How Insulating Concrete Form vs. Conventional Construction of Exterior Walls Affects Whole Building Energy Consumption: Results from a Field Study and Simulation of Side-by-Side Houses

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ABSTRACT

Results are given from a field investigation of side-by-side houses in Knoxville, Tennessee. The houses were identical except one had insulating concrete form (ICF) exterior walls and the other had conventional wood-framed exterior walls. Monitoring commenced in July 2000 and continued for eleven months. The houses were unoccupied and operated on the same simple schedules. The total energy consumption from July 2000 through June 2001 (estimated for June 2001) showed that the ICF house used 7.5% less energy than the conventional house.

The monitoring provided data sufficient to validate annual energy usage models of the two houses as they were tested. The validated models for the unoccupied houses on simple schedules were exercised for a range of climates that included heating dominated and cooling dominated. TMY2 weather data were used to simulate the different climates. The ICF house used 5.5% to 8.5% (6.8% in the Knoxville climate) less energy annually than the conventional house. In Knoxville, changing from unoccupied houses with simple operation to normal occupancy and operation increased the annual savings for the ICF house relative to the conventional house to 9.2%. This advantage of the ICF house over the conventional house decreased only slightly to 9.0% when minimal energy usage was postulated for both houses during the swing season in East Tennessee. During this approximately 15 week period of mild weather the test houses were operated without any heating or cooling. There were wider variations of air temperature in the conventional house than in the ICF house.

Introduction

For some time, lightweight wood-framed exterior envelopes have been the conventional choice in the North American residential construction industry. That does not say that they are the traditional choice. In certain climates, thermally massive building envelopes, made, for example, from masonry, concrete or earth, are the traditional choice. Thermally massive construction techniques can provide comfortable, sturdy, aesthetically pleasing, environmentally friendly and energy efficient building envelopes.

Among the thermally massive construction techniques, insulating concrete form (ICF) construction has become a well-developed and popular choice. In ICF construction, the concrete forms are two layers of foam insulation that are held apart by webbing. The webbing is capable of supporting reinforcing bars and allows concrete to be poured between the layers of foam insulation to form a continuous concrete exterior wall from the footing to the roof. Temporary supports are used during the concrete pours to ensure that the walls are plumb. When the temporary supports are removed, the foam insulation and webbing stay in place along with the concrete core. A well-insulated and thermally massive exterior envelope results to which conventional finishes can be applied on the inside and outside.

This paper gives results from a field investigation and simulation of two side-by-side houses. The houses were identical except one had ICF exterior walls and the other had conventional wood-framed exterior walls. The single-story houses with 102 m² (1094 ft²) of floor area were constructed in the Knoxville, Tennessee area beginning in April 2000. Eleven months of monitoring commenced in July 2000. Monitoring and analysis were performed by the Oak Ridge National Laboratory with support of the Insulating Concrete Forms Association and Loudon County (Tennessee) Habitat for Humanity, Inc.

The monitoring provided data sufficient to validate annual energy usage models of the two houses as they were tested in the Knoxville climate. Validated models can be exercised for other climates and operating conditions. The project sought to extend our understanding of the benefits of thermal mass that has been developed in previous work, especially at the Oak Ridge National Laboratory (Burch 1984a, Burch 1984b, Burch 1984c, Christian 1991, Kosny 1998, Kosny 2001, Kossecka 1998). This work has shown that the principal benefit of thermal mass on thermal performance is to dampen fluctuations in interior conditions during significant fluctuations in outside conditions.

Besides continuous monitoring of the thermal performance of the test houses, we did blower door tests at several times during the year. Insights from them are given. Out of the records of measured energy consumption, results for four weeks during the cooling season and four weeks during the heating season are extracted for detailed comparison to the hour-by-hour predictions of energy usage. Parameters to which the models were most sensitive are listed. The house models with no occupants and simple operation are exercised for other climates. In the Knoxville climate, alternate occupancy and schedules of operation are imposed. These exercises enhance the lessons of the side-by-side monitoring. Special attention is paid to the long periods in spring and fall when weather is very mild in East Tennessee and little heating or cooling is required. A significant effect of thermal mass was noticed.

House Construction and Operation

The software that was used to predict hour-by-hour energy usage in the side-by-side test houses was DOE2.1E and, for a few cases, DOE2.2 (LBNL 1993). The features of house construction and operation presented in Table 1 focus on the detailed but simple description that DOE2 required.

Two heat flux transducers in each house under the attic insulation were used to estimate center-of-cavity R-value of the loose-fill attic insulation. Ceiling R-value included corrections for the trusses and less insulation depth at the eaves. For the R-value of the floor over the vented crawlspace in each house, joists were counted to estimate the framing effect. The R-value of the batt insulation was degraded to correct for flaws and penetrations. The R-values of the finished exterior walls were specified using the whole-wall R-value estimation procedure developed at the Oak Ridge National Laboratory (Christian 1998). We tested the unfinished wall system for the ICF house in a guarded hot box.

The Sherman-Grimsrud infiltration method was specified in DOE2. It requires an estimate of leakage area divided by floor area for the building. Blower door tests on the side-by-side houses in March 2001 yielded the maximum leakage area divided by floor area that was observed during the project. These fractional leakage areas in Table 1 fall between 0.0003, which is considered typical of tight construction, and 0.0005, which is considered typical of average construction.

To achieve agreement between measured and predicted crawlspace air temperatures during summer and winter, heat transfer with the dirt floors of the crawlspaces and ventilation flow through the crawlspace vents were different in each house. About half of the ICF crawlspace floor was not covered by plastic in order to encourage drying of the water that leaked into the ICF crawlspace before landscaping was complete. This also justified leaving the ICF crawlspace vented during the whole experiment, contrary to original plans. Louvers in the vents for the conventional house were partially closed at the end of the summer to achieve equal vent areas in both crawlspaces for the rest of the monitoring period.

The ventilation rates and the heat transfer coefficients in Table 1 allowed for the effect of the return and supply ducts that ran through the crawlspaces. Temperature changes from inlet to outlet of the supply ducts were measured as part of the data monitoring. Measurements of duct leakage were done during the blower door tests. Duct air leakage at 25 Pa is presented in Table 1 as a percentage of the nominal supply air flow rate of 22.7 m^3/min (801 cfm). Inspection of the duct system did not reveal any noticeable leaks. To achieve agreement between measurements and modeling of overall energy usage, 7% air loss was used in the model. The measured values were judged to be uncertain enough that loss as low as 7% was reasonable.

Table 1. Construction and Operational Features of the Side-by-Side Houses

Feature	ICF House	Conventional House
Ceiling R-value	5.0 m^2·K/W [28.4 h·ft^2·°F/Btu]	5.0 m^2·K/W [28.4 h·ft^2·°F/Btu]
Floor R-value	3.2 m^2·K/W [17.9 h·ft^2·°F/Btu]	3.2 m^2·K/W [17.9 h·ft^2·°F/Btu]
Exterior Wall R-value	2.6 m^2·K/W [15.0 h·ft^2·°F/Btu]	1.9 m^2·K/W [10.6 h·ft^2·°F/Btu]
Leakage/Floor Area	0.00038	0.00042
Crawlspace Ventilation	0.03 m/min [0.1 cfm/ ft^2]	0.03 m/min [0.1 cfm/ ft^2][1]
Heat Transfer Coeff. with Crawlspace Floor	5.7 W/(m^2·K) [1.0 Btu/(h·ft^2·°F)]	2.8 W/(m^2·K) [0.5 Btu/(h·ft^2·°F)]
Duct Air Loss to Outside/Supply Air	7.7% to 7.9% (used 7%)	7.9% to 8.7% (used 7%)

[1] Crawlspace ventilation rate in the conventional house was twice this value during summer before adjustment of louvers on the vents.

Because the supply ducts in the side-by-side houses ran through unconditioned spaces, DOE2 was very sensitive to duct air loss. Duct air loss of 7% relative to no duct air loss had an effect comparable to doubling the fractional leakage area for infiltration. Both increased annual energy usage more than 11%. The measured temperature changes in the supply ducts were at most a few degrees. Their effect relative to no temperature changes was not very significant. They increased annual energy usage less than 1.5%. Fractional leakage area for infiltration and the R-values of the roofs, floors and walls were judged to be more certain than the duct air loss. Although DOE2 was also very sensitive to the values of these parameters, they were not changed from the values indicated by the measurements.

For most of the year, the internal load in both houses was the same and equal to 0.130 kW. Equal internal loads required a dummy load in the ICF house to offset the effects of a computer in the conventional house. The dominant user of electrical power in the houses was the heating/cooling systems. Pulse-generating kilowatt-hour meters were used to meter the total energy usage in the all-electric houses. Uncertainty in the total rate of electricity usage in the houses is estimated to be ±0.014 kW. This corresponds to the power indicated by a half revolution of the pulse generator disks in the kilowatt-hour meters in the 15 minute interval that was selected for reporting of raw data.

Heating in both houses was done with electrical resistance heaters in order to decrease the uncertainty of measuring the heating energy delivered to the living spaces. A total of 10 kW capacity was installed in each house. Cooling in both houses was done with the air-to-air heat pumps in air-conditioning mode. Capacities of 7 kW (2 Ton) and seasonal coefficients of performance of 3.5 were taken from manufacturer specifications. Inside and outside fan energy requirements and part load compressor performance were allowed to default to DOE2 curves for its RESYS2 system that was selected to model the house systems.

Thermostat set point in the houses was a constant 22°C (72°F) summer and winter. The circulation fans were continuously on during heating and cooling except for a few weeks in spring when we tried intermittent operation. There were 15 weeks during the fall and spring when neither heating nor cooling nor fans were used in the houses. Living space temperatures in the houses floated up and down in response to external conditions.

Accurate monitoring of the rate of total electricity usage was done continuously for eleven months from July 2000 through May 2001. The month of June 2000 was needed to install the instrumentation and the data acquisition systems. Energy usage for the ICF house was corrected for imbalances in internal loads between the two houses early on in the project, before the proper size of the dummy load in the ICF house was achieved. To produce total electricity usage for a calendar year from the measurements, an estimate of usage for each of the four weeks of June 2001 was made as follows. The average usage for the two weeks in May 2001 that needed cooling was multiplied by the ratio of cooling degree days for each week in June 2001 and the average cooling degree days for the two weeks in May 2001.

The measured total electricity usage for the calendar year July 2000 through June 2001 (including the estimate of usage in June 2001) was 12150 kWh for the conventional house and 11242 kWh for the ICF house. The ICF house used 7.5% less energy than the conventional house when unoccupied and for very simple operation. Simple operation means electrical resistance heat only for heating and, during heating and cooling, circulation fans continuously on and constant thermostat set points. It also includes no heating or cooling during 15 weeks in spring and fall despite times when occupants would likely use heating or cooling rather than open or close windows to keep conditions acceptably comfortable.

Results of Blower Door Tests

A state-of-the-art blower door was used on the side-by-side houses at three times during the project year to determine infiltration characteristics of the houses. The blower door fan was controlled by automatic pressure testing software. A series that comprised repetitions of four different blower door tests was done on each house at each time during the year. The footnotes to Table 2 describe the four tests. The series consisted of at least eight tests by performing the tests in the order listed in Table 2 and then in the reverse order.

The seals over objects were wide transparent tape that was used alone or polyethylene that was the size of the objects and taped around the edges with masking tape. Once conditions were set, it took about five minutes for the software to generate a curve of building leakage vs. building pressure at seven to eight pressures between 50 Pa and 15 Pa below atmospheric pressure. Once the software began to generate data, we walked around the house and checked on any seals to ensure that they remained tight. An individual run was repeated if there was any question about the integrity of any seal or about proper conditions being maintained.

One common measure of airtightness for buildings undergoing blower door tests is the flow rate of air in cubic feet per minute to keep the house depressurized by 50 Pa relative to the outdoors (CFM_{50}). This result was one of several reported by the software from the best-fit line it generated through the measurements during each test. Results for leakage area per unit floor area were given in Table 1. Table 2 lists average CFM_{50} for the blower door tests that were done on the side-by-side houses at the three times during the project.

Table 2. Results of Blower Door Tests on the Side-by-Side Houses

CFM_{50}	June 2000		Conv. - ICF	March 2001		Conv. - ICF	May 2001		Conv. - ICF
	Conv.	ICF		Conv.	ICF		Conv.	ICF	
Test 1[1]	784	707	77	1109	1046	63	958	845	113
Test 2[2]	742	658	84	1079	996	83	914	799	115
Test 3[3]	593	459	134	905	840	65	723	617	106
Test 4[4]	560	448	112	900	809	91	687	592	95

[1] Test 1: No seals and open all internal doors, including those to closets.
[2] Test 2: Like test 1, except seals over supply outlets and return grille of duct system.
[3] Test 3: Like test 2, except seals also over vents and attic access hatch.
[4] Test 4: Like test 3, except seals also over the windows and one of two outside doors. The other was used for the blower door.

A difficult question to answer with computer-generated results in general and blower door test results in particular is "How uncertain are the results?" Our answer is that, when tests 1 through 4 were repeated in reverse order, results reproduced well. The largest range of individual results about any average shown in Table 2 was ±17 CFM_{50}. The smallest range was ±1 CFM_{50}. Our judgment is that the data in Table 2 have uncertainty of ±10 CFM_{50}.

Table 2 shows the effect of climatic conditions on the infiltration characteristics of these side-by-side houses. Because of the care that was exercised when building both houses and the lack of occupants during the project, we assume that the effect of aging out to a year is not significant. The houses are leakiest in winter when the wood, especially the trusses in both houses, has shrunk the most. The houses are tightest in summer when the wood has swelled the most. Intermediate results occur in late spring when swelling after winter shrinkage has not yet reached the summer situation.

The ICF house exhibits CFM_{50} values in Table 2 that average 95 CFM_{50} less than those for the conventional house. The differences vary randomly from 63 to 134 $CFM_{50.}$ This level of differences persists for test 4, which is the most sensitive of all the tests to the exterior wall construction. There is a foundation-to-exterior wall joint in the conventional house. The ICF wall is continuous from footing to roof. The persistent differences in Table 2 are taken as evidence that the foundation-to-exterior wall joint in the conventional house causes 95 CFM_{50} more leakage and leads to the higher fractional leakage area for the conventional house compared to the ICF house in Table 1.

Measured and Predicted Energy Usage during Peak Cooling and Heating

Measured energy usage was averaged over one hour intervals for direct comparison to the hour-by-hour predictions. Hourly reports were generated in DOE2 to produce predicted electricity usage for a month of cooling that included the peak week of cooling and a month of heating that included the peak week of heating. An example of the agreement that was obtained between measurements and predictions is shown by Figures 1 and 2. Rates of electricity usage for the houses with ICF and wood-framed exterior walls, respectively, are plotted hour-by-hour during the peak week of heating. The daily variations in predicted electricity usage follow the daily variations in measured electricity usage for both houses. Moreover, predictions of daily peaks are essentially identical to the measured peaks.

One reason for the excellent agreement is that measured meteorological data were input to DOE2. The Knoxville TMY2 file (NREL 1995) was modified to substitute data derived from measurements at the Oak Ridge National Laboratory site. The laboratory was less than 10 miles from the side-by-side houses. Measurements were adapted to DOE2 weather file format for August 4 through August 31 and for December 15 through January 11. Another reason for the excellent agreement is the care that was taken to match the actual construction and operational parameters of the houses as was documented in Table 1.

Table 3 shows measured and predicted electricity usage for the side-by-side houses for the entire months of cooling and heating for which on-site weather data were prepared for DOE2. The excellent agreement between measured and predicted electricity usage in Figures

Figure 1. Comparison of Measured and Predicted Total Power Demand of the House with Insulating Concrete Form Exterior Walls during the Week of Peak Heating

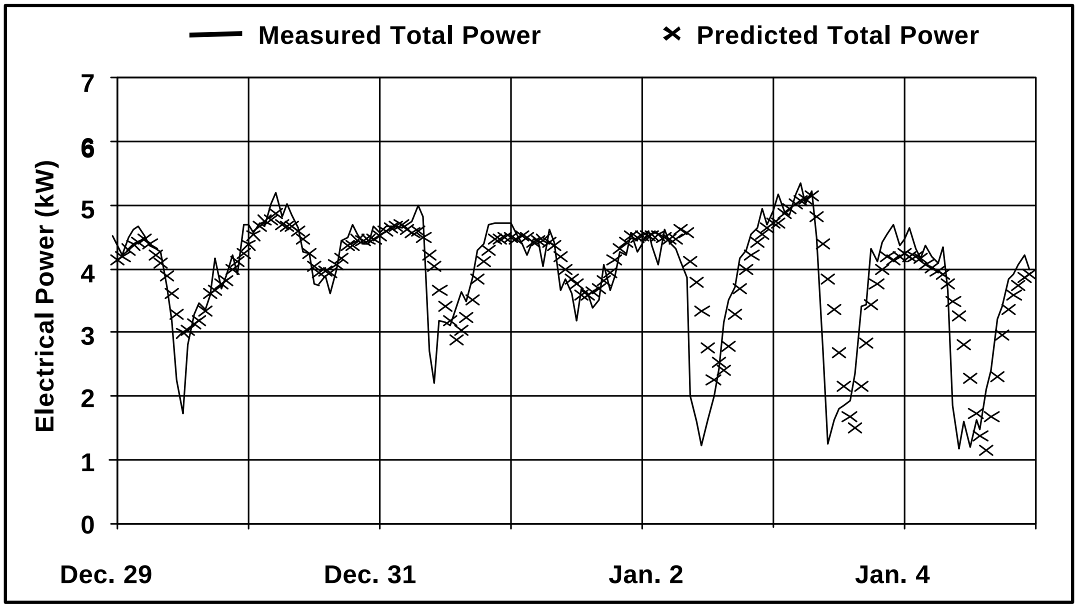
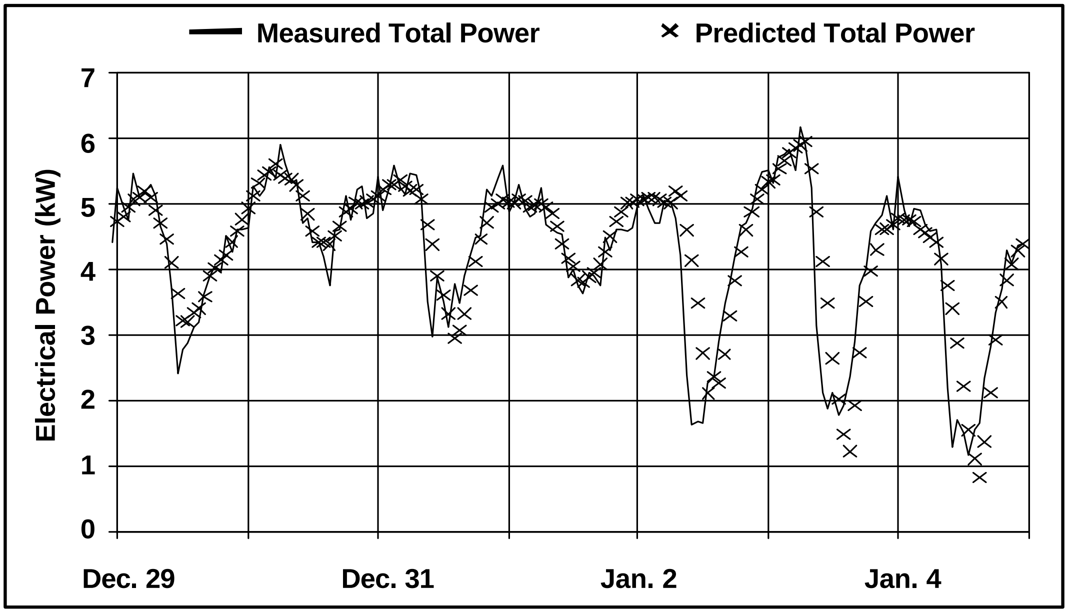


Figure 2. Comparison of Measured and Predicted Total Power Demand of the House with Conventional Wood-Framed Exterior Walls during the Week of Peak Heating



1 and 2 continued for the entire two months. Even the -4.1% deviation for the conventional house in the summer month is acceptable. The fixed uncertainty of the power measurements is significant for small powers during cooling. Predicted electricity usage is also more uncertain during cooling. The 7 kW (2 Ton) single package heat pumps were the smallest units commercially available. According to conventional sizing methods (ACCA 1986), they were ½ to 1 Ton too large for these houses, especially without any internal load due to occupants and their activities. There was frequent cycling even at peak load and modeling of cycling operation can be expected to be more uncertain than modeling of steady cooling.

Table 3. Comparison of Measured and Predicted Electricity Usage for the Side-by-Side Houses for a Month of Cooling and a Month of Heating

	Conventional House (kWh)			ICF House (kWh)		
	Measure	Predict	% Diff.[1]	Measure	Predict	% Diff.[1]
Month of Cooling	559	536	-4.1	528	530	+0.4
Month of Heating	2566	2570	+0.2	2343	2323	-0.9

[1] (Predict – Measure)/Measure · 100

Effects of Different Climates, Occupancy and Operation

To generalize the lessons from the side-by-side houses, validated models of the side-by-side houses can predict the difference in energy consumption due to ICF construction as the houses are subjected to different climates and to different occupancy and operation. As an example of generalization of the behavior of the side-by-side houses, Table 4 shows results in six different climates including Knoxville. Annual electricity usage is predicted for the houses as configured and operated during the side-by-side monitoring in Knoxville. Meteorological data for Knoxville and the other locations were directly from the TMY2 data set compiled by DOE2's weather processor. No changes from the validation runs were made to the DOE2 input files to model the houses in the different climates. DOE2 automatically uses the latitude, longitude and elevation for the location in the weather file.

Cooling and heating capacities were not changed for the different climates. Cooling had significant excess capacity for Knoxville and peak use during heating was less than 60% of the capacity of the electrical resistance heaters. The cooling capacity appeared to be sufficient for all locations except Phoenix. There, DOE2 output indicated that hourly ICF house energy demand was not 1% less than system capacity for 0.2% of annual hours. For the conventional house, the percentage of annual hours was 2.2%. For all other locations and both houses, DOE2 reported that 0.0% of annual hours failed the criterion. Cooling and heating capacities were judged adequate. A simulation for Phoenix with 11 KW (3 Ton) heat pumps yielded 0.0% of annual hours for the ICF house and 1.4% for the conventional house. The data in Table 4 for Phoenix (3T) show the effect of the increased capacity on energy use. Further increases in cooling capacity to 4 Ton and 5 Ton did not affect the 0.0% for the ICF house and the 1.4% for the conventional house. Total energy use for each house increased about 4% for each Ton of increased capacity. The percentage difference in total energy use continued to decrease to 7.7% and 7.4%, respectively.

Table 4. Annual Electricity Use from the Validated Models of the Side-by-Side Houses as Built and Operated in Knoxville, Tennessee but with TMY2 Weather Data for Various Locations

	Cooling (kWh)		Heating (kWh)		Total (kWh)		
City	Conv.	ICF	Conv.	ICF	Conv.	ICF	% Diff.[1]
Phoenix	2800	2650	2920	2440	7540	6900	8.5
Phoenix (3T)	3130	2980	2920	2440	7870	7230	8.1
Minneapolis	890	820	15260	13920	17970	16550	7.9
Dallas	2230	2120	5450	4840	9500	8780	7.6
Boulder	750	690	9460	8620	12030	11130	7.5
Knoxville	1490	1450	7460	6770	10770	10040	6.8
Miami	2550	2440	380	230	4750	4490	5.5

[1] (Conv. Total – ICF Total)/Conv. Total · 100

The results for cooling, heating and total electricity usage at each location for the conventional wood-framed and ICF houses are arranged in Table 4 in descending order of total savings realized by the ICF house over the conventional house. Besides cooling and heating needs, total annual electricity usage includes 1140 kWh of usage for internal equipment and 680 kWh of usage for circulation fans. The city with the most cooling energy usage, Phoenix, and the city with the most heating energy usage, Minneapolis, rank first and second, respectively, in total electricity savings of the ICF house compared to the conventional house. Thermal mass has benefits for both cooling and heating. The range of savings from 5.5% to 8.5% agrees very well with Kosny's prediction of 4% to 10% savings with ICF exterior walls compared to conventional wood-framed exterior walls due to thermal mass only. Kosny (2001) predicted this range for ten U.S. climates that included the cities in Table 4 except Atlanta was used instead of Knoxville. The agreement is despite the differences in exterior wall R-value and house leakage areas in the side-by-side houses that are shown in Table 1. The differences should favor the ICF house.

Table 5 shows, for the Knoxville TMY2 weather file, the annual energy usage in the side-by-side houses when features of occupancy and operation are changed one at a time. The first column of data in Table 5 gives details about the Knoxville data in Table 4. TMY2 weather files are compilations of typical months of weather from a 30 year database. The winter of the side-by-side tests was colder than is typical in the Knoxville area. The total electricity usage of 10040 kWh for the ICF house with TMY2 weather is less than the measured amount of 11242 kWh (including an estimate for June 2001). Similarly, the total of 10770 kWh for the conventional house with TMY2 weather is less than the measured 12150 kWh. The predicted totals with TMY2 weather are each 11% less than their respective measured totals. This is consistent with the severe winter during the tests.

As the occupancy and operational characteristics of the houses are changed from the as-tested case in the first column of Table 5, the total energy used by each house varies widely. The percentage savings for the ICF house relative to the conventional house also vary. Switching from continuous to intermittent fan operation yields the highest ICF savings in Table 5. ICF savings for heat pump heating are both more and less than for the as-tested case. The most realistic occupancy and operational characteristics are those for the last column in Table 5. Cooling is with an electric air conditioner and heating is with a natural gas furnace. Thermostat setback at night from 10 p.m. to 6 a.m during the heating season and setup at night from 10 p.m. to 6 a.m. during the cooling season are also applied. The units of gas energy are converted to kWh to produce the heating and total values. The ICF savings of 9.2% for this case imply that changing from unoccupied houses with simple operation to normal occupancy and operation may slightly increase savings due to ICF construction.

Table 5. Energy Usage (kWh) and Percentage Savings [(Conv. - ICF) / Conv. · 100] as Occupancy and Operational Characteristics are Changed

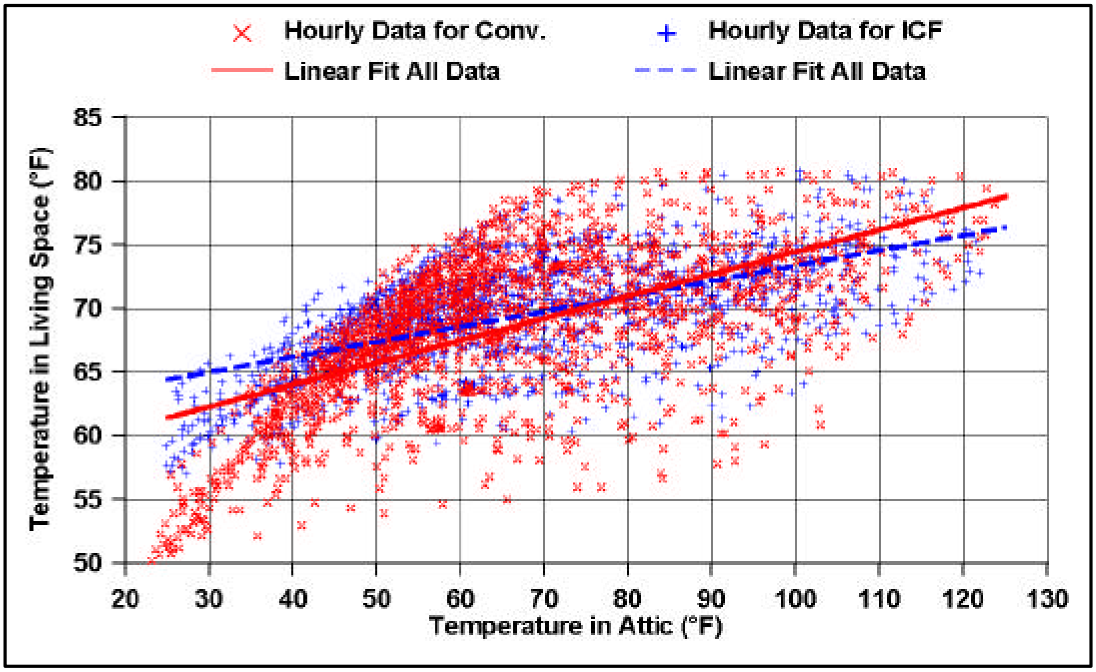
Occupants	No people	No people	No people	No people	2 people	2 people
Internal Load	0.14 kW	0.14 kW	0.14 kW	0.14 kW	0.77 kW	0.77 kW
Heating Method	Strip heat	Strip heat	Heat pump	Heat pump	Heat pump	Gas furnace
Circulation Fan	Continuous	Intermittent	Intermittent	Intermittent	Intermittent	Intermittent
Heat Set Point	72°F	72°F	72°F	68°	68°F	68°F
Cool Set Point	72°F	72°F	72°F	78°F	78°F	78°F
Note about Operation	No heat/cool for 15 weeks	No heat/cool for 15 weeks	No heat/cool for 15 weeks	No setback No setup	No setback No setup	Setback 60° Setup 86°F
ICF Cool	1450	950	950	480	1210	1130
ICF Heat	6770	5760	3530	3710	2470	3750
ICF Total	10040	7990	5910	5580	10620	11710
Conv. Cool	1490	1080	1080	610	1300	1210
Conv. Heat	7460	6530	3680	4000	2910	4830
Conv. Total	10770	8910	6210	6030	11210	12900
ICF Savings	6.8%	10.4%	4.9%	7.5%	5.2%	9.2%

Increasing Time without Heating or Cooling Because of Thermal Mass

During the year of continuous monitoring of the side-by-side houses, we had the opportunity to observe directly the ability of thermal mass to diminish temperature fluctuations inside the houses. For 15 weeks of anticipated mild weather from late September through mid-November and from mid-March until early May, in the swing season between heating and cooling, the heating/cooling systems were turned off in the houses. Air temperature was allowed to float at whatever level the outside conditions dictated. Figure 3 shows the result. Attic air temperature is selected as the variable against which living space temperature is plotted. In the ventilated attics of the side-by-side houses, it was affected by both outside air temperature and solar radiation on the dark roofs. It should give a better measure of changes in outside conditions than outside air temperature alone.

The attic air temperatures ranged from 4°C to 52°C (25°F to 125°F) during the swing season. The hourly temperatures in the living space of the ICF house, shown with **+** symbols, remained relatively comfortable throughout. The hourly temperatures in the living space of the conventional house, shown with **x** symbols, did not get too hot but did get too cold during this time. Linear fits of all the data (**---** for the ICF house and **—** for the conventional house) obtained during the swing season are shown, too. The scatter of the data about these lines is very large. Living space temperatures without heating or cooling do not correlate well to attic temperature alone. However, the shallower slope of the line for the ICF house does serve to further illustrate the narrower range of fluctuations of air temperatures in the ICF house.

Figure 3. Air Temperatures in the Unoccupied Living Spaces of Conventional and ICF Houses vs. Air Temperatures in Their Attics with No Heating or Cooling



In actual houses in East Tennessee during the swing season, residential heating/cooling systems would be operated occasionally when opening or closing windows was not sufficient to maintain comfortable conditions. Residents would make individual decisions about when to close windows and start their systems. The decisions would be based on perceptions of thermal comfort and tolerance to high and low air temperatures. The main factor affecting the decisions would likely be the anticipated daily fluctuation of temperatures in the residence.

An extremely energy-conserving swing season usage pattern was postulated based on the lead author's experience. Variations in living space temperature between 17°C (62°F) and 25°C (77°F) were assumed tolerable. Energy usage to hold living space temperatures inside this range was based on the measurements and the DOE2 models. For the ICF house in the last column of Table 5, 330 kWh of the 11710 kWh were used during the swing season. Minimal heating and cooling would save 290 kWh of the 330 kWh yielding 11430 kWh for the year. For the conventional house under the same conditions, 540 kWh of the 12900 kWh were used during the swing season. Minimal heating and cooling would save 340 kWh of the 540 kWh, leaving 12560 kWh for the year. Extreme conservation can save more energy in the conventional house than in the ICF house because greater temperature fluctuations give residents more opportunities to save energy. Energy savings for the ICF house compared to the conventional house drop slightly from 9.2% for the last column in Table 5 to 9.0% for minimal energy usage during the swing season. Even with minimal energy usage during the swing season, the ICF house maintains its advantage over the conventional house in terms of annual energy consumption for normal occupancy and operation.

Conclusions

A field investigation was done in East Tennessee to monitor and analyze the thermal performance of two side-by-side houses. They were identical except one had insulating concrete form (ICF) exterior walls and the other had conventional wood-framed exterior walls. The walls differed in thermal mass and thermal resistance. Blower door tests showed that the ICF house was about 10% more airtight than the conventional wood-framed house. Air leakage in both houses was less than anticipated based on literature values for conventional construction. The total energy consumption for the eleven months of monitoring that began in July 2000 plus an estimate for the twelfth month showed that the ICF house used 7.5% less energy than the conventional house for no occupants and simple operation.

Models of the two houses were made in the annual energy estimating tool DOE2. Values of parameters in the models matched the as-tested characteristics of the houses. Air loss from the ducts running through the crawlspaces of the houses was adjusted within the uncertainty of measurements to obtain final validation of the models. The models did not show more than ±1% bias for both houses between measurements and predictions during a month of heating that included the peak week of heating. This implies that the models do not bias comparisons of the houses for or against either type of construction.

When the validated models were exercised for a range of climates that included heating dominated and cooling dominated climates, the ICF house used 5.5% to 8.5% (6.8% in the Knoxville climate) less energy annually than the conventional house. TMY2 weather data were used to simulate the different climates. With the Knoxville TMY2 weather data, changing from unoccupied houses with simple operation to normal occupancy and operation increased the savings for the ICF house relative to the conventional house to 9.2%. This advantage of the ICF house decreased only slightly to 9.0% when minimal energy usage was postulated during the swing season in East Tennessee. For this approximately 15 week period of mild weather during which the test houses were operated without any heating or cooling, we observed wider variations in air temperature in the conventional house than in the ICF house.

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