1
General Characteristics of Scottsdale Test Houses

House	Living Area, sq ft	Orientlon Deg from N	Infiltration Area Ratio	A/C Capacity Tons	Assumed EER
1	1402	-45	0.00052	3	6.5
2	1400	-5	0.00054	3	6.5
3	1148	-45	0.00054	3	6.5
4	1120	-45	0.00038	3	8.5
5	1302	175	0.00066	4	8.5
6	1283	170	0.00050	3.5	6.0
7	1585	10	0.00067	4	8.5
8	1225	-10	0.00052	3	6.0

For the interior walls separating the garages and utility rooms from the conditioned living spaces, cellulose insulation was blown into the cavity areas during the retrofit operation. The thermal resistivity of this insulation is reported in the literature to be about 3.7 h·ft^2·°F/Btu·in. (LBL 1989; ASHRAE 1989). Using this value, insulating the interior wall increases the wall thermal resistance from 1.9 h·ft^2·°F/Btu to 11.9 h·ft^2·°F/Btu.

MONITORED DATA

During the entire test period—June 1, 1991, through October 19, 1991—the total electricity consumed by the whole house and that consumed by the air-conditioning system were recorded each half-hour by instruments installed at each house. In addition, instruments were installed in the living space of each house to measure and record the indoor temperature each hour. The averages of these temperatures for the pre-retrofit and post-retrofit periods selected for analysis are listed in Table 2. The houses were surveyed for geometrical construction features and for the number and type of occupants. As stated previously, the blower door tests were done prior to and following the installation of the wall insulation to measure the air leakage characteristics.

Hourly meteorological data were obtained from nearby weather stations. The ambient air data used in the analysis are the averages of the data collected at two stations, one located about five miles northwest of the test houses and the other located about five miles south of the houses. These data include ambient air temperature, relative humidity, hourly average wind speed, and barometric pressure. The average ambient air temperature for the two periods selected for the analysis are listed in Table 2. Total horizontal solar radiation data were obtained at a weather station located about 15 miles southeast of the test houses.

TABLE 2
Average Air Temperatures Recorded in the Scottsdale Test Houses, °F

House	Pre-retrofit test period, 6/2/91 - 7/27/91	Post-retrofit test period, 8/25/91 - 10/19/91
1	80.3	79.2
2	81.3	81.6
3	78.1	79.0
4	76.7	76.5
5	78.4	78.2
6	78.7	78.2
7	78.2	76.3
8	81.4	80.6
Ambient air	88.8	84.9

ANALYTICAL PROCEDURE

The DOE-2.1D building program (LBL 1989) was used to simulate the test houses using the indoor temperatures listed in Table 2 and the measured local weather data. These results were then normalized to a full year using the DOE-2 program and Phoenix, Arizona, Typical Meteorological Year (TMY) weather data (NOAA 1992) and assuming a 79°F indoor temperature. The 79°F value was about the average of the indoor temperatures in all the measured test houses. The DOE-2 program was then used to predict the impact of the external wall insulation measure for a prototypical house located in several cities.

The DOE-2 program is structured into four parts. For this analysis, only the first two parts, called LOADS and SYSTEMS, were used. In LOADS, the heat gain or loss is calculated hourly in each thermal zone at a preselected indoor temperature. Heat flows through the external walls and ceilings are calculated using response factors, and the heat flows through the internal walls and to the ground are calculated using steady-state relations. The portion of the heat gain that is transferred into the room air each hour is then calculated using the heat gain weighting factors. Each thermal zone air heat gain or loss is then adjusted in SYSTEMS for the actual zone temperature, heating and cooling system characteristics, and any window ventilation using the air temperature weighting factors. Heat flows through the zone walls are corrected in SYSTEMS for the adjusted air temperatures using steady-state heat transfer relations (LBL 1982).

In this study, the DOE-2 calculated heat flows through the ceilings of the conditioned spaces were replaced with those calculated using Wilkes' thermal model for attics (Wilkes 1991a). They were replaced in LOADS at the point before the weighting factors were applied. The steady-state wall and ceiling heat transfer adjustment in SYSTEMS was assumed to be valid.

In Wilkes' model, exterior surface (including the ceiling) heat gains and losses are also calculated hourly using response factors. However, the attic air temperature is allowed to change hourly and is determined using a direct heat balance instead of weighting factors. This gave more direct control over the attic internal radiation and convective heat transfer calculations. The air temperature on the conditioned-zone side of the ceiling was assumed to be equal to that specified for LOADS in the DOE-2 program.

The internal loads for the test houses were estimated somewhat subjectively using differences of the measured total and air conditioner electricity consumption values, house occupancy data, appliance data, and internal load data reported in the literature (ASHRAE 1989; Huang et al. 1987). These estimated loads are listed in Table 3. The internal loads in house 2 are higher, and different values were assumed for the weekends and holidays since it had a child care facility.

For the test house air conditioners, the EERs were assumed to be those listed in Table 1, and the degradation

TABLE 3
Estimated Internal Loads
for the Scottsdale Test Houses, Btu/day

House	Living space		Utility room	Garage
	Sensible	Latent	Sensible	Sensible
1	61,750	11,070	-	10,840
2	115,350 WD* 102,480 WEH	28,010 WD* 18,300 WEH	1,260	-
3	48,260	16,840	10,840	-
4	67,590	12,280	10,470	16,400
5	39,660	12,710	-	10,470
6	66,830	10,520	10,840	10,520
7	60,630	19,180	8,200	-
8	54,900	18,240	11,200	-

* WD refers to weekdays; WEH refers to weekdays and holidays

coefficient was assumed to be 0.25. No allowance was made for duct heat gains or leakage. The DOE-2.1D default relations were used for the other performance parameters.

COMPARISON OF PREDICTED AND MEASURED DATA

For data comparison, an eight-week period from June 2, 1991, through July 27, 1991, was selected for the pre-retrofit calculations, and a second eight-week period from August 25, 1991, through October 19, 1991, was selected for the post-retrofit calculations. The exterior and interior wall insulation measures were essentially completed between these two test periods. Painting of the stucco walls for some of the houses was not completed until the first week in September, but this did not appear to have a significant impact on the analysis.

A number of DOE-2 runs were made, adjusting the input parameters to try to match the test data. For each house, the air conditioner setpoint temperature for each eight-week period was specified to be the average value listed in Table 2. The comparisons of the predicted and measured air-conditioning electricity consumptions are presented in Table 4. The values are within 10% for four of the houses, about 17% low for one house, and about 30% to 40% low for three houses.

A number of reasons could be suggested for why the predicted values for some of the houses were low. Detailed investigation of these was beyond the scope of this study. Factors such as much higher internal loads and greater window shade openings than the assumed values could contribute to the difference. One strong possibility is heat gains and leaks in the air-conditioning system's circulating air ducts. The central units for many of the houses (including the ones having low ratios) were mounted on the roof, with the supply and return air ducts penetrating through the roof. The effective efficiency of the air-conditioning system could be degraded for the air distribution systems located in the attics, where air temperatures can be relatively high during the summer. This degradation could be very significant if there are air leaks in the duct or if there is missing or limited thermal insulation on the ducts.

Tables 5 and 6 show comparisons of the predicted and measured weekly values for air-conditioning system electricity for two of the houses. Table 5 data are for a house having a good comparison, and Table 6 data are for a house having a predicted to measured ratio of about 0.7. In all cases, the consistency between the weekly ratios and the total test period ratios is generally within 10%. Moreover, the ratios are consistent for each house before and after the wall insulation measure was done. This leads to the conclusion that the measured data are internally consistent. Since a primary purpose of this analysis is to estimate the percentage energy savings that would be realized for this measure, the simulation model is sufficient.

NORMALIZATION OF THE TEST HOUSE DATA

The measured electricity consumption of the air conditioner during the eight-week post-retrofit period averaged about 30% less than that for the pre-retrofit period. These data, however, must be corrected for differences in indoor temperatures and weather conditions. Ambient air temperatures and solar radiation were lower during the post-retrofit period.

TABLE 4
Comparison of Predicted and Measured Air-Conditioner Electricity Consumption for the Scottsdale Test Houses

House	Pre-retrofit test period, 6/2/91 - 7/27/91			Post-retrofit test period, 8/25/91 - 10/19/91		
	Measured, kWh	DOE-2.1D predicted, kWh	Predicted / Measured	Measured, kWh	DOE-2.1D predicted, kWh	Predicted / Measured
1	3064	1838	0.60	2060	1316	0.64
2	2376	1949	0.83	1754	1463	0.83
3	1956	1977	1.01	1166	1258	1.08
4	1488	1563	1.05	1155	1169	1.01
5	2153	1492	0.69	1474	959	0.65
6	2913	2121	0.73	2102	1520	0.72
7	1879	1735	0.92	1466	1385	0.94
8	1661	1600	0.96	1069	1190	1.11

TABLE 5
Comparison of Predicted and Measured Air-Conditioner Electricity Consumption for Scottsdale Test House 4

Week	Pre-retrofit test period, 6/2/91 - 7/27/91			Post-retrofit test period, 8/25/91 - 10/19/91		
	Measured, kWh	DOE-2.1D predicted, kWh	Predicted / Measured	Measured, kWh	DOE-2.1D predicted, kWh	Predicted / Measured
1	44*	50*	1.15	197	195	0.99
2	132	153	1.16	175	169	0.97
3	174	189	1.09	130	139	1.07
4	138	161	1.17	135	148	1.10
5	241	267	1.11	157	157	1.01
6	242	244	1.01	149	132	0.89
7	266	261	0.98	117	129	1.10
8	253	238	0.94	96	99	1.03
Total	1488	1563	1.05	1155	1169	1.01

* Electricity consumption measured only the last two days.

The energy savings data were normalized using the DOE-2.1D program to predict the electrical energy consumption of the air conditioners in the houses for an entire year with and without the walls being insulated. The thermostat setpoints were assumed to be 70°F for heating and 79°F for cooling. The 79°F value is about the average of all the indoor temperatures measured in the houses during the test. Phoenix TMY weather data were used for these calculations.

Results of these calculations are shown in Table 7. The average normalized air-conditioner electricity saving for these houses is about 640 kWh, or 11.5%. The percent savings range from about 7% to 14%. The lowest savings are for house 2, which had a much greater internal load (Table 3). The average peak-hour saving for the year is about 0.7 kWh, or about 14%. This is somewhat dependent, of course, on internal load schedule.

TABLE 6
Comparison of Predicted and Measured Air-Conditioner Electricity Consumption for Scottsdale Test House 6

Week	Pre-retrofit test period, 6/2/91 - 7/27/91			Post-retrofit test period, 8/25/91 - 10/19/91		
	Measured, kWh	DOE-2.1D predicted, kWh	Predicted / Measured	Measured, kWh	DOE-2.1D predicted, kWh	Predicted / Measured
1	241	165	0.68	361	267	0.74
2	252	178	0.71	312	224	0.72
3	328	238	0.73	241	175	0.72
4	285	194	0.68	263	190	0.72
5	472	360	0.76	289	207	0.71
6	429	325	0.76	238	169	0.71
7	476	350	0.73	222	166	0.75
8	432	312	0.72	176	123	0.70
Total	2913	2121	0.73	2102	1520	0.72

TABLE 7
Predicted Annual Air-Conditioner Electricity Consumption for the Scottsdale Test Houses, Phoenix TMY Weather Data, 79°F Indoor Temperature

House	Annual				Peak hour			
	Pre-retro, kWh	Post-retro, kWh	Chg, kWh	Chg, %	Pre-retro, kWh	Post-retro, kWh	Chg, kWh	Chg, %
1	6152	5325	827	13.4	5.27	4.82	0.46	8.7
2	7066	6582	484	6.8	5.47	4.78	0.69	12.6
3	5697	5035	662	11.6	5.04	4.36	0.68	13.4
4	4373	3902	471	10.8	3.69	3.13	0.56	15.2
5	4413	3794	619	14.0	4.52	3.79	0.72	16.0
6	6334	5688	646	10.2	6.12	5.27	0.85	13.9
7	5111	4426	685	13.4	4.85	4.04	0.81	16.6
8	6249	5533	716	11.5	5.59	4.78	0.81	14.6
Average			639	11.5			0.70	13.9

PROTOTYPICAL HOUSE DESCRIPTION

The calculations were extended to predict the impact of selected independent parameters and location on the retrofit energy savings. For this part of the study, a 1,540 ft^2 ranch-style prototypical house was selected. This 55-ft-long by 28-ft-wide house has been used in several other studies (Huang et al. 1987; Labs et al. 1988; Wilkes 1991b). In its base configuration, the house has no attached unconditioned garage or utility room. It has a 184.8-ft^2 window area, or 12% of the floor area. When the front of the house faces south, 88.8 ft^2 of the window area is on the north wall, 70.4 ft^2 is on the south wall, and 25.6 ft^2 is on the west wall. Additional details of the house can be found in the cited references.

The exterior masonry wall construction for the prototypical house was assumed to be the same as that for the Scottsdale test houses, and the same materials and construction were used for the retrofit. The calculated 10-year average XEPS insulation thermal resistance value and single-glazed windows were assumed. Furthermore, the walls were specified to be painted with a light tan paint having a solar absorptance of 0.45. A solar absorptance of 0.7 was used for the roof. The floor was considered to be an uninsulated, carpeted concrete slab.

The calculations were done with the house in both an east-west orientation (front facing south) and a north-south orientation (front facing east). Both R-19 and R-30 blown fiberglass ceiling insulations were considered. These are the insulation values recommended by the Department of Energy for a large portion of the country's southern region (DOE 1988). Moreover, many of the existing houses in this region now have ceiling insulation with R-values in the neighborhood of R-19 (DOE 1987).

The internal loads used for the prototypical house were those suggested by Huang et al. (1987), which are 56,100 Btu/day sensible heat and 12,150 Btu/day latent heat. The thermostat was set at 78°F for cooling and 70°F for heating. When conditions permitted, the windows were opened for cooling, provided the outside air enthalpy was lower than the inside air enthalpy. They were closed during nighttime hours. The house infiltration area ratio was taken to be 0.0005, that for a typical house (Sherman and Grimsrud 1980).

An EER of 8.0 was used for the air conditioner, which is a typical value for medium-efficiency units (Peterson 1989). As for the test houses, no allowance was made for heat gains or losses in the air distribution systems, although it is recognized that systems located in attics can have such losses. Ignoring these losses will not have an impact on the percent savings predicted for the measure but would decrease the absolute energy savings.

IMPACTS OF SELECTED PARAMETERS

The impacts of a number of independent parameters on the expected annual cooling energy savings by insulating the external wall were calculated for the prototypical house using Phoenix TMY weather data. In its base configuration, the house is assumed to have R-19 ceiling insulation and no shading except for the eaves. Results of these calculations are presented in Table 8. The impact of the external wall insulation measure for the house is 11% and 13%, depending on the orientation of the house.

For Phoenix, the impacts of the selected parameters are small compared to the impact of adding the wall insulation. Increasing the thermostat cooling setpoint from 78°F to 79°F reduces the cooling load and slightly reduces the savings to 10.9% and 12.8%, depending on the orientation of the house. These values are in general agreement with

TABLE 8
Predicted Impacts of Selected Parameters on the Annual Air-Conditioning Electricity Savings for the Prototypical House in Phoenix

House configuration	East-west orientation			North-south orientation		
	Base, kWh	Savings, kWh	Savings, %	Base, kWh	Savings, kWh	Savings, %
Base configuration	5430	704	13.0	6171	677	11.0
Cooling setpoint increased from 78°F to 79°F	4984	639	12.8	5176	623	10.9
Original wall R-value reduced from 3.1 to 2.5	5592	862	15.4	6326	829	13.1
Internal load reduced 25%	5132	729	14.2	5871	705	12.0
Added garage	5389	789	14.6	6041	732	12.1
Added garage and porch shade	5319	795	14.9	5595	749	13.4
Added garage, porch shade, and lot boundary wall	5247	774	14.8	5545	742	13.8
Ceiling insulation increased from R-19 to R-30	5236	717	13.7	5987	694	11.6

the 11.5% normalized average for the Scottsdale test houses.

Houses with walls constructed of materials having a lower thermal resistance than those of the Scottsdale test houses (heavyweight concrete block, for example) exhibit greater cooling loads and greater retrofit energy savings. (Here the uninsulated wall R-value was reduced from 3.1 to 2.5 and that of the insulated wall from 12.4 to 11.5.) Reducing the internal loads, adding a 20-ft-by-20-ft garage to the front of the house, adding porch roofs, and adding opaque property walls all resulted in lower cooling energy consumption but a small increase in the percentage of retrofit energy savings (due to the reduced base load). Increasing the ceiling thermal resistance also results in decreased cooling loads and slightly higher percentage savings.

LOCATION IMPACTS

The impacts of adding external wall insulation were calculated using TMY weather data for a number of cities in the southern region of the country. The base prototypical house was used for these simulations, and both R-19 and R-30 ceiling insulation values were considered.

The predicted annual air-conditioning electrical energy savings are presented in Table 9. For the locations investigated, the savings are the greatest—10% to 14%—for the houses in Phoenix and Las Vegas. In contrast, they are the lowest—1% to 5%—for the houses in Florida. In many locations, the expected savings are in the range of 8% to 10%.

Subsequent investigations showed that the wall heat gain, together with the internal load and the glazing solar heat gain is the major component of the cooling load in Phoenix. Insulating the walls results in significant cooling load reductions there. There is a relatively rapid decrease in the cooling load in October due to substantial drops in the ambient air temperatures and the large infrared sky temperature depressions (Martin and Berdahl 1984). At these times, the wall heat loss becomes sufficiently large that the addition of insulation does not cause an increase in the cooling load from the other heat gain components.

In Miami, the contribution of the external wall heat gains to the cooling load is much smaller due to the lower ambient air temperatures. The load reductions due to the addition of wall insulation are smaller, and there can even be an increase in the loads in the fall. This is because the ambient air temperature does not decrease very rapidly and the infrared sky temperature depression is small (Martin and Berdahl 1984). Under these conditions, the wall insulation results in a sufficient retention of the other heat gain components to cause an increase in the cooling load.

The effect of the ceiling insulation on the total energy is small, but the percentage is again higher for the R-30 insulation since the energy consumed for the base case is lower. The effect of the house orientation is noticeable, reflecting the differences in the wall and window areas in each direction.

For the peak hour, the percentage savings are more uniform, as shown in Table 10. They are generally in the range of 8% to 12%, although there are a few cases where they are higher. These percentages translate to peak-hour savings generally in the range of 0.25 kWh to 0.5 kWh.

The predicted electricity savings, presented in Tables 9 and 10, included the effects of assumed air conditioner operating performance relations. These often result in higher energy use values when the unit is operating at off-design conditions. For comparison, the percentage reductions in the annual cooling load and the peak-hour cooling load are presented in Tables 11 and 12. For most cases, the percentages are about 1 to 4 points higher than the electricity savings.

Although this investigation focused on cooling energy savings, the model included the heating energy savings that would be realized by adding the exterior wall insulation. These results are presented in Figure 2 as a function of heating degree-days. For the locations considered, about a third of the heating energy could be saved. The energy used in the base configuration is a nearly linear function of the heating degree-days.

CONCLUSIONS

For the purpose of estimating energy savings that could be realized by insulating the external walls, the DOE-2.1D simulation program, coupled with Wilkes' attic thermal program, successfully matched the performance data obtained for the Scottsdale test houses. Predicted energy use data were low for some of the houses, but they were low by the same fraction before and after the insulation was installed. This suggests that other factors, such as exterior heat gains or leaks in the circulating air distribution system, added to the cooling load.

Using the programs to normalize the test house data for a typical year, the wall insulation measure resulted in about 12% annual cooling energy savings and 14% peak-hour savings for the test houses. These values are equivalent to a 640-kWh annual cooling saving and a 0.7-kWh peak-hour saving. Parameters such as the presence of attached unconditioned spaces or shading can result in reduced cooling loads but do not have a strong influence on the percentage savings associated with the wall insulation measure.

For a prototypical house having the same basic construction as the masonry test houses, the predicted annual cooling energy savings are in the range of 10% to 14% for the houses located in Las Vegas and Phoenix. They are in the range of 8% to 10% in many other locations, but they drop considerably in the more humid regions, such as Florida, where they were only 1% to 5%. Further investigations indicated that the low values are due to the relative uniformity of the ambient air temperature and low infrared sky temperature during the year. The percentage peak-hour cooling load reductions are predicted to be more uniform with location, generally being in the range of 8% to 12%.

TABLE 9
Predicted Annual Air-Conditioning Electricity Savings for the Prototypical House at Selected Locations

Location	East-west orientation			North-south orientation		
	Base, kWh	Savings, kWh	Savings, %	Base, kWh	Savings, kWh	Savings, %
	R-19 ceiling insulation					
Albuquerque, NM	928	99	10.7	1274	80	6.3
Atlanta, GA	1077	91	8.4	1389	68	4.9
El Paso, TX	2231	227	10.2	2851	205	7.2
El Toro, CA	550	41	7.5	718	30	4.2
Fort Worth, TX	3130	356	11.4	3616	340	9.4
Fresno, CA	1940	211	10.9	2508	187	7.5
Houston, TX	3129	225	7.2	3537	207	5.9
Jackson, MS	2050	185	9.0	2454	167	6.8
Lake Charles, LA	2423	150	6.2	2798	132	4.7
Las Vegas, NV	4159	493	11.9	4901	468	9.5
Memphis, TN	1958	191	9.8	2356	183	7.8
Miami, FL	4308	71	1.6	4805	36	0.7
Orlando, FL	3121	137	4.4	3558	113	3.2
Phoenix, AZ	5430	704	13.0	6171	677	11.0
	R-30 ceiling insulation					
Albuquerque, NM	858	98	11.4	1205	85	7.1
Atlanta, GA	1008	92	9.1	1324	75	5.7
El Paso, TX	2113	233	11.0	2741	212	7.7
El Toro, CA	718	30	8.1	681	37	5.4
Fort Worth, TX	3025	364	12.0	3517	369	9.9
Fresno, CA	1825	215	11.8	2399	193	8.0
Houston, TX	3028	229	7.6	3442	211	6.1
Jackson, MS	1944	188	9.7	2354	172	7.3
Lake Charles, LA	2329	154	6.6	2708	136	5.0
Las Vegas, NV	4011	502	12.5	4762	477	10.0
Memphis, TN	1868	195	10.4	2273	189	8.3
Miami, FL	4185	71	1.7	4686	33	0.7
Orlando, FL	3011	139	4.6	3453	108	3.1
Phoenix, AZ	5236	717	13.7	5987	674	11.6

TABLE 10
Predicted Peak Hour Air-Conditioning Electricity Savings for the Prototypical House at Selected Locations

Location	East-west orientation			North-south orientation		
	Base, kWh	Savings, kWh	Savings, %	Base, kWh	Savings, kWh	Savings, %
	R-19 ceiling insulation					
Albuquerque, NM	2.66	0.43	16.3	3.19	0.40	12.4
Atlanta, GA	2.38	0.25	10.6	2.56	0.25	9.6
El Paso, TX	2.67	0.33	12.2	3.14	0.30	9.5
El Toro, CA	1.72	0.32	18.4	2.16	0.30	14.0
Fort Worth, TX	3.60	0.48	13.3	3.93	0.40	10.2
Fresno, CA	3.19	0.36	11.4	3.56	0.53	9.9
Houston, TX	3.56	0.41	11.4	3.85	0.37	9.6
Jackson, MS	2.58	0.32	12.4	2.87	0.33	11.6
Lake Charles, LA	2.67	0.30	11.1	3.03	0.28	9.1
Las Vegas, NV	4.62	0.66	14.2	4.74	0.33	7.0
Memphis, TN	2.63	0.32	12.0	2.92	0.32	10.9
Miami, FL	2.45	0.25	10.0	2.72	0.25	9.1
Orlando, FL	2.80	0.26	9.1	2.96	0.24	8.1
Phoenix, AZ	4.71	0.67	14.1	4.90	0.42	8.6
	R-30 ceiling insulation					
Albuquerque, NM	2.52	0.47	18.6	3.06	0.41	13.5
Atlanta, GA	2.28	0.26	11.3	2.46	0.25	10.2
El Paso, TX	2.57	0.33	13.0	3.04	0.31	10.1
El Toro, CA	1.64	0.33	20.0	2.09	0.31	15.0
Fort Worth, TX	3.51	0.49	13.9	3.85	0.41	10.6
Fresno, CA	3.07	0.38	12.2	3.46	0.37	10.7
Houston, TX	3.47	0.41	11.7	3.76	0.38	10.1
Jackson, MS	2.50	0.33	13.2	2.80	0.34	12.1
Lake Charles, LA	2.59	0.31	12.1	2.96	0.28	9.5
Las Vegas, NV	4.49	0.68	15.2	4.74	0.47	10.0
Memphis, TN	2.54	0.33	12.8	2.83	0.33	11.6
Miami, FL	2.39	0.24	9.9	2.66	0.25	9.5
Orlando, FL	2.73	0.26	9.5	2.90	0.25	8.5
Phoenix, AZ	4.58	0.69	15.0	4.90	0.57	11.6

TABLE 11
Predicted Annual Cooling Load Reductions for the Prototypical House at Selected Locations

Location	East-west orientation		North-south orientation	
	Base, MBtu	Savings, %	Base, MBtu	Savings, %
	R-19 ceiling insulation			
Albuquerque, NM	4.2	17.2	6.7	9.4
Atlanta, GA	6.0	12.2	8.4	6.7
El Paso, TX	13.6	12.5	18.2	8.7
El Toro, CA	1.8	18.9	3.0	9.2
Fort Worth, TX	20.4	13.3	24.1	10.9
Fresno, CA	11.2	14.4	15.4	9.7
Houston, TX	21.5	8.4	24.7	6.9
Jackson, MS	13.4	11.0	16.5	8.3
Lake Charles, LA	16.6	7.6	19.5	5.8
Las Vegas, NV	25.5	14.1	30.9	11.3
Memphis, TN	12.5	12.0	15.6	9.5
Miami, FL	31.9	2.3	35.9	1.3
Orlando, FL	22.1	5.3	25.6	3.9
Phoenix, AZ	34.4	14.8	39.9	12.6
	R-30 ceiling insulation			
Albuquerque, NM	3.7	19.2	6.2	10.5
Atlanta, GA	5.5	13.0	7.9	7.7
El Paso, TX	12.7	13.5	17.4	9.3
El Toro, CA	1.5	21.7	2.8	11.9
Fort Worth, TX	19.6	14.0	23.4	11.5
Fresno, CA	10.4	15.7	14.6	10.5
Houston, TX	20.7	8.8	23.9	7.2
Jackson, MS	12.6	11.9	15.7	8.9
Lake Charles, LA	15.8	8.0	18.8	6.2
Las Vegas, NV	24.4	14.8	29.9	11.8
Memphis, TN	11.8	12.8	14.9	10.1
Miami, FL	31.0	2.4	34.9	1.3
Orlando, FL	21.3	5.6	24.7	3.9
Phoenix, AZ	33.0	15.6	38.6	13.2

TABLE 12
Predicted Peak Hour Cooling Load Reductions for the Prototypical House at Selected Locations

Location	East-west orientation		North-south orientation	
	Base, MBtu	Savings, %	Base, MBtu	Savings, %
	R-19 ceiling insulation			
Albuquerque, NM	16.6	19.0	20.7	15.3
Atlanta, GA	16.7	12.0	18.2	11.0
El Paso, TX	17.4	14.3	21.5	7.6
El Toro, CA	11.9	20.6	15.1	15.5
Fort Worth, TX	24.9	15.5	27.6	12.5
Fresno, CA	20.0	13.8	24.1	13.1
Houston, TX	25.9	13.1	28.5	11.6
Jackson, MS	18.7	14.1	21.5	13.6
Lake Charles, LA	20.3	13.0	23.7	11.0
Las Vegas, NV	27.0	18.4	29.7	14.7
Memphis, TN	18.8	13.7	21.2	12.6
Miami, FL	18.9	11.2	21.2	10.4
Orlando, FL	21.0	10.6	22.5	9.6
Phoenix, AZ	27.7	18.2	29.8	13.2
	R-30 ceiling insulation			
Albuquerque, NM	15.5	20.4	19.7	16.3
Atlanta, GA	15.9	12.7	17.7	11.9
El Paso, TX	16.6	14.6	20.9	7.9
El Toro, CA	11.2	22.0	14.9	16.2
Fort Worth, TX	24.2	16.1	26.9	12.9
Fresno, CA	19.1	14.6	23.3	13.6
Houston, TX	25.1	13.6	27.8	12.1
Jackson, MS	18.0	14.8	20.8	14.1
Lake Charles, LA	19.6	13.6	23.0	11.4
Las Vegas, NV	26.0	19.3	29.0	16.5
Memphis, TN	18.1	14.5	20.5	13.2
Miami, FL	18.5	10.6	20.7	10.1
Orlando, FL	20.4	11.0	21.9	10.0
Phoenix, AZ	26.6	19.1	29.2	15.4

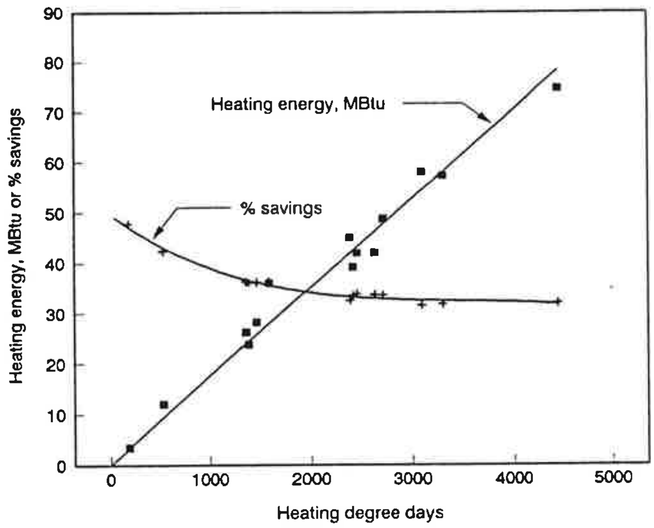

Figure 2 *Predicted annual heating energy and retrofit energy savings for the prototypical house at selected locations.*

Although the study did not focus on the heating energy savings, the calculations indicate that about a third of the heating energy could be saved by the wall insulation measure.

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