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Wall R-Values that Tell It Like It Is

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There's a lot more to most walls than meets the eye, and the R-value of a whole wall can be considerably lower than the R-value of the insulation that fills it. At DOE's Buildings Technology Center, scientists have developed a system for measuring whole-wall R-value, and have already tested several types of wall system.

DOE's rotatable guarded hot box is the workhorse behind the whole-wall rating label system. Sample wall sections are placed in the box, where their thermal properties can be tested in a controlled environment.

Several new wall systems are gaining popularity, due to increasing interest in energy efficiency, alternatives to dimensional wood framing, and building sustainable structures. Steel framing, insulating concrete forms, autoclave cellular concretes, structural insulated core panels, engineered wood wall framing, and a variety of hybrid wall systems are a few of the new types. But accurately comparing the thermal performance of these systems has been difficult. How Wall R-Value Is Usually Calculated Currently, most wall R-value calculation procedures are based on calculations developed for conventional wood frame construction, and they don't factor in all of the effects of additional structural members at windows, doors, and exterior wall corners. Thus they tend to overestimate the actual field thermal performance of the whole wall system.

In these common procedures, the user enters a framing factor (ratio of stud area to whole opaque exterior wall area). The framing factor is usually estimated, is seldom verified against actual site construction, and is frequently underestimated (see Is an R-19 Wall Really R-19? *HE* Mar/Apr '95, p. 5). Framing factors range from 15% to 40% of the opaque exterior wall area, yet lower values are commonly used. Unfortunately, the wall's energy efficiency is usually marketed solely by the misleading clear-wall R-value (Rcw).

Clear-wall R-value accounts for the exterior wall area that contains only insulation and necessary framing materials for a clear section. This means a section with no windows, doors necessary framing materials for a clear section. This means a section with no windows, doors, corners, or connections with roofs and foundations. Even worse is the center-of-cavity R-value, an R-value estimation at the point in the wall containing the most insulation. This converts to a 0% framing factor and does not account for any of the thermal short circuits through the framing.

The consequences of poorly selected connections between envelope components are severe. These interface details can affect more than half of the overall opaque wall area (see Figure 1). For some conventional wall systems, the whole-wall R-value (Rww) is as much as 40% less than the clear-wall value. Poor interface details may also cause excessive moisture condensation and lead to stains and dust markings on the interior finish, which reveal envelope thermal shorts in an unsightly manner. This moist surface area can encourage the growth of molds and mildews, leading to poor indoor air quality.

Metal-framed walls are particularly vulnerable to thermal shorts. Unfortunately, builders often attempt to solve metal wall problems by making thicker walls and adding more insulation in the cavity between the metal studs. In fact, the thicker walls have an even higher percentage difference between clear-wall and whole-wall R-value.

Figure 1. Interface details for metal and wood framing.

Measuring Whole-Wall R-values To compare wall systems more accurately, we have developed a procedure for estimating the Rww for various system types and construction materials (see Wall R-Value Terms). The methodology is based on laboratory measurements and simulations of heat flow in a variety of wood, metal, and masonry systems (see How We Evaluate Wall Performance). The whole-wall R-value includes the thermal performance not only of the clear-wall area, with its insulation and structural elements, but also of typical envelope interface details. These details include wall/wall (corner), wall/roof, wall/floor, wall/door, and wall/window connections.

Table 1. Clear-Wall and Whole-Wall R-Values for Tested Wall Systems

No.	System Description	Clear Wall R-Value (Rcw)	Whole Wall R-Value (Rww)	(Rww/Rcw) x 100%
1.	12-in two-core insulating units concrete 120lb/ft3, EPS inserts 1 7/8-in thick, grout fillings 24 in o.c.	3.7	3.6	97%
2.	12-in two-core insulating units wood concrete 40lb/ft3, EPS inserts 1 7/8-in thick, grout fillings 24 in o.c.	9.4	8.6	92%
3.	12-in cut-web insulating units concrete 120lb/ft3, EPS inserts 2 1/2 in thick, grout fillings 16 in o.c.	4.7	4.1	88%
4.	12-in cut-web insulating units wood concrete 40lb/ft3, EPS inserts 2 1/2 in thick, grout fillings 16 in o.c.	10.7	9.2	86%

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5.	12-in multicore insulating units polystyrene beads concrete 30lb/ft3, EPS inserts in all cores	19.2	14.7	77%
6.	EPS block forms poured in place with concrete, block walls 1 7/8 in thick	15.2	15.7	103%
7.	2 x 4 wood stud wall 16 in o.c., R-11 batts, 1/2-in plywood exterior, 1/2-in gypsum board interior	10.6	9.6	91%
8.	2 x 4 wood stud wall 24 in o.c., R-11 batts, 1/2-in plywood exterior, 1/2-in gypsum board interior	10.8	9.9	91%
9.	2 x 6 wood stud wall 24 in o.c., R-19 batts, 1/2-in plywood exterior, 1/2-in gypsum board interior	16.4	13.7	84%
10.	Larsen truss walls 2 x 4 wood stud wall 16 in o.c., R-11 batts + 8-in-thick Larsen trusses insulated by 8-in-thick batts, 1/2-in plywood exterior, 1/2-in gypsum board interior	40.4	38.5	95%
11.	Stressed-skin panel wall, 6-in-thick foam core + 1/2-in oriented strand board (OSB) boards, 1/2-in plywood exterior, 1/2-in gypsum board interior	24.7	21.6	88%
12.	4-in metal stud wall 24 in o.c., R-11 batts, 1/2-in plywood exterior + 1-in EPS sheathing + 1/2-in wood siding, 1/2-in gypsum board interior. NAHB Energy Conservation House Details.	14.8	10.9	74%
13.	3 1/2-in metal stud wall 16 in o.c., R-11 batts, 1/2-in plywood exterior + 1/2-in wood siding, 1/2-in gypsum board interior	7.4	6.1	83%
14.	3 1/2-in metal stud wall 16 in o.c., R-11 batts, 1/2-in plywood exterior + 1/2-in EPS sheathing + 1/2-in wood siding, 1/2-in gypsum board interior. AISI Manual details	9.9	8.0	81%
15.	3 1/2-in metal stud wall 16 in o.c., R-11 batts, 1/2-in plywood exterior + 1-in EPS sheathing + 1/2-in wood siding, 1/2-in gypsum board interior. AISI Manual details	11.8	9.5	81%
16.	3 1/2-in metal stud wall 24 in o.c., R-11 batts, 1/2-in plywood exterior + 1/2-in wood siding, 1/2-in gypsum board interior. AISI Manual details	9.4	7.1	75%
17.	3 1/2-in metal stud wall 24 in o.c., R-11 batts, 1/2-in plywood exterior + 1/2-in EPS sheathing + 1/2-in wood siding, 1/2-in gypsum board interior. AISI Manual details	11.8	8.9	76%
18.	3 1/2-in metal stud wall 24 in o.c., R-11 batts, 1/2-in plywood exterior + 1-in EPS sheathing + 1/2-in wood siding, 1/2-in gypsum board interior. AISI Manual details	13.3	10.2	77%

We estimated whole-wall R-values for 18 wall systems, using a computer model. We validated the accuracy of the modeling using the results of 28 experimental tests on masonry, wood frame, and metal stud walls. The model was sufficiently accurate at reproducing the experimental data.

The whole-wall R-values estimated for the 18 wall systems are shown in Table 1 along with the clear-wall R-values. A reference building was used to establish the location and area weighing of all the interface details. The comparison of these two values gives a good overall perspective of the importance of wall interface details for conventional wood, metal, masonry, and several high-performance wall systems.

In general, construction details for the wall systems chosen come from the ASHRAE *Handbook* and from the respective manufacturers. In the case of the metal frame systems, the details come from the American Iron and Steel Institute and other common sources.

A wall's thermal performance is often simply described at the point of sale as the clear-wall value. The results shown in Table 1 indicate that the whole-wall value could be overstated by up to 26% for these systems. These differences can be even greater with interface details that are easier to construct but that may have more thermal shorts.

Whole-Wall versus Clear-Wall

Interesting comparisons can be made using the data in Table 1 to illustrate the importance of using a whole-wall value to select the most energy-efficient wall system. It could be argued that the difference between the clear wall and whole-wall R-value represents the energy savings potential of adopting the rating procedure proposed in this paper. Most building owners assume that they have the higher clear-wall value, rather than the more realistic whole-wall value.

An insulating concrete form with metal ties is prepared for testing at the Buildings Technology Center. Its whole-wall R-value and thermal mass will be measured.

Knowing whole-wall R-value could affect consumer choices. Systems 5 and 6 in Table 1 show two different high-performance masonry units. If one used the clear-wall data to choose the unit with the highest R-value, one would pick System 5, the low-density concrete multicore insulation unit, because its clear-wall value is 19.2 compared to 15.2 for System 6, expanded polystyrene (EPS) block forms. However, if one used the whole-wall data, one would choose just the opposite, because System 6 has the higher value--15.7 compared to 14.7 for System 5. Also, the whole-wall value of the foam form system is actually higher than the clear-wall value by more than 3%. This illustrates the effect of the high thermal resistance of the interface details.

Systems 7, 8, and 9 are all conventional wood frame systems. Note that the details affect the whole-wall R-value more for 2 x 6 walls than for 2 x 4 walls. The ratio of Rww to Rcw is about 90% for the 2 x 4 walls and 84% for the 2 x 6 wall.

Comparing System 11, the 6-inch stressed-skin panel wall, to System 9, the conventional 2 x 6 wood frame wall, shows that the Rcw for the former (R-24.7) is 51% higher than that for the latter (R-16.4). However, the figures for the Rww are R-21.6 to R-13.7 respectively, an improvement of 58%. As this example shows, advanced systems will generally benefit from a performance criterion that reflects whole-wall rather than clear-wall values.

How We Evaluate Wall Performance

To determine whole-wall R-value, we test a clear-wall section, 8 ft x 8 ft, in a guarded hot box. We compare experimental results with sophisticated heat conduction model predictions to get a calibrated model. Next, we make simulations of the clear-wall area with insulation, structural elements, and eight interface details--corner, wall/roof, wall/foundation, window header, windowsill, doorjamb, door header, and window jamb--that make up a representative residential whole-wall elevation. Results from these detailed computer simulations are combined into a single whole-wall steady-state R-value estimation. This estimation is compared with simplified calculation procedures and results from other wall systems. The user defines a reference wall elevation to weigh the impact of each interface detail.
For each wall system for which the whole-wall R-value is to be determined, all details commonly used and recommended (outside corner, wall/floor, wall/flat ceiling, wall/cathedral ceiling, doorjamb, window jamb, windowsill, and door header) must be included. The detail descriptions include drawings, with all physical dimensions, and thermal property data for all material components contained in the details.

Beyond R-Value

The R-value is only the first of five elements that are needed to compare whole-wall performance. The other four elements are thermal mass, airtightness, moisture tolerance, and sustainability. We are working on standard ways to measure thermal mass, airtightness, and moisture tolerance. For some systems all five factors are important; for others, only whole-wall R-value is relevant. Thermal Mass Benefit Wall systems with significant thermal mass have the potential--depending on the climate--to reduce annual heating and cooling energy requirements below those required by standard wood frame construction with similar steady-state R-value. The thermal mass benefit is a function of climate.
Effective R-values for massive walls are obtained by comparing the massive wall to light-weight wood frame walls. However this effective R-value is only a way to determine the link between the thermal mass of the wall and annual space heating and cooling loads, or a way to answer the question what R-value would an identical house with wood frame walls need to obtain the same space heating and cooling loads as the massive walled house? The term cannot be generally applied to a given wall type.

A procedure to account for thermal mass was used to create the generic tables found in the Model Energy Code (MEC) for all thermal mass walls with more than 6.0 Btu/ft2 of wall thermal capacitance. The tables have been in use since 1988. Customized tables can be used to show code compliance with the prescriptive Uw requirements in the MEC that are based on wood frame construction.

Airtightness Users of the DOE Buildings Technology Center follow a combination of ASTM Standards C236 or C976 (ASTM 1989) or E1424 and E283 (ASTM 1995) to measure air leakage and heat loss through clear-wall assemblies under simulated wind conditions ranging from 0 to 15 mph. Varying the differential pressures from 0 to 25-50 Pascals (Pa) simulates the extremes to which a wall is exposed in a real building. The test specimens contain one light switch and one duplex outlet connected with 14-gauge wiring that spans the width of the wall. Because heat loss in a building can be as high as 40% due to infiltration, it is important to include this performance parameter, but the quality of workmanship on the construction site, as compared to a laboratory specimen, must be considered. A second complicating factor is that materials may shrink or crack over time, and this will change the leakage. We will never completely predict the impact of workmanship on energy loss in buildings. What is important is to establish a uniform baseline for all wall systems.

Moisture Tolerance The wall's moisture behavior, like the benefit of thermal mass, is a function of climate and building operation. Annual moisture accumulation due to vapor diffusion of a particular wall system can be estimated by computer simulation. It is harder to estimate moisture accumulation due to air flow into the wall. It is important, in a long-lasting wall assembly, that the wall have the ability to dry itself out if it is built wet or picks up moisture due to a leak. The drying rate can be modeled and measured in the laboratory. The potential for moisture accumulation over specific full annual climatic cycles can also be modeled by heat and mass transfer codes such as MOIST (available from the National Institute of Standards and Technology, Special Publications 853, Release 2.1) and MATCH (available from Carston Rode, Technical University of Denmark, Department of Buildings and Energy, Building 188, DK-2800, Lyngby).

Systems 12 through 18 are all metal-framed. On average, the whole-wall value for these seven systems is 22% less than the clear-wall value. Metal can be used to build energy-efficient envelopes, but not by using techniques common to wood frame construction. The conventional metal residential systems reflected in Table 1 do not fare as well, compared to the other systems, when the whole-wall value is used as the reference. For example, if one is considering either System 6 (EPS block forms) or System 12 (a 4-inch metal stud wall), the clear-wall R-value is about the same--R-15. However, if the comparison is made using the whole-wall R-value, the EPS block form system has a 45% higher value--R-15.7 compared to R-10.9.

A standard metal frame wall section before insulation and drywall is installed.

Whole-Wall versus Center-of-Cavity

We also compared whole-wall R-values to center-of-cavity R-values. When a real estate agent or contractor states the R-value of insulation across the cavity to a potential home buyer, the implied whole-wall R-value is often overstated by 27% to 58%. If one compared metal (System 13) and wood (System 7) frames using center-of-cavity R-values, one would conclude that there was no difference, since both have center-of-cavity values of about R-14. However, the whole-wall value of the 2 x 4 wood wall system is 56% better than the whole-wall value for the metal system -- R-9.6 compared to R-6.1.

These comparisons are not meant to imply that one type of construction is always better than another. They are all based on representative details. Whole-wall R-values could change if certain key interface details were changed. The purpose of making these sample comparisons is simply to show the importance of having the whole-wall value available in the marketplace, to guide designers, manufacturers, and buyers to more energy-efficient systems.

An autoclave concrete wall is stuccoed in preparation for the hot box test.

Coming Soon: A Wall Rating Label? A number of innovative wall systems offer advantages that will continue to gain acceptance as the cost of dimensional lumber rises, the quality of framing lumber declines, availability fluctuates, and consumers remain concerned about the environmental impact of the nonsustainable harvesting of wood. For instance, while common dimensional lumber systems historically represent about 90% of the market, metal framing manufacturers anticipate attaining 25% of the residential wall market by the year 2000. This projection may be a bit optimistic, but it is clear that cold form steel is set to make major inroads into the residential market.

Now that a growing wall database and an evaluation procedure are available, the building industry can develop a national whole-wall thermal performance rating label. This would establish in the marketplace a more realistic energy savings indicator for builders and homeowners faced with selecting a wall system for their buildings.

Labels could also help specific systems to gain the acceptance of code officials, building designers, builders, and building energy-rating programs such as Home Energy Rating Systems (HERS) and EPA Energy Star Buildings. The whole-wall R-value procedure has been proposed for adoption in the ASHRAE Standard 90.2, the Council of American Building Officials Model Energy Code, and U.S. Department of Energy's national voluntary guidelines for HERS. Many of the documents that are available to show builders how to comply with applicable codes, standards, and energy efficiency incentive programs would benefit by using the whole-wall R-value comparison procedure.

Ultimately, wall comparisons should include five elements: whole-wall R-value, thermal mass benefits, airtightness, moisture tolerance, and sustainability (see Beyond R-Value). *Publication of this article was supported by the U.S. Department of Energy's Office of State and Community Programs, Energy Efficiency and Renewable Energy.*

Wall R-Value Terms

Center-of-cavity R-value: R-value estimation at the point in the wall that contains the most insulation.

Clear-wall R-value (Rcw): R-value estimation for the exterior wall area that contains only insulation and necessary framing materials for a clear section, with no windows, doors, corners, or connections between other envelope elements, such as roofs and foundations.

Interface details: A set of common structural connections between the exterior wall and other envelope components--such as wall/wall (corners), wall/roof, wall/floor, window header, windowsill, doorjamb, door header, and window jamb--that make up a representative residential whole-wall elevation.

Whole-wall R-value (Rww): R-value estimation for the whole opaque wall, including the thermal performance of both the clear wall area and typical interface details.

Opaque wall area: The total wall area, not including windows and doors.

Continuing research is being cofunded by DOE's Office of Buildings Technology and Community Programs and by private industry to add more advanced wall systems to the database, and to address not only thermal shorts, but thermal mass benefits, airtightness, and moisture tolerance. Industry participants so far include American Polysteel, Integrated Building and Construction Solutions (IBACOS), Icynene Incorporated, Society for the Plastics Industry Spray Foam Contractors, Hebel USA L.P., Composite Technologies, Structural Insulated Panel Systems Association, LeRoy Landers Incorporated, Florida Solar Energy Center, American Society of Heating, Refrigerating and Air-Conditioning Engineers and Enermodal.

The database of advanced wall systems is available on the Internet (http://www.cad.ornl.gov/kch/demo.html). For more information, contact Jeffrey E. Christian at Oak Ridge National Laboratory, P. O. Box 2008, MS 6070 Oak Ridge, TN 37831-6070. Tel:(423) 574-4345; Fax:(423)574-9338; E-mail: jef@ornl.gov.

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