The Whole Wall Thermal Performance Calculator—On the Net

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ABSTRACT

The trend toward system performance codes, standards, and contracts leads to the need for a quick method of estimating the whole wall R-value for exterior envelope systems. Calculation of the actual whole wall R-value of traditional dimensional wood-framed wall systems is, in general, well understood by the residential designer and building contractor. However, the accuracy of estimating the thermal performance of other viable wall systems falls off rapidly, particularly if several different types of wall systems are being considered at the building conceptual design stages. At the Envelopes VI conference in 1995, a new methodology was presented for addressing this need. Three years later, more than 15 wall system manufacturers have submitted 40 different wall systems for generation of a whole wall R-value based on full-scale wall hot box tests. The hot box tests occasionally generated some unexpected results but provide a very credible check on computer modeling.

This paper describes results from both steady-state and dynamic hot box tests using ASTM C-1363-97. The tests are the starting point for development of uniform whole wall R-values for inclusion in "The Whole-Wall Thermal Performance Calculator." The following wall systems have been tested and are available for comparison: structural insulating panels with compressed straw core, conventional steel C-stud frame (2 in. × 6 in. [5 cm × 15.4 cm] and 2 in. × 4 in. [5 cm × 10 cm]), conventional metal frame with different types of sprayed foam insulation, novel metal studs, autoclaved concrete block, structural straw bale, and an insulating concrete form. This paper describes "The Whole-Wall Thermal Performance Calculator," which is available at <http://www.ornl.gov/roofs+walls/whole_wall/wallsys.html>. This interactive calculation tool can accept a simple description of custom building plans and enable the Internet user to compare uniform whole wall R-values of at least 40 different wall systems. This provides the comfort of knowing that all are based on hot box measurements by a recognized, objective, and qualified third party in cooperation with the manufacturers of each wall system.

INTRODUCTION

The whole wall thermal performance rating label concept was conceived to address the number one wall research need, identified by the *National Program Plan for the Thermal Performance of Building Envelope Systems and Materials* (NIBS 1994). Whole wall performance was ranked by 270 private building industry contributors as the most important public sector R&D need to accelerate the development and application of energy-efficient building walls (BETEC 1994). The procedure described in this report is for the entire opaque wall portion of a residential building. The National Fenestration Rating Council provides the thermal performance label for windows and doors. The approach was first presented at the Building Envelopes VI conference in 1995 (Christian and Kosny 1995).

The complete whole wall rating procedure provides a means to compare the performance of wall systems with respect to five elements:

1. thermal shorts,
2. exterior envelope thermal mass benefit, for walls with more mass than conventional 2 in. × 4 in. (5 cm × 10 cm) dimensional wood frame,
3. airtightness relative to typical wood-frame opaque wall construction,
4. moisture control, and

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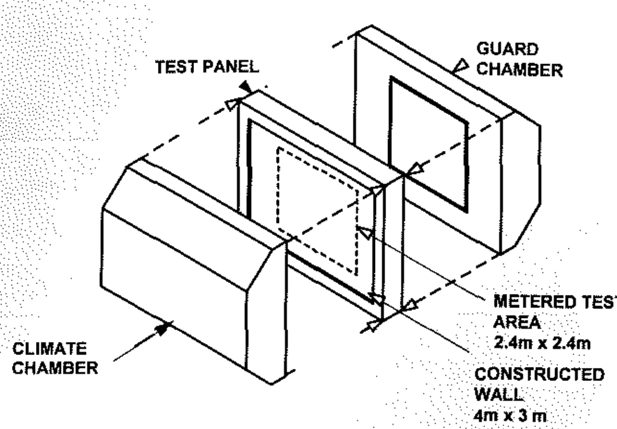

Figure 1 *Guarded hot box.*

5. sustainability to account for the relative total life-cycle environmental impacts of different wall systems.

This paper presents comparative values accounting for wall thermal shorts and thermal mass benefits for 17 different residential systems. For each wall discussed, the first step in acquiring the whole wall rating label was to construct and test an 8 ft × 8 ft (2.4 m × 2.4 m) clear wall section in a guarded hot box, as shown in Figure 1. A guarded hot box is a test apparatus that measures the thermal conductivity of full-size walls according to ASTM C 1363-97 (ASTM 1997).

The results from the hot box test are compared with a three-dimensional finite difference model, HEATING 7 (Childs 1993). Once acceptable (within +5%), agreement between the model and the test result is attained, the interface details are modeled using the calibrated HEATING model for that wall. A database of validated thermal conductivities is generated for the clear wall and all of the interface details for each wall system. An interactive tool available on the Internet accesses this data base.

The *Whole Wall Thermal Performance Calculator* utilizes the conductivity of areas associated with different details of a residential opaque wall system. The whole wall R-value is the major output of this interactive tool and can be used to compare the thermal performance of alternative walls. The whole wall R-value accounts for all of the major thermal shorts in the opaque wall. For instance, if the corner detail area has proportionally more highly conductive structural material than insulation when compared to the clear wall area, the whole wall R-value will be less than the clear wall R-value. The percentage difference between the whole wall and clear wall R-value is an excellent metric to describe the severity of thermal shorts that exist in a wall system option for a particular building. The lower the percentage difference between the whole wall and clear wall R-values, the less thermal shorting. Thermal shorts result in additional unwanted heat loss in the winter and heat gain in the summer. They also contribute to nonuniform interior surface temperatures, which can lead to "ghosting" and interior moisture condensation, which, if severe, propagates mold, mildew, and poor indoor air quality. For illustrative purposes in this paper, a standard house is used to select the quantity of each interface detail and to present a set of comparable results. The reference house, shown in Figure 2, has four wall-to-wall corners, seven windows, and two doors. The one-story wall has a 164 ft (50 m) perimeter.

Before presenting the whole wall R-values for the 17 wall systems applied to the simple 1540 ft^2 (143 m^2) ranch style home, a few definitions of terms used in this paper are provided. The *clear wall R-value*, measured in the hot box and predicted by the computer model, represents the area of the wall containing insulation and only the necessary structural members away from all interface details. The *interface details* are the wall connections to other envelope components (wall-corner, wall-floor, wall-ceiling, window surround, and door

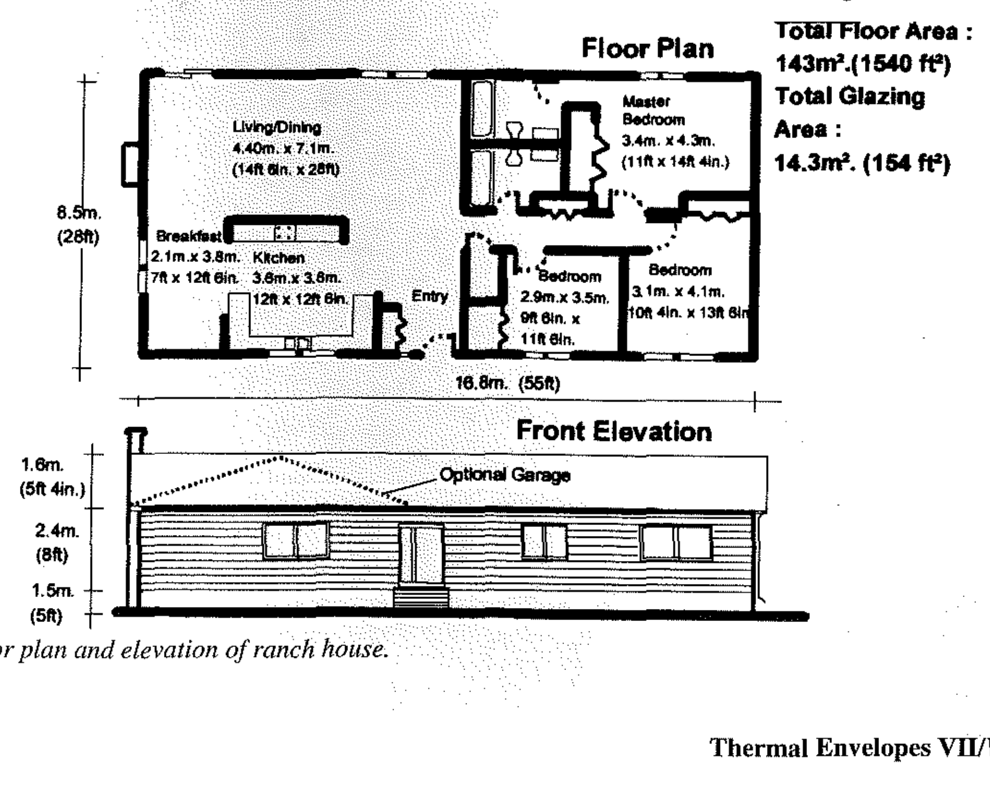

Figure 2 *Floor plan and elevation of ranch house.*

surround). The *whole wall R-value* reflects the weighted thermal performance of the total clear wall area and the actual number of envelope interface details for any given user-input building plan and wall elevations. The total time to input the building description into the *Whole Wall Thermal Performance Calculator* on the Internet is less than 10 minutes per wall system. The major output of interest is the whole wall R-value comparison to the clear wall R-value.

RESULTS

Wood Frame

In North America, more than 90% of residential housing is stick built and, with careful design and construction, energy-efficient walls can be built with dimensional lumber. However, there are many reasons why building owners, contractors, and designers are interested in alternatives: thermal comfort, lower cost, fire safety, hurricane resistance and enhanced protection from other natural disasters, durability, noise reduction, architectural flexibility, use of available recycled and/or reused materials, and energy savings.

Perfectly Installed Batt Insulation. Both 2 × 4 and 2 × 6 wood-frame whole wall R-values have been calculated as shown in Figure 3. For the standard 2 × 4 wall, the whole wall R-value is 10% less than the clear wall value. It is interesting to note that, in contrast, the whole wall R-value for the 2 × 6 wood-frame wall is 17% less than its clear wall value. Typically, a 2 × 4 wall is referred to as R-11 and a 2 × 6 wall as R-19. The clear wall R-value for the 2 × 6 wall is 55% higher than for the 2 × 4 wall. However, using the more appropriate whole-wall R-value metric for comparison, the 2 × 6 wall is really only 41% better than the 2 × 4 wall. Unfortunately, many times the selection of the thicker wall is based on an estimated increase in R-value comprising the R-8 (1.5) difference between the insulation materials labeled R-19 and R-11 h·ft^2·°F/Btu at 75°F (3.4 and 1.9 m^2·K/W). From the whole wall R-value comparison, the energy savings determination should use an increase in R-value of only 4 not 8 h·ft^2·°F/Btu at 75°F (0.7 not 1.5 m^2·K/W).

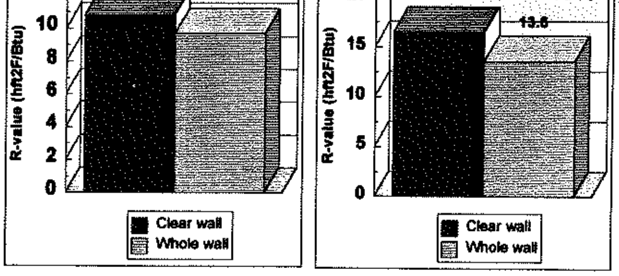

Figure 3 *Wood frame has diminishing returns as higher R-values are pursued.*

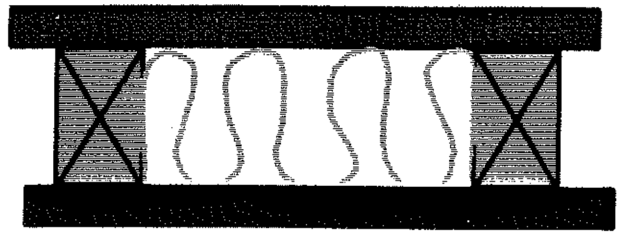

Figure 4 *Perfectly installed batts.*

A hot box test for a 2 × 6 wood-frame 24 in. (0.61 m) o.c. wall, with R-19 h·ft^2·°F/Btu at 75°F (3.3 m^2·K/W) fiberglass batt insulation very carefully installed in the cavity with typical electrical wiring, was conducted in September 1998. The insulation was installed in the cavity, as shown in Figure 4, before installing the interior or exterior sheathing to allow visual inspection of the "perfect" batt fit from both sides. The test wall was constructed with an electrical switch box at mid-height and an electrical duplex box 14 in. (36 cm) from the bottom of the 8 ft × 8 ft (2.4 m × 2.4 m) test wall. An electric wire was connected between these two boxes and strung at midpoint of the 5.5 in. (14 cm) thick cavity. The batt was cut to accommodate the wire and no insulation was compressed. The hot box measured surface-to-surface R-value for a 2 × 6 wall cavity with perfectly installed insulation, exterior OSB (orientated strand board) sheathing, and interior gypsum drywall board was 15.4 h·ft^2·°F/Btu at 75°F(2.7 m^2·K/W). The fiberglass batt with 5.5 in. (14 cm) thickness was tested according to ASTM C-518 and found to have a resistivity of 3.16 h·ft^2·°F/Btu·in. at 75°F (22 m·K/W). The R-value calculated for the appropriate clear wall without the presence of the electrical boxes and wire and an assumed resistivity of 3.45 h·ft^2·°F/Btu·in. at 75°F(24 m·K/W), as shown in Figure 3, was 16.5 h·ft^2·°F/Btu at 75°F (2.9 m^2·K/W) (Christian and Kosny 1996). The test wall was constructed with no intentional holes into the cavity from either side other than through the electrical boxes. Secondly, zero pressure difference was fixed across the wall for the entire test. The one other 2 × 6 wood-frame wall that was tested earlier for comparison to structural insulated panels (panels composed of a rigid insulating core between skins of sheathing, typically made of oriented strand board) was found to have an R-value of 14.8 h·ft^2·°F/Btu at 75°F(2.6 m^2·K/W). This earlier panel did not have any electrical wiring and had fiberglass batt insulation with a similar resistivity of 3.16 h·ft^2·°F/Btu·in. at 75°F (22 m·K/W). A second test was run with perfectly installed insulation with a lower climate-side temperature of 20°F for this paper, resulting in a mean insulation temperature of 60°F (16°C). This resulted in an identical R-value of 15.4 h·ft^2·°F/Btu at 75°F (2.7 m^2·K/W) at 24°C.

It is assumed that the same 17% reduction of whole wall from clear wall R-value for 2 × 6 construction, reported above in the calculations for Figure 3, applies to the tested

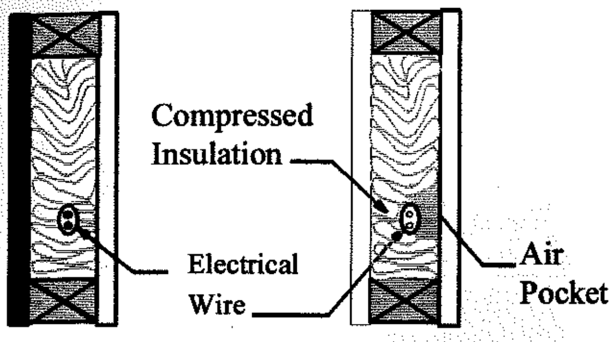

Figure 5 *Compressed batt due to electrical wiring.*

wall with 3.16 h·ft^2·°F/Btu in batts. Then the whole wall R-value for the as-tested 2 × 6 assembly is 12.8 h·ft^2·°F/Btu at 75°F (2.25 m^2·K/W) at 24°C. This is a surface-to-surface R-value and accounts for gypsum interior finish but does not account for the final exterior finish, such as face brick or wood siding, nor the air film resistances on the interior and exterior surfaces.

Batt Insulation Installed with Rounded Shoulders and Excessive Compression Due to Cavity Electrical Wiring. The batts from the test described above were removed and installed in a very typical fashion. The procedure was to just push the batts in from the inside without cutting them to fit around the electrical wires and outlet boxes, as shown in Figure 5. The friction between the batts and the vertical studs, the horizontal bottom plate and the horizontal top plate, results in linear air pockets with no insulation around the entire perimeter of each cavity space. These air pockets, shown in Figure 5 and Figure 6, are speculated to enable natural convection to occur within the wall. The resulting hot box measured R-value of this test wall was 14.1 h·ft^2·°F/Btu at 75°F (2.5 m^2·K/W) at a mean temperature of 75°F (24°C)—50°F(10°C) on the outside and 100°F (38°C) on the inside. The natural convection is more likely to occur under conditions of greater temperature difference across the wall. However, the resulting hot box tests did not measure any noticeable reduction in R-value when the batts were installed with likely linear air pockets in each cavity on the exterior side of the batts. The measured R-value at a temperature difference of 80°F (27°C)—20°F (7°C) on the outside and 100°F (38°C) on the inside—was 14.4 h·ft^2·°F/Btu (2.5 m^2·K/W). The expected increase in fiberglass resistivity at lower temperatures is enough to account for the increase in R-value. There is no suggestion of increasing natural convection, leading to lower R-value.

The same 17% reduction of whole wall R-value from clear wall R-value for 2 × 6 wood-frame walls reported above for the calculations shown in Figure 3 results in a whole wall R-value for the as-tested assembly of 11.7 h·ft^2·°F/Btu (2.1 m^2·K/W). This is 9% less than the R-12.8 for perfectly installed batt insulation, a significant penalty incurred throughout the building's life as a result of insufficient care during construction.

Batt Insulation Installed with Rounded Shoulders Only. The same test wall described above was again opened

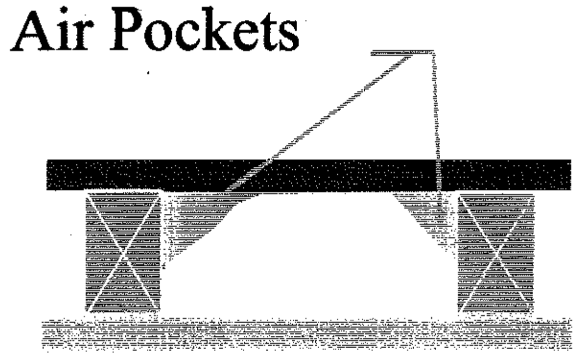

Figure 6 *Batt with rounded shoulders.*

and the insulation was carefully placed to accommodate the wiring without batt compression, as shown in Figure 5. This is frequently the way insulation crews install fiberglass batts. The hot box test result showed very little impact of the remaining rounded shoulders, shown in Figure 6. The resulting R-value at 80°F (27°C) temperature difference across the wall, 20°F (−7°C) on the outside and 100°F (38°C) on the inside, was 14.7 h·ft^2·°F/Btu (2.6 m^2·K/W). This can be compared to the "perfect case" at these same test conditions of 15.4 h·ft^2·°F/Btu (2.7 m^2·K/W).

The same 17% reduction of whole wall from clear wall R-value for the 2 × 6 wood frame wall shown in Figure 3, along with an adjustment for the mean insulation temperature from 60°F (16°C) to the nominal 75°F (24°C), is used to estimate the whole wall R-value for the as-tested assembly. The result is 12.2 h·ft^2·°F/Btu at 75°F (2.15 m^2·K/W) at 24°C. This is 5% less than the R-12.8 for perfectly installed batt insulation.

Batt Insulation Installed with Rounded Shoulders and 2% Cavity Voids. This test was the same as described above in "Batt Insulation Installed with Rounded Shoulders" except 1 in. (2.5 cm) strips of the batts were cut off at the top and bottom in each cavity. The impact of this added 2% batt void in a cavity that already had rounded shoulders was surprisingly small. The resulting R-value was 14.0 h·ft^2·°F/Btu at 60°F (2.5 m^2·K/W), only 0.7 h·ft^2·°F/Btu at 75°F (0.1 m^2·K/W) at 24°C less than in the rounded shoulder test (14.7 h·ft^2·°F/Btu at 60°F [2.4 m^2·K/W at 24°C]) under the same test conditions of 80°F (27°C) temperature difference with 20°F (−7°C) on the outside and 100°F (38°C) on the inside.

Using a 17% reduction of whole wall from clear wall R-value for 2 × 6 wood frame and an adjustment for mean insulation temperature from 60°F(16°C) to nominal 75°F (24°C), the whole wall R-value for the as-tested assembly is calculated. The resulting whole wall R-value for this case is 11.4 h·ft^2·°F/Btu at 75°F (2.0 m^2·K/W at 24°C), 11% less than the perfect case of 12.8.

Batt Insulation Installed with Rounded Shoulders, 2% Cavity Voids, and the Paper Facer Fastened to the Inside Surface of Each 2 × 6 Stud. This was judged to be the worst case commonly found of procedures for installing batt insulation: rounded shoulders, 2% cavity voids, and the paper facer fastened to the inside surface of each 2 × 6 stud. This batt

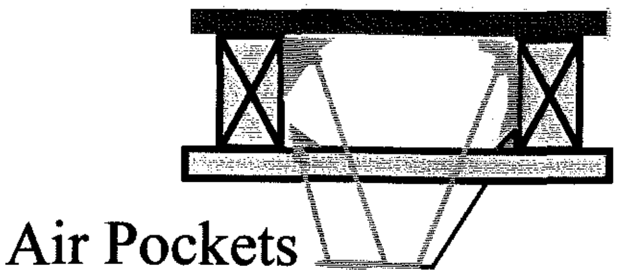

Figure 7 *Rounded shoulders and facer fastened to inside of stud.*

installation is depicted in Figure 7. The potential natural convection path would be up the wall on the inside as a result of the linear air pocket created by fastening the paper facer to the inside surface of the 2 × 6 studs on each side of the cavity, over the top of the batt where it was cut 1 in. (2.5c m) short, down the wall in the air space formed by the rounded shoulders of the batts, and back to the interior base of the wall as a result of the air space formed at the bottom of the cavity due to the 1 in. (2. 5cm) of batt cut off at the bottom. Once again, the impact was not significant at the 60°F mean temperature imposed in the tests. The resulting R-value of 13.2 h·ft^2·°F/Btu (2.2 m^2·K/W) is only 0.8 h·ft^2·°F/Btu (0.14 m^2·K/W) less than the rounded shoulder and 2% void test reported above (14.0 h·ft^2·°F/Btu [2.5 m^2·K/W]) under the same test conditions of 80°F(27°C) temperature difference with 20°F(−7°C) on the outside and 100°F (38°C) on the inside.

Using a 17% reduction of whole wall from clear wall R-value for a 2 × 6 wood frame and an adjustment from mean insulation temperature of 60°F (16°C) to nominal 75°F (24°C), the whole wall R-value for the as-tested assembly is calculated. The result is 11.0 h·ft^2·°F/Btu at 75°F (1.9 m^2·K/W at 24°C), which is 14% less than the perfect case of 12.8 h·ft^2·°F/Btu at 75°F. If the expectation of the consumer is based on the material label of R-19 h·ft^2·°F/Btu at 75°F (3.4 m^2·K/W), then the whole wall R-value based on this "worst case typical installation" of batts in a 2 × 6 in. wood-frame wall represents a 42% reduction. The seemingly insignificant insulation installation errors and thermal shorts resulting from interface details accumulate to significant impacts.

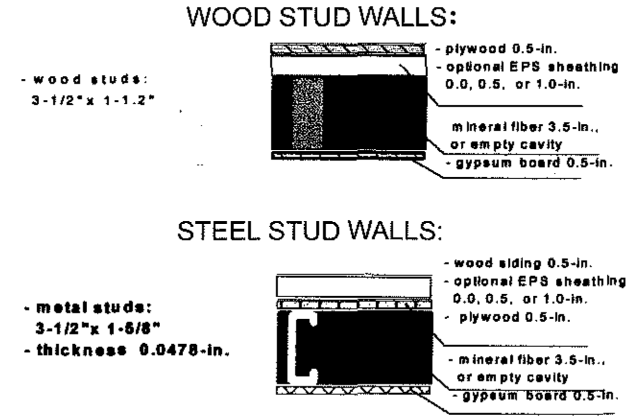

Figure 8 *Wood and steel frame walls.*

Steel C-Stud

Cold-Formed Steel-Frame C-Stud. A conventional metal-frame wall was constructed as shown in the bottom half of Figure 8: ½ in. (1.3 cm) OSB board, R-11 h·ft^2·°F/Btu at 75°F (1.9 m^2·K/W at 24°C) 3 ½ in. (9 cm) fiberglass batts between 3 ½ in. (9 cm) steel studs 24 in. (61cm) o.c. and ½ in. (1.3 cm) gypsum board. The hot box test of it yielded an R-value of 7.3 h·ft^2·°F/Btu at 75°F (1.29 m^2·K/W at 24°C). The HEATING 7 simulation yielded 7.5 h·ft^2·°F/Btu at 75°F(1.3 m^2·K/W at 24°C), which was within 3%. Using the validated model's clear wall R-value and the 25% reduction to account for the lower R-values of the interface details results in a whole wall R-value of only 5.6 h·ft^2·°F/Btu at 75°F (1.0 m^2·K/W at 24°C). In the study from which Figure 3 was obtained (Christian and Kosny 1996), we also found a 25% reduction to account for the lower R-values of the interface details in a steel-framed house like

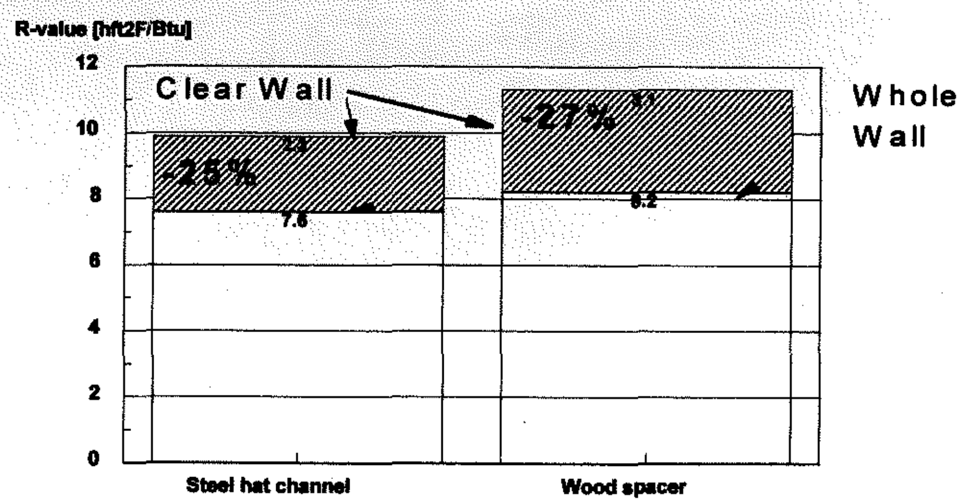

Figure 9 *Metal or wood horizontal spacers.*

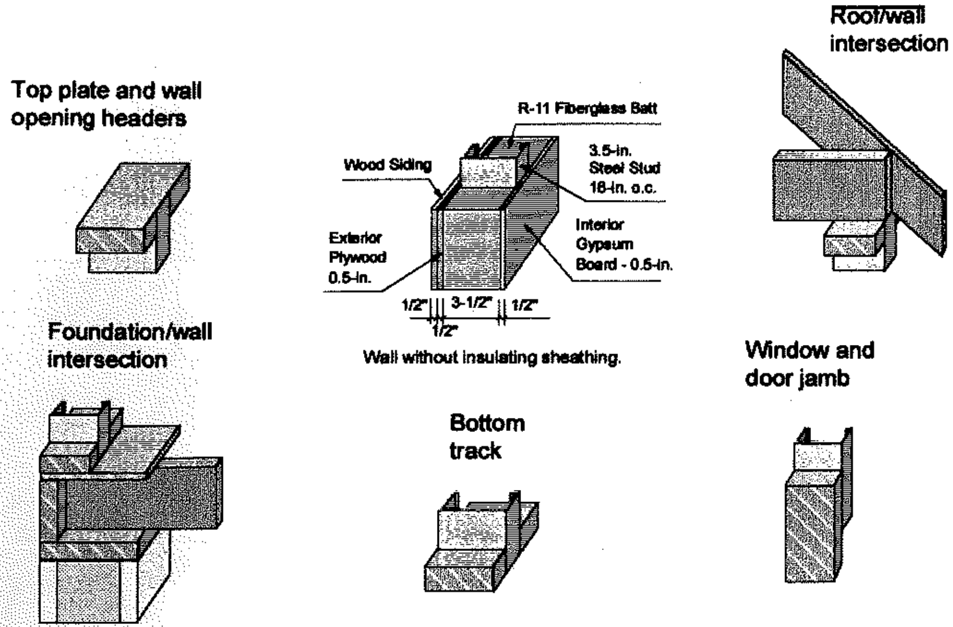

Figure 10 *Interface details of metal-framed walls with wood components.*

that in Figure 2. This is larger than the 17% reduction for wood-framed construction because of the more severe thermal bridges in conventional steel-framed structures.

Horizontal Hat Channeling. A conventional steel-frame wall was built and steel horizontal hat channeling added prior to attachment of the exterior sheathing. The left bar of Figure 9 shows the clear wall R-value was measured at 9.9 $h \cdot ft^2 \cdot °F/Btu$ at 75° F(1.7 $m^2 \cdot K/W$ at 24°C), which led to a calculated whole wall R-value of 7.6 $h \cdot ft^2 \cdot °F/Btu$ at 75° F (1.3 $m^2 \cdot K/W$ at 24°C). This wall, with full cavity spray foam insulation, was tested in the hot box. The horizontal hat channels create a thermal break between the steel and the exterior sheathing. It is traditional metal stud wall construction, 3.5 in. (9 cm) C-shaped studs made of 18 gauge steel installed 16 in. (41cm) o.c. The 1 in. (1.3 cm) metal hat channels were attached horizontally with 24 in. (61cm) o.c spacing to the exterior stud flange surfaces. The 1 in. (1.3 cm) thick cavities created by the hat channels were filled with spray foam. The foam insulation alone was tested according to ASTM C518 and found to have a resistivity of 3.4 $h \cdot ft^2/Btu \cdot in.$ (23.8 $m \cdot K/W$). The interior wall surface was finished with 0.5 in. (1.3 cm) thick gypsum board. The exterior surface was finished with 0.5 in. (1.3 cm) thick plywood. Although this wall appears to minimize the direct metal thermal short through the insulation, the net effect is not very impressive. The additional effort of installing the hat channels yielded R-7.6 only 2 $h \cdot ft^2 \cdot °F/Btu$ (0.35 $m^2 \cdot K/W$) above the conventional C-stud wall described below (Kosny et al. 1997b). The furring strips and additional 1 in. (1.3 cm) of foam improved the R-value 36% above conventional metal frame with no exterior foam sheathing.

Alternative Steel Frame Technology Wood and Steel

Horizontal Wood Furring. A wall similar to that in Figure 8 (lower) except using wood furring strips (right bar of Figure 9) instead of metal hat channels was hot box tested. The simulated clear wall R-value is R-11.3 $h \cdot ft^2/Btu \cdot in.$ (2.0 $m^2 \cdot K/W$). The whole wall R-value for this wall is 8.2 $h \cdot ft^2 \cdot °F/Btu$ (1.45 $m^2 \cdot K/W$), 46% better than the conventional metal base case of 5.6 $h \cdot ft^2 \cdot °F/Btu$ (1.0 /W). Compared to using metal hat channels, installing wood spacers adds less than 1 R $h \cdot ft^2 \cdot °F/Btu$ (0.18 $m^2 \cdot K/W$) at 24°C (Kosny et al. 1998c).

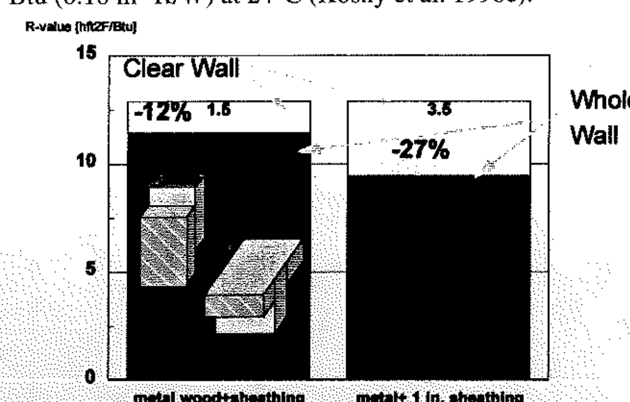

Figure 11 *Wood member placement at interface details and 1 in. sheathing perform well.*

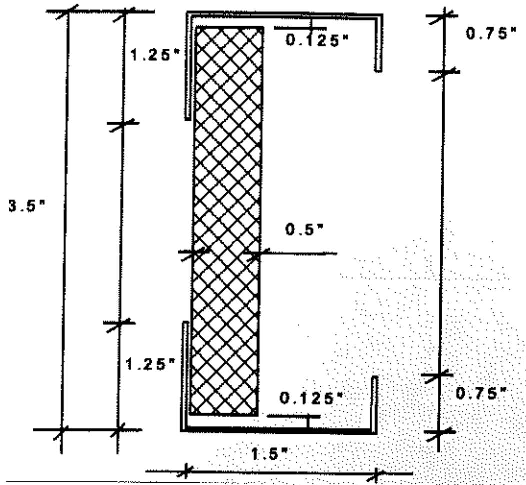

Figure 12 Steel and wood stud.

Figure 13 Spray polyurethane foam air sealed steel wall.

Wood Detailing. This wall is the same as the steel base case with one exception. Instead of using metal C-studs for the added structural needs in the interface details, standard wood-frame 2 × 4s are used, as shown in Figure 10. This technique has the advantage of simplifying window and door installation into wood-framed rough openings. This system also utilizes wooden top and bottom track plates. The clear wall R-value for metal walls with these wooden components is 7.2 h·ft^2·°F/Btu at 75°F(1.3 m^2·K/W). The whole wall R-value is 6.8 h·ft^2·°F/Btu (1.2 m^2·K/W), only 6% less. The use of wood for the fenestration rough openings and the top and bottom plates results in small differences between the whole and clear wall R-values (Kosny et al. 1998c).

Figure 11 shows that, although the clear wall R-values are the same for a conventional steel-frame wall and a steel wall with wood interface details and 1 in. (1.3 cm) foam sheathing (13 h·ft^2·°F/Btu (2.3 m^2·K/W)), the whole wall values reveal a different story. Replacement of steel components in wall details by similarly shaped wood profiles is an efficient thermal improvement in steel-framed wall performance. With 1 in. (1.3 cm) of foam sheathing, the difference between clear wall and whole wall R-value is only 12%, which is similar to what is found in all-wood framing. This will result in less interior surface temperature depressions, which reduces the risk of ghosting. Steel-frame wall systems with 1 in. of foam insulation yield a difference between clear and whole wall R-values of 27%, as shown in Figure 11.

Steel and Wood Stud Wall. This wall is assembled from a stud that has steel flange profiles attached to a ½ in. (1.3 cm) OSB web. The web is the part of the stud that runs perpendicular to the wall surfaces, as shown in Figure 12 for this configuration that had OSB exterior and gypsum interior sheathing. Hot box tests yielded 9.85 h·ft^2·°F/Btu (1.7 m^2·K/W). Modeling showed that the whole wall R-value was 23% lower than the clear wall, which converts to a whole wall R-value of 7.6 h·ft^2·°F/Btu (1.3 m^2·K/W). At the time this paper was prepared, the system was not commercially available. However, this system's thermal performance approaches that of 2 × 4 wood frame.

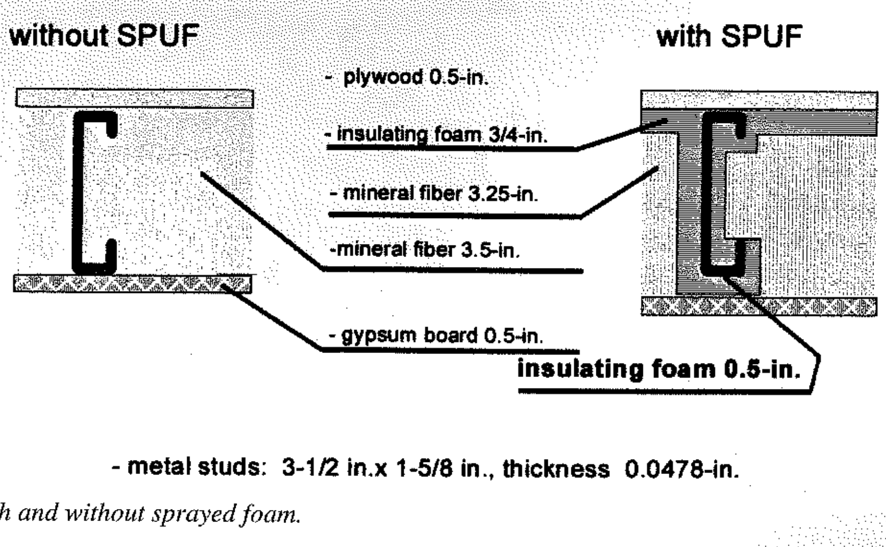

Figure 14 Wall with and without sprayed foam.

Spray Foam Cavity Seal and Flange Cover. Figure 13 shows that this wall starts with a conventional steel frame. Polyurethane insulation is then sprayed into the cavity from the open interior side over the metal flange, at thickness shown in Figure 14. Once the spray foam is in the cavity, conventional fiberglass batts and drywall are installed from the inside of the wall. The hot box test of the clear wall, using 3 ½ in. (9 cm) steel studs 24 in. (61cm) o.c., yielded 11.1 h·ft^2·°F/Btu (2.0 m^2·K/W). Material test results (ASTM C518) showed a resistivity of 7.0 h·ft^2·°F/Btu·in. (1.2 m^2·K/W) using a freshly measured spray-polyurethane specimen ½ in. (1.3 cm) thick and less than one month old. The whole wall R-value was predicted to be 26% lower than the clear wall, which converts to a whole wall R-value of 8.2 h·ft^2·°F/Btu (1.5 m^2·K/W). The comparative whole-wall R-value for a similarly constructed conventional metal-frame wall system is about 35% less than the whole wall R-value of the spray foam and steel system and is described in more detail in Kosny et al. (1998a). The application of the sprayed polyurethane foam reduced local interior temperature depressions from 8.8°F (5.5°C) to 2°F (1.2°C) and increased the average interior wall surface temperature by 1.3°F(0.8°C). This will reduce the risk of "ghosting" (dark markings on the wall at locations with embedded thermal shorts). The ghosting is caused by nonuniform internal wall surface temperatures. Placing the thermal break on the interior flange allows exterior wood sheathing to be installed directly to the exterior flange and enables easier installation of siding without having to mechanically fasten the siding directly to each stud.

Structural Insulated Panel with Compressed Straw Core

The straw structural insulated panel (StrawSIP) wall system is based on structural insulating panel technology. Double-core compressed straw panels (96 in. × 96 in. × 7 7/8 in. [2.4 m × 2.4 m × 0.2 m]) consist of two 3.5 in. (9 cm) thick core panels made of compressed straw (density approximately 14 lb/ft^3 [224 kg/m^3]) and two layers of OSB. StrawSIP panels are joined using solid wood profiles.

The hot box test yielded 16.5 h·ft^2·°F/Btu (2.9 m^2·K/W). The HEATING 7 simulated clear wall R-value was 16.7 h·ft^2/Btu·in. (2.9 m^2·K/W). The whole wall R-value was 15.7 h·ft^2/Btu·in. (2.7 m^2·K/W), which is only 6.0% less than the clear wall (Kosny et al. 1998b).

A dynamic hot box test and finite difference computer modeling were utilized to examine the dynamic thermal performance of the StrawSIP wall system (Kosny et al. 1998b). The whole building computer model DOE-2.1E (LBL 1993) simulated a representative single-family residence in six U.S. climates. The thermal performances of ranch-style residential houses containing StrawSIP and wood-frame walls were analyzed. The building load data generated for StrawSIP walls were compared with the data obtained for lightweight wood-frame walls. The results provide DBMS (dynamic benefit for massive envelope systems) values for the StrawSIP wall that reflect the thermal mass benefits inherent in this wall system. The product: "[steady-state R-value (for StrawSIP wall)] × DBMS × (100 - difference between clear and whole wall R-value)%/100" expresses the whole wall R-value that would be needed in conventional wood-frame construction to produce the same loads as the StrawSIP wall system in each of the six climates. This product not only accounts for the steady-state R-value but also the inherent thermal mass benefit and inherit thermal shorts in both the massive and wood-frame walls. There is no physical property associated with the product "R-value × DBMS." DBMS is a function of climate, building type, and base envelope system (i.e., conventional 2×4 wood-frame technology). The dynamic responses of these walls are compared to steady-state clear and whole wall R-values in Figure 15.

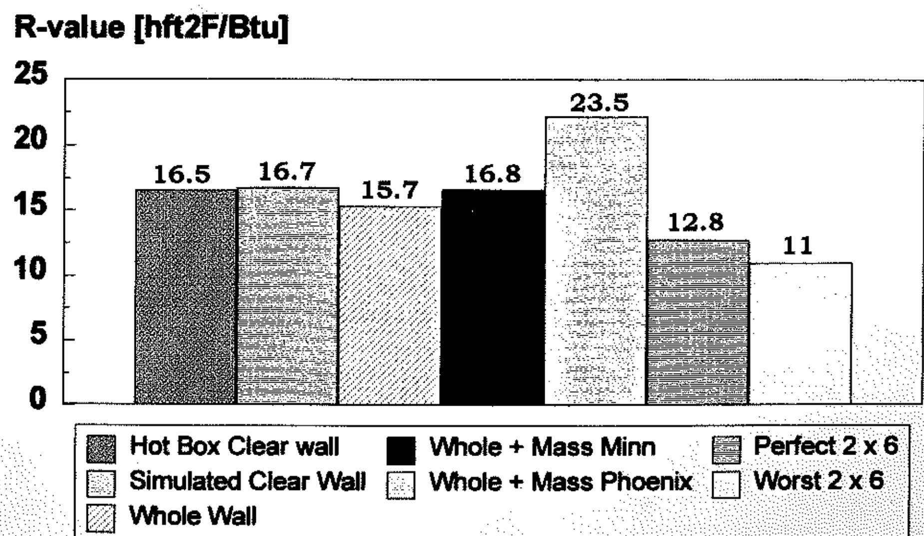

Figure 15 Comparison of clear and whole wall R-values compared to dynamic response in different climates.

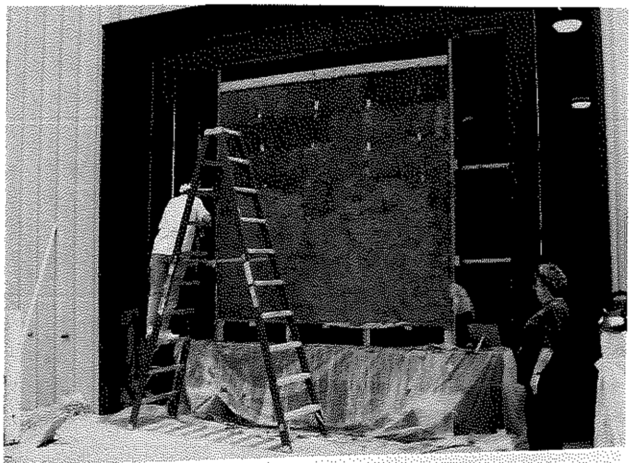

Figure 16 *The first straw bale wall was hand stuccoed.*

Because compressed straw insulating cores have a density of about 14 lb/ft^3 (224 kg/m^3), the total space heating and cooling load of the house built with the StrawSIP wall can be reduced when compared to a light frame wall with equivalent steady-state R-value. Even for very severe climatic conditions (e.g., Minneapolis), StrawSIP walls perform as well as wood frame whole wall R-16.8 h·ft^2/Btu·in. (2.9 m^2·K/W). The StrawSIP wall thermal performance was best in Phoenix, where the comparative wood-frame whole wall R-value would need to be 23.5 h·ft^2/Btu·in. (4.1 m^2·K/W).

Straw Bale

Hand Stuccoed. A hand-stuccoed straw bale wall was constructed for a hot box test in the summer of 1997. Total thickness of the complete wall was about 20 in. (51 cm). The layers were composed of 18 in. (47 cm) thick bales stacked with the straw oriented perpendicular to the wall surfaces, the outside surfaced with stucco containing chicken wire lath, and the inside surfaced with two layers of 1/2 in. (1.3 cm) thick gypsum drywall mechanically fastened to 2 × 4 in. (5 × 10 cm) stakes. The stakes were pounded into the straw bales on 2 ft (61 cm) centers.

The first test of a structural straw bale wall resulted in about a 50% lower R-value—16 h·ft^2°F/Btu (2.8 m^{-2}K/W)—than is calculated from our measured material thermal conductivity and airflow permeability properties of the anisotropic straw alone (Christian et al. 1998). The data analysis and computational fluid dynamic computer modeling confirmed that internal natural convection was a very likely cause for this discrepancy. However, only 5% to 17% of the convection occurred within the straw itself. Most of the convection occurred in the discontinuous gaps between the drywall and the straw bales and the stucco and the straw bales.

In those buildings where drywall or sheet paneling is used, efforts should be made to fill the void between the bales and the back of the sheathing with a material of permeability similar to that of straw bales. This straw bale test wall was hand stuccoed on the exterior, and drywall was applied on the interior surface. The exterior surface with the first stucco coat half done is shown in Figure 16. The wall was built with the help of a team of high school science teachers during a teacher leadership project.

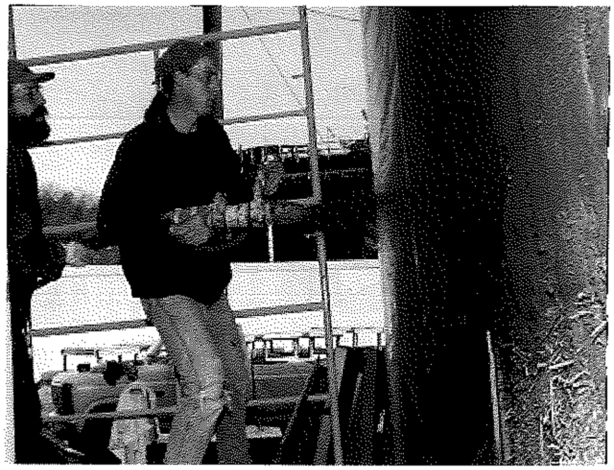

Figure 17 *Stucco mechanically applied to the second straw bale wall.*

Shot Stuccoed with Pumper and Concrete Trucks. A second straw bale wall was built and tested in the spring of 1998. Wall surface treatment was changed for this wall. Figure 17 shows how both sides were mechanically stuccoed with concrete and pumper trucks. The option of applying the stucco with a pumper truck enables air pressure to apply the cementitious material against the wall with good penetration into the straw, virtually eliminating air gaps. Mechanical stucco application requires on-site cement and pumper trucks and operators.

This wall was constructed at a national building energy research laboratory equipped with a guarded hot box. Live digital photographs of the test wall construction and live hot box data were available on the Internet while this experiment was ongoing. The straw was under 14% moisture content at time of construction but picked up moisture after stucco application. The wall was given time to dry out in the laboratory from February 1998 until the wall was placed in the hot box for testing in May 1998. The hot box was set with the meter side at 100°F and the climate side at 50°F. Data taken at 15-minute intervals were placed on the Internet and science students were challenged to take these raw data and calculate the resulting R-value for themselves.

The resulting clear wall steady-state R-value hot box result for the second straw bale wall with mechanically installed stucco was 26 h·ft^2·°F/Btu·in. at 75°F (4.6 m^2·K/W). There was no evidence of natural convection in this wall, which was constructed under the supervision of David Esinberg, director of the Center for Appropriate Technology in Tucson, Arizona, and Tav Cummins, California Energy Commission. The State of California used this test result to base line straw bale construction in California for compliance with Title 24.

Autoclaved Concrete Block

An autoclaved lightweight concrete solid block wall system was tested and analyzed (Kosny et al. 1997a). The blocks were 7 ¾ in. wide, 24 ½ in. long, and 9 ¾ in. high (20 cm × 62 cm × 25 cm) and had an average density of 31 lb/ft^3 (496 kg/m^3). The blocks were joined using thin insulating mortar, 3/8 in. (1cm). The surfaces were covered with latex stucco on the exterior and plaster on the interior. The clear wall hot box test result was 9.4 h·ft^2·°F/Btu·in. at 75°F (1.7 m^2·K/W). The whole wall R-value is 8.6 h·ft^2·°F/Btu·in. at 75°F (1.5 m^2·K/W), only 8% less than the clear wall value. For a conventional 2 × 4 wood-frame wall system, the whole wall R-value is reduced by about 9% from the clear wall R-value in a typical residence such as the one shown in Figure 2 (Christian and Konsy 1996). The thermal resistivity of a 1 in. (2.5 cm) thick slab of the autoclaved concrete block, kept in the same temperature and humidity conditions as the test wall, was measured according to ASTM C518 and found to be 1.26 h·ft^2·°F/Btu·in. (7.2 m·K/W). For an 8 in. (20 cm) thick wall, that would be equivalent to an R-value at 10.1 h·ft^2·°F/Btu (1.8 m^2·K/W).

Dynamic hot box testing and finite difference computer modeling were utilized to examine the dynamic thermal performance of an autoclaved concrete (ACC) block wall system. DOE-2.1E was used to simulate representative single-family residences in six U.S. climates. The thermal performance of a ranch-style residential house, shown in Figure 2, containing ACC block and wood-frame walls was analyzed. The building load data generated for ACC block walls were compared with the data obtained for lightweight wood-frame walls. The results provide DBMS (dynamic benefit for massive systems) values for the ACC block wall that reflect the thermal mass benefits inherent in this wall system. The product; "[steady-state R-value (for ACC block wall)] × DBMS × (100 - difference between clear and whole wall R-value)%/100" expresses the R-value that would be needed in conventional wood-frame construction to produce the same loads as the ACC block wall system in each of the six climates. The resulting product not only accounts for the steady-state R-value but also the inherent thermal mass benefit and the thermal shorts in both the autoclave and wood frame walls. As stated earlier, there is no physical property associated with the product "R-value × DBMS." DBMS is a function of climate, building type, and base envelope system (i.e., conventional 2 × 4 wood-frame technology).

Because of the solid concrete walls, the total space heating and cooling loads of houses built with the ACC block wall are reduced when compared to a light frame wall with equivalent steady-state R-value. As shown in Figure 18, even for very severe climatic conditions (e.g., Minneapolis), ACC block walls perform as well as R-12.1 wood-frame whole wall (the whole wall equivalent value accounts for the 8% difference between the clear and whole wall). In Washington, D.C., ACC block wall performs as well as R-13.4 wood-frame whole wall. The ACC block wall thermal performance rate was best in Phoenix, where the comparative wood-frame whole wall R-value should be R-16.8 (Christian and Kosny 1996).

Insulated Concrete Forms

A wall was built with insulated concrete form (ICF) blocks 9¼ in. (0.23 m) thick for testing in a guarded hot-box under steady-state conditions. The exterior surface of the wall was finished with a ½ in. (1.3 cm) thick layer of stucco and on the interior surface, ½ in. (1.3 cm) thick gypsum boards. Reinforced high-density concrete was poured into the expanded polystyrene and sheet-metal wall forms.

The steady-state hot box measured R-value was 11.6 h·ft^2·°F/Btu (2.04 K·m^2/W) (Kosny et al. 1998d). The simulated clear-wall R-value was 12.0 h·ft^2·°F/Btu (2.11m^2·K/W),

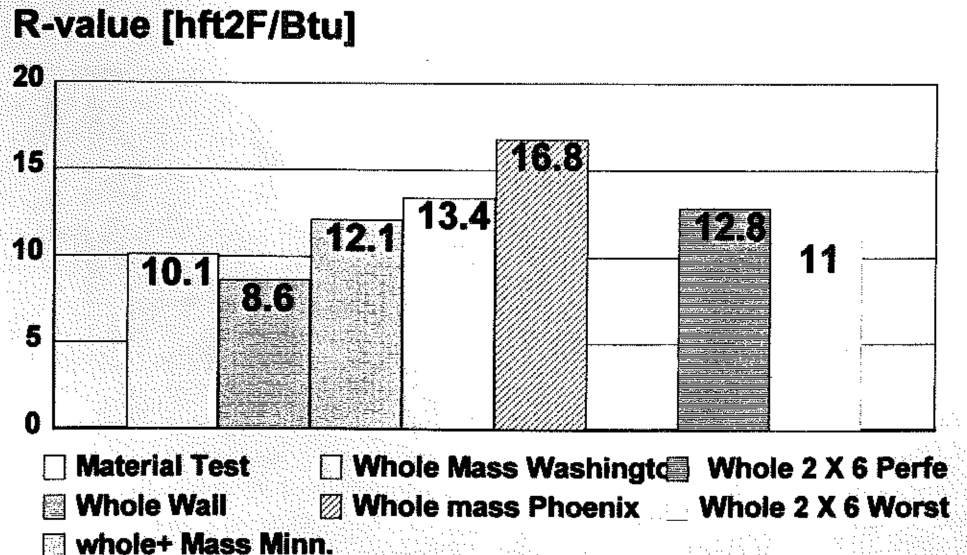

Figure 18 Comparison of R-values for ACC block wall with thermal mass benefits and 2 in. x 6 in. wood-frame wall.

3% higher than the R-value obtained during the test. This is within the range of error of the simulation method.

The whole wall R-value is 11.1 $h \cdot ft^2 \cdot °F/Btu$ (1.96 $m^2 \cdot K/W$). The whole wall R-value is only 9.5% lower than the clear wall R-value. For many masonry and concrete wall systems, whole wall R-values are 10% to 25% lower than clear-wall R-values (Kosny et al. 1998d).

Dynamic hot box testing and finite difference computer modeling were used to create a "thermally equivalent wall" like the three-dimensional ICF form wall system. The equivalent ICF wall was used to predict the dynamic thermal performance of the ICF wall system. DOE-2.1E was used to simulate a representative single-family residence in six U.S. climates with both ICF and wood-frame walls. The equivalent wall generated for the ICF wall system was used in the DOE-2.1E computer modeling. The building load data generated for ICF walls were compared to those obtained for lightweight wood-frame walls. The results provide a metric with units of R-value for the ICF wall that reflect the thermal mass benefits inherent in this wall system (Kosny 1998d). Due to the solid concrete core, the total space heating and cooling load of houses built with ICF walls are less than for light frame walls with the same steady-state R-value in the same climate. For very cold climatic conditions (Minneapolis), the R-11.6 ICF wall performs as well as an R-14.5 $h \cdot ft^2 \cdot °F/Btu$ (2.8 $K \cdot m^2/W$) wood-frame equivalent whole wall (using the clear-whole wall difference of 9.5%). In Washington, D.C., the ICF wall performs as well as an R-17.2 $h \cdot ft^2 \cdot °F/Btu$ (3.3 $K \cdot m^2/W$) wood-frame whole wall. In the other simulated U.S. climates, the thermal performance of the ICF wall was as high as R-20.5 $h \cdot ft^2 \cdot °F/Btu$ (4.0 $K \cdot m^2/W$) in Phoenix. The range of effective R-values reflecting the thermal mass benefit and accounting for thermal shorts in both the ICF and wood frame walls is shown in Figure 19.

Seven ICF houses were blower door tested and found to be 20% more airtight than conventional wood-frame construction (Kosny et al. 1998d). These benefits are reflected in the effective R-value analysis in addition to the thermal mass benefits by assuming a 20% reduction in infiltration in the whole building simulation, as shown in Figure 20. The "dynamic plus airtightness effective R-values" fall in the range of 26 to 44 $h \cdot ft^2 \cdot °F/Btu$ (4.8 to 7.8 $m^2 \cdot K/W$) for the six climates examined.

Another way of looking at these equivalent R-values for an ICF house with 20% lower infiltration than an equivalent frame house is as follows. To attain the same total space heating and cooling load with frame construction and 20% more infiltration than a 6 in (153 mm) core ICF house with a clear-wall steady-state R-value of 11.5 $h \cdot ft^2 \cdot °F/Btu$ (2.0 $m^2 \cdot K/W$) would require exterior wood-framed wall R-values of 26 in. to 44 in. $h \cdot ft^2 \cdot °F/Btu$ (4.8 to 7.8 $m^2 \cdot K/W$). For example, a 2 in. × 6 in. (5.0 cm × 15.3 cm) wood-frame house in Atlanta will perform with a whole-wall R-value of 11 to 12.8 $h \cdot ft^2 \cdot °F/Btu$ (1.9 to 2.3 $m^2 \cdot K/W$). A 6 in. (15.3 cm) ICF wall system will have a "dynamic plus airtightness effective R-value" of around 27.5 $h \cdot ft^2 \cdot °F/Btu$ (5.3 $m^2 \cdot K/W$). This comparison accounts for thermal shorts in both the wood frame and ICF walls.

THERMAL WALL CALCULATOR

The above whole wall results are presented for one particular building type. The same database is available on the Internet to allow comparisons of the clear wall and whole wall values for the wall systems described in this paper and, furthermore, for any user inputed residential house plan. The total estimated time to obtain customized results for a given house plan will be less than 10 minutes per wall option.

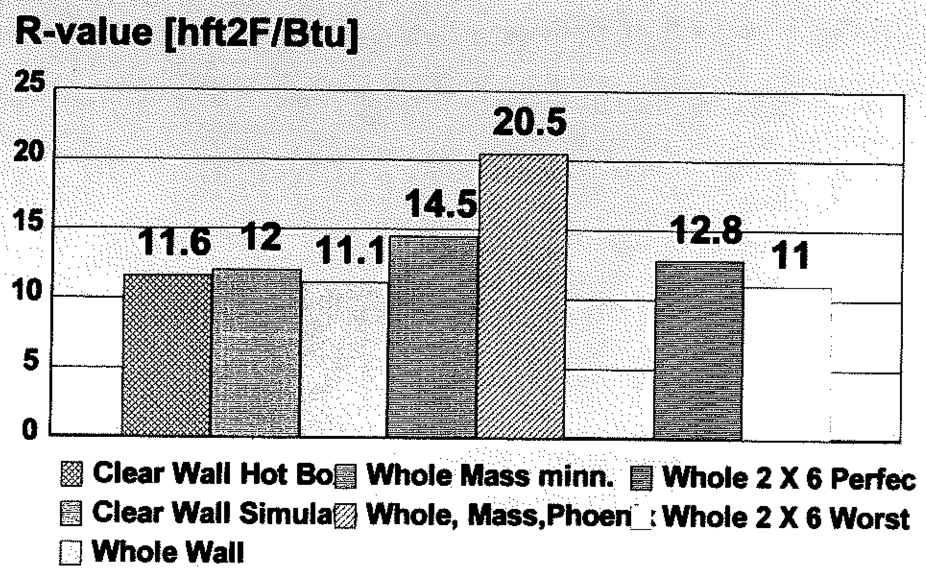

Figure 19 Comparison of R-values for ICF wall and 2 in. × 6 in. wood-frame wall with thermal mass benefits for ICF wall.

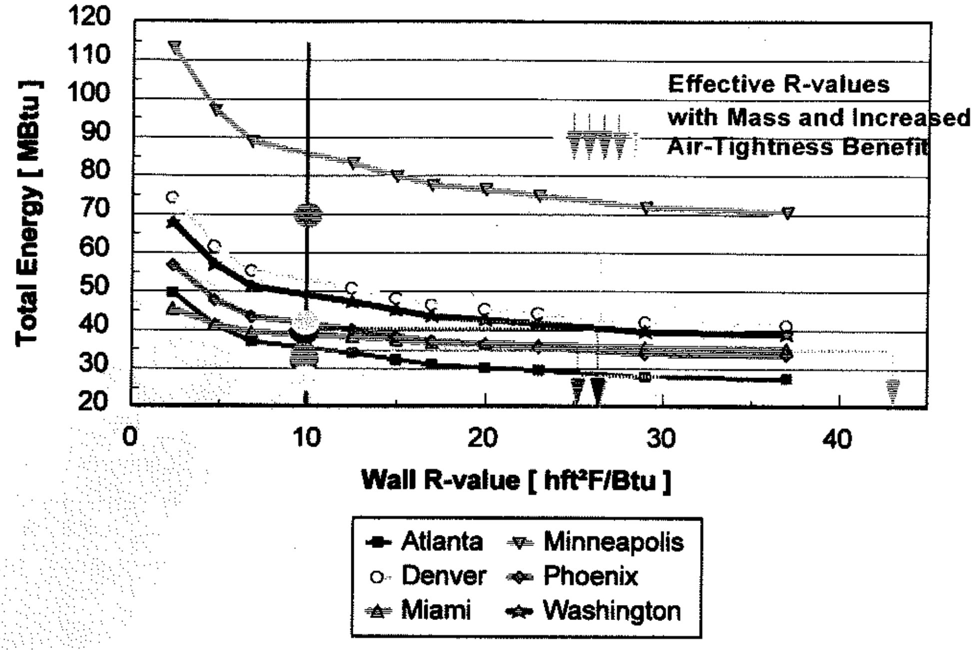

Figure 20 *Total (heating and cooling) energy required for ranch house built of lightweight wood-frame walls and ICF walls with thermal mass and attributing all the airtightness benefits to the walls.*

The steps are:

1. Connect to the home page <http://www.ornl.gov/roofs+walls/>.
2. Select from the list of Interactive Calculators the tool "Whole-Wall Thermal Performance Calculator."
3. Select a wall type; for example, steel frame.
4. (Optional) View and download a copy of the interface details used for each wall system. These drawings are available both as line format and rendered to fill in objects on the drawings.
5. Continue to select either a Standard House or Custom House.
6. If a Custom House is chosen, five simple questions must be answered to characterize the house sufficiently to weight the thermal performance of interface details properly, relative to the clear wall performance.
7. After one more page, the results will be displayed to show the clear and whole wall R-value. Repeat the above process for as many alternative wall system comparisons as desired.

CONCLUSIONS

A new building envelope selection tool is available to quickly compare different residential building wall constructions. The procedure captures many of the performance features commonly referred to in qualitative terms. Thermal shorts, thermal mass, natural convection within wall cavities, and potentially inherent airtightness of some walls over others is addressed.

A very simple formula is proposed in this paper that attempts to capture the thermal shorts, thermal mass, and inherent airtightness of walls in order to derive a metric that homeowners can use for comparison of conventional wood-frame walls to other wall types (it involves the concept of using an equivalent R-value to compare performance with the system of interest of a conventional system in a particular climate).

A series of hot box measurements are made of 2 × 6, 24 o.c. wood-frame walls with batt cavity installation flaws. This wall, typically described as R-19 h·ft^2·°F/Btu (3.3 m^2·K/W), was found to perform as low as R-11 h·ft^2·°F/Btu (1.9 m^2·K/W). However, the degree of natural convection appeared quite small despite very large temperature differences held across the test walls during tests.

ACKNOWLEDGMENTS

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