Insulating Concrete Forms:

Comparative Thermal Performance

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Upper Marlboro, MD

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Foreword

As we near the end of the 1990s, we have reason to celebrate some of our successes in identifying and improving innovative materials that can help reduce our dependence on lumber and improve the building industry's efforts to deliver affordable housing to our citizens. Throughout much of the decade, the U.S. Department of Housing and Urban Development has supported joint efforts with the Nation's builders and manufacturers to accelerate the adoption of innovative materials for home construction. This includes efforts to improve the efficiency of lumber construction as well as researching alternatives such as cold-formed steel, panel construction, and insulating concrete form systems.

Despite these initial successes, we realize that our work is just beginning. The President's new initiative, the Partnership for Advancing Technology in Housing (PATH), will insure that we continue to aggressively pursue innovation in the homebuilding industry to build more durable and resource-efficient homes. We look forward to that challenge and to continue working closely with industry to achieve our goals.

Insulating concrete forms (ICFs) are an example of one of the technologies that the PATH program can capitalize on to improve our housing. This report contains results of one of our latest studies on this intriguing technology innovation. This report will allow builders to better evaluate the thermal performance of ICFs. It also identifies many opportunities to optimize the construction of homes using this technology. We hope you not only find this report valuable, but that you help us continue to improve these types of technologies by passing your experience and suggestions for improvements on to the many excellent manufacturers of these products.

Xavier de Souza Briggs
Deputy Assistant Secretary

ICF Report

Acknowledgments

The NAHB Research Center Inc., located in Prince George's County, MD, was established in 1964 as a separately incorporated, wholly-owned, not-for-profit subsidiary of the National Association of Home Builders (NAHB), whose 197,000 members are involved in the construction of over 80% of U.S. homes. The Research Center studies all aspects of home building, tests and certifies building products in a fully equipped laboratory, and conducts a wide range of dissemination and training activities for builders, remodelors, and other participants in the housing industry. Our research is sponsored by NAHB, public agencies, and private-sector clients.

This report was prepared by the NAHB Research Center for the Portland Cement Association, National Association of Home Builders and the U.S. Department of Housing and Urban Development. Product donations were provided by Reddi-Form, Lite-Form, and Owens Corning. The homes studied in this work were constructed by Romak & Associates of Chestertown, Maryland.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Executive Summary

The NAHB Research Center conducted a study to compare the cost and performance of Insulating Concrete Form (ICF) walls to conventional wood-frame exterior walls. This report contains results on energy and thermal comfort performance as well as computer modeling of energy use.

Three homes were built and monitored. One home has an ICF plank system, one has an ICF block system, and one is of conventional 2X4 lumber construction. The homes have identical floor plans. They are located side-by-side on the same street in Chestertown, Maryland.

All three homes, which were unoccupied, were set up for long-term energy monitoring. Two of the homes were also monitored for thermal comfort analysis per ASHRAE Standard 55-1992. Weather data from the site were used in the energy use computer modeling program, Building Loads Analysis and System Thermodynamics (BLAST), to compare predicted energy performance of the homes to actual energy use.

Key findings include the following:

- There was not significant difference in air leakage test results among the three homes. This lack of difference may reflect the dimensions, volume, and relatively limited wall area of these simple, affordable homes.

- The two ICF homes were approximately 20%more energy efficient than the wood-frame house. This difference is largely due to the higher effective R-value of the ICF walls and continuous insulation at the slab.

- BLAST modeling of energy use produced results very similar to actual energy use. The results suggest that the contribution of thermal mass and ground-coupling effects to the overall energy efficiency of the ICF homes was not significant.

- While no dramatic thermal comfort differences were apparent between the ICF and the wood-frame homes, several thermal comfort measures showed slight but significant better performance for the ICF homes.

INTRODUCTION

NAHB Research Center evaluated three side-by-side homes to gain a better understanding of the performance of Insulating Concrete Form systems relative to more-conventional construction. Two of the homes were constructed with insulating concrete forms (ICF) and one home was constructed with traditional 2x4 wood walls. All three homes have identical orientation, window area, roof construction, footprint, ductwork, and air handler systems. The methods and materials used to build these homes represent current practice to construct modest, affordable single-family homes in this region of the United States. The homes were constructed specifically for this project.

This report addresses long-term energy performance monitoring, energy modeling, and thermal comfort analysis. The testing was conducted over a one-year period beginning in April 1998. Previous evaluation of these homes for construction costs and sound transmission characteristics were reported in *Insulating Concrete Forms: Installed Cost and Acoustic Performance*, March 1999.

Figure 1 - View of Completed Homes

BACKGROUND / OBJECTIVES

Insulating concrete form (ICF) systems initially began to enter the home construction market as an innovative approach to building a fully insulated basement wall. Prior to the 1990s, above-grade walls in homes were typically built with wood framing, except in certain areas of the United States. In the past 10 years, however, concrete walls have taken a larger share of the market for above-grade walls in homes. The Portland Cement Association estimates over 19,000 homes were built in 1998 with above-grade ICF walls. Despite the number of ICF above-grade walls reaching nearly 16% of the overall concrete wall market and an increasing number of ICF manufacturers entering the market over the past decade, information regarding the cost and performance of ICFs compared to more conventional home building systems is needed for builders to better evaluate their use.

The objectives of the thermal testing were:

- to determine and contrast actual energy used for space conditioning in each home;
- to compare measured energy use to predicted values using BLAST, an hourly energy simulation program; and
- to evaluate thermal comfort parameters in the homes.

Insulated Concrete Forms

ICFs are basically a concrete wall forming system where the forms stay in place. The forms are typically made of polystyrene foam insulation (or other types of insulating materials) into which concrete is cast. ICFs provide a structural wall that is insulated, and depending on the specific system, allow attachment of exterior and interior wall coverings with moderate to no modifications to the wall.

ICF systems are typically described with respect to the type of form and the resulting shape of the concrete wall. ICF forms consist of either insulating panels or planks held together with special ties, or formed insulating block systems. ICF systems can also be categorized based on the resulting form of the concrete wall (see Figure 2).

A *flat* ICF wall system is a solid concrete wall of uniform thickness with sheets of insulation forming the interior and exterior surfaces of the system. The *waffle-grid* ICF wall system is a concrete wall composed of closely spaced vertical (maximum 12 inches on center) and horizontal (maximum 16 inches on center) concrete members with concrete webs between the members. The thicker vertical and horizontal concrete members and the thinner concrete webs create the appearance of a breakfast waffle made of concrete “batter”. The *screen-grid* ICF wall system is similar to a waffle-grid ICF wall system without concrete webs in between the vertical and horizontal members. The thicker vertical and horizontal concrete members and the voids in between create the appearance of a window screen made of thick concrete “wire”. The *post-and-beam* ICF wall system has vertical and/or horizontal concrete members spaced farther than 12 inches on center. The post-and-beam ICF wall system resembles a concrete frame rather than a monolithic concrete wall.

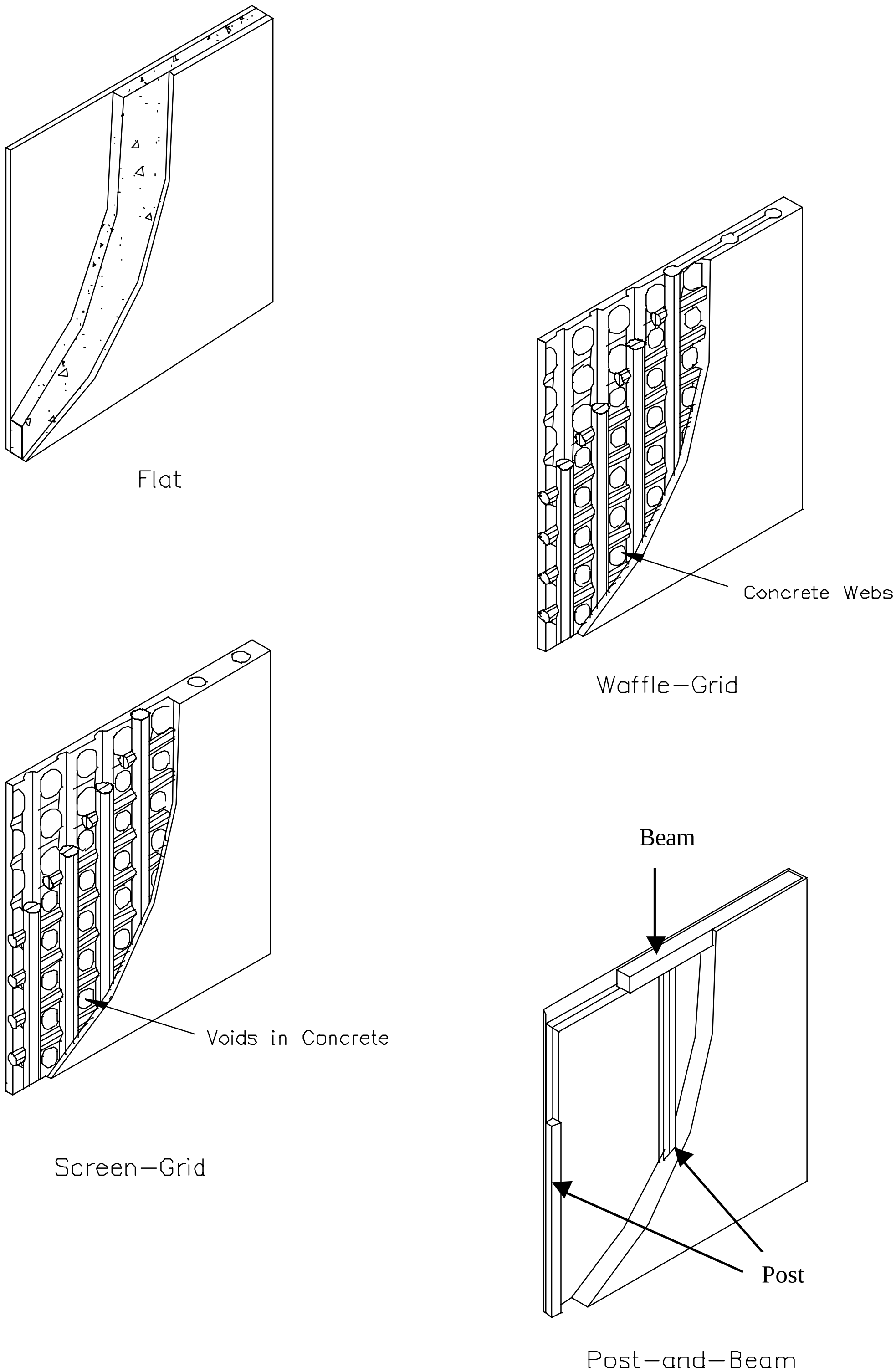

Figure 2 - ICF Wall System Types

Description of Homes

All three homes were built next to each other specifically for this project. All are single-story homes on a slab-on-grade foundation. An identical floor plan of 1098 square foot (sf) was used in the homes, as shown in Figure 3.

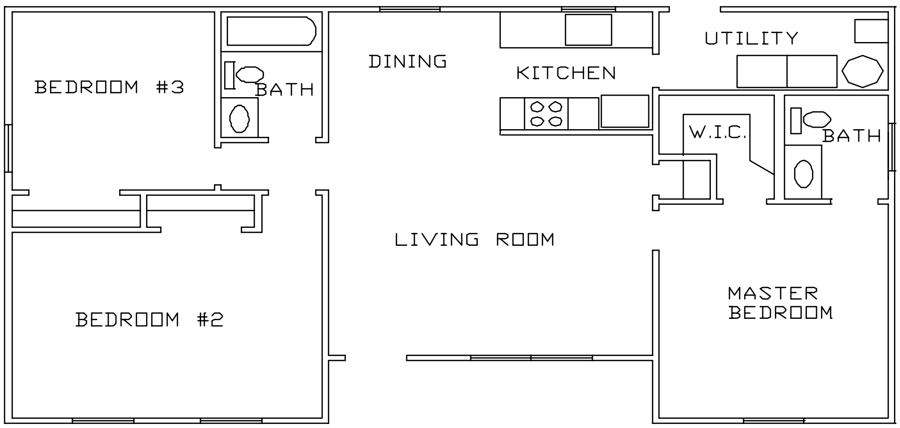

Figure 3 - Floor Plan of Test Homes

The home with wood-frame walls was used as the baseline for comparison to the ICF homes. It represents the prevalent type of modest above-grade wall construction in this part of the United States. The other two homes have ICF walls, one with a block system called "Reddi-Form" (see Figure 4) and the other a plank system called "Lite-Form" (see Figure 5). The ICF systems are used for the above-grade exterior walls and the foundation walls. The wood-framed home is constructed with 2x4 wall stud framing, sheathed with oriented strand-board (OSB), covered in house wrap, and insulated with R-13 fiberglass batt insulation in the wall cavities. It has a conventional concrete masonry unit (CMU) foundation (see Figure 6). All three homes have separate conventional concrete strip footings supporting the foundation walls. Other than the house wrap on the wood house, none of the homes had any air-sealing details such as caulking or foaming of wall and ceiling penetrations, etc.

Figure 4 - Reddi-Form System

Figure 5 - Lite-Form System

Figure 6 – CMU Foundation Wall

The homes are located in Chestertown, Maryland, a rural county on the Eastern Shore of Maryland. The Eastern Shore is the part of Maryland separated from the rest of the state by the Chesapeake Bay. Figures 7 and 8 show the location of the site and the site plat. The Reddi-Form house is on Lot 61, the wood frame house on Lot 62, and the Lite-Form house on Lot 63.

The Builder had previously constructed the same house model multiple times using both wood framing and Reddi-form. This was the builder's first experience with Lite-Form.

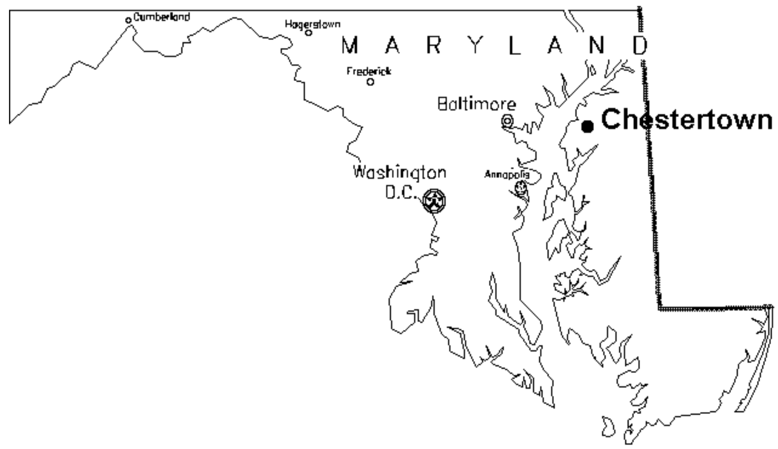

Figure 7- Location Map

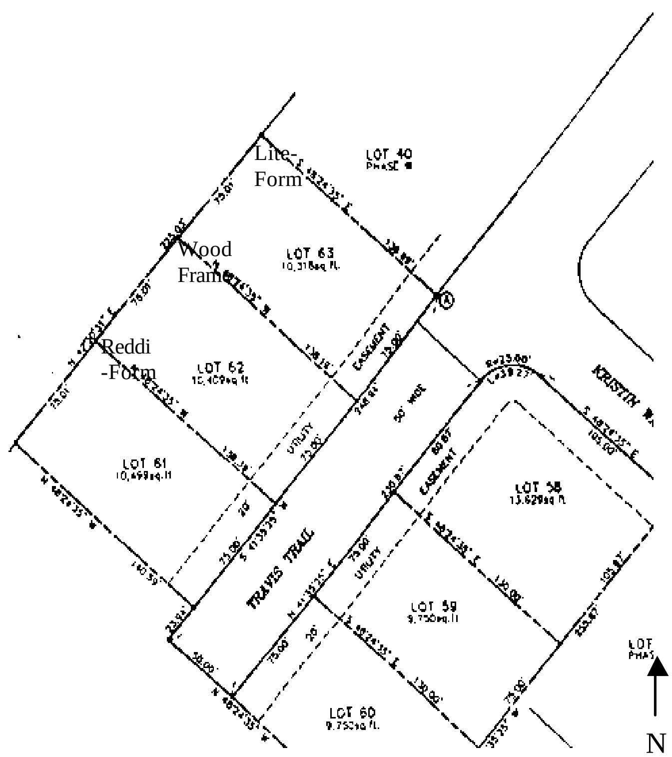

Figure 8 -Site Plat

ENERGY MONITORING APPROACH

Measured Energy Use

Use of nearly identical homes allowed a direct energy consumption comparison among the different wall construction types. The homes were unoccupied during the energy-monitoring period, did not contain any operating appliances, and had disconnected water heaters. The heating season thermostat set-point was 70°F and the cooling season thermostat set-point was 75°F. There were no window coverings of any type. Consequently all the energy to maintain internal temperature came from the HVAC equipment or solar gain. Each house had a Bryant® 2-ton heat pump, Model 661CJ024. Energy consumed by the heat pump was measured using a watt meter. The total measured wattage over time was used to determine the input energy.

A Campbell Scientific data acquisition system (DAS) was installed and used to compile and send data to the NAHB Research Center via modem. Sensors attached to the system were used to record both indoor and outdoor environmental parameters as well as energy consumption data.

The DAS system recorded measurements every five seconds. The software was programmed to sum the energy use and average indoor, outdoor, and slab data over 15-minute intervals. The resultant data were downloaded each morning. Table 1 summarizes the data recorded by the DAS in each house.

Table 1 – Description of Recorded Data[1]

Data ID	Description	Units
ID	Identifier used to differentiate data needed for different applications	N/A
Year	Calendar year stamp	N/A
Day	Ordinal day stamp (1-365)	N/A
hr:min	Time stamp for end of 15 minute interval	N/A
T_RH_IN	Dry bulb temperature of indoor relative humidity sensor	deg F
RH_RH_IN	Measured indoor relative humidity	%
H1	average temperature of front bedroom, 6' level	deg F
H2	average temperature of front bedroom, 2' level	deg F
H3	average temperature of back bedroom, 6' level	deg F
H4	average temperature of back bedroom, 2' level	deg F
H5	average temperature of living room, 6' level	deg F
H6	average temperature of living room, 2' level	deg F
H7	average temperature of kitchen, 6' level	deg F
H8	average temperature of kitchen, 2' level	deg F
H9	average temperature of master bedroom, 6' level	deg F
H10	average temperature of master bedroom, 2' level	deg F
A1	average attic temperature over back bedroom	deg F
A2	average attic temperature over living room	deg F

[1] A number of temperature and heat flux sensors installed below grade are not shown here. Most of the heat flux sensors did not provide reliable data over the course of the project and the remaining ground temperature sensors were used to support or validate listed sensors.

A3	average attic temperature over master bathroom/closet	deg F

Table 1 – Description of Recorded Data (continued)

T Stat	average temperature measured at thermostat	deg F
T Out	outside air temperature	deg F
HT111/112	Surface temperature edge of slab – Lite-Form and Wood frame homes	deg F
HT 196/197	Surface temperature center of slab – Lite-Form and Wood frame homes	deg F
G10/52	temperature center of foundation cavity wall – 24” from top of footing – Lite-Form and Wood frame homes	deg F
Solar	solar intensity	mv
Wind_Dir	wind direction	degrees
Wind_Mph	wind speed	mph
Rh_Out	outside relative humidity	%
COND	number of condensate tips	5 ml/tip
HP_KW_C	Σ(HP power, sampled every 5 seconds)	W x 5 sec
ON_15	time fan on cycle	seconds

Predicted Energy Use

Predicted energy consumption for all three homes was modeled using BLAST, a computer software program which calculates energy consumption. BLAST calculates thermal loads using an implementation of the heat balance method[2].

The program computes hourly space loads in a building or zone based on user input and weather data. For each hour simulated, BLAST performs a complete radiant, convective, and conductive heat balance for each surface and a heat balance on the room air. This heat balance includes transmission loads, solar loads, internal heat gains, infiltration loads, and the temperature control strategy used to maintain the space temperature.

Zone thermal loads, such as lights, equipment, people, and outside air are calculated on an hourly basis for either a single design day or an entire year. Given the controlled and unoccupied condition of these homes, the thermal loads associated with lights, occupants, and equipment were held constant at zero for our BLAST modeling.

Weather data are typically read from a library file for each hour. For our analysis, actual weather data obtained from the DAS were inputted into BLAST to allow a direct comparison between the measured and predicted energy performance of the three homes. This analysis was limited to selected periods of the heating and cooling season during which we had the most complete and reliable weather and input data. The following items comprise a BLAST weather input file:

- dry bulb temperatures for each hour (degrees c),
- wet bulb temperatures for each hour (degrees c),
- humidity ratio for each hour,

[2] Information on the BLAST methodology was obtained from the BLAST Support Office, University of Illinois, http://www.bso.uiuc.edu.

- wind speed for each hour (meters/second),
- wind direction for each hour (degrees),
- beam radiation for each hour (watts/meters^2) (normal to rays), and
- diffuse radiation for each hour (watts/meters^2) (global).

A BLAST input file contains the following information:

- general information (e.g., output units, project title, location, ground temperatures, building category code),
- building description (e.g., exterior walls, interior walls, partitions, floors, ceilings, roofs, windows and doors), and
- HVAC system description.

Thermal Comfort Analysis

ASHRAE Standard 55-1992 *Thermal Environmental Conditions for Human Occupancy* contains a process for determining thermal comfort based on the assumption that site environmental conditions would be categorized as "comfortable" by 90 per cent of the occupants. The site environmental conditions consist of direct data measurements. Basic data requirements necessary to evaluate thermal comfort conditions are:

- Operative Temperature,
- Relative Humidity,
- Temperature Cycling,
- Temperature Drifts or Ramps,
- Vertical Air Temperature Difference,
- Radiant Temperature Asymmetry,
- Floor Temperature, and
- Drafts.

The operative temperature is the primary factor affecting thermal comfort[3], principally because it is the overall temperature that an individual experiences in the home. Temperature cycling and drifts/ramps are all factors that affect the operative temperature. Relative humidity affects a person's sensation of comfort, with a major effect in cooling situations. The remaining factors are important since they impact localized comfort conditions experienced by exposing the different parts of the body to different temperatures[4]. Data requirements and the instrumentation used for thermal measurements are shown in Table 2.

Table 2 - Equipment Requirements

Measurement	Equipment Type	Product Used
Air Temperature	Thermocouples	Omega Model TT-T-20-1000
Mean Radiant Temperature	Radiometer	Qualimetrics Model Z001899
Air Motion	Hot-wire anemometer	Solomat Model MPM 500e

[3] NAHB Research Center, *ENERJOY CASE STUDY – A Comparitive Analysis of Thermal Comfort Conditions and Energy Consumption for Enerjoy PeopleHeaters and a Conventional Heating System*, December 1, 1993, page 14
[4] ASHRAE. *1997 Fundamentals Handbook*, page 8.13.

Table 2 - Equipment Requirements

Operative Temperature	N/A	Calculated
Humidity	Humidity	Vaisala Humitter Model 50Y
Radiant Temperature Asymmetry	Thermocouples	Omega Model TT-T-20-1000

ASHRAE Standard 55-1992 requires that measurements be "made in occupied zones … where the occupants are known or expected to spend their time" (ASRAE 55-1992, 7.1.1). Two locations, as shown in Figure 9, were monitored as part of this study. One location was in the living room, the other location was in the dining area. Thermal comfort measurements were taken for both the Lite-Form and wood-frame homes.

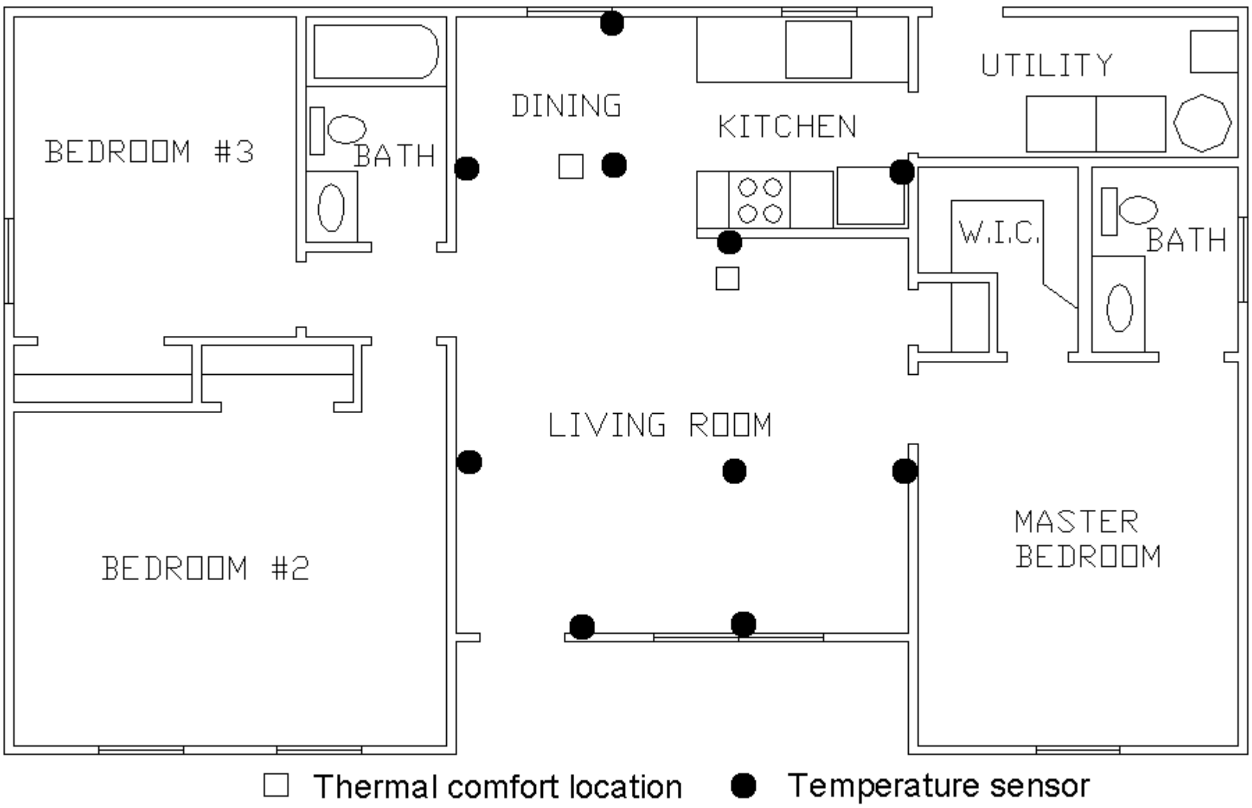

Figure 9 - Sensor Locations

The thermal comfort standard specifies that temperature measurements should be taken at three different heights for each location. These heights are different for sedentary and standing activity. Our measurements corresponded to sedentary activity, taken at 4", 24", and 43" above the floor.[5] Sedentary activity was selected since it represents the most likely position encountered in a residential setting as well as the position a person would remain in for the longest continuous time. Previous work done for the Gas Research Institute used to simulate occupant activities

[5] The air temperature stratification measurements for thermal comfort are more specific and detailed than the basic two and six foot high measurements taken as part of the energy analysis. Both sensors and the DAS were reconfigured to conduct the thermal comfort analysis.

indicates that, after eliminating time spent out of the house and sleep time, greater than 50% of a persons activities involve sedentary activity.[6]

The standard also specifies ambient conditions for meaningful thermal comfort readings. Our assessment was limited to winter conditions, which require cloudy to partly cloudy sky conditions and outside air temperatures less than 43 degrees F. These conditions need to be met for at least a two hour interval.

FINDINGS[7]

Diagnostic Measurements

The air infiltration rates of the homes were assessed using both the tracer gas decay method (ASTM E741 - Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution) and the blower door test (ASTM E779 - e1 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization). The tracer gas testing was performed on April 7, 1998, by a representative of Florida Solar Energy Center. The analysis was performed by Lawrence Berkeley Laboratory. A small amount of SF_6 gas was released in each house with the concentration measured in either one or two minute intervals for approximately one-half hour. The infiltration rate is obtained by performing a regression analysis of the natural logarithm of SF_6 concentration against the natural logarithm of elapsed time. The results of these measurements along with weather conditions during each test are found in Table 3.

Table 3 - Tracer Gas Infiltration Results

	Reddi-Form	Wood frame	Lite-Form
Measuring Period (minutes)	30	26	28
Average Outside Temperature (degrees F)	58.1	55.5	61.8
Average Wind Speed (mph)	2.14	2.42	3.24
Calculated Infiltration Rate (ACH)	0.485	0.463	0.502
Infiltration Flow (cfm)	62.7	64.8	66.6

Air leakage data were obtained by performing multiple blower door tests on each home. The air leakage in cfm was measured at seven different depressurizations, from which a pressurization curve was derived. This curve was used to calculate the building envelope leakage at 50 Pa. This process was performed at each house with the ducts both open and sealed. Data from the September 9, 1998, tests are presented in Table 4.

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[6] *GRI's Research House Utilization Plan*, January 1988, Report IE-1872.

[7] A previous report documents the approach and findings related to the cost and sound evaluations. NAHB Research Center, *Insulating Concrete Forms: Installed Cost and Acoustic Performance*, December 1998.

Table 4 - Blower Door Results

	Reddi-Form	Wood frame	Lite-Form
CFM_{50} (ducts open)	1032.8	1038.2	949.5
CFM_{50} (ducts sealed)	885.1	927.9	845.2

Since blower door test results are calculated for a home pressurized to 50 pascals, an adjustment factor is typically used to estimate a natural infiltration rate. A typical "rule-of-thumb" adjustment factor is 20. Table 5 presents the blower door data as estimated natural air changes per hour (ACH).[8]

Table 5 – Estimated Natural ACH
(based on "divide by 20" rule)

	Reddi-Form	Wood Frame	Lite-Form
CFM_{50} (ducts open)	0.40	0.37	0.36
CFM_{50} (ducts sealed)	0.34	0.33	0.32

The air leakage performance of these three homes was very similar. While some reduction of air leakage in ICF homes may be attributed to the continuous nature of the wall systems, this effect is less likely to be significant in smaller, slab-on-grade, single-story homes. In these homes, air leakage associated with the ceiling plane and the wall-roof junction is likely to dominate the air leakage characterization.

House Energy Use

The measured weekly energy consumption of all three homes is shown in Figure 10. Weekly consumption values were tabulated for clarity of presentation. The energy performance of the three homes was consistent with expectations except for one event, discussed below, that affected the energy performance of the Reddi-form home.

In early June, 1998, the Reddi-Form home was vandalized, involving a broken bedroom window. The house was open to exterior air temperatures, had intermittent occupants, and had the cooling set-point changed to below 60°F. This incident affected the cooling energy monitoring results of the Reddi-Form house, resulting in the spike as marked in Figure 10 between weeks 11 and 14.

[8] Even though the homes were built to the same exterior footprint, differences in exterior wall thickness yield different internal volumes and must be taken into account for estimated natural ACH. These volumes are 7768 cubic feet for the Reddi-Form home, 8392 cubic feet for the wood frame home, and 7960 cubic feet for the Lite-Form home.

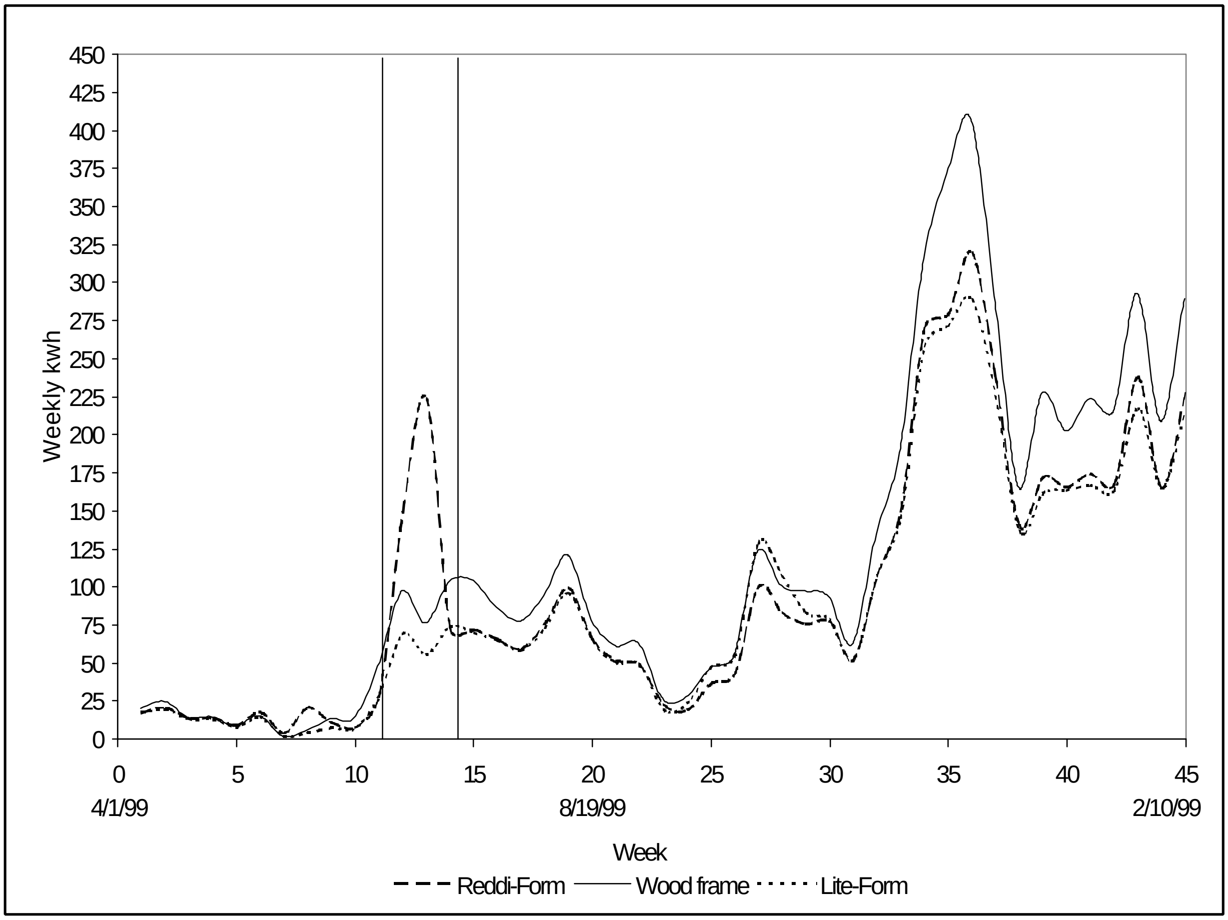


Figure 10 - Energy Consumption

The area under each curve represents the total energy use of each home. An inspection of the areas shows that, in general, the total energy use results are consistent with the overall insulation levels of the three homes. The wood frame home had the lowest effective R-value and the highest energy consumption. The two ICF homes show similar consumption patterns although the Lite-Form house performs slightly better than the Reddi-Form house during extreme weather conditions due to its slightly higher R-value.

The heating consumption in Table 6 is composed of two time periods, April 1, 1998 through June 1, 1998 and October 6, 1998 through March 16, 1999. The results are consistent with the results as expressed in Figure 10.

Table 6 - Total Heating Consumption
(during the monitoring period)

House	Energy Consumption (kWh)
Reddi-Form	3,484

Wood frame	4,311
Lite-Form	3,413

Cooling data in Table 7 represent the period from June 1, 1998 through September 22, 1998. The Reddi-Form data in Table 7 were adjusted to remove the impact of the vandalism. The adjustment was based on the relationship between Lite-Form and Reddi-Form energy consumption patterns. These results are also consistent with the results as expressed in Figure 10.

Table 7 – Total Cooling Consumption
(during the monitoring period)

House	Energy Consumption (kWh)
Reddi-Form	813
wood frame	1,037
Lite-Form	772

Because these three homes were unoccupied and unused for the monitoring period, the utility bills almost exclusively represent power consumption for heating and cooling. Utility bill totals, including all charges, are given in Table 8 for the period of July 17, 1998 through March 18, 1999. All monthly bills from the local utility company were reported as actual readings for the period. The energy consumption data consistently supports energy savings of approximately 20% for the ICF homes in comparison to the wood-frame home. Note that the energy consumption anomaly caused by the vandalism in one of the units occurred prior to July 17, 1998 and is therefore not included in this utility bill analysis.

Table 8 – Utility Bill Totals
July17, 1998 – March 18, 1999

House	Total Cost	Total kWh
Reddi-Form	$385.31	4297
Wood	$465.58	5348
Lite-Form	$375.68	4185

The superior energy performance of the ICF homes in comparison to the wood-framed home can be attributed primarily to two aspects of their construction:

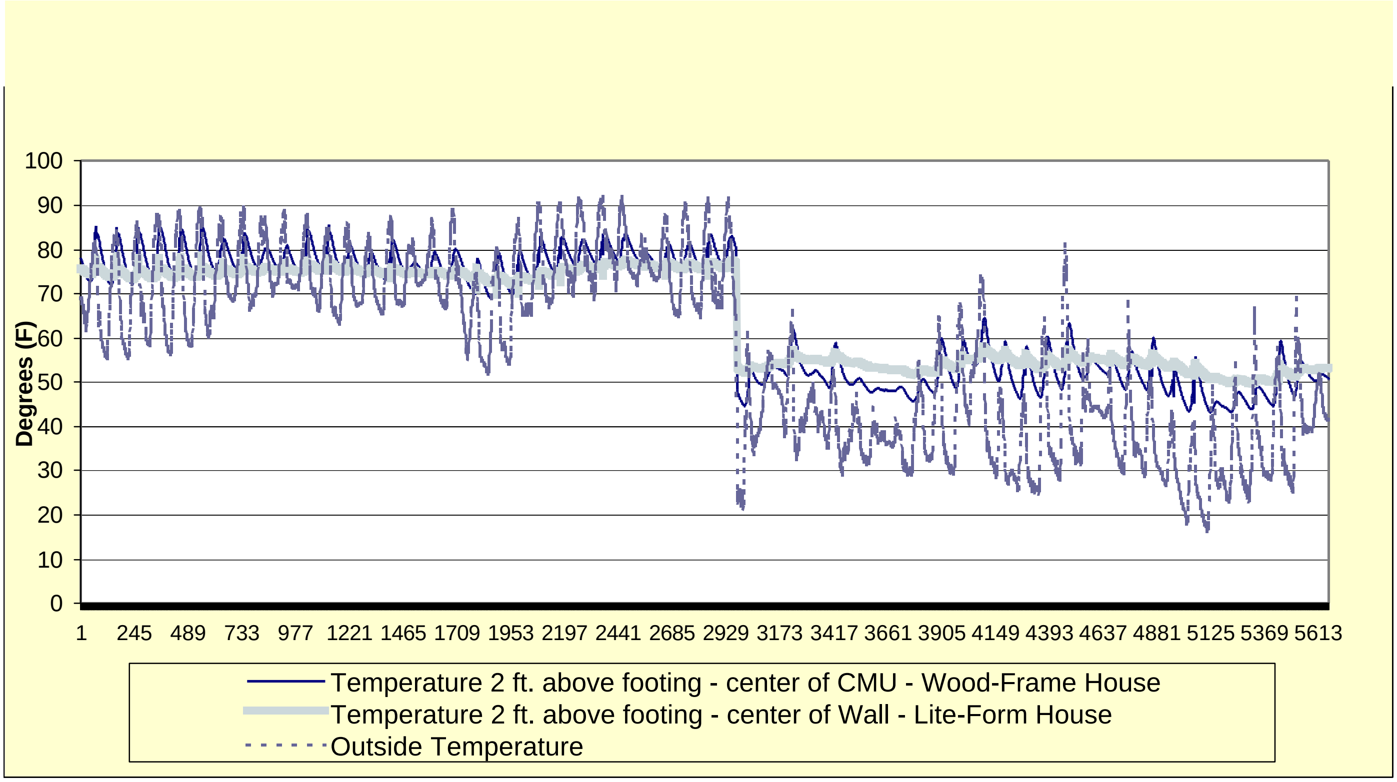
1. Higher wall R-value – The insulation for the walls of the ICF homes is R-20 while the wall insulation of the wood-framed home is R-13. The solid wall surfaces for all three homes make up approximately 44% of the total surface area of the homes (the remainder being made up of the ceiling area, windows, and doors). A 50% increase in the solid wall surface area resistance to conductive heat loss (R-13 compared to R-20) represents significant increased energy-efficiency.

2. Slab/foundation wall construction – A common foundation insulation detail in the wood-framed home led to a direct contact between the slab and the foundation block wall that does not exist in ICF homes.[9] As shown in Figure 11, the rigid insulation extends only to the top inside edge of the step block, a level to which fill was added and at which the slab begins. There is vertical and horizontal contact area between the slab and the step block, with the outside face of the step block being above grade. In the ICF homes as shown in Figures 4 and 5, the two-inch insulation forms extend from footer to roof line, effectively separating the slab and the concrete cavity from the outside.

Figure 11 - Foundation Insulation Detail - Wood-Frame Home

Figure 12 shows the impact of the foundation/slab details. Clearly the wood-frame home is demonstrating greater heat loss in February and greater heat gain in August as evidenced by the wood-frame home's more pronounced and direct response to outdoor temperature changes. Given the total area and the thermal conductivity of materials involved, the

[9] The foundation/insulation/slab detail shown here represents common construction practice for slab-on-grade homes in this climate. In general, foundation insulation details on conventional basement and wall assemblies can make a continuous thermal break difficult to detail in the field and communicate to trade contractors.



foundation/insulation/slab detail of the wood-frame home represents a significant source of heat loss and gain not evidenced in the ICF homes.

Figure 12 - Comparison on Sensor Readings with Outdoor Temperature

Comparison to BLAST Prediction

In an effort to address concerns regarding the nature of the relationship between energy modeling and real-world results for ICF homes, the three homes were modeled using the Building Loads Analysis and System Thermodynamics or BLAST model. The modeling was performed using actual weather data collected at the site for one cooling and one heating monthly period, August 1998 and February 1999 respectively. Figures 13 and 14 present the actual energy use on a daily basis for all three homes.

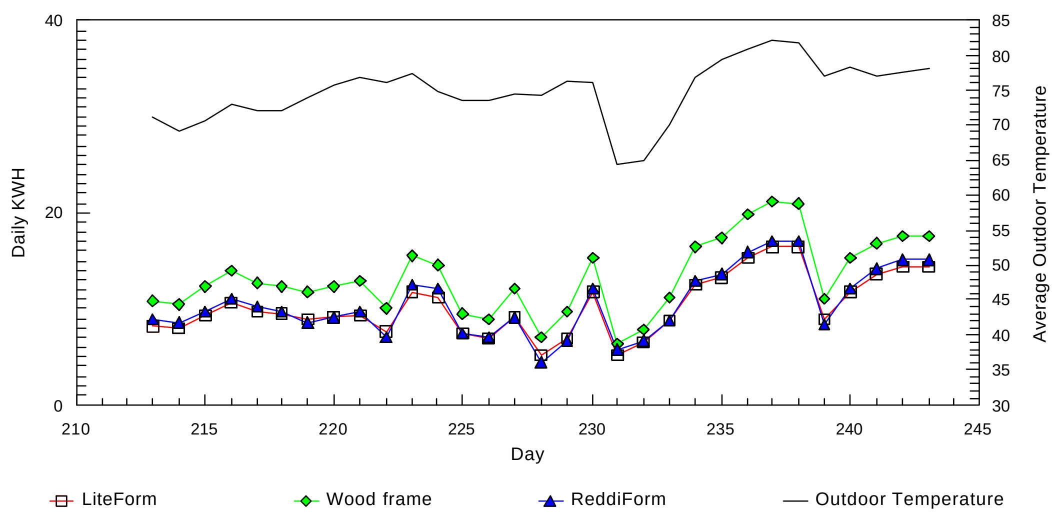


Figure 13 - Actual Summer Consumption (August 1998)

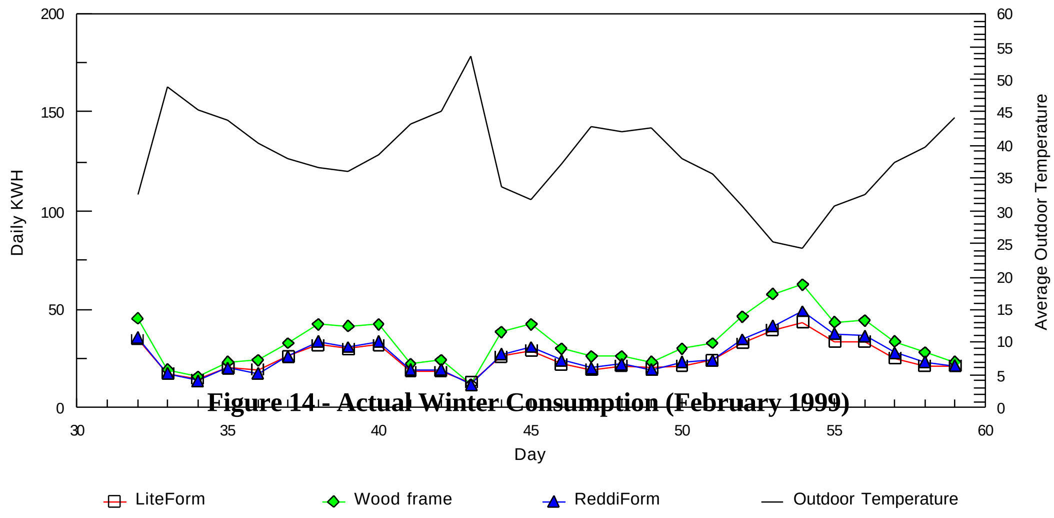


Figure 14 - Actual Winter Consumption (February 1999)

On the following two pages, Figures 15 through 20 present comparisons between the actual and BLAST-predicted energy use for each home during August—for cooling—and February—for heating. Figures 15, 16, and 17 present the comparisons during August and Figures 18, 19, and 20 during February. Tables 9 and 10 presented below summarize the total energy use comparison for all three homes for cooling and the heating.

In general, the shapes of the BLAST curves closely track that of actual consumption. While the BLAST curve during cooling in the Lite-Form house (Figure 15) is not always below that of the actual consumption during the graphed period, the total predicted consumption (198 KWh) is only 92 percent of actual consumption of 216 KWh for the graphed period.

Figure 18 shows the predicted and actual consumption for heating in the Lite-Form house. The BLAST curve lies on or above that of the actual consumption for the entire period. Total predicted consumption of 911 KWh is 28 percent greater than the actual consumption of 711 KWh.

Table 9 – Cooling Consumption Comparison

House Type	**BLAST (Total kWh)**	**Actual (Total kWh)**	**Difference (%)**
Lite-Form	198.5	215.6	-8
Wood-Frame	218.5	276.3	-21
Reddi-Form	203.5	221.5	-8

Table 10 – Heating Consumption Comparison

House Type	BLAST (Total kWh)	Actual (Total kWh)	Difference (%)
Lite-Form	911.3	711.4	+28
Wood-Frame	996.1	932.8	+7
Reddi-Form	803.3	745.1	+8

Figure 15 – Lite-Form Energy Consumption, Predicted vs. Actual (August 1998)

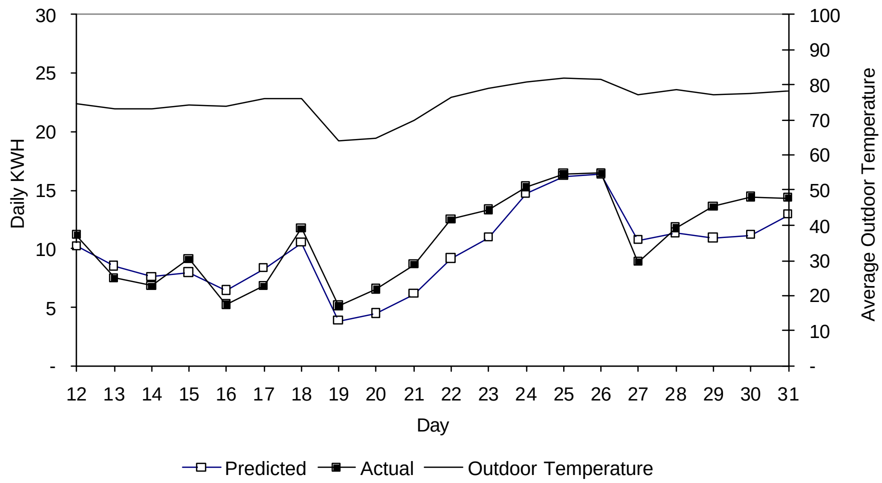
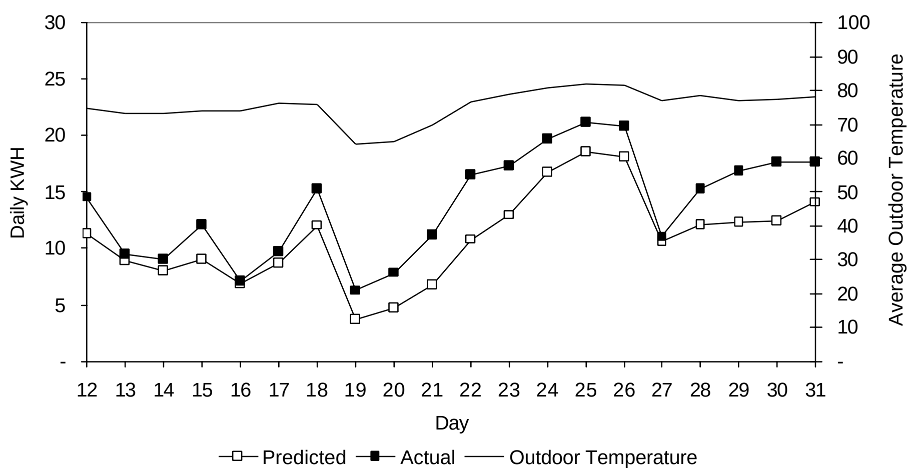


Figure 16 – Wood frame Energy Consumption, Predicted vs. Actual (August 1998)



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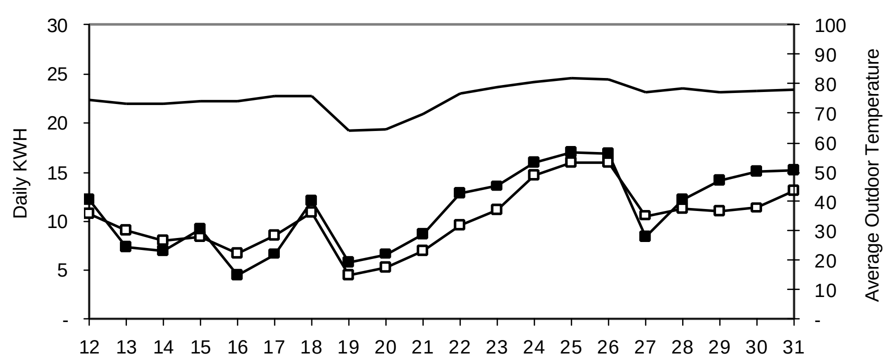


Figure 18 - Lite-Form Energy Consumption, Predicted vs. Actual (February 1999)

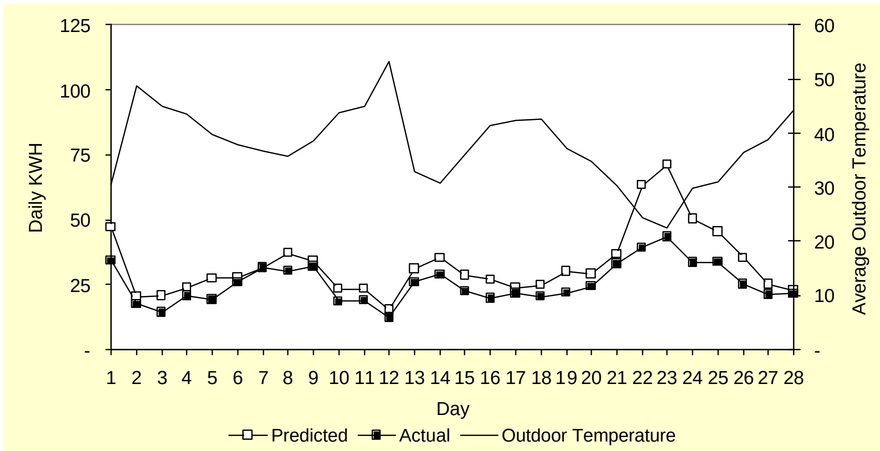


Figure 19 – Wood frame Energy Consumption, Predicted vs. Actual (February 1999)

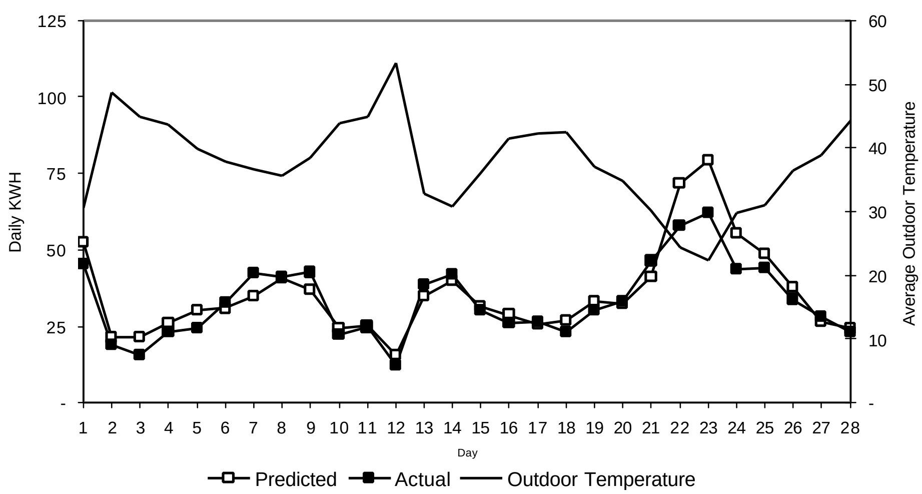
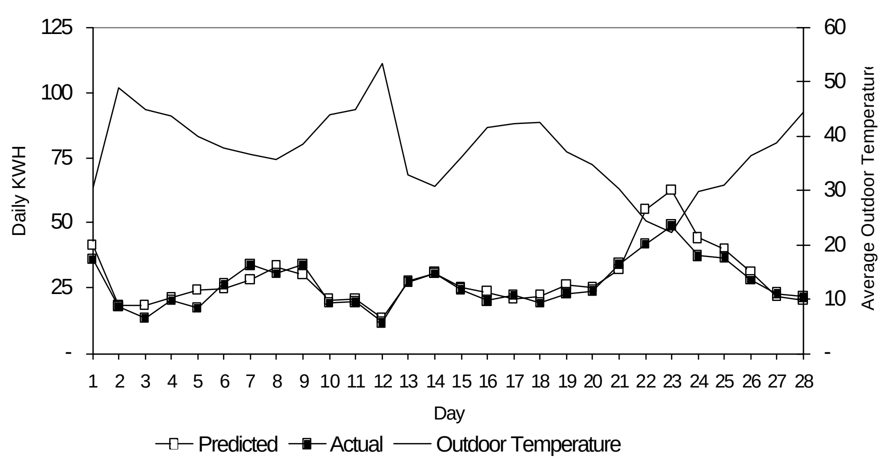


Figure 20 – Reddi-Form Energy Consumption, Predicted vs. Actual (February 1999)



The information presented in Tables 9 and 10 and Figures 15 through 20 combine to permit the following observations and comments.

1. With the exception of the days discussed below, the curves and fit suggest that BLAST did as good a job predicting the energy consumption of the ICF homes as it did the wood-framed home (generally within 2 to 5 percent). In fact, the fit for the ICF homes is slightly better than for the wood-framed home for days 12 through 26. These results suggest that thermal mass and ground-coupling effects are not significant drivers of differences between actual energy consumption and BLAST-predictions. It should be noted here that three building parameters have been identified as problematic for energy modeling software: thermal mass, solar gains through windows, and ground-coupling.[10] Thermal mass concerns have proven not to be significant when the mass is insulated from the conditioned space, as is the case for all ICF homes. On the other hand, given the slab-on-grade foundations and lack of window treatments on any windows of the three homes, some difficulties with modeling are to be expected, particularly on clear, sunny days.
2. In the case of cooling days 28 through 31, there is a consistent under-prediction of daily energy use and opposite shapes of the curves for these four days. In the case of heating days 21 through 26, there is a consistent over-prediction of energy consumption for the only days during the time period when the outdoor temperature fell significantly below freezing or the set point of the heat pump for engagement of auxiliary heat.
3. The fact that both observations 2 and 3 follow a consistent pattern in all three homes suggests a model mis-specification or problem in the weather data. Two phenomena may be driving both the under prediction and over-prediction observed:

    a. The pyranometer used to measure insulation takes only one measurement of solar radiation and the split between beam and diffuse is accomplished via a software calculation. It is possible if not likely that the software the Research Center used involves different calculations than the BLAST model for apportioning beam and diffuse radiation. Also related to solar radiation is the fact that the pyranometer is set to read in a plane parallel to the ground when the solar radiation that windows "see" is at some angle that changes during the day but is never at the angle at which the pyranometer is set. When data were inspected on an hourly basis for periods of time in which the actual and predicted deviate substantially, total solar radiation for day time hours was quite high on a basis relative to other day time periods.
    b. The BLAST model does not provide a mechanism for transparent conversion of heat pump performance specifications to BLAST equipment parameters. Nor do BLAST defaults include a heat pump capacity smaller than 3 ½ tons (All three of the homes were equipped with the same model 2-ton heat pump). The consistent over-prediction for these outdoor temperatures suggests that a mis-specification relating to auxiliary heat set-point for the 2-ton heat pump performance is driving this over-prediction.

[10] NREL Report on BESTEST, April, 1996 *EDU*.

Comfort Analysis

A heating thermal comfort analysis consistent with ASHRAE Standard 55 was conducted on both the Lite-Form and the wood-framed houses as part of this study. The analysis considered operative temperatures, relative humidity, temperature cycling and rifts, vertical air temperature differences, radiant temperature asymmetry and floor temperature.

Heating thermal comfort data were collected between December 22nd and December 29th 1998. Additional verification data of the temperature stratification and operative temperature, cycling, and drifts/raps were obtained on January 8-9 and 14-15, 1999 from the temperature trees used for the energy monitoring. Four days were selected which had solar radiation readings corresponding to cloudy to partly cloudy conditions. ASHRAE Standard 55 requires that monitoring data be recorded over at least a 2-hour interval.

Tabulations of the resulting data are presented in the Appendix. Daily data on daylight readings for the time period 8:00 a.m. through 5:00 p.m. are presented, along with darkness readings for the time period 5:00 p.m. through 8:00 a.m. Daylight period, darkness period and overall averages are also presented.

In general, the thermal comfort analysis showed consistent and similar results for the wood and Lite-Form homes, with a minor improvement associated with the Lite-Form house in operative temperature, temperature cycling, and vertical air temperature difference.

The Lite-Form house rarely exceeded comfort conditions with regard to the ASHRAE standard for the rate of temperature change. The wood house experienced several sub-intervals when the cycling significantly exceeded the comfort parameters. Additionally, the Lite-Form house had minimal occurrences of temperature stratification, while the wood house showed stratification about 10 percent of the time, with one time period approaching 25 percent of the time.

Table 11 presents the results of the operative temperature analysis. The data are presented as the percentage of each interval that the temperature exceeded the ASHRAE winter range of 68° F to 70°F in the Kitchen and Living Room in each home. As can be seen in the bottom row of the table, the performance of the Lite-Form home is slightly superior to that of the wood frame house. The temperature in the Lite-Form house fell outside the acceptable range only about 25 percent of the time as compared with about 34 percent for the wood frame house.

Table 11 - Operative Temperature Exceeding Limits

Status	Wood frame		Lite-Form	
	Kitchen	**Living Room**	**Kitchen**	**Living Room**
Day 1 - Daylight	3%	11%	33%	33%
Day 1 - Darkness	13%	17%	43%	35%
Day 2 - Daylight	47%	50%	36%	31%

Table 11 - Operative Temperature Exceeding Limits

Day 2 - Darkness	71%	75%	16%	12%
Day 3 - Daylight	14%	22%	8%	17%
Day 3 - Darkness	28%	32%	8%	12%
Day 4 - Daylight	61%	64%	31%	17%
Day 4 - Darkness	20%	22%	35%	35%
Average daylight	31%	37%	27%	24%
Average darkness	33%	36%	26%	23%
Overall average	32%	36%	26%	24%

It is interesting to note that thermal comfort determinations per the ASHRAE standard assume a clothing ensemble that includes socks and shoes thereby eliminating any consideration of conductive effects that individuals might sense between bare feet and the structure's floor. It is true that floor temperatures are indirectly included in terms of contribution to the mean radiant temperature but not directly included for conductive impact. This can be important in that bare feet are relatively common in residential determination of thermal comfort.

Figure 21 presents the slab surface temperatures for both the center of slab and slab perimeter for the wood-frame and Lite-Form homes. The slightly higher floor temperatures under heating conditions and slightly lower floor temperatures under cooling conditions of the ICF homes may contribute to improved thermal comfort in a manner not included in the ASHRAE standard.

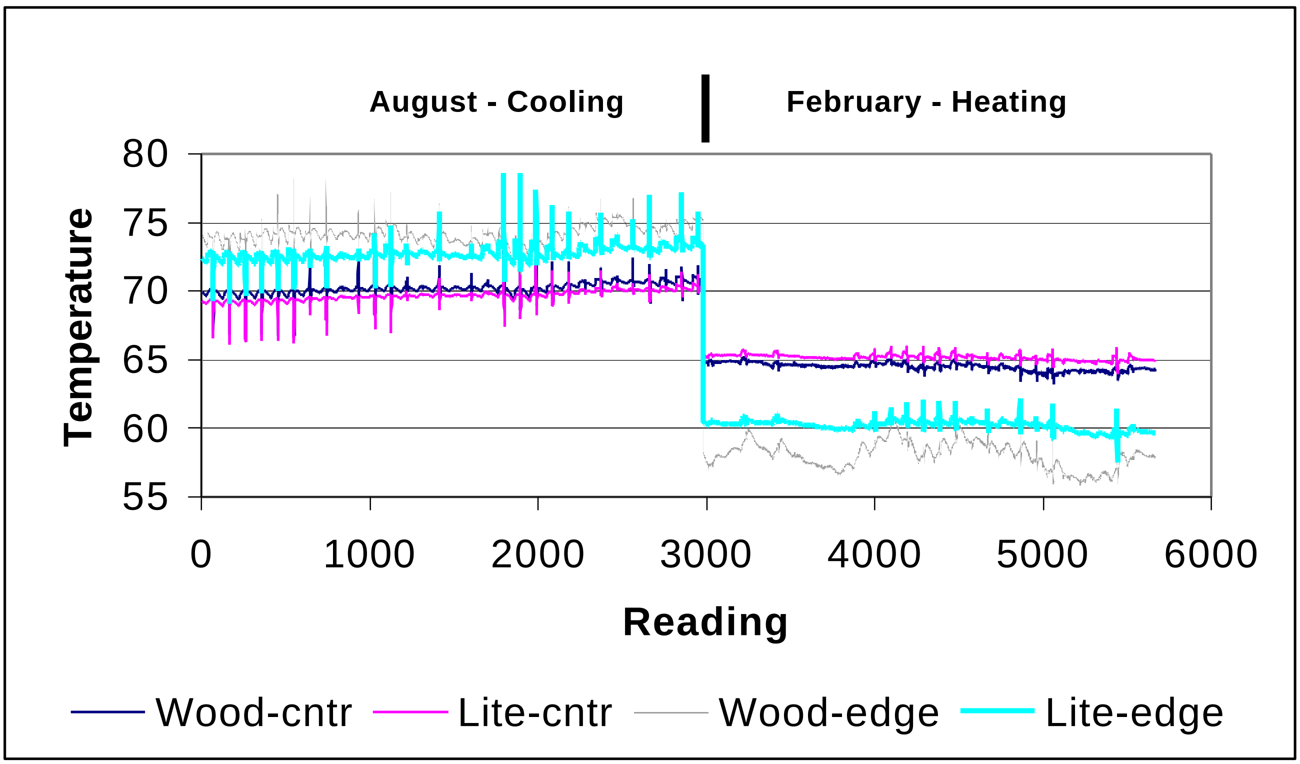


Figure 21 - Comparison of Slab Temperatures

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are supported by our findings.

- In general, the ICF homes were approximately 20% more energy efficient than the wood frame house. Given the three homes similarities in air tightness, the increased energy-efficiency is largely due to the higher effective R-value of the walls and continuous insulation at the slab. The Lite-Form home consumed only 79 percent as much energy as did the wood frame house for heating, while the Reddi-form home consumed 81 percent. During the cooling season, the Lite-Form home consumed 74 percent as much energy as the wood frame house. The Reddi-Form consumed 78 percent as much.

- BLAST predicted results were similar to measured results. Based on our data, we cannot recommend adjustments to BLAST that would improve the ability to predict energy use in the area of the study or in other climates. BLAST tended to over-predict the amount of energy used for heating and under-predict the amount used for cooling. Most of the deviations between actual and predicted energy use can be attributed to model assumptions related to heat pump specifications and differences between measured and calculated beam and diffuse solar radiation.

- No dramatic comfort differences were noted between ICF and wood-framed construction, but the ICF home had several thermal comfort measures showing a slight improvement. The minor improvements were noted in operative temperature, temperature cycling, and vertical air temperature difference. Some positive contribution to thermal comfort may be associated with preferable floor surface temperatures in the ICF home tested but this could not be accounted for under the ASHRAE standard.

APPENDIX

THERMAL COMFORT RESULTS

Operative Temperature

Standard 55-1992, Section 5.1.2 specifies that the indoor temperature range between 68°F and 74°F during the winter. Table 5 in the body of the report presents the study findings on the indoor or operative temperature.

Relative Humidity

Standard 55-1992, Section 5.1.3 specifies in general the winter range of relative humidity to be between 30% and 70%. Figure 2 of the standard provides information on relative humidity limits for acceptable thermal comfort. Since relative humidity limits are a function of operative temperature, the relative humidity limits are not an absolute range. In all cases the relative humidity was less than the recommended range of Standard 55-1992. The maximum recorded relative humidity was 27%. No conclusion can be drawn on the comparative performance of the wood frame and ICF home.

Temperature Cycling

Standard 55-1992, Section 5.1.5.1 specifies the rate of temperature change shall not exceed 4°F per hour when the peak cycle variation within a 15 minute interval exceeds 2°F per hour. The Lite-Form house had minimal occurrences exceeding comfort conditions. These occurrences did not even show up when data were aggregated over the entire monitoring interval. The wood house experienced several sub-intervals when the cycling significantly exceeded the comfort parameters, with one period (Day 2 – Daylight) exceeding the comfort parameter nearly one time in five (18%).

Table 12 - Temperature Cycling

Status	Wood frame		Lite-Form	
	Dining room > 4°F	Living room > 4°F	Dining room > 4°F	Living room > 4°F
Day 1 - Daylight	3%	4%	0%	0%
Day 1 - Darkness	8%	8%	0%	0%
Day 2 - Daylight	18%	18%	0%	0%
Day 2 - Darkness	8%	8%	0%	0%
Day 4 - Daylight	0%	0%	1%	1%
Day 4 - Darkness	2%	2%	0%	2%
Day 5 - Daylight	0%	0%	0%	0%
Day 5 - Darkness	3%	0%	1%	1%
average daylight	4%	4%	0%	0%
average darkness	4%	3%	0%	1%
overall average	4%	4%	0%	0%

Temperature Drifts or Ramps

Standard 55-1992, Section 5.1.5.2 defines drifts or ramps as "monotonic, steady, *noncyclic* temperature changes." The maximum allowable change is 1°F per hour. In this study drifting or ramping was assessed by taking and comparing hourly average temperatures. Each hour interval was directly compared to the preceding hourly interval, if the absolute value of the difference was greater than one degree F, then drifting or ramping was assumed to be occurring. Both houses showed a steady-state temperature without any measurable change.

Vertical Air Temperature Difference

The maximum temperature differential measured between the 4" and the 67"heights is limited by the standard to 5°F. In this study, we assessed thermal comfort in the sedentary position, since that is the most common position in the home environment. The temperature differential of 5°F specified in the standard was adjusted to 3.1°F at the 43" height. The Lite-Form house had minimal occurrences of stratification, while the wood house showed stratification about 10 per cent of the time, with one time period approaching 25 percent of the time.

Table 13 - Vertical Stratification

Status	Wood frame		Lite-Form	
	Dining room > 5°F	Living room > 5°F	Dining room > 5°F	Living room > 5°F
Day 1 - Daylight	0%	0%	0%	0%
Day 1 - Darkness	5%	5%	0%	2%
Day 2 - Daylight	0%	0%	0%	0%
Day 2 - Darkness	24%	22%	0%	0%
Day 3 - Daylight	11%	6%	0%	3%
Day 3 - Darkness	17%	17%	0%	2%
Day 4 - Daylight	6%	6%	0%	0%
Day 4 - Darkness	10%	8%	0%	0%
average daylight	4%	3%	0%	1%
average darkness	14%	13%	0%	1%
overall average	9%	8%	0%	1%

Radiant Temperature Asymmetry

This measure reflects the phenomena that discomfort is experienced when there is a distinct temperature difference between two diametrically opposing directions. A good example of this discomfort is experience by a person standing in front of a blazing fire on a cold winter night. One can adjust position to be comfortable on the warm side but they will experience discomfort on the cold side. Standard 55-1992, Section 5.1.6.2 defines the maximum allowable difference across vertical surfaces (walls) as 18°F and the maximum allowable difference across horizontal surfaces (walls) as 9°F. With both homes there were few instances when this measure exceeded operational limits.

Floor Temperature

Standard 55-1992, Section specifies that the floor temperature should fall between 65°F and 84°F. Minimal occurrences of floor temperatures out of specification were noted.

Drafts

Standard 55-1992, Section 5.1.6.4 calculates comfort based on a function of mean air speed, turbulence intensity, and air temperature. Measured air speed was zero, so this comfort criteria was not calculated.