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# Performance Check Between Whole Building Thermal Performance Criteria and Exterior Wall Measured Clear Wall R-Value, Thermal Bridging, Thermal Mass, and Airtightness

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## ABSTRACT

*The dynamic thermal performance of an insulated concrete form (ICF) system was analyzed based on a dynamic guarded hot box test at a national laboratory. The same wall configuration was modeled for dynamically changing boundary conditions using the finite difference computer code HEATING 7.2. Thermal mass validation of the model was made by comparing model heat flow predictions to the hot box measured heat flow through an 8 ft by 8 ft ICF clear test wall exposed to dynamic boundary conditions. Good agreement was found between test and computer modeling results.*

*A series of response factors, heat capacity, and R-values were computed using finite difference computer modeling. They enabled a calculation of the wall structure factors and estimation of the simplified one-dimensional "thermally equivalent wall" configuration. A thermally equivalent wall has a simple multilayer structure and the same thermal properties as a nominal wall. Its dynamic thermal behavior is identical to the ICF test wall. The thermal and physical properties describing the equivalent wall can be used in whole building one-dimensional energy simulation programs with hourly time steps. The usage of the equivalent wall theory provides a direct linkage from dynamic hot box test to accurate modeling of buildings with walls that contain considerable three-dimensional heat flow within the structure.*

*The equivalent wall generated for the ICF system was used in a whole building computer model to simulate a single-family residence in six representative U.S. climates. The space heating and cooling loads from the residence with massive ICF were compared to an identical building simulated with lightweight wood- frame exterior walls. Nine lightweight wood-frame walls with R-values from 2.3 - 29.0 ($h{\cdot}ft^2{\cdot}{}^\circ F/Btu$) were simulated. The heating and cooling loads generated from these building simulations were used to estimate the R-value that would be needed in conventional wood-frame construction to produce the same loads as the ICF system. The resulting R-value is considered an effective R-value for the ICFs, which not only accounts for the steady-state R-value but also the inherent thermal mass benefit. "Effective R-values" for the ICF were obtained by comparison of the thermal performance of the ICF and lightweight wood-frame walls, and they should be understood only as an answer to the question, "what R-value would an identical house with wood-frame walls need to obtain the same space heating and cooling loads as a specific ICF?"*

*A second major benefit of this ICF system is the airtightness. This paper also analyzes the impact of a 20% reduction in uncontrolled infiltration for the ICF house compared to the wood-frame structure. The 20% reduction is supported by blower door tests on seven ICF houses with a measured 0.0004 leakage area dived by floor area.*

## BACKGROUND

At the last IEA Annex 32 meeting in Utrecht, The Netherlands, it was proposed that the Annex develop the links between level one (whole building performance) and level two (envelope system). This paper provides a case study of just that type of connection. An exterior wall mockup is hot box tested and modeled in the laboratory. Measurements of the steady-state and dynamic behavior of this mockup are used as the basis to define the thermal bridging, thermal mass benefit, and airtightness of the whole wall system. These level-two performance characteristics are related to the whole building performance. They can be analyzed by a finite-difference modeling of the wall assembly. An equivalent wall theory (Kossecka and Kosny 1996, 1997; Koussecka 1998) is used to convert three-dimensional heat flow to one-dimensional terms that capture thermal mass effects, which, in turn, are used in a

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common whole-building simulation model. This paper illustrates a performance check between the thermal performance of a massive ICF (insulating concrete form) wall system mockup (level two) and whole-building performance criteria (level one) such as total space heating and cooling loads (thermal comfort).

Steady-state thermal performance of an ICF wall system was first tested in a guarded hot box according to a test procedure described by ASTM C 236 (ASTM 1989). This same wall mockup was then modeled by use of finite-difference numerical techniques. The hot-box test and finite-difference computer code HEATING 7.2 (Childs 1993) were used to analyze the clear-wall area and wall details where frequently most of the thermal bridging occurs.

At present, most thermal calculations for wall systems are based on the measured or calculated thermal performance of the flat wall area without the effect of wall components included. In this paper, that method is referred to as only the performance of the clear wall (the clear wall is the part of the wall that is free of thermal anomalies due to wall subsystems or intersections with the other building surfaces). It was observed for many wall systems that a change in a wall detail configuration can notably affect proportions in wall area distribution and overall wall R-value. One level-two performance criterion could be that local thermal resistances created by wall details should not reduce the whole-wall resistance by more than 10% below that of the clear-wall value.

## WHOLE WALL STEADY-STATE PERFORMANCE

### Guarded Hot Box Test of the Clear Wall

Measurements of wall systems are typically carried out by apparatus such as the one described in ASTM C 236 (ASTM 1989). A relatively large (approximately 2.4 m × 2.4 m (8 × 8 ft) or larger] cross section of the clear wall area of the wall system is used to determine its thermal performance. The precision of this test method is reported to be approximately 8% (ASTM 1989).

A wall built with ICF 0.23 m (9.25 in.) thick foam blocks, as shown in Figure 1a, was tested in the guarded hot box under steady-state conditions. The basic ICF wall component was the 0.23 m. (9.25 in.) thick EPS foam wall form. The thickness of the exterior and interior foam walls creating the ICF wall component varied from 3.8 to 8.8 cm. (1.5-3.5 in.). Inside the ICF wall form, the vertical and horizontal channels (about 15.75 cm. or 6.25 in. diameter) were created. These channels were filled with concrete during construction of the wall. The exterior surface of the wall was finished with a 13 mm (2 in.) thick layer of stucco and on the interior surface, 13 mm (2 in.) of thick gypsum boards. Reinforced high-density concrete was poured into the expanded polystyrene and sheet-metal wall forms. Test results are presented in Table 1.

For comparison, the clear-wall R-value of a 50 mm × 100 mm (2 × 4) wood-frame wall with 0.6 m (24 in.) on center, without insulating sheathing, is 1.91 $m^2 \cdot K$ / W (10.8 h·$ft^2 \cdot$°F/Btu). For the similar wall with 2.5 cm (1 in.) EPS sheathing

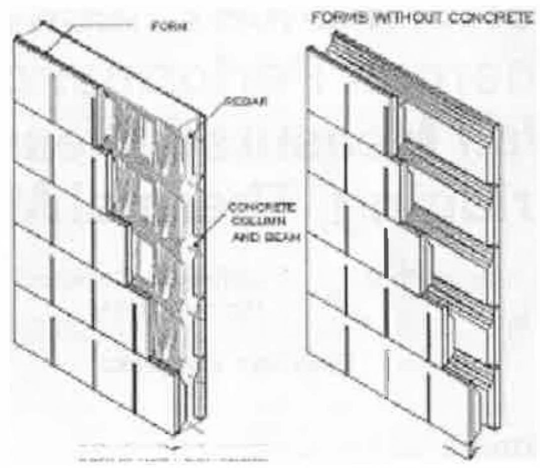


*Figure 1a ICF clear wall section.*

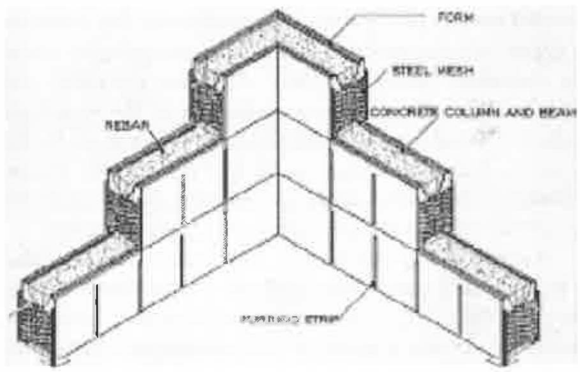


*Figure 1b ICF corner detail.*

**TABLE 1**
**Test Results of the Insulating Concrete Form Wall**

| Clear Wall R-Value | 2.04 $m^2 \cdot$K/W (11.57 h·$ft^2 \cdot$°F/Btu) |
|---|---|
| Climate chamber air temperature | 11°C (52.25°F) |
| Meter chamber air temperature | 37.6°C (99.7°F) |
| Climate side wall surface temperature | 13.4°C (56.17°F) |
| Meter side wall surface temperature | 36.6°C (97.9°F) |
| Meter chamber air velocity | 1 km/h (0.6 mph) |
| Climate chamber air velocity | 0.64 km/h (0.4 mph) |

clear wall R-value is 2.58 $m^2 \cdot$K / W (14.7 h·$ft^2 \cdot$°F/Btu). For a metal-frame system the clear wall R-value of a 50 mm x 100 mm (2x4 in.) frame with 0.4 m (16-in.) on-center without insulating sheathing) is 1.31 $m^2 \cdot$K/W (7.44 h·$ft^2 \cdot$°F/Btu). For the similar metal stud wall with 2.5 cm. (1 in.) EPS sheathing, clear wall R-value is 2.06 $m^2 \cdot$K/W (11.7 h·$ft^2 \cdot$°F/Btu). For a 30 cm. (12 in.) two-core unit wall insulated by 4.7 cm. (1-7/8 in.) foam inserts, clear wall R-value is 0.65 $m^2 \cdot$K / W (3.7 h·$ft^2 \cdot$F/Btu) (Christian and Kosny 1996).

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**TABLE 2**
**Material Properties (Level 3)**

| | | |
|---|---|---|
| Thermal conductivity of stucco | 1.3 W/m·K | (9 Btu·in./h·ft$^2$·°F) |
| Thermal conductivity of concrete | 2.2 W/m·K | (12.5 Btu·in./hft$^2$F) |
| Thermal conductivity of EPS | 0.03 W/m·K | (0.24 Btu·in./h·ft$^2$·°F) |
| Thermal conductivity of steel | 46 W/m·K | (320 Btu·in./h·ft$^2$·F) |

## Computer Simulation of the Clear Wall

A three-dimensional computer model of heat conduction, using a finite-difference computer code HEATING 7.2 (Childs 1993), was used for this analysis. The resultant isotherm maps were used to calculate average heat fluxes and then wall system R-values. The accuracy of HEATING 7.2's ability to predict wall system R-values was verified by comparing simulation results with published test results for 28 masonry, wood frame, and metal frame walls tested at several laboratories (Kosny and Christian 1995). The model predicted the measurements of these walls within 5% of reported measurements. Considering that the precision of the guarded hot box method is reported to be approximately 8%, the ability of HEATING 7.2 to reproduce the experimental data is within the accuracy of the test method.

The ICF wall was modeled using dimensions measured from the actual components used to construct the test wall. Table 2 shows thermal properties of materials that were used for modeling (ASHRAE 1997).

The simulated clear-wall R-value was 2.11 Km$^2$/W (11.96 h·ft$^2$·°F/Btu), 3% higher than the R-value obtained during the test, 2.04 K·m$^2$/W (11.57 h·ft$^2$·°F/Btu). This is within the range of error of the simulation method.

## Overall Wall Thermal Performance

For most concrete and masonry walls, wall details play a significant role in the overall wall R-value calculations. The area of the thermal disturbances created by wall details may reach 60% of the opaque wall area for these walls (cut-web wall system) (Kosny and Desjarlais 1994). Very often, low R-values of wall details lower the overall wall R-value. However, for some systems, wall details may have higher R-values than the clear-wall area, so the overall wall R-value may be increased. Table 3 contains the source for the set of details used in modeling of the ICF wall system. R-values of wall details and their modifications are presented in Table 4.

**TABLE 3**
**ICF Detail Source**

| | |
|---|---|
| Figure 1. | Corner (p.20, APF 1995) |
| Figure 2. | Wall/roof (p.42, APF1995) |
| Figure 3. | Wall/floor (pp.42-43, APF 1995) |

Three-dimensional computer modeling enabled analysis of the temperature distribution in the wall and precise calculations of local heat fluxes in the clear wall area and in areas of wall details. Maps of the temperature distribution in the wall and wall details (the areas where walls intersect with other envelope components) were developed. These maps were used as an aid to estimate the areas of zones affected by existing thermal bridges and to calculate R-values for these areas. Then these R-values were used to calculate an average overall wall (a whole-wall) R-value that includes the thermal effect of all wall details. The overall wall R-value is calculated from an area-weighted average U-factor for clear wall and for wall details (Kosny and Desjarlais 1994). Similar calculations for other wall technologies and for different buildings can be

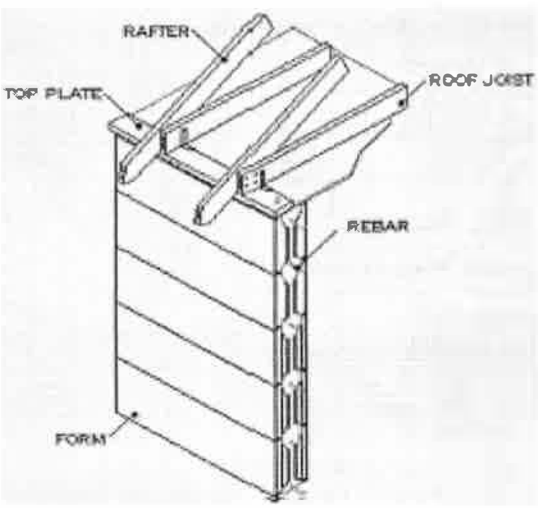


***Figure 2*** *Wall/roof interface detail.*

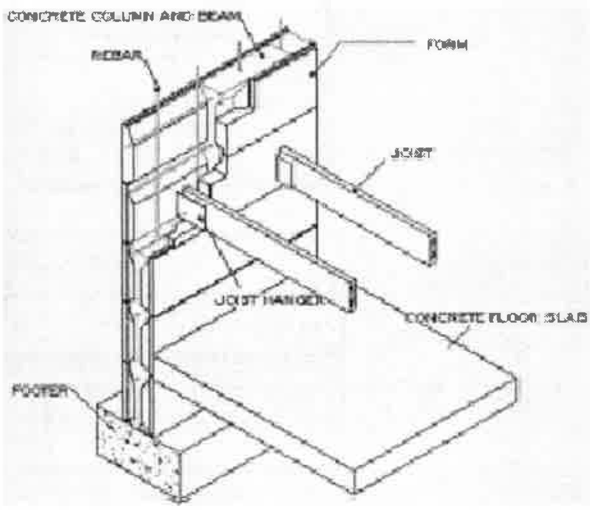


***Figure 3*** *Wall/floor interface detail.*

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**TABLE 4**
**R-Values of Wall Details***

| Wall Detail | R-Value of Detail Area K·m²/W (h·ft²·F/Btu) | Size of Detail Area m (in.) |
|---|---|---|
| External corner (Figure 1b) | 1.72 (9.79) | 0.46 (18.0) Distance from the center of the corner to the edge of the corner zone. |
| Wall/floor (Figure 3) | 2.11 (12.00) | 0.34 (13.5) Distance from the surface of the floor to the edge of the wall/ceiling detail zone. |
| Wall/roof (Figure 2) | 1.45 (8.22) | 00.2 (17.0) Distance from the surface of the ceiling to the edge of the wall/roof detail zone. |

* Detail zones were estimated based on the analysis of the isotherms (normally it is the closest area where isotherms are parallel to the surfaces of the wall— no transverse heat transfer).

performed using the Internet Whole Wall R-value Calculator (http://www.ORNL.gov/roofs+walls).

For the one-story ranch house shown in Figure 4, ICF wall details represent 46.5% of the opaque wall area. The wall detail heat losses represent 51.5% of the total heat losses. The most significant wall detail—wall/ roof connection—represents about 20% of the area and 28% of the total wall heat losses. Wall opening details were not considered in this study because they were not structurally different from the clear wall area.

The overall wall U-factor was calculated as an area-weighted average of U-factors of all wall details. Then, the overall wall R-value was computed. For the set of details recommended by the producer (APS 1995), overall wall R-value is 1.89 K·m²/W (10.76 h·ft²·°F/Btu). The overall wall R-value is only 10% lower than the clear wall R-value. For many masonry and concrete wall systems, overall wall R-values are 10% to 25% lower than clear-wall R-values. Comparison of the clear-wall and overall wall R-values of several wall systems (including wood and metal frame systems) are presented in Table 5. This suggests that a reasonable performance criterion is that the whole-wall steady-state R-value be within 10% to 15% of the clear wall R-value.

## THERMAL MASS BENEFIT

### General Procedure

The same ICF wall was tested dynamically in a guarded hot box and was modeled for dynamically changing boundary conditions using the finite-difference computer code HEATING 7.2 (Childs 1993). The computer model was calibrated using the steady-state hot box test results as described previously (Kosny and Christian 1995; Kosny and Desjarlais 1994). Thermal storage behavior of the wall model was confirmed by comparing model heat flow predictions to the hot box measured heat flow through the 2.4 m by 2.4 m (8 ft

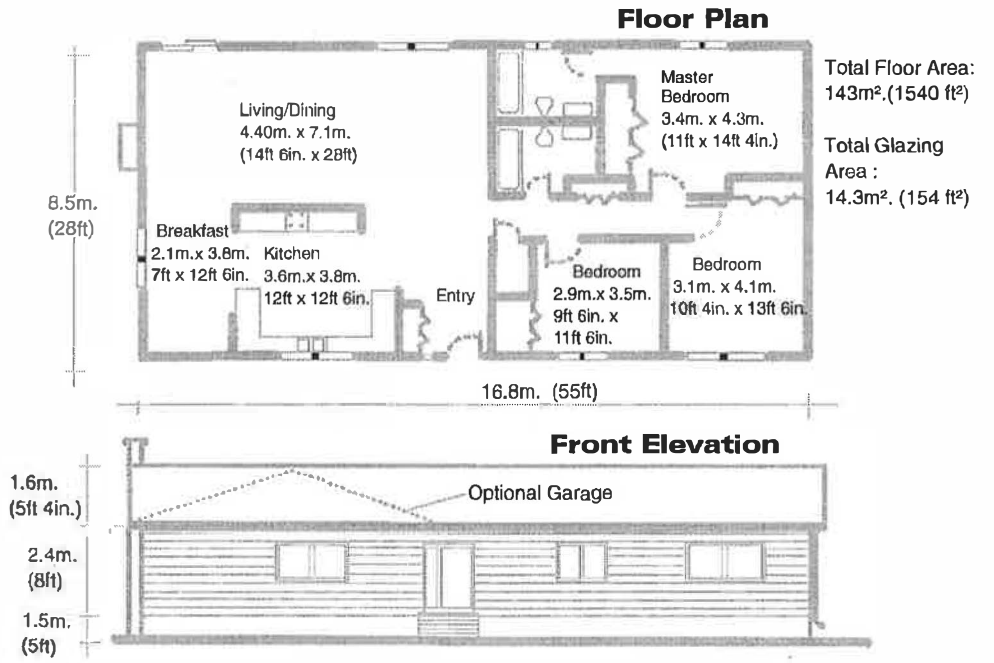


***Figure 4*** *Floor plane and elevation of one-story ranch house.*

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**TABLE 5**
**Comparison Between the Clear Wall and Overall Wall R-Values for Some Wall Systems**

| Name of the Wall System | Difference Between Clear Wall R-Value and Overall Wall R-Value (%) |
|---|---|
| ICF wall | 9.5 |
| Insulated concrete cut-web units 12-in. | 12.0 |
| 12-in. multicore units with insulation inserts | 24.0 |
| Larsen truss wall | 23.5 |
| 2×4 wood-frame wall 24 in. o.c. | 9.1 |
| 2×6 wood-frame wall 24 in. o.c. | 17.4 |
| Stress skin panel 6 in. | 12.5 |
| 2×4 metal frame wall 16-in. o.c. | 18.2 |

by 8 ft) ICF clear test wall exposed to dynamic boundary conditions. The computer program reproduced all data recorded during the test boundary conditions (temperature and heat transfer coefficients). Values of heat flux on the surface of the wall generated by the computer program were compared with the values measured during the dynamic hot box test. Good agreement was found between test and computer modeling results. The maximum discrepancy between test generated and simulated heat fluxes was less than 10%.

A series of response factors, heat capacity, and R-values were computed using finite-difference computer modeling. They enabled a calculation of the wall structure factors and estimation of the simplified one-dimensional "thermally equivalent wall" configuration (Kossecka and Kosny 1996, 1997; Kossecka 1998). Structure factors reflect the thermal mass heat storage characteristics of wall systems. A thermally equivalent wall has a simple multiple-layer structure and the same thermal properties as the nominal wall. Its dynamic thermal behavior is identical to the ICF wall measured in the hot box. The thermal and physical properties describing the equivalent wall can be used, very simply, in whole-building energy simulation programs with hourly time steps (DOE-2 or BLAST). These whole building simulation programs require simple one-dimensional descriptions of the building envelope components. The usage of the equivalent wall concept provides a direct linkage from dynamic hot box test to accurate modeling of buildings with walls that contain considerable three-dimensional heat flow within the structure, such as the ICF wall system (APF 1995).

The equivalent wall generated for the ICF wall system was used in DOE 2.1E, a whole-building computer model. The DOE-2.1E computer code was used to simulate a single-family residence in six representative U.S. climates. The space heating and cooling loads from the residence with massive ICF walls were compared to an identical building simulated with lightweight wood-frame exterior walls. Twelve lightweight wood-frame walls with R-values from 0.4 to 5.1 $K\cdot m^2/W$ (2.3-29.0 $h\cdot ft^2\cdot °F/Btu$) were simulated in six U.S. climates using TMY (Typical Meteorological Year) climate data. The heating and cooling loads generated from these building simulations were used to estimate the R-value that would be needed in conventional wood-frame construction to produce the same loads as the ICF wall system in each of the six climates. The resulting R-value is considered an effective R-value for the ICF form wall system, which accounts not only for the steady-state R-value but also the inherent thermal mass benefit. This procedure is almost identical to those used to create the thermal mass benefits tables in the *Model Energy Code* (CABO 1995). The thermal mass benefit is a function of climate. Effective R-values for the ICF wall were obtained by comparison of the thermal performance of the ICF wall and lightweight wood-frame walls and they should be understood only as

- a performance link between level two characteristics of thermal mass and level one performance criteria; annual space heating, and cooling loads;
- an answer to the question of what R-value would be needed by an identical house with wood-frame walls to obtain the same space heating and cooling loads as a ICF house. There is no physical meaning for the term "effective R-value."

A third major level-two characteristic that describes the wall thermal performance is the airtightness. This paper presents an analysis of the impact of a 20% reduction in uncontrolled infiltration for the ICF house compared to the wood-frame structure. The 20% reduction is supported by blower-door tests on seven ICF houses with a measured 0.0004 effective leakage area divided by floor area (Dickerhoff et al. 1982; Harrje and Born 1982; Sherman and Grimsrud 1980).

## Dynamic Hot Box Test and Thermal Modelings

Dynamic three-dimensional computer modeling was used to analyze the response of the ICF wall to the triangular surface temperature pulse as shown in Figure 5a. This analysis enabled estimation of the dynamic R-value of the wall, ther-

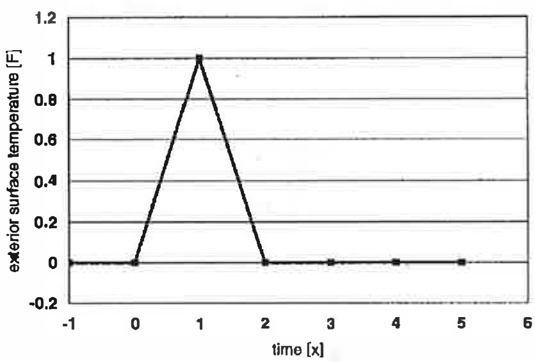


*Figure 5a Triangular pulse used in dynamic modeling.*

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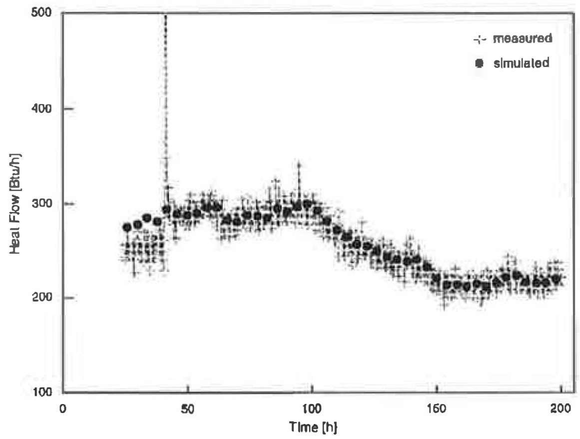


*Figure 5b* *Comparison of tested and simulated heat fluxes for ICF wall.*

mal capacity, response factors, and wall structural coefficients. The wall structural coefficients were used to create a one-dimensional equivalent wall, necessary for whole-building thermal modeling.

A calibrated heat conduction, finite-difference computer code was used for this analysis (Childs 1993). The accuracy of the program was validated by examining its ability to predict the dynamic process measured during the dynamic hot box data for the ICF test wall. The computer program reproduced all recorded test boundary conditions (temperatures and heat transfer coefficients) with one-hour time intervals.

Values of heat flux on the surface of the wall generated by the program were compared with the values measured during the dynamic test. As depicted in Figure 5b, the program reproduced the test data very well. The maximum discrepancy between test-generated and simulated heat fluxes was less than 10%. This comparison confirms the ability of the program to reproduce the dynamic heat transfer process measured during the dynamic hot box test of the actual ICF wall.

## Equivalent Wall Defined for Use in One-Dimensional Whole-Building Models

A series of response factors, heat capacity, and R-values were computed based on results of the dynamic hot box test and finite-difference computer modeling. They enabled a calculation of the wall structure factors and generation of the simplified one-dimensional equivalent wall configuration. The equivalent wall has a simple multi-layer structure and the same thermal response as the real wall (Kossecka and Kosny 1997). Its dynamic thermal behavior is identical to the actual ICF test wall. This equivalent wall can be used in whole-building energy simulation programs such as DOE 2.1E or BLAST. These programs require simple one-dimensional descriptions of the building envelope components. A real three-dimensional description of the ICF wall cannot be used directly by these whole-building simulations. Due to their complicated geometry, such walls must be simplified to the one-dimensional form. The usage of an equivalent wall enables more accurate modeling of buildings containing complicated three-dimensional composites, such as a complicated wall composed of several different materials with drastically different thermal properties.

**TABLE 6**
**Material Configurations of the Equivalent ICF Wall**

| | |
|---|---|
| Number of layers of the equivalent wall | 6 |
| Thickness of the equivalent wall | 0.23 m (9.25 in.) |
| Equivalent wall steady-state R-value | 2.11 $K \cdot m^2/W$ (12 $h \cdot ft^2 \cdot °F/Btu$)* |
| Fraction of total R-value in each layer | 0.33, 0.1, 0.07, 0.07, 0.1, 0.33 |
| Equivalent wall capacitance | 36 $W/m^2 \cdot K$ (11.6 $Btu/ft^2 \cdot °F$) |
| Fraction of total capacitance in each layer | 0.02, 0.08, 0.4, 0.4, 0.08, 0.02 |

* This is consistent with the measured steady-state hot box test of the ICF wall.

Material configurations of the ICF equivalent wall are presented in Table 6. Thermal properties of all materials in the equivalent wall are only theoretical, and they can be used in whole-building energy simulations.

An equivalent ICF wall has the same steady-state thermal properties and dynamic thermal performance as a real ICF wall. A comparison of the response factors for the real and equivalent ICF wall are depicted in Figure 6. As shown, response factors for both walls are almost the same. This warrants that for both walls, dynamic thermal performances are identical. Material thermal properties of the equivalent ICF wall are presented in Table 7.

## Dynamic Thermal Performance of the ICF Wall

The equivalent wall generated for the ICF wall system was used in DOE 2.1E whole-building computer modeling.

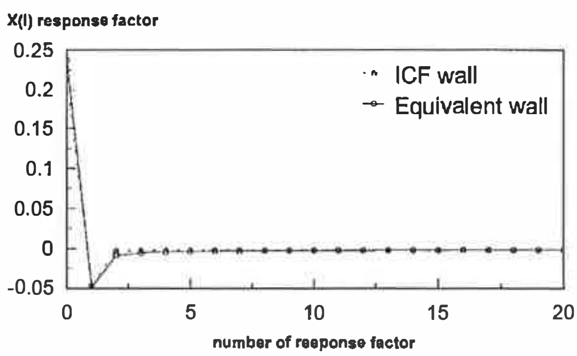


*Figure 6* *Comparison of X response factors for ICF wall and equivalent wall.*

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**TABLE 7**
**Material Thermal Properties of ICF Equivalent Wall (Finish Layers Not Included)**

| Layer | Thickness mm (in.) | Thermal Conductivity (Btu/h·in.·°F) | Density × Specific Heat (Btu/h·in.$^3$) |
|---|---|---|---|
| 1 | 39 mm (1.54) | 2.563e-3 | 7.712e-4 |
| 2 | 39 mm (1.54) | 9.411e-3 | 4.027e-3 |
| 3 | 39 mm (1.54) | 1.444e-2 | 2.083e-2 |
| 4 | 39 mm (1.54) | 1.566e-2 | 2.125e-2 |
| 5 | 39 mm (1.54) | 1.032e-2 | 4.457e-3 |
| 6 | 39 mm (1.54) | 2.560e-3 | 8.074e-4 |

DOE 2.1E is a detailed multi-zone hourly simulation program widely used in the United States and abroad for calculating the energy consumption of buildings. DOE 2.1E can model the impact of hourly variations in ambient climate conditions and internal loads on the building load, as well as varying equipment performance characteristics and realistic operating conditions such as thermostat setbacks and window venting. DOE 2.1E contains two main programs: LOADS and SYSTEMS. The LOADS program calculates the hourly heating and cooling loads of a building or thermal zone at a set indoor temperature. The SYSTEMS program contains algorithms for simulating the performance of the heating, ventilating, and air-conditioning (HVAC) equipment used to control the temperature and humidity of the building or zone. SYSTEMS combines the loads output from the LOADS program with the building description inputs to find the capacity, airflow rate, efficiency, part-load characteristics, and thermostat settings of the system, as well as the temperature and schedule for window venting. It also solves for the indoor air temperature, the true hourly load on the system, and its energy consumption. The analysis to determine the effective R-value of the ICF wall uses the space heating and cooling load data, which are output from the LOADS portion of DOE 2.1E, not results from the SYSTEMS.

Six U.S. climates were used for whole-building thermal modeling and determination of the effective R-value of the ICF wall system. A list of cities and climate data are presented in Table 8.

To normalize the calculations, a standard North American residential building was used. The standard building selected for this purpose is a single-story ranch style house that has been the subject of previous energy-efficiency modeling studies (Christian and Kosny 1996; Kosny and Desjarlais 1994). A schematic of the house is shown in Figure 4. The house has

**TABLE 8**
**Six U.S.Climates Used for DOE 2.1E Computer Modeling**

| Cities | HDD 18.3°C (65°F) | CDD 18.3°C (65°F) |
|---|---|---|
| Atlanta | 1705 (3070) | 870 (1566) |
| Denver | 3379 (6083) | 315 (567) |
| Miami | 103 (185) | 2247 (4045) |
| Minneapolis | 4478 (8060) | 429 (773) |
| Phoenix | 768 (1382) | 2026 (3647) |
| Washington D.C. | 2682 (4828) | 602 (1083) |

approximately 143 m$^2$ (1540 ft$^2$) floor area, 123 m$^2$ (1328 ft$^2$) of exterior wall elevation area, eight windows, and two doors (one door is a glass slider, and its impact is included with the windows). The elevation wall area includes 106 m$^2$ (1146 ft$^2$) of opaque (or overall) wall area, 14.3 m$^2$ (154 ft$^2$) of window area, and 2.6 m$^2$ (28 ft$^2$) of door area. The following building design characteristics and operating conditions were used during computer modeling:

*Interior walls*:
Mass: 3.57 lb/ft$^2$ of floor area
Specific heat: 0.26 Btu/lb·°F

*Furniture*:
Mass: 3.30 lb/ft$^2$ of floor area
Specific heat: 0.30 Btu/lb·°F
Thickness: 51 mm (2 in.)

*Thermostat set point*:
21°C (70°F) heating
26°C (78°F) cooling

*Window type*:
Double-pane clear glass
Transmittance: 0.81
Reflectance: 0.15

*Roof insulation*:
R-value 5.3 K·m$^2$/W (30 h·ft$^2$·°F/Btu)

For the base-case calculation of infiltration, we used the Sherman-Grimsrud infiltration method option in the DOE 2.1E whole-building simulation model (Sherman and Grimsrud 1980). We assumed an average total leakage area expressed as a fraction of the floor area of 0.0005 (Dickerhoff et al. 1982; Harje and Born 1982; Sherman and Grimsrud 1980). This is considered average for a single-zone wood-framed residential structure. This number cannot be converted directly to an average air change per hour because it is used in an equation driven by hourly wind speed and temperature difference between the inside and ambient air data, which vary for the six climates analyzed for this study. For the six climates, this represents an air

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**TABLE 9**
**Simulated Heating and Cooling Loads for the Ranch House* Built with the ICF Walls (for Six U.S. Locations)**

| Location | Cooling Energy Kwh (MBtu) | Heating Energy Kwh (MBtu) | Total Energy Kwh (MBtu) |
|---|---|---|---|
| Atlanta | 2079 (7.098) | 6083 (20.768) | 8162 (27.867) |
| Denver | 472 (1.612) | 12046 (41.128) | 12518 (42.740) |
| Miami | 10107 (34.505) | 13 (0.43) | 10120 (34.935) |
| Minneapolis | 576 (1.968) | 20747 (70.832) | 21323 (72.800) |
| Phoenix | 8698 (29.698) | 1409 (4.812) | 10107 (34.510) |
| Washington, D.C. | 1207 (4.122) | 10539 (35.983) | 11746 (40.105) |

* RSI-5.3 (R-30) roof insulation; walls have 25 mm (1 in.) stucco and 13 mm (0.5 in.) drywall.

change per hour range that will not fall below an annual average of 0.35 ACH.

For the house described above, cooling, heating, and total load (heating+cooling) were estimated for the ICF walls. For a building with RSI-5.3 (R-30) roof insulation and finished wall with 25 mm (1in.) stucco exterior and 13 mm (0.5 in.) gypsum board interior, for the six climates simulated, results are presented in Table 9.

For the same building and climates, similar energy simulations were performed for lightweight wood-frame (50 mm by 200 mm [2 by 4 in.] construction) walls of R-value from 0.4-6.5 $m^2$·K/W (2-37 h·$ft^2$·°F/Btu). The total space heating and cooling load consumption data for the lightweight wood-frame walls are used for the analysis of the dynamic thermal performance of the ICF wall. Configurations and R-values for lightweight wood-frame wall are presented in Table 10. The thermal mass benefit is expressed in terms of the effective R-value, which is the lightweight wall R-value, for the same climate and the same heating and cooling loads as the building with ICF walls.

Cooling, heating, and total loads needed for the lightweight wood-frame wall building are presented in Figures 7, 8, and 9, respectively (for double-pane windows and RSI-5.3 [R-30] roof insulation). In addition, the total loads needed for heating and cooling the ICF house are depicted in Figure 9. Based on this comparison, effective R-values for the finished ICF wall are estimated for six U.S. climates. They are presented in Table 11 for the double-pane window house.

## AIRTIGHTNESS

Walls of typical North American residential buildings have been found to represent between 18% and 50% of whole-building leakage area. The mean value found by Dickeroff et

**TABLE 10**
**Configurations and R-Values for Lightweight Wood-Frame Walls**

| Steady-State Clear Wall R-Value $m^2$·K/W (h·$ft^2$·F/Btu) | Wall Configuration |
|---|---|
| 0.4 (2.3) | Aluminum siding, 2 in. insul. sheathing (R=1.32), 3½ in. wood stud, empty cavity, 2 in. gypsum board. |
| 0.83 (4.7) | Aluminum siding, 2 in. insul. sheathing (R=1.32), 2 in. EPS foam, 3½ in. wood stud, empty cavity, 2-in. gypsum board. |
| 1.2 (6.8) | Aluminum siding, 2 in. insul. sheathing (R=1.32), 1 in EPS foam, 3½ in. wood stud, empty cavity, 2 in. gypsum board. |
| 2.2 (12.5) | Aluminum siding, 2 in. insul. sheathing (R=1.32), 3½ in. wood stud, R-11 batts, ½ in. gypsum board. |
| 2.6 (15.0) | Aluminum siding, ½ in. insul.sheathing (R=1.32), ½ in. EPS foam, 3½ in. wood stud, R-11 batts, ½ in. gypsum board. |
| 3.0 (17.0) | Aluminum siding, ½ in. insul.sheathing (R=1.32), 1 in. EPS foam, 3½ in. wood stud, R-11 batts, ½ in. gypsum board. |
| 3.5 (20.0) | Aluminum siding, ½ in. insul.sheathing (R=1.32), 5½ in. wood stud, R-19 batts, ½ in. gypsum board. |
| 4.0 (23.0) | Aluminum siding, ½ in. insul.sheathing (R=1.32), ½ in. EPS foam, 5½ in. wood stud, R-19 batts, ½ in. gypsum board. |
| 5.1 (29.0) | Aluminum siding, 2 in. insul.sheathing (R=1.32), 1½ in. EPS foam, 5½ in. wood stud, R-19 batts, ½ in. gypsum board. |
| 6.5 (37.0) | Aluminum siding, 2 in. insul.sheathing (R=1.32), 2-in. polyurethane foam, 5½ in. wood stud, R-30 insul., 2 in. gypsum board. |

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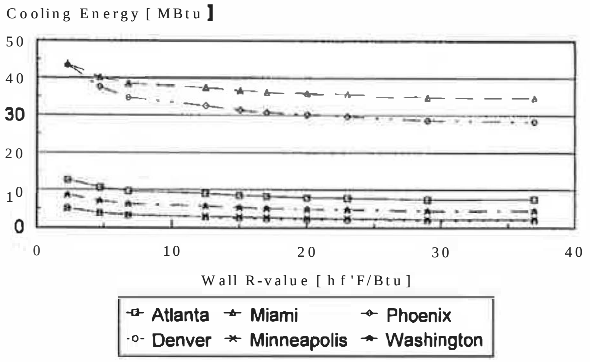


*Figure 7* *Cooling energy required for one-story ranch house (with R-30 roof insulation) built of lightweight wood-frame walls.*

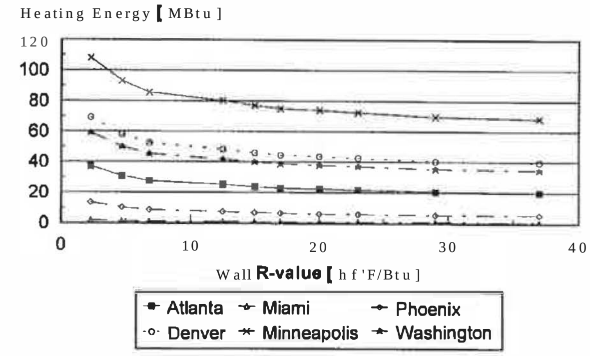


*Figure 8* *Heating energy required for one-story ranch house (with R-30 roof insulation) built of lightweight wood-frame walls.*

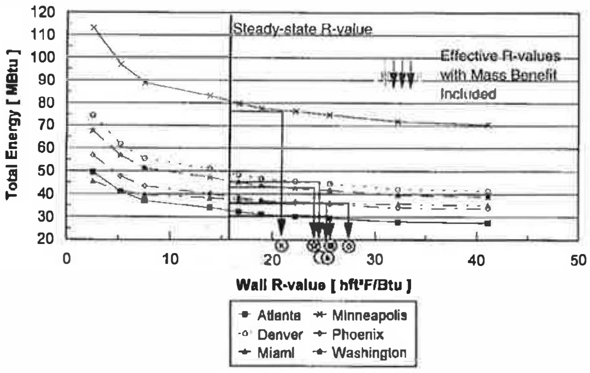


*Figure 9* *Total (heating and cooling) energy required for one-story ranch house built of lightweight wood-frame walls and ICF walls.*

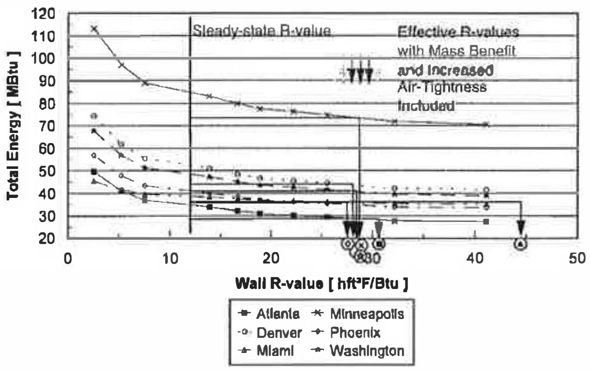


*Figure 10* *Total (heating and cooling) energy required for one-story ranch house built of lightweight wood-frame walls and ICF walls with thermal mass benefit and increased air-tightness included.*

al. (1982) and Harrje and Born (1982) is reported as 35%. The major locations within the walls of these air leakage paths are between the sill plate and the foundation, cracks below the bottom of the gypsum wall board, electrical outlets, and plumbing penetrations. The inherent construction of the ICF system is amenable to building much more airtight walls than conventional wood frame, as is supported by a series of blower door tests on seven homes (Thompson 1995). The calculated natural air changes per hour varied from 0.257 to 0.051, with an average of 0.147. These values were determined by obtaining the effective leakage area from the blower door tests, assuming a 8 km/h (5 mph) wind speed and a differential temperature of 5.5°C (10°F). The average leakage area estimated by the blower door tests, expressed as a fraction of the floor area for each of the seven homes, is shown in Table 12 to be 0.0004, ranging from 0.0003 to 0.0006.

Based on the potential to build tighter houses and utilize mechanical ventilation with heat recovery to provide minimum fresh air requirements of 0.4 $m^3/m$ (15 cfm) in accordance with *ANSI/ASHRAE Standard 62-1989* with an ICF house, an analytical approach is taken to examine the energy savings of reducing infiltration by 20% from that assumed for the base-case analysis. We simulated the ICF house with RSI-5.3 (R-30) roof insulation and with an average total leakage area expressed as a fraction of the floor area of 0.0004, which is consistent with the seven blower-door test results shown in Table 12, and compared these loads to the base-case wood-frame house with 0.0005. This resulted in a total heating and cooling load reduction of 4% for Miami to 6.5% for Washington D.C. Using the lower resulting total-load savings, we then used Figure 10 to estimate the dynamic plus airtightness effective R-values ($h \cdot ft^2 \cdot °F/Btu$). The R-values are shown in Table 13. They fall in the range of 4.8-7.8 $m^2 \cdot K/W$ (26-44 $h \cdot ft^2 \cdot F/Btu$) as shown in Figure 10. Another way of looking at these equivalent R-values for a ICF house with 20% lower infiltration than an equivalent frame house is this: to attain the same total space heating and cooling load with frame construction and 20% more infiltration than an 150 mm (6 in.) (core) ICF house with a steady-state R-value of 2.0 $m^2 \cdot K/W$ (11.5 $h \cdot ft^2 \cdot °F/Btu$) would require exterior wall R-values of 4.8-7.8 $m^2 \cdot K/W$ (26-44 $h \cdot ft^2 \cdot °F/Btu$).

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**TABLE 11**
**Effective R-Values for the ICF Wall Finished with 25 mm (1 in.) Stucco Exterior and 13 mm (0.5 in.) Gypsum Board Interior (Double-Pane Windows)**

| Location | HDD 18.3°C (65°F) | Dynamic R-values $m^2 \cdot K/W$ ($h \cdot ft^2 \cdot °F/Btu$) |
|---|---|---|
| Atlanta | 1705 (3070) | 3.7 (21.1) |
| Denver | 3379 (6083) | 3.5 (20.0) |
| Miami | 103 (185) | 3.7 (21.1) |
| Minneapolis | 4478 (8060) | 2.6 (16.2) |
| Phoenix | 768 (1382) | 4.9 (22.6) |
| Washington, D.C. | 2682 (4828) | 3.4 (19.2) |

**TABLE 12**
**Blower Door Estimated Equivalent Total Leakage Area**

| Home | ELA | Floor Area | ELA/Floor Area |
|---|---|---|---|
| 1 | 185 | 3700 | 0.0003 |
| 2 | 101 | 1160 | 0.0006 |
| 3 | 213 | 3100 | 0.0005 |
| 4 | 133 | 2100 | 0.0004 |
| 5 | 127 | 2700 | 0.0003 |
| 6 | 120 | 2200 | 0.0004 |
| 7 | 76 | 1984 | 0.0003 |
| Average | 136 | 2421 | 0.0004 |

**TABLE 13**
**Dynamic Plus Airtightness R-Values for the ICF Wall Finished with 25 mm (1 in.) Stucco Exterior and 13 mm (0.5 in.) Gypsum Board Interior**

| Location | HDD 18.3°C(65°F) | Dynamic Plus Airtightness Effective R-Values, $m^2 \cdot K/W$($h \cdot ft^2 \cdot °F/Btu$) |
|---|---|---|
| Atlanta | 1704 (3070) | 5.4 (30.4) |
| Denver | 3379 (6083) | 4.8 (27.5) |
| Miami | 103 (185) | 7.8 (44.2) |
| Minneapolis | 4478 (8060) | 4.9 (27.8) |
| Phoenix | 768(1382) | 4.7 (26.8) |
| Washington, D.C. | 2682 (4828) | 4.9 (27.6) |

## CONCLUSIONS

Steady-state hot-box testing and finite-difference computer modeling were used to examine the steady-state thermal performance of the ICF wall system. The measured clear-wall R-value 2.0 $m^2 \cdot K/W$(11.57 $h \cdot ft^2 \cdot °F/Btu$) is higher than for 50 mm by 200 mm (2 by 4 in) wood-frame wall with 0.6 m (24 in.) on center (without insulating sheathing). The whole wall steady-state R-value is less than 10% lower than the clear-wall measured value.

Dynamic hot-box testing and finite-difference computer modeling were used to create the thermally equivalent wall for the ICF form wall system. The equivalent ICF wall was used to examine the dynamic thermal performance of the ICF wall system. The whole-building computer model DOE 2.1E simulated a representative single-family residence in six U.S. climates. The thermal performance of the building contained ICF and wood-frame walls. The equivalent wall generated for the ICF wall system was used in the whole-building computer modeling. The building load data generated for ICF walls were compared with the data obtained for lightweight wood-frame walls. The results provide an effective R-value for the ICF wall that reflects the thermal mass benefits inherent in this wall system. Due to the solid concrete core, the total space heating and cooling load of the house built with the ICF wall can be reduced when compared to a light-frame wall with equivalent steady-state R-value. Even for very severe climate conditions (Minneapolis), the ICF wall performs as well as an RSI-2.8 (R-16) wood-frame wall. In Washington, D.C., the ICF wall performs as well as an RSI-3.3 (R-19) wood-frame wall. In the other simulated U.S. climates, the ICF wall thermal performance was better than RSI-3.5 (R-20) wood-frame walls and walls with RSI-4.0 (R-22.7) in Phoenix. It is suggested that this procedure be used to provide a link between the level two characteristics of thermal mass and the thermal mass benefit of thermal comfort and minimum energy demand for space heating and cooling.

When ICF walls reported better airtightness, these benefits are reflected in the effective R-value analysis in addition to the thermal mass benefits by assuming a 20% reduction in infiltration, and even larger effective R-values are estimated. The dynamic plus airtightness effective R-values fall in the range of 4.8 to 7.8 $m^2 \cdot K/W$ (26-44 $h \cdot ft^2 \cdot °F/Btu$).

Another way of looking at these equivalent R-values for an ICF house with 20% lower infiltration than an equivalent frame house is this: to attain the same total space heating and cooling load with frame construction and 20% more infiltration than a 153 mm (6 in.) core ICF house with a clear-wall steady-state R-value of 2.0 $m^2 \cdot K/W$ (11.5 $h \cdot ft^2 \cdot °F/Btu$) would require exterior wall R-values of 4.8 to 7.8 $m^2 \cdot K/W$ (26 to 44 $h \cdot ft^2 \cdot °F/Btu$). The steady-state whole-wall R-value for the ICF system, which accounts for the thermal bridges created at the interface with windows, doors, ceilings, and floors is estimated as 1.96 $m^2 \times K/W$ (11.11 $h \cdot ft^2 \cdot °F/Btu$). For reference purposes, a whole-wall R-value for standard 50 mm by 153 mm (2 in. by 6 in.) wood-frame wall with 0.6 m (24 in.) O.C. and 13 mm (2 in.) plywood exterior and 13 mm (2 in.) gypsum board interior is 2.4 $m^2 \cdot K/W$ (13.7 $h \cdot ft^2 \cdot °F/Btu$) (Christian and Kosny 1996). For example, a 50 mm by 153 mm (2 in. by 6 in.) wood-frame house in Atlanta will perform with a whole-wall R-value of 2.4 $m^2 \cdot K/W$ (13.7 $h \cdot ft^2 \cdot °F/Btu$) compared to the

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153 mm (6 in.) ICF wall system with a dynamic plus airtightness effective R-value of around 5.3 $m^2 \cdot K/W$ (30 $h \cdot ft^2 \cdot F/Btu$).

It is recommended that Annex 32 attempt to correlate laboratory mockups of air leakage measurements to the whole-building air tightness. This will be necessary to provide useful performance links between exterior wall construction (level two) and whole-building airtightness (level one).

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