Whole Wall Rating/Label for Structural Insulated Panels: Steady-State Thermal Analysis

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Executive Summary

The objective of the whole wall rating project at Oak Ridge National Laboratory (ORNL) is to demonstrate the impact of real-world construction techniques on the reported R-value of construction systems. Previous testing on 2 x 4 and 2 x 6 wood frame walls insulated using fiberglass batts indicates that although the clear walls (that portion of the wall that is between the framing members) are R-10.55 (2 x 4 at 16 in. o.c.), R-10.83 (2 x 4 at 24 in. o.c.), and R-16.36 (2 x 6 at 24 in. o.c.) the wall details and other framing play a significant role in determining overall thermal performance. Whole wall R-values are substantially reduced by framing members and construction details in these assemblies. Guarded hot-box testing reveals that actual R-values are R-9.58. R-9.81, and R-13.69, respectively. For the tested 3.5-in. core structural insulated panel (SIP) wall, the clear wall R-value is R-15.17 and the whole wall R-value is as high as R-14.09.

The whole wall R-value comparison between the SIP wall with added exterior wood siding and 0.5-in. interior gypsum board and typical 2 x 4 and 2 x 6 wood frame walls with added wood siding and 0.5-in. gypsum board shows that the SIP wall outperforms the 2 x 4 wood frame walls by more than R-4 and 2 x 6 wood frame walls by R-0.2 to R-0.4.

The analyses performed at ORNL show that for most wall systems, construction details reduce R-values stated for clear wall configurations. However, test results and three-dimensional finite difference computer modeling prove that such reductions in SIP wall constructions are small. This indicates that the SIP wall system is designed and engineered to be thermally efficient.

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Abstract

Hot-box testing and finite difference computer modeling were used to analyze the steady-state thermal performance of the clear wall area and wall interface details for the Structural Insulated Panel Association (SIPA) wall system with structural insulated panels (SIPs) made of expanded polystyrene (EPS) and oriented strand board (OSB). Guarded hot-box testing formed the basis for a finite difference computer model calibration. This computer model was then used to calculate local R-values for all typical wall interface details and the whole wall R-value. Local R-values for all wall interface details and the whole wall R-value, together with three-dimensional AutoCad-rendered images for wall interface details, are presented on the Oak Ridge National Laboratory (ORNL) Buildings Technology Center (BTC) home page at www.ornl.gov/roofs+walls.

Introduction

The steady-state thermal performance of three SIP walls was measured in the ORNL BTC rotatable guarded hot box. In addition, for one wall configuration, the clear wall and whole wall thermal analysis was performed using computer modeling. Hot-box testing and the finite difference computer code Heating 7.2 [Childs 1993] were used to analyze the clear wall area and wall interface details. Three-dimensional computer modeling enabled analysis of the temperature distribution in the wall and precisely calculated local heat fluxes in the clear wall area and in areas influenced by interface details. Maps of the temperature distribution in the wall and wall details were developed. Wall details are defined as the areas where walls intersect with other envelope components. These maps were used to estimate the areas affected by existing thermal bridges and to calculate R-values for these areas. R-values for individual areas, each representing a part of the whole wall (corner, roof/wall intersection, window header, etc.) were used to calculate an average overall wall (whole wall) R-value that includes the thermal effect of all wall interface details. Whole wall R-value is calculated as an area weighted average R-value for clear wall and wall interface details.

Currently, most thermal calculations for wall systems made by designers are based on the measured or calculated thermal performance of the flat wall area, without including the effects of wall interfaces. In this report, that method is called the “clear wall” method (the clear wall is the area of the wall that is free of thermal anomalies caused by wall subsystems or intersections with the other building surfaces). For some wall systems, a change in a wall detail configuration can notably affect proportions in wall area distribution and overall wall R-value [Kośny and Desjarlais 1994]. *For an “ideal” wall system, the local thermal resistances created by wall details should be as “good” thermally as the clear wall area.* In well-designed wall systems, the heat losses through details should be proportional only to the wall area distribution.

Description of SIP Wall

The SIP wall system is based on the SIP technology. As shown in details contained in Appendix B, SIP wall panels consist of 3.5-in.- or 5.5-in.-thick core panel made of EPS and two layers of OSB. SIP panels are joined using splines and solid wood profiles. During the hot-box testing, the SIP wall was not covered by any finish materials, as shown in Figure 1. For computer thermal modeling, exterior wooden siding and interior gypsum board finishes were considered.

Guarded Hot Box Thermal Test of SIP Walls

Measurements of wall systems are typically carried out using an apparatus such as the one described in American Society for Testing and Materials (ASTM) C236, “Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box” [ASTM C236-89]. A relatively large (approximately 8 x 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 C236-89]. The calibration of the ORNL BTC guarded hot box is described in Appendix A.

At the ORNL BTC, the three SIP walls were tested in the guarded hot box under steady-state conditions. During the test, steady air temperatures and air velocities were set on both surfaces of the tested wall. As depicted in Figure 1, the SIP wall was not covered by any finish materials. Exterior wooden siding and interior gypsum board finish were considered only for computer modeling, as shown in Figure 2. Test results are presented in Table 1.

Table 1 details the experimental data that were compiled during hot-box testing. The temperature data that are presented represent the average temperature for the time interval after steady state had been achieved. When multiple temperature sensors are used to define a temperature, these sensors are averaged for each scan and then integrated over 4-hour time intervals. The thermal resistance (R-value) is calculated by

$$R = \frac{A(t_1 - t_2)}{(Q_h + Q_f)} \quad , \tag{1}$$

Figure 1. SIP wall prepared for hot box testing.

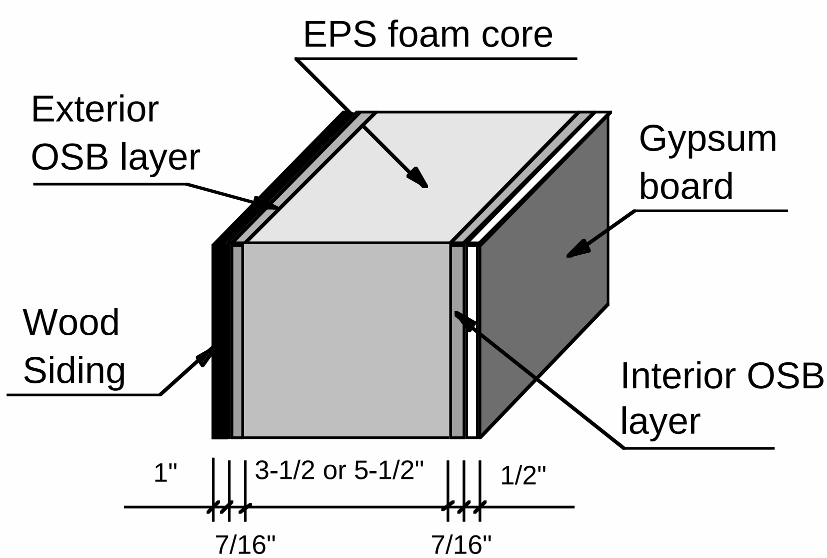


Figure 2. SIP wall section with finish layers.

Table 1. Summary of test results complied on SIP test walls

SIP wall	Panel 1[a] 50/100 °F	Panel 1 10/75 °F	Panel 2[b] 50/100 °F	Panel 2 10/75 °F	Panel 3[c] 50/100 °F	Panel 3 10/75 °F
Meter Chamber Air, °F (t_h)	100.99	75.49	102.06	78.58	100.09	74.98
Meter Air Speed, MPH	0.55	0.51	0.84	0.49	0.58	0.56
Meter Chamber Average Surface, °F (t_1)	98.51	72.82	99.94	75.06	97.82	72.57
Climate Air, °F (t_c)	49.83	10.16	48.93	9.31	50.08	9.86
Climate Air Speed, MPH	3.61	3.65	3.51	3.47	3.38	3.40
Climate Side-Average Surface, °F (t_2)	50.81	10.93	50.18	10.48	50.75	10.66
Panel Mean Temperature, °F	100.13	74.78	101.72	77.78	99.73	74.52
Meter Chamber Energy Input, Btu/h ($Q_h + Q_f$)	218.68	272.81	235.49	283.13	138.64	177.89
R-value, h • ft^2 • °F/Btu (surface to surface)	**13.95**	**14.51**	**13.52**	**14.59**	**21.72**	**22.26**
R_u-value, ($R_{ms\ air} + R + R_{cs\ air}$) h • ft^2 • °F/Btu (air to air)	14.85	15.30	14.43	15.65	23.08	23.38
$R_{ms\ air}$, h • ft^2 • °F/Btu (meter chamber air film resistant)	0.61	0.61	0.58	0.80	1.05	0.87
$R_{cs\ air}$, h • ft^2 • °F/Btu (climate chamber air film resistant)	0.29	0.18	0.34	0.27	0.31	0.25

[a]Panel 1—3.5-in. foam core with spline.
[b]Panel 2—3.5-in. foam core without spline.
[c]Panel 3—5.5-in. foam core without spline

where

- R = thermal resistance of wall assembly, h • ft^2 • °F/Btu (m^2 • K/W);
- A = area of metering chamber, 64 ft^2 (5.3 m^2);
- t_1 = average surface temperature of the wall assembly on the metering side, °F (°C);
- t_2 = average surface temperature of the wall assembly on the climate side, °F (°C);
- Q_h = metering heater energy input, Btu/h (W);
- Q_f = metering fan energy input, Btu/h (W).

The overall thermal resistance (R_u-value) is calculated by

$$R_u = \frac{A(t_h - t_c)}{(Q_h + Q_f)} \quad , \qquad (2)$$

where

R_u	=	overall thermal resistance of wall assembly, h • ft^2 • °F/Btu (m^2 • K/W);
A	=	area of metering chamber, 64 ft^2 (5.3 m^2);
t_h	=	average meter side air temperature, °F (°C);
t_c	=	average climate side air temperature, °F (°C);
Q_h	=	metering heater energy input, Btu/h (W);
Q_f	=	metering fan energy input, Btu/h (W).

The meter side air film thermal resistance ($R_{ms\ air}$) is calculated by

$$R_{ms\ air} = \frac{A(t_h - t_1)}{(Q_h + Q_f)} \quad , \tag{3}$$

where

$R_{ms\ air}$	=	overall thermal resistance of wall assembly, h • ft^2 • °F/Btu (m^2 • K/W);
A	=	area of metering chamber, 64 ft^2 (5.3 m^2);
t_h	=	average meter side air temperature, °F (°C);
t_1	=	average surface temperature of the wall assembly on the metering side, °F (°C);
Q_h	=	metering heater energy input, Btu/h (W);
Q_f	=	metering fan energy input, Btu/h (W).

The climate side air film thermal resistance ($R_{cms\ air}$) is calculated by

$$R_{cs\ air} = \frac{A(t_2 - t_c)}{(Q_h + Q_f)} \quad , \tag{4}$$

where

$R_{cs\ air}$	=	overall thermal resistance of wall assembly, h • ft^2 • °F/Btu (m^2 • K/W);
A	=	area of metering chamber, 64 ft^2 (5.3 m^2);
t_2	=	average surface temperature of the wall assembly on the climate side,°F (°C);
t_c	=	average climate side air temperature, °F (°C);
Q_h	=	metering heater energy input, Btu/h (W);
Q_f	=	metering fan energy input, Btu/h (W).

Metering box wall losses were not included in any of the energy balance calculations. In the worst case, the metering box wall loss represents less than 0.2° of the energy input ($Q_{h.}$ + Q_f).

Guarded Hot-Box Testing Summary

At the ORNL BTC, the three SIP walls were tested in the guarded hot box under steady-state conditions. Each wall went through two hot-box tests. Steady air temperatures and air velocities were set on both surfaces of the tested wall during the test. During the first test, the meter chamber temperature was 100°F and the climate chamber temperature was 50°F. During the second test, the meter chamber temperature was set on 75°F and the climate chamber temperature on 10°F. Relatively large (approximately 8 x 8 ft or larger) cross sections of the SIP walls were tested.

Two tested SIP wall panels contained 3.5-in.-thick cores made of EPS, and one had a 5.5-in.-thick EPS core. In all cases, two 7/16-in. thick layers of OSB were used for exterior and interior wall surfaces. SIP panels were joined using splines and solid wood profiles. One SIP wall containing a 3.5-in.-thick EPS core had 7/16 x 3.5-in. plywood splines in the center of the wall. The other two walls had no splines in the center. During the hot-box testing, the SIP wall was not covered by any finish materials, as shown in Figure 1. Face-to-face R-values for both hot-box tests of the walls are as follows:

	Test 1 (50/100°F)	Test 2 (10/75°F)
Panel 1—3.5-in. foam core with spline	13.95	14.51
Panel 2—3.5-in. foam core without spline	13.52	14.59
Panel 3—5.5-in. foam core without spline	22.26	21.72

Thermal Analysis Method

Three-dimensional computer modeling was performed on SIP Panel 1 with a 3.5-in. EPS core. A heat conduction, finite difference computer code Heating 7.2 [Childs 1993] was used for this analysis. The resulting isotherm maps were used to calculate average heat fluxes and 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 other laboratories. The average difference between laboratory tests and Heating 7.2 simulation results for these walls was ±4.7% [Kośny and Desjarlais 1994]. 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 [ASTM C236-89].

The results of the ORNL BTC guarded hot-box test for the SIP wall were used to calibrate the computer model of the SIP wall. Then, the calibrated computer model was used to simulate clear wall and wall interface details. Computer-generated heat fluxes were used in R-value calculations for clear wall and wall interface details.

The SIP wall was modeled using dimensions obtained from the SIP test walls. The results of the computer modeling were then compared with R-values measured by the hot-box test. In this phase of thermal modeling, actual tested thermal properties of materials were used. Thermal conductivity of each material used in tests was measured in the ORNL Material Properties Laboratory using ASTM C518 procedure. These material conductivities were used as an input to the finite difference computer code for calibration of the computer model. The calibrated computer model was then used to simulate clear wall and wall interface details.

Clear Wall Thermal Performance

A three-dimensional computer model of the wall identical to the tested SIP wall was developed using material thermal properties as measured on the samples received from the experimental SIP Panel 1 with a 3.5-in. EPS core. Thermal conductivity of the EPS core used in tests was measured at the ORNL Material Properties Laboratory using ASTM C518 procedure. Wall dimensions were obtained from the test walls sketched in Figure 2.

Heating 7.2 finite difference computer code was used to simulate the SIP wall. The results of the computer modeling were then compared with hot box experimental R-value measurements. This procedure enabled calibration of the computer model. Thermal conductivities for the EPS panels are presented in Table 2. For thermal modeling, a thermal resistivity of 3.73 h • ft^2 • °F/Btu-in. (26.1 m^2 • K/W) was used. Test and simulated R-values are within 0.5% of each other, as shown in Table 3.

Table 2. Thermal conductivity EPS board measured at the ORNL Material Properties Laboratory using ASTM C518 procedure

Material	Sample thickness in. [cm]	Test mean temperature, °F [°C]	Conductivity k_a, Btu-in./h •ft^2 • °F [W/m^2 • K]	Resistivity R/in. h • ft^2 • °F/Btu-in. [m^2 • K/W]
from 3.5-in. panel	3.5 [8.78]	75 [23.8]	0.26908 [0.0388]	3.7163 [25.99]
from 5.5-in. panel	5.5 [13.81]	75 [23.8]	0.2670 [0.0385]	3.7453 [26.19]

Table 3. Comparison of guarded hot-box measured R-values with computer prediction results

Wall	ORNL Hot-Box Test R-value, h • ft^2 • °F/Btu [m^2 • K/W]	Simulated R-value h • ft^2 • °F/Btu [m^2 • K/W]	Difference %
SIP wall (Panel 1)	13.95 [2.46]	14.02 [2.47]	0.5

Comparison of Clear Wall Thermal Performance of SIP Wall and Conventional Wood Stud Wall

Currently, 2 x 4 and 2 x 6 wood frame constructions are the most popular building wall technologies used for residential buildings in North America. To compare steady-state thermal performance of the SIP wall and conventional 2 x 4 wood frame wall, computer thermal modeling was performed on a typical wood frame wall. Thermal properties of wall materials are shown in Table 4. The following three wall material configurations for the conventional wood stud wall were considered:

- wood siding, 0.5-in. OSB, 3.5-in. fiberglass with 2 x 4 wood studs at 16-in. o.c., 0.5-in. gypsum board,
- wood siding, 0.5-in. OSB, 3.5-in. fiberglass with 2 x 4 wood studs at 24-in. o.c., 0.5-in. gypsum board, and
- wood siding, 0.5-in. OSB, 5.5-in. fiberglass with 2 x 6 wood studs at 24-in. o.c., 0.5-in. gypsum board.

Table 4. Thermal conductivities of wood frame wall materials used for thermal analysis 2 x 4 and 2 x 6 wood stud walls

Material	k_a Btu-in./h • ft^2 • °F [W/m^2 • K]	R/in. h • ft^2 • °F/Btu-in. [m^2 • K/W]
Fiberglass (3.5 in.)	0.32 [0.046]	3.14 [22.0]
Gypsum Board (0.5 in.)	1.11 [0.16]	0.90 [6.25]
OSB (0.5 in.)	0.8 [0.12]	1.25 [8.33]

R-Value

The R-value comparison between the SIP wall with added wood siding and 0.5-in. gypsum board and typical 2 x 4 and 2 x 6 wood frame walls are presented in Figure 3. The figure shows the SIP wall outperforming the 2 x 4 wood frame walls by more than R-4, whereas the clear wall performance of the 2 x 6 wall exceeds the SIP by about R-1.2.

Surface Temperatures

Internal surface temperatures for the SIP clear wall and conventional 2 x 4 and 2 x 6 wood frame clear walls are compared in Figure 4 for an outside temperature of 20°F and interior air temperature of 70°F. Internal surface temperature is almost uniform, without local temperature depressions at stud locations for wood stud walls, as shown in Figure 4. Thermal properties of wall materials used in computer modeling are presented in Table 4.

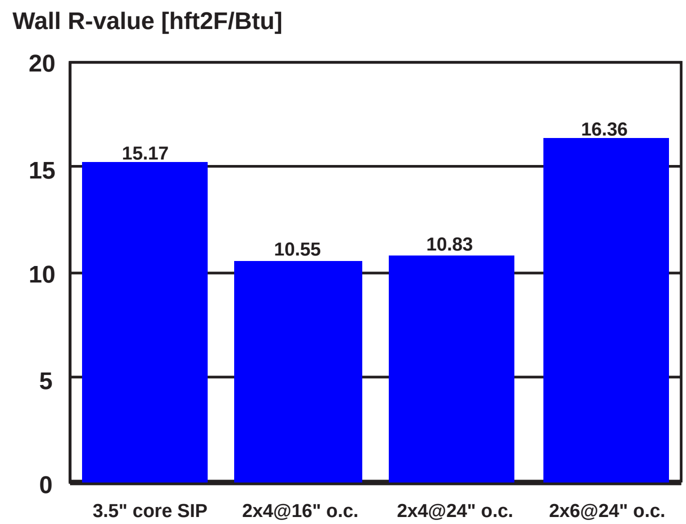


Figure 3. R-value comparisons between SIP wall and conventional 2x4 and 2x6 wood frame walls.

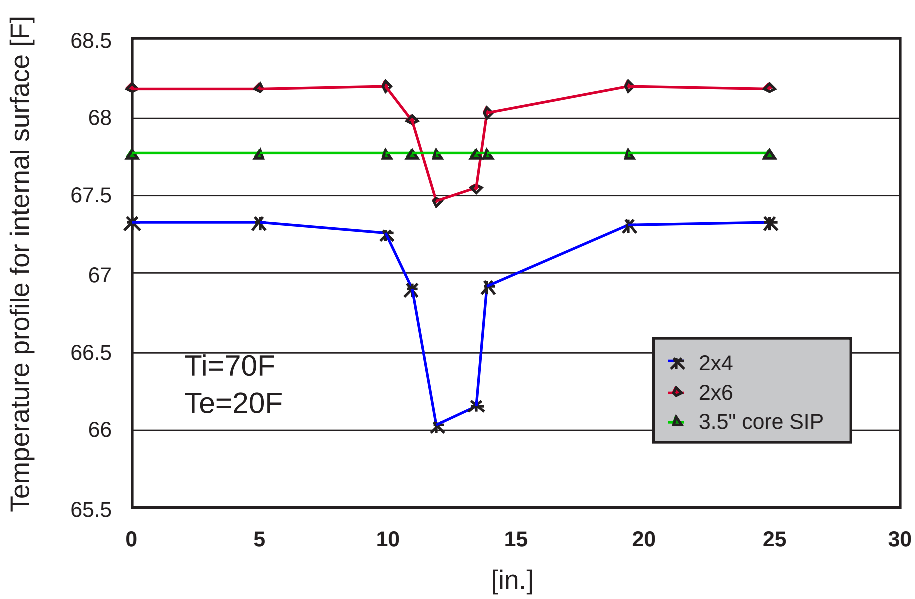


Figure 4. Local temperature comparisons for SIP wall and conventional 2x4 and 2x6 wood frame walls.

The average internal surface temperature for the SIP wall is about 0.4°F higher than the center of cavity surface temperatures for the 2 x 4 wood frame wall. SIP wall surface temperature is also about 0.8°F higher than the lowest surface temperature in a stud location for the 2 x 4 wood stud wall. Center of cavity surface temperatures for the 2 x 6 wood frame wall is about 0.4°F higher than the average internal surface temperature for the SIP wall. However, SIP wall surface temperature is still about 0.2°F higher than the lowest surface temperature in the stud location for the 2 x 6 wood stud wall.

Overall Wall Thermal Performance

For most wall systems evaluated at the ORNL BTC, wall details play a significant role in the overall wall R-value calculations [Christian and Kośny 1996]. The area of thermal disturbances created by wall details may reach up to 60% of the opaque wall area for some wall assemblies, such as the masonry cut-web wall system. For wood and steel frame wall systems, the area influenced by wall details is close to 30% of the opaque wall area.

Frequently, low R-values of wall interface details reduce overall wall R-value. However, for some systems, wall details have higher R-values than the clear wall area, resulting in the higher overall wall R-value than clear wall R-value (in the insulated 2-core CMU wall system, the clear wall has strong thermal bridges that yield a low clear wall R-value; while at the same time, wall details are relatively well insulated by the rigid foam) [Christian and Kośny 1996]. For the SIP wall system, three-dimensional schematics of the wall interface details are presented in Appendix B. These details were used in computer modeling to determine the whole wall R-value:

- clear wall (material configuration as tested in the ORNL BTC guarded hot box)—*Figure B1*,
- corner—*Figure B2*,
- wall/roof connection—*Figure B3*,
- foundation/wall connection—*Figure B4*,
- window and door headers—*Figures B5 and B6*,
- window and door jambs—*Figures B6 and B6*, and
- window sill—*Figure B5*.

For the one-story ranch-style house presented in Appendix C, a whole wall analysis was performed. The whole wall R-value was defined as R-value for the whole opaque wall, including the thermal performance of not only the clear wall area but also all typical envelope interface details [e.g., wall/wall (corners), wall/roof, wall/floor, wall/door, and wall/window connections]. The detailed description of the whole wall R-value methodology can be found at www.ornl.gov/roofs+walls.

Three-dimensional computer models were developed for the SIP clear wall and wall details. Using wall materials as presented in Table 2, the simulated *clear wall R-value of the SIP wall with added wood siding and 0.5-in. interior gypsum board is R-15.17 [h • ft^2 • °F/Btu]*, as shown in Figure 5. Two sets of wall details were simulated: "normal practice" and "best practice" details. The best practice details were thermally improved to reduce thermal bridge effects. For the normal practice details, interface detail R-values and overall wall R-value are

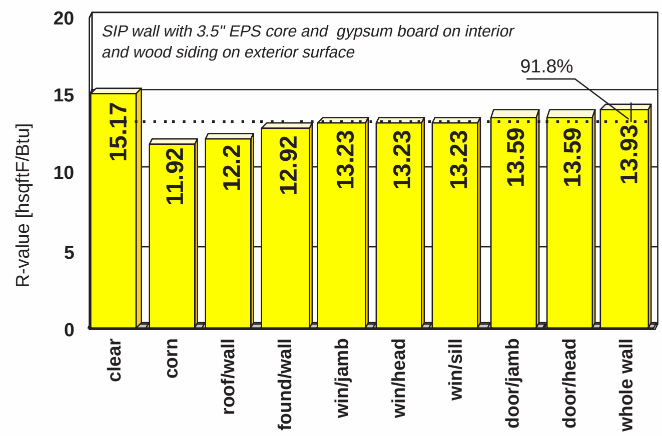


Figure 5. Whole wall R-values for SIP wall system with 3.5" EPS core.

presented in Figure 5 for the SIP wall system. For the selected set of interface details, *the overall wall R-value of the SIP wall system is R-13.93 [h • ft^2 • °F/Btu]*. The overall wall R-value is only reduced by about 8.2% from the clear wall R-value. For the conventional wood frame wall system, the overall wall R-value is reduced by about 9% from the clear wall R-value [Christian and Kośny 1996].

For the best practice details, interface detail R-values and overall wall R-value are presented in Figure 6. Two improved details were considered in this set of whole wall R-value computations: wall/roof and wall/floor intersections. *The overall wall R-value of the SIP wall system with improved details is R-14.09 [h • ft^2 • °F/Btu]*. The overall wall R-value is reduced only by about 7.1% from the clear wall R-value.

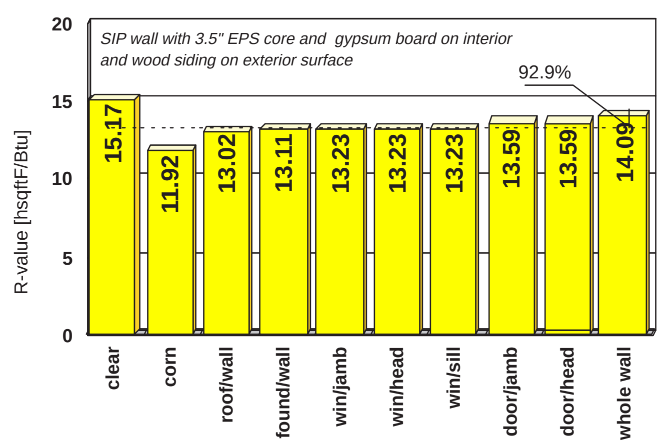


Figure 6. Whole wall R-values for SIP wall system with 3.5" EPS core and the "best practice" details.

For normal practice details, the impacts of wall interface details on the whole wall R-value for the SIP wall system is illustrated in Figure 7. The left portion of the chart represents distribution of wall area. The right side depicts distribution of wall heat losses. *For the wall system containing thermally well-designed details, distribution of wall heat losses should be identical to distribution of wall area.* As shown in Figure 7, the total area influenced by wall details represents about 46% of the opaque wall area (clear wall area represents 54%). These wall details generate about 50% of the whole wall heat losses. The most significant impacts can be observed at the wall/roof interface (12.5% of wall area and 14.2% of wall heat losses) and wall/foundation detail (15.6% of wall area and 16.8% of wall heat losses).

For best practice details, the impacts of wall interface details on the whole wall R-value for the SIP wall system is illustrated in Figure 8. The total area influenced by wall details represents about 46% of the opaque wall area (clear wall area represents 54%). These wall details generate about 50% of the whole wall heat losses. A slight improvement can be observed in the case of the wall/roof interface (12.5% of wall area and 13.5% of wall heat losses).

The following conclusion can be derived based on results of the whole wall R-value analysis:

> The overall wall R-value is reduced only by about 7 to 8% by the thermal influence of wall details. This indicates that in the SIP wall system, the thermal influence of wall details on whole wall thermal performance is insignificant, which is not the case with conventional 2 x 4 and 2 x 6 wood frame wall systems.

In Tables 5 and 6, R-values of SIP wall interface details are presented as they are at www.ornl.gov/roofs+walls.

These R-values and geometric dimensions of wall interface details enable use of the "Whole-Wall Thermal Performance Calculator," which permits comparisons with alternative

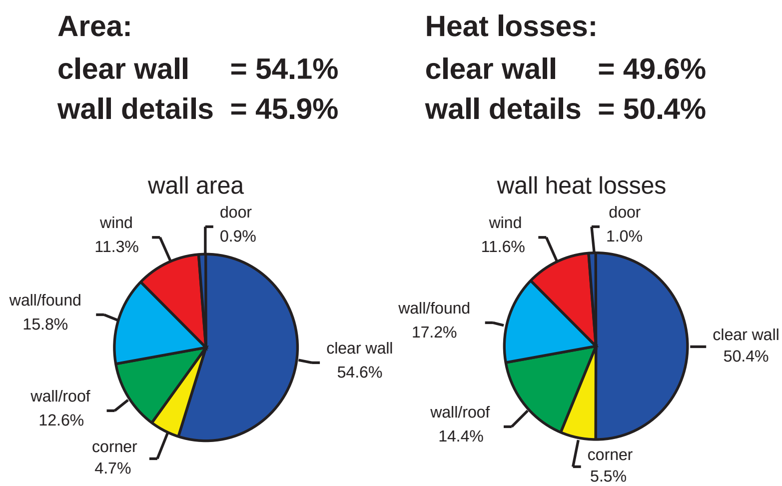


Figure 7. Wall area and wall heat losses distributions for SIP wall system.

Area:
clear wall = 54.1%
wall details = 45.9%

Heat losses:
clear wall = 50.0%
wall details = 50.0%

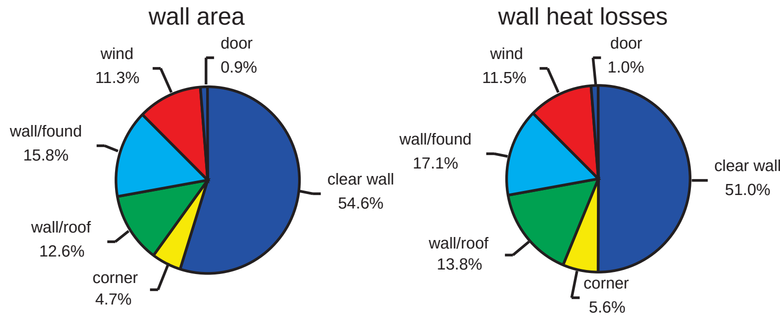


Figure 8. Wall area and wall heat losses distributions for SIP wall system with "best practice" details.

wall systems. The geometric dimensions sketched for each detail in Tables 5 and 6 show the opaque areas influenced by the thermal shorts.

Whole Wall R-Value Comparisons

Whole wall R-values for 2 x 4 and 2 x 6 wood frame wall systems are compared with the SIP whole wall R-value. Thermal properties of wall materials used in computer modeling of clear wall and wall details are shown in Table 4. The following three wall material configurations for the conventional wood stud wall were considered:

- wood siding, 0.5-in. OSB, 3.5-in. fiberglass with 2 x 4 wood studs at 16-in. o.c., 0.5-in. gypsum board;
- wood siding, 0.5-in. OSB, 3.5-in. fiberglass with 2 x 4 wood studs at 24-in. o.c., 0.5-in. gypsum board; and
- wood siding, 0.5-in. OSB, 5.5-in. fiberglass with 2 x 6 wood studs at 24-in. o.c., 0.5-in. gypsum board.

The whole R-value comparison between the SIP wall with added wood siding and 0.5-in. gypsum board and typical 2 x 4 and 2 x 6 wood frame walls is presented in Figure 9. Two sets of wall details are analyzed for the SIP wall system: normal practice and best practice details. Figure 9 shows the SIP wall outperforming the 2 x 4 wood frame walls by more than R- 4 and 2 x 6 wood stud walls by R-0.2 and 0.4 for best practice details.

Table 5. Summary of clear wall and whole wall R-values for the SIP wall system with typical details

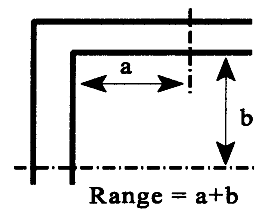
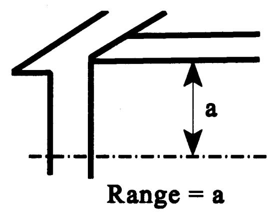
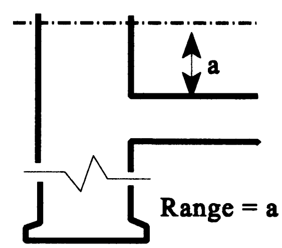
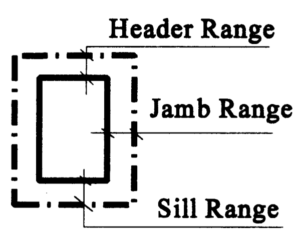
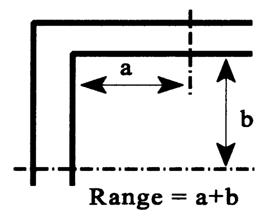
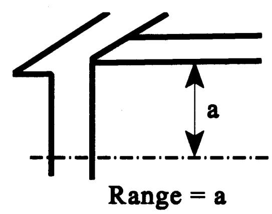
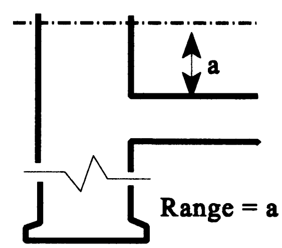
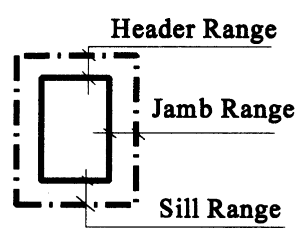
Wall detail		R-value, h • ft² • °F/Btu	[m² • K/W]	Geometric range of detail, ft [cm]
Clear wall	*Figure B1*	15.17	[2.67]	
Corner	*Figure B2*	11.92	[2.1]	0.83 [25.1] 
Roof/wall intersection	*Figure B3*	12.2	[2.15]	0.86 [26.2] 
Foundation/wall intersection	*Figure B4*	12.92	[2.28]	1.08 [32.9] 
Window jamb Window header Window sill Door jamb Door header	*Figure B5* *Figure B5* *Figure B5* *Figure B6* *Figure B6*	13.23 13.23 13.23 13.59 13.59	[2.33] [2.33] [2.33] [2.39] [2.39]	For jambs, headers and sill 1.0 [30.1] 
Whole wall R-value		13.93	[2.45]	

Table 6. Summary of clear wall and whole wall R-values for the SIP wall system with best practice details

Wall detail		R-value, h • ft^2 • °F/Btu	[m^2 • K/W]	Geometric range of detail, ft [cm]
Clear wall	*Figure B1*	15.17	[2.67]	
Corner	*Figure B2*	11.92	[2.1]	0.83 [25.1] 
Roof/wall intersection	*Figure B3*	13.02	[2.29]	0.86 [26.2] 
Foundation/wall intersection	*Figure B4*	13.11	[2.31]	1.08 [32.9] 
Window jamb	*Figure B5*	13.23	[2.33]	For jambs, headers and sill 1.0 [30.1] 
Window header	*Figure B5*	13.23	[2.33]	
Window sill	*Figure B5*	13.23	[2.33]	
Door jamb	*Figure B6*	13.59	[2.39]	
Door header	*Figure B6*	13.59	[2.39]	
Whole wall R-value		14.09	[2.48]	

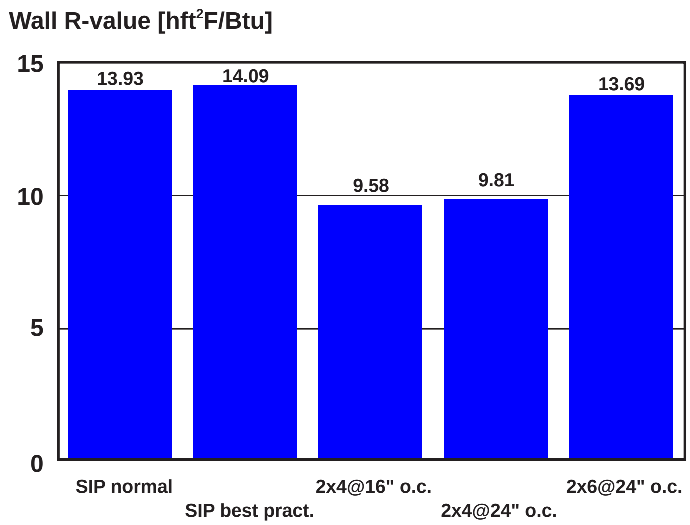


Figure 9. Whole wall R-value comparisons between 3.5" core SIP wall and conventional 2x4 and 2x6 wood frame walls.

Conclusions

Steady-state hot box tests and finite difference computer modeling were used to examine the steady-state thermal performance of the SIP wall system with a 3.5-in. EPS core. *The hot box (ASTM C236) clear wall R-value for this SIP wall was 13.95-h • ft^2 • °F/Btu.*

The simulated *clear wall R-value of the SIP wall with added wood siding and 0.5-in. interior gypsum board is R-15.17 [h • ft^2 • °F/Btu]*. The SIP wall outperforms the 2 x 4 wood frame walls by more than R-4, whereas the clear wall performance of the 2 x 6 wall exceeds the SIP by about R-1.2.

For the considered set of typical wall details where exterior wood siding and an interior 0.5-in.-thick layer of gypsum board was added to the SIP wall and all details, *the whole wall R-value of the SIP wall system is R-13.93 h • ft^2 • °F/Btu*. This is about 8.2% lower than the clear wall R-value. For the best practice wall details where exterior wood siding and an interior 0.5-in.-thick layer of gypsum board was added to the SIP wall and all details, *the whole wall R-value of the SIP wall system is R-14.09 h • ft^2 • °F/Btu*. This is only about 7.1% lower than the clear wall R-value. *This indicates that the SIP wall system is thermally very well designed.*

The whole wall R-value comparison between the SIP wall with added wood siding and 0.5-in. gypsum board and typical 2 x 4 and 2 x 6 wood frame walls shows that the SIP wall outperforms the 2 x 4 wood frame walls by more than R-4 and the 2 x 6 wood stud walls by R-0.2 and 0.4 for best practice details.

References

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Appendix A: Hot Box Test Procedure

The wall assemblies were tested in accordance with ASTM C236-89, “Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box,” using the Oak Ridge National Laboratory (ORNL) Rotatable Guarded Hot Box (RGHB). A photograph of the test facility is shown in Figure A1.

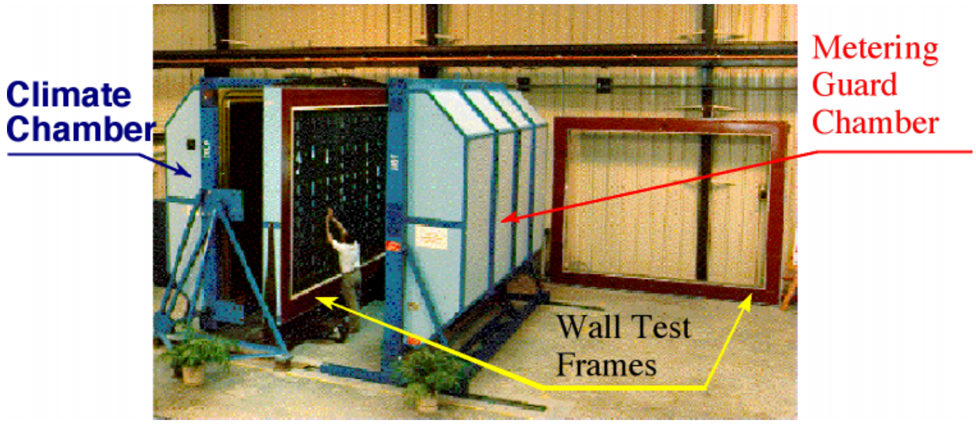

Figure A1. ORNL guarded hot box.

The test wall assemblies were installed into a specimen frame, which is mounted on a movable dolly. The specimen frame has an aperture of 4 by 3 m (13 ft 1 in. by 9 ft 10 in.), as shown in Figure A2. Because the wall assemblies being evaluated are all smaller than this aperture, the remaining area is filled with a thermally resistive insulation material and the thickness of the fill material is adjusted to match the thickness of the test wall assembly. The specimen frame/test wall assembly is inserted between two chambers of identical cross section.

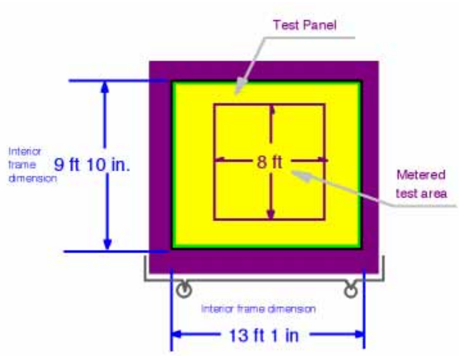

Figure A2. ORNL Buildngs Technology Center hot box test panel schematic.

The insertion of the test wall assembly between the chambers allows the chamber temperatures to be independently controlled. These chambers are designated as the climate (cold) and metering/guard (hot) chambers.

In the climate chamber, a full-size baffle is mounted approximately 10 in. (250 mm) from the test wall assembly. Temperature control in this chamber is accomplished by the insertion of refrigerated air and electrical resistance heaters in series with an array of air blowers. An external refrigeration system is operated continuously, and cooled air is transferred from the refrigeration system through insulated flexible ducting into the rear of the climate chamber behind the baffle. Five centrifugal air blowers, installed in the climate chamber behind the baffle, are used to circulate the air through a bank of electrical resistance heaters and through the airspace between the baffle and test wall assembly. Temperature control is accomplished by a combination of controlling the airstream temperature entering the climate chamber and fine-tuning that temperature with the resistance heaters. The air velocity parallel to the climate side of the test wall assembly is controlled by adjusting the electric power input frequency to the air blowers. An anemometer continuously measures the wind speed in the airspace.

In the center of the metering/guard chamber, a metering chamber is pressed against the test wall assembly. A photograph of the metering chamber is shown in Figure A3. The metering chamber is dimensioned approximately 8 ft (2.3 m) square by 1.3 ft (0.4 m) deep. The walls of the metering chamber are constructed with 3-in.- (76-mm-) thick aged extruded polystyrene foam having an approximate thermal resistance of 15 h • ft^2 • °F/Btu (2.6 m^2 • K/W) at 75°F (24°C). The walls of the metering chamber are reinforced with aluminum frames on the interior and exterior sides and are interconnected with fiberglass threaded rods. The edge of the metering chamber that contacts the test assembly is tapered to a thickness of 0.75 in. (19 mm), and a 0.5-$in.^2$ (13 mm^2) neoprene rubber gasket is affixed to this tapered edge. This gasket is very compressible and readily follows the conture of the test wall surface to minimize air leakage from the metering to the guard chamber. A baffle is mounted inside the metering chamber 6 in. (150 mm) from the exposed edge of the gasket. Behind the baffle, an array of eight fans and four electric resistance heaters are installed. These components are installed such that air is pulled downward behind the baffle, through the resistance heaters, and upward through the airspace

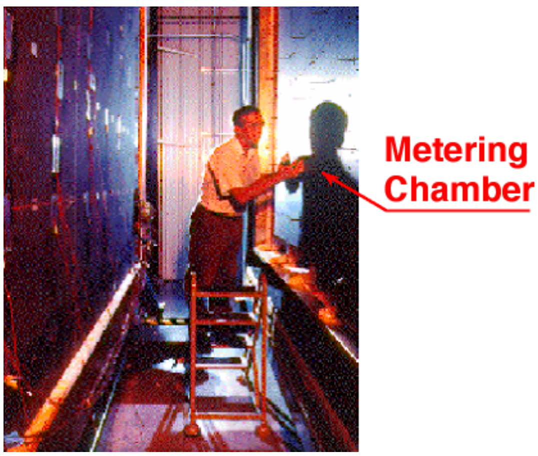

Figure A3. Metering chamber.

between the baffle and test assembly. The upper and lower rear corners of the metering box are tapered to minimize air impingement onto the metering box walls and to provide a smooth transition into the baffle space.

A 96-junction (48-pair) differential thermopile is applied on the interior and exterior walls of the metering chamber to sense the temperature imbalance between the metering and guard chambers. Each thermopile junction is mounted in the center of equivalent surface areas; the interior junction is mounted directly opposite to the corresponding exterior junction. Four heaters and six fans are installed in the guard box to supply heat and circulate the air. These heaters and fans are situated to uniformly distribute the heat and not impinge directly onto the metering chamber.

All temperature measurements were performed using Type T copper/constantan thermocouples calibrated to the special limits of error specified in ASTM E 230, “Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples.” All thermocouples were fabricated with No. 26 AWG wire prepared from the same spool. Arrays of 36 and 48 thermocouples were used to measure the meter and climate chamber air temperatures. Additional arrays of temperature sensors are affixed to each side of the test wall assembly to measure the surface temperature of each wall system component. All of the thermocouples that were attached to the surface of the test wall assemblies were affixed with duct tape. To determine the average surface temperature, the average temperature of the individual wall system components are area-weighted.

In operation, the temperature of the climate chamber is set at the desired level. A controllable ac source is used to energize the metering chamber heaters while the metering chamber fans are powered using a programmable dc power supply. The power to the fans is fixed to maintain the desired wind speed in the airspace between the baffle and the test wall assembly. An anemometer is used to set and monitor this wind speed. The power to the metering heaters is adjusted to obtain the required metering chamber air temperature. The output of the differential thermopile is used to energize the heaters in the guard chamber by using a differential temperature controller. Use of this technique allowed the temperature difference across the metering chamber walls to be minimized, thereby permitting negligible heat leaks into or out of the metering chamber.

These conditions are maintained until temperatures and heat flows are equilibrated. The heat flow generated by the heaters is measured using a watt-hour transducer, and the energy dissipated by the fans is metered with precision resistor networks. Once steady-state conditions have been achieved, the test period is continued until two successive 4-hour periods produce results that varied nonmonotonically by less than 1%. The data for each period are the average of 1-minute scans for that period.

The thermal resistance is calculated by

$$R = \frac{A\left(t_1 - t_2\right)}{\left(Q_h + Q_f + Q_{mb}\right)} \quad , \tag{A1}$$

where

R	=	thermal resistance of wall assembly, h • ft^2 • °F/Btu (m^2 • K/W);
A	=	area of metering chamber, ft^2 (m^2);
t_1	=	average surface temperature of the wall assembly on the metering side, °F (°C);
t_2	=	average surface temperature of the wall assembly on the climate side, °F (°C);
Q_h	=	metering heater energy input, Btu/h (W);
Q_f	=	metering fan energy input, Btu/h (W);
Q_{mb}	=	metering chamber wall energy exchange between the metering and guard chambers, Btu/h (W).

To verify the performance of the rotatable guarded hot box, we performed a series of five verification experiments on a homogeneous panel composed of a 5-in.- (127-mm-) thick expanded polystyrene foam core faced on both sides with a 0.12-in. (3-mm), high-impact polystyrene sheet. In these experiments, we varied the test conditions (temperatures of the metering and climate chambers) and the differential thermopile setting. These experiments were performed to assess how closely we needed to maintain the null balance of the thermopile and to determine the precision of the RGHB. A summary of these results is presented in Table A1.

The R-value data presented in Table A1 have already been corrected for any deliberate thermopile imbalance. The metering chamber input heat flow is corrected for any losses through the metering chamber walls to determine the specimen heat flow. The metering chamber wall heat flow was calculated by

$$Q_{mb} = \frac{A_{mb} * \Delta T_{mb}}{R_{mb}} , \tag{A2}$$

where

Q_{mb}	=	heat flow through metering chamber walls, Btu/h (W);
A_{mb}	=	surface area of the metering chamber, ft^2 (m^2);
ΔT_{mb}	=	temperature imbalance across the metering chamber walls, °F (°C);
R_{mb}	=	thermal resistance of the metering chamber walls, h • ft^2 • °F/Btu (m^2 • K/W).

At mean temperatures of 50 and 75°F (10 and 24°C), the differential thermopile bias correction yields R-values that are within 0.05 and 0.02 h • ft^2 • °F/Btu (0.009 and 0.004 m^2 • K/W) of the average values, respectively. To obtain a 10 Btu/h (2.9 W) bias from the metering chamber requires a 1.5°F (0.8°C) temperature imbalance across the metering chamber walls.

In addition to testing the verification panel in the RGHB, specimens of the expanded polystyrene (EPS) foam used to fabricate the verification panel were submitted to the Materials Thermal Analysis Group at ORNL. The group measured the thermal resistance of these specimens in accordance with ASTM C518-91, "Steady-State Heat Flux and Thermal Transmission Properties by Means of a Heat Flow Meter Apparatus." Using handbook values for the thermal resistance of the polystyrene sheet (0.36 h • ft^2 • °F/Btu or R = 0.063 m^2 • K/W) and adding this thermal resistance to the R-value of the EPS foam, the R-value vs temperature for the specimen of the verification panel was determined. These data were linearly regressed and compared with the data compiled in the RGHB. Table A2 summarizes these results.

Tables A1a and A1b. Summary of experimental results obtained on the expanded polystyrene foam verification panel. The effects of mean temperature and differential thermopile balance are sought.

Table A1a.

Test	Temperature				Heat Flow			R-value
	Meter (°F)	Climate (°F)	Mean (°F)	Thermopile (°F)	Input (Btu/h)	Metering Box (Btu/h)	Specimen (Btu/h)	h • ft^2 • °F/Btu
1	98.9	52.3	75.6	–0.04	142.5	–0.3	142.2	21.14
2	98.8	52.7	75.7	–1.03	149.0	–6.9	142.1	21.14
3	99.0	51.1	75.0	0.87	135.3	5.8	141.1	21.16
4	96.6	4.6	50.6	–0.05	267.0	–0.3	266.7	22.07
5	97.5	6.6	52.0	0.87	258.7	5.8	264.5	22.02

Table A1b.

Test	Temperature				Heat Flow			R-value
	Meter (°C)	Climate (°C)	Mean (°C)	Thermopile (°C)	Input (W)	Metering Box (W)	Specimen (W)	m^2 • K/W
1	37.2	11.3	24.2	–0.02	41.7	–0.1	41.6	3.725
2	37.1	11.5	24.3	–0.57	43.6	–2.0	41.6	3.725
3	37.2	10.6	23.9	0.48	39.6	1.7	41.3	3.728
4	35.9	–15.2	10.3	–0.03	78.2	–0.1	78.1	3.889
5	36.4	–14.1	11.1	0.48	75.8	1.7	77.5	3.880

We find excellent agreement between the test results generated between the two test apparatus; all five of the ASTM C236 experiments performed in the RGHB are within ±0.2% of the ASTM C518 results from the heat flow meter apparatus. Even if our estimate of the thermal resistance of the polystyrene sheets were in error by 50%, the results from the two procedures would still agree to within 1.1%. The need to estimate the R-value of the polystyrene sheets does not appreciably compromise the results that are presented.

Tables A2a and A2b. A comparison of the ASTM C236 (RGHB) and ASTM C518 test results on specimens of the expanded polystyrene foam verification panel. The ASTM C518 results are based on a linear regression of the results of the actual experiments as a function of temperature and are computed at the same mean temperature as the RGHB results.

Table A2a.

Test	Mean Temperature (°F)	R-value (h • ft^2 • °F/Btu)		% Difference (C236-C518)/C518
		ASTM C236	ASTM C518	
1	75.6	21.14	21.14	0.0
2	75.7	21.14	21.14	0.0
3	75.0	21.16	21.20	–0.2
4	50.6	22.07	22.07	0.0
5	52.0	22.07	22.01	0.1

Table A2b.

Test	Mean Temperature (°C)	R-value (h • ft^2 • °F/Btu)		% Difference (C236-C518)/C518
		ASTM C236	ASTM C518	
1	24.2	3.725	3.725	0.0
2	24.3	3.725	3.725	0.0
3	23.9	3.728	3.735	–0.2
4	10.3	3.889	3.889	0.0
5	11.1	3.880	3.878	0.1

Appendix B: AutoCAD drawings for SIPA wall system interface details

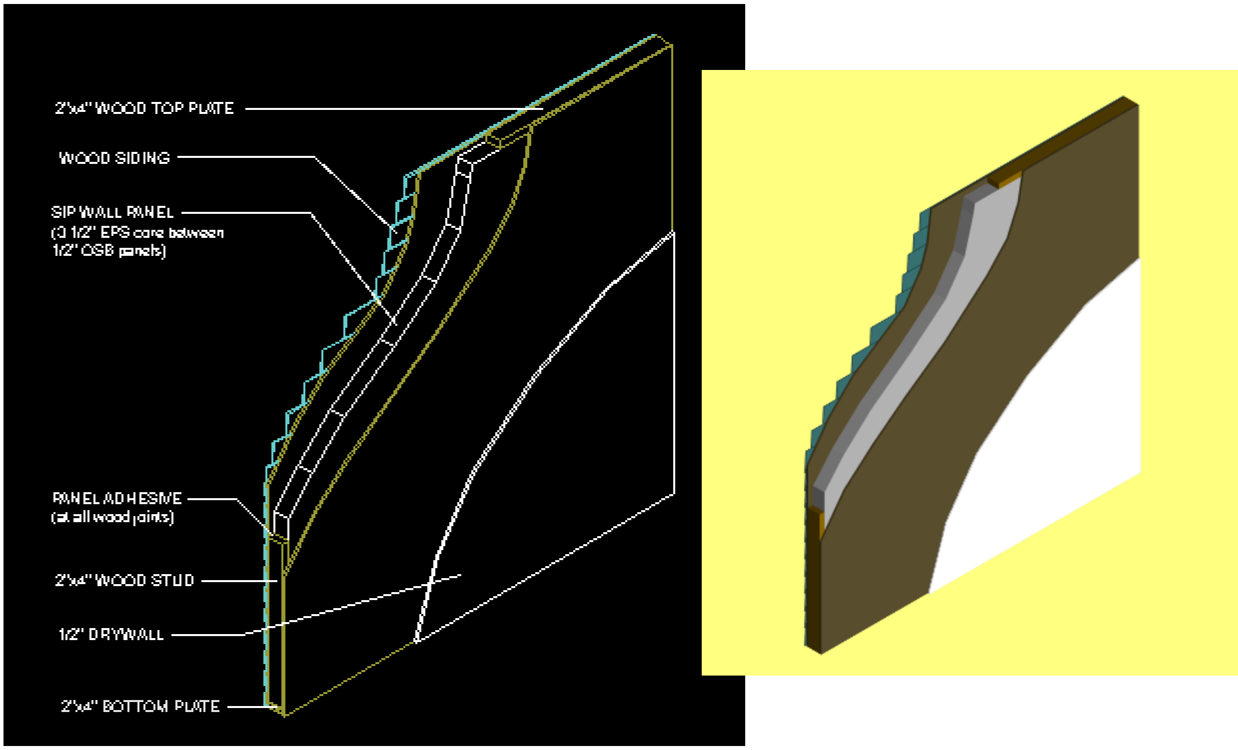

Figure B1. SIPA wall system—clear wall area (R-value = 15.17 h • ft^2 • °F/Btu).

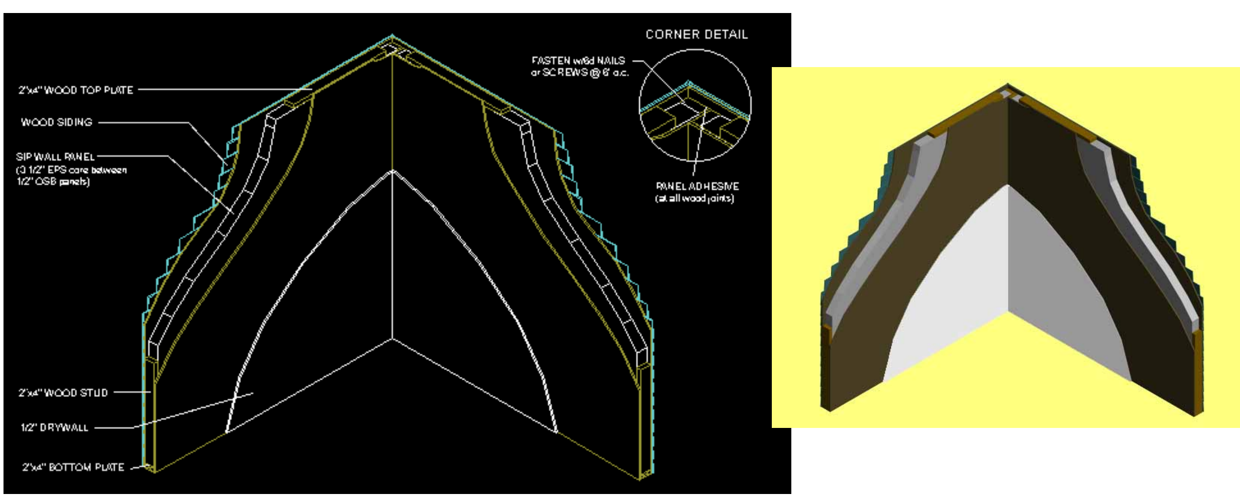

Figure B2. SIPA wall system—corner (R-value = 11.92 h • ft^2 • °F/Btu, range 1.67 ft).

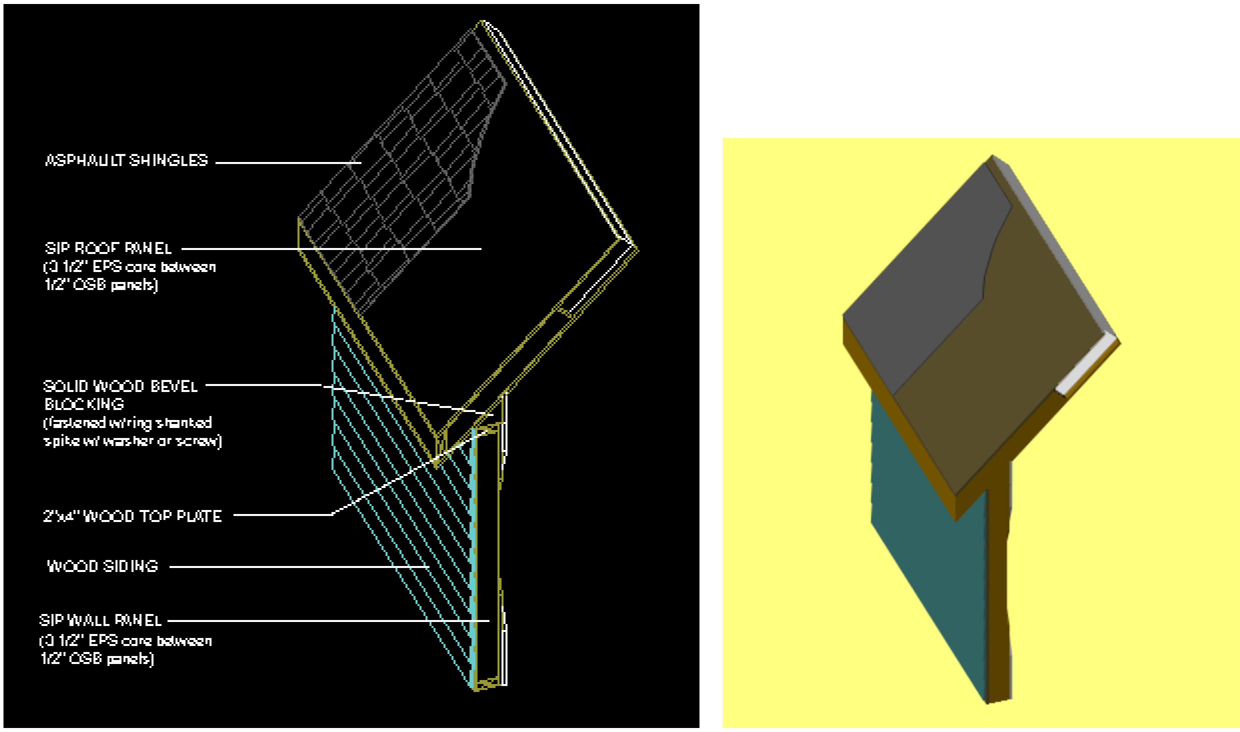

Figure B3a. SIPA wall system—roof/wall intersection—typical detail
(R-value = 12.20 h • ft^2 • °F/Btu, range 0.86 ft).

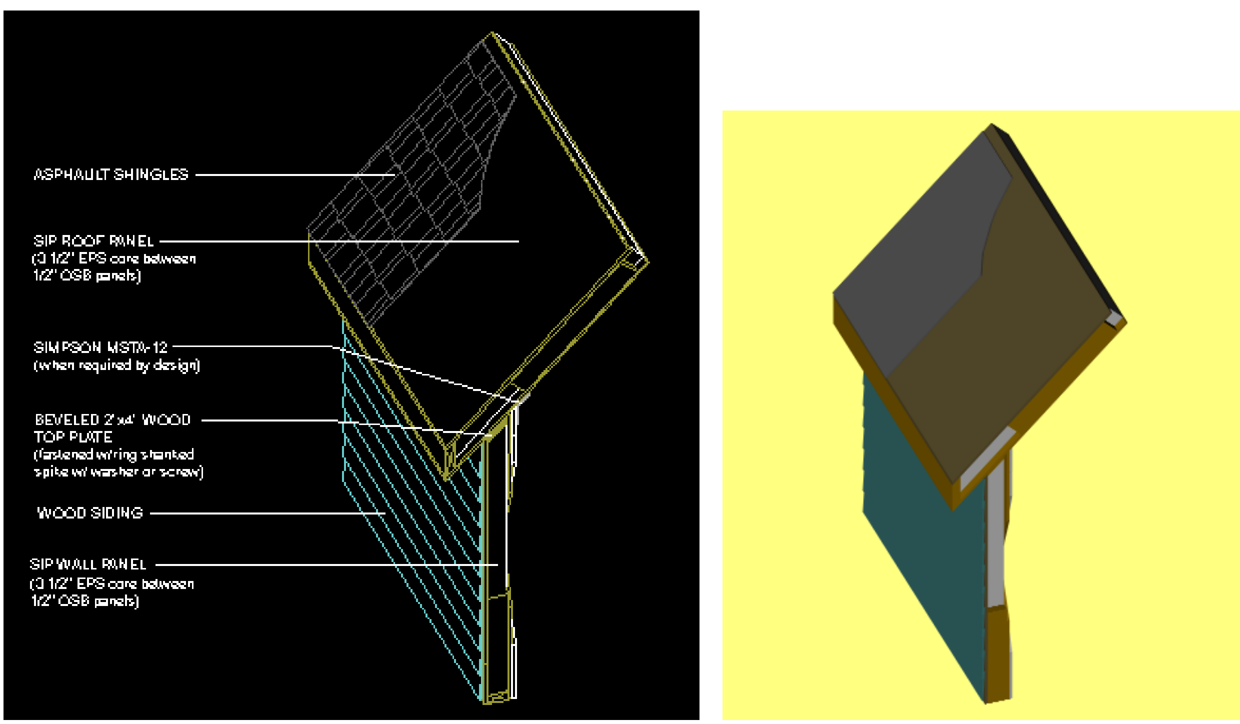

Figure B3b. SIPA wall system—roof/wall intersection—best practice detail
(R-value = 13.02 h • ft^2 • °F/Btu, range 0.86 ft).

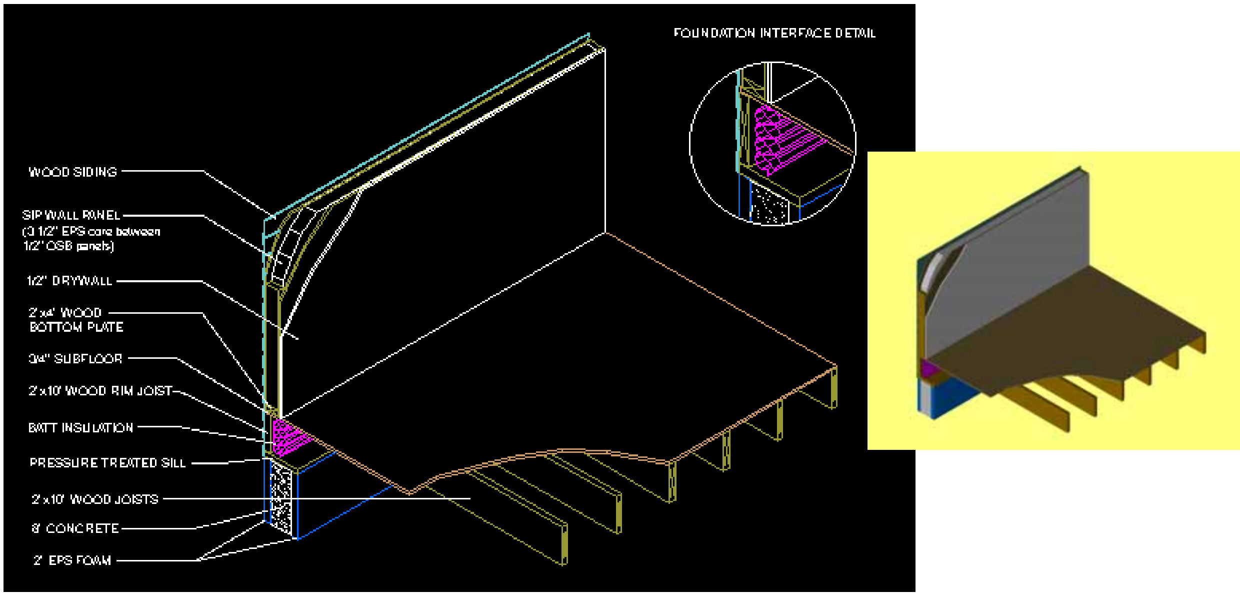

Figure B4a. SIPA wall system—foundation/wall intersection—typical detail (R-value = 12.92 h • ft^2 • °F/Btu, range 1.08 ft).

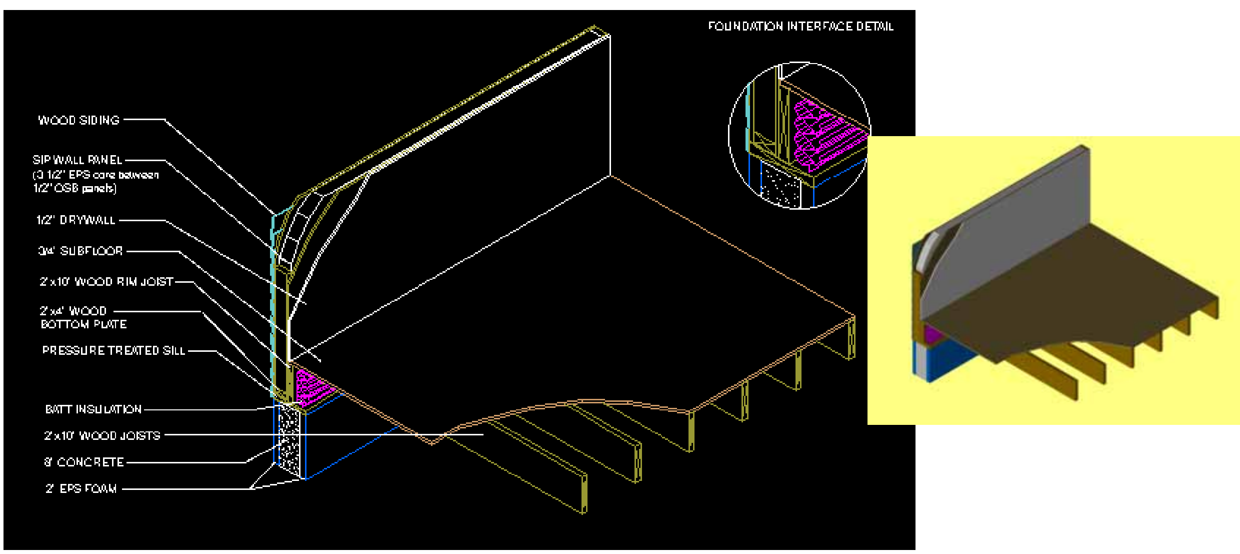

Figure B4b. SIPA wall system—foundation/wall intersection—best practice detail (R-value = 13.11 h • ft^2 • °F/Btu, range 1.08 ft)

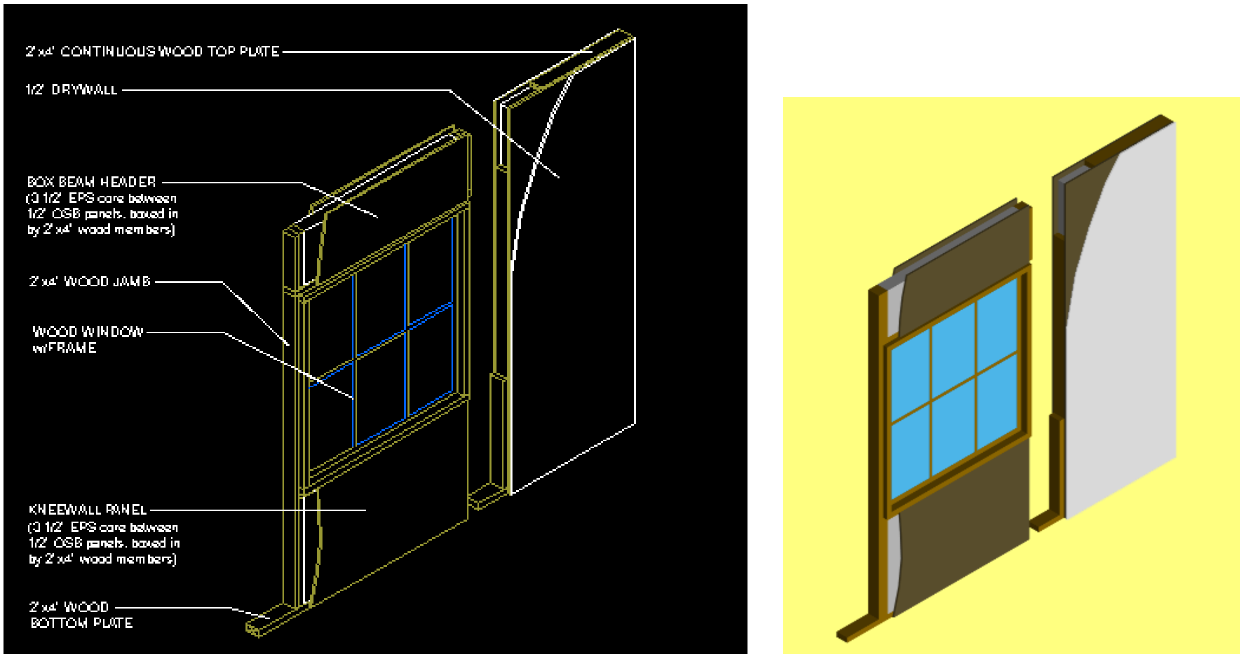

Figure B5. SIPA wall system—window header R-value = 13.23 h • ft^2 • °F/Btu, range 1.0 ft; window jamb R-value = 13.23 h • ft^2 • °F/Btu, range 1.0 ft; window sill R-value = 13.23 h • ft^2 • °F/Btu, range 1.0 ft.

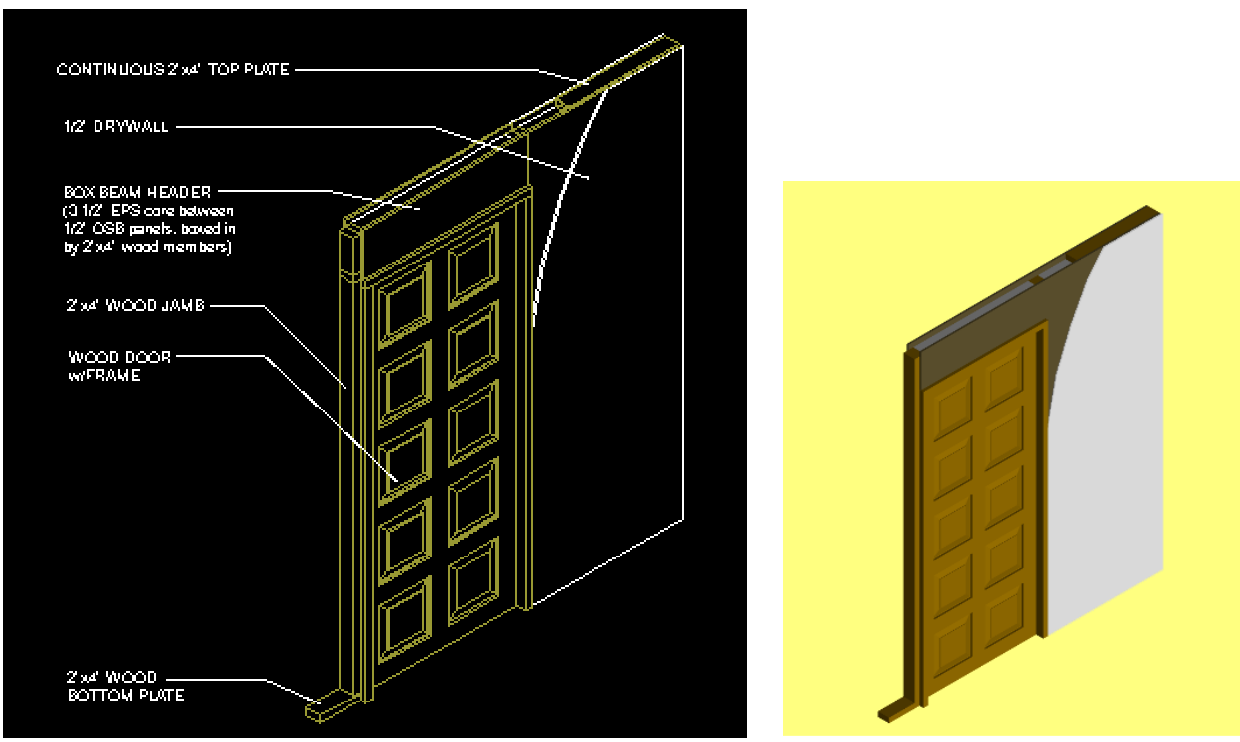

Figure B6. SIPA wall system—door header R-value = 13.59 h • ft^2 • °F/Btu, range 1.0 ft; door jamb R-value = 13.59 h • ft^2 • °F/Btu, range 1.0 ft.

Appendix C: One-story ranch-style house used in thermal modeling

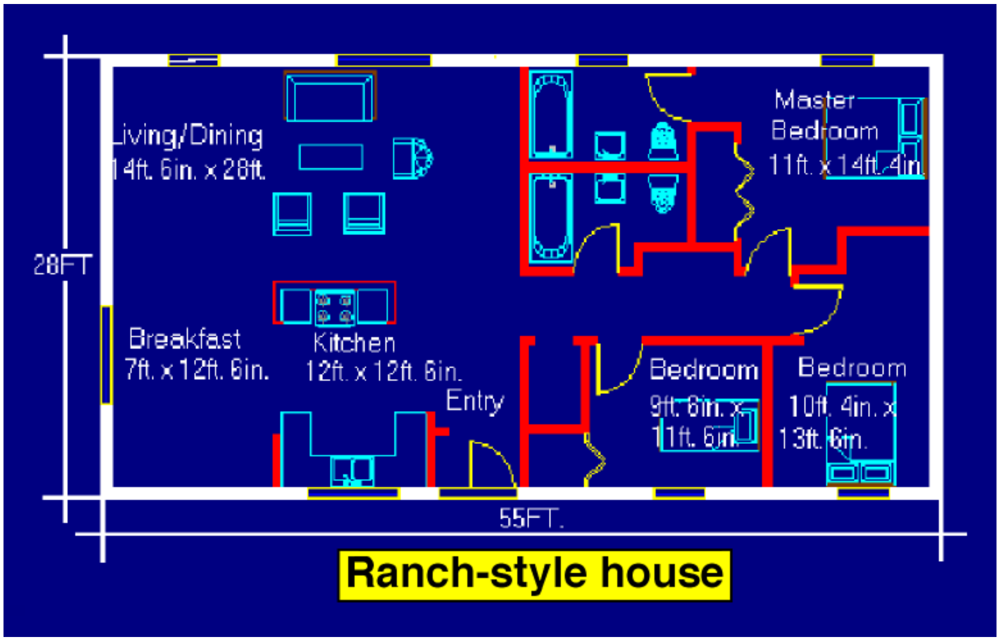

Figure C1. Perspective of the one-story ranch-style house used in thermal modeling.

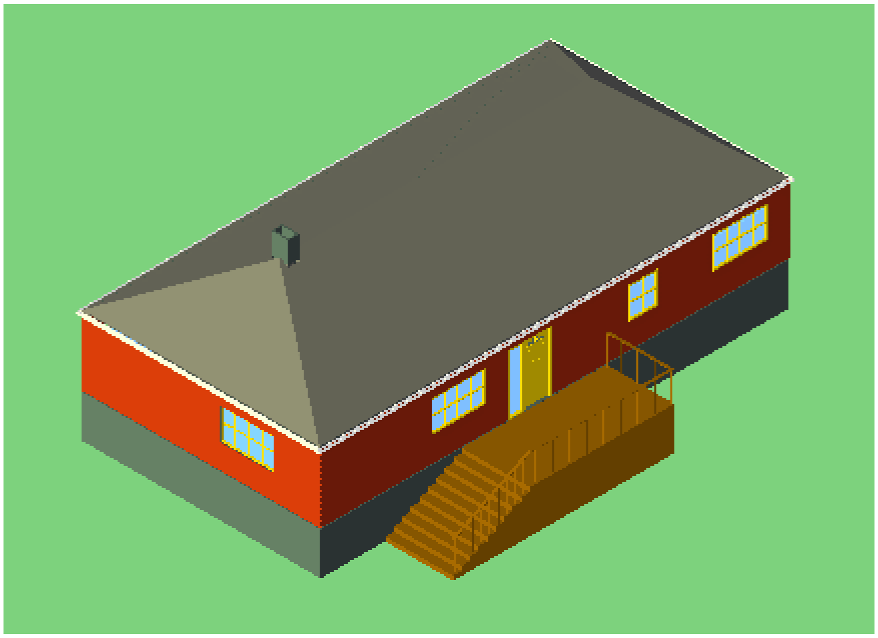

Figure C2. Floor plan of the one-story ranch-style house used in thermal modeling.