Thermal Performance and Wall Rating

Web address of report: http://www.ornl.gov/sci/roofs+walls/articles/WallRating.html
Whole-wall thermal performance calculator: http://www.ornl.gov/sci/roofs+walls/whole_wall/
Jeffrey E. Christian and Jan Kosny, Oak Ridge National Laboratory

Abstract

The persistent interest in residential energy efficiency and alternatives to dimensional wood-frame wall constructions have increased the popularity of steel frame, insulating concrete forms, low-density concretes, structural insulated core panels, engineered wood wall framing, concrete block with insulated core, and a variety of hybrid wall systems. The full market consideration of these wall systems is inhibited, in part, by the lack of an acceptable, scientifically valid, uniform thermal performance comparison procedure.

Currently, most of the simplified calculation procedures readily available to decision makers for selecting building wall systems are based on the parallel path calculations used for conventional wood-frame systems. This approach requires the user to enter a framing factor (ratio of stud area to whole opaque exterior wall area). The framing factor usually is estimated, seldom verified against actual site construction, and frequently is underestimated. Framing factors vary from 15 to 40% of the opaque exterior wall area, yet lower values down to 0% are commonly used. Unfortunately, the wall energy efficiency usually is marketed solely by the misleading "clear wall" R-value (exterior wall area containing only insulation and necessary framing materials for a clear section with no fenestrations, corners or connections between other envelope elements such as roofs, foundations and other walls), or even worse "center-of-cavity" R-value (R-value estimation at a wall cross-sectional point containing the most insulation), which converts to a 0% framing factor and does not account for any of the framing material thermal shorts through the insulation.

This paper proposes for consideration as a nationally accepted consensus methodology a procedure for estimating the whole opaque wall R-value (whole-wall R-value), independent of system type and construction materials. The methodology is based on results from a three-dimensional heat conduction model capable of simulating heat flow in a variety of wood, metal, and masonry systems. These simulation results lead to a "whole-wall" R-value which include the thermal performance of not only the "clear wall"

area, with insulation and structural elements, but also typical envelope interface details, including wall/wall (corners), wall /roof, wall/floor, wall/door, and wall/window connections. Results from these detailed computer simulations are combined into a single "whole-wall" R-value estimation and compared with simplified "center-of-cavity" and "clear wall" R-values.

Keywords heat transfer, energy calculation, building code, load calculation, rating, walls, thermal performance,

Background

One mission of the Department of Energy's Office of Building Technology is to work with private industry to accelerate the application of energy-efficient building wall systems. One initiative is to develop scientifically supported performance data on enhanced, energy-efficient wall systems and disseminate this information in an easy-to-use form to enable home builders and buyers to make informed wall selections. A logical progression from the development of the database and evaluation procedure described in this paper is for the building industry to develop a national consensus whole-wall thermal performance-rating label. This will establish in the marketplace a more realistic energy savings indicator for consumers (builders, home owners...) faced with the decision of what wall system to select for their building.

A nationally accepted wall evaluation procedure will provide consumers with experimentally based information with which to determine the thermal performance differences between common dimensional lumber systems, which historically represent about 90% of the market (HUD 1993), and alternatives. At least one of the alternative systems (metal frame) anticipates attaining 25% of the residential wall market by the year 1997 (Nisson 1994, Dennis 1995).

A number of innovative wall systems offer advantages that will continue to gain acceptance for the systems as the cost of dimensional lumber rises, framing lumber quality continues to decline, availability fluctuates, and consumers' confusion about the environmental correctness of harvesting "old growth" wood as a building material remains. One constraint to greater acceptance of advanced walls is that there is no nationally accepted method of comparing the whole-wall thermal performance of different systems to each other and to wood-frame construction. Industries that are interested in establishing this uniform rating procedure are steel frame, insulating concrete forms, low-density concrete block, structural insulated core panels, straw bale, engineered wood wall framing, concrete block with insulated cores, and hybrid systems. Several thermal performance terms used throughout this paper are.

Center-of-Cavity R-value: R-value estimation at a point in the wall's cross-sectional R-value containing the most insulation.

Clear wall R-value: R-value estimation for the exterior wall area containing only insulation and necessary framing materials for a clear section with no fenestrations, corners, or connections between other envelope elements such as roofs, foundations, and other walls.

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, window sill, door jam, door header, and window jamb, that make up a representative residential whole-wall elevation.

Whole-wall R-value: R-value estimation for the whole opaque wall including the thermal performance of not only the "clear wall" area, with insulation and structural elements, but also typical envelope interface details, including wall/wall (corners), wall /roof, wall/floor, wall/door, and wall/window connections.

The most commonly used calculation procedures for conventional residential wood-frame construction tend to overestimate the actual field thermal performance of many of today's popular housing designs, which feature large fenestration areas and floor plans with many exterior wall corners. This leads to the need for a thermal performance indicator to represent the whole wood-frame wall including thermal shorts created at wall interfaces with other envelope components. For this procedure to gain popular acceptance it must be accurate yet simple enough to be understood by home buyers and builders, and permit thermal performance comparisons of alternative wall systems to wood frame walls.

Currently, in the typical thermal evaluation of wood-frame wall systems, the wood framing effect (percentage reduction of clear wall area R-value from that estimated at the center of cavity) is handled by conducting a simple parallel-path calculation for the cavity and stud area. The area ratio between framing and cavity is almost always suggested by an authoritative source, such as the latest ASHRAE Handbook--*Fundamentals* (ASHRAE 1993a). Then the resulting whole-wall thermal transmittance is compared to the desired value prescribed by either an enforced building energy code, volunteer home energy rating program, or standard. Sometimes only the center-of-cavity insulation material R-value is used for comparison to alternatives. With today's residential buildings increasingly constructed with materials such as metal, stress skin-insulated core panels, and novel composites, a more accurate rating is necessary. Opaque envelopes can no longer be compared by frequently misleading "center-of-cavity" insulation material or clear wall R-values. The development of more accurate, consumer-understandable wall labels will spur greater market acceptance of energy-efficient envelope systems.

The benefit of advanced systems with only a few thermal shorts will be clearly discernible by comparing whole-wall thermal performance ratings. The effect of extensive thermal shorts on performance is not accurately reflected in commonly used simplified energy calculations that are the current bases for consumer wall thermal comparisons.

Major energy-consuming appliances and windows now have labels that tell consumers the energy cost implications of their purchase. However, when it comes to the walls, a dominant architectural feature of buildings, the consumer, along with designers, builders, and manufacturers, is uncertain at the least and misled at the worst about the energy implications of opaque wall systems. In addition to more representative R-values, opaque wall labels also have the potential to identify the impact of thermal mass, air tightness, and moisture tolerance (inherent moisture control attributes that minimize the potential for moisture problems).

Introduction

Currently the market place is not fully accounting for the thermal shorts that exist in building walls. This results in the consumer not realizing the full energy cost savings anticipated by complying with energy codes and standards or meeting requirements of home energy rating systems. With the improvement in window efficiency, the potential exists for residential structures to have more windows. When more windows are installed in a building, more framing is needed. The greater the framing factor, the higher the overall thermal transmittance of the opaque wall. With metal-frame construction gaining popularity in residential construction, the thermal shorts potentially resulting from the relatively higher thermal conductivity of metal compared to wood can mean much more severe heat loss than can be accounted for by traditional simplified calculations.

Why are the effects of interface details important? First of all, they are needed to properly baseline the thermal performance of common residential wood-framing systems and to more comprehensively evaluate alternatives. Second, their inclusion creates incentives for alternative wall system manufacturers to focus on the whole-wall, including the critical connections to other parts of the building, not just the "clear wall." Interface details make a difference. The consequences of poorly selected connections between envelope components are severe. Taking into account the interface details can have an impact on as much as 50% of the overall wall area. For some conventional wall systems, the whole-wall R-value can be as much as 40% less than what is measured for the clear wall section. This procedure highlights the importance of using interface details that minimize thermal shorts. Local heat loss through some wall interface details may be twice that estimated by simplified design calculation procedures that focus only on the clear wall. Poor interface details also may 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 propagation of molds and mildews, which can lead to poor indoor air quality.

The whole-wall steady-state R-value is the first element of four that are needed to compare whole- wall performance. The other three elements are the thermal mass benefits for some systems all four of the factors are important; for others only the first is relevant. A fifth factor growing in importance is sustainability.

The individual wall system results from this procedure will help gain system-specific acceptance by code officials, building energy-rating programs such as HERS Home Energy Rating System and EPA Energy Star Buildings, building designers, and builders. In addition, each individual system evaluation will contribute toward a larger effort to build an easily accessible database of advanced wall systems. A user-friendly computer-accessed database is under development that could be used by the public to make whole-wall thermal performance comparisons. This database eventually encompass all the critical wall performance elements. The package is being developed for access on the Internet (http://www.ornl.gov/sci/roofs+walls/whole_wall/wallsys.html). Features of the package will include:

An easily accessible archive of experimental results for all tested wall systems, including downloadable drawings.

A database of material thermal properties.

An easy-to-use interface to a computer-generated database that allows the determination of the whole-wall thermal performance rating for a wide variety of building envelope systems and user specified wall elevations.

It has been demonstrated that the first element, whole-wall R-value can be determined for residential wall systems using a computer model (Childs 1993). More than 40 types of building wall systems already have been analyzed by this method (Kosny and Desjarlais 1994; Kosny and Christian 1995a; Kosny 1994). This approach requires expertise in three-dimensional, finite-difference heat transfer modeling that is beyond the level normally available in residential building design and construction offices. Therefore, the preferred approach for making this procedure available is a user-friendly interface to a three-dimensional computer model database that incorporates this methodology for determining a whole-wall R-value for residential buildings. The interface allows users to define the building envelope in terms familiar to the industry rather than in the more complex three-dimensional analytical models. This database retrieval tool builds upon specific experimental hotbox results, allowing easy modification for particular details and computation of the whole-wall rating for the specific system. The user of this program will see the effect of interface detail improvements and be able to use them in envelope system design-cost optimization. This evaluation procedure is based on not only a computer model, but also a synthesis of experimental measurements and validated computer simulation, significantly strengthening its accuracy and building market acceptance potential.

The first two performance elements involve 1.) Testing full-scale walls under steady state and dynamic hotbox conditions, 2.) Three-dimensional finite-difference computer modeling, and 3) Thermal analysis of alternative interface details. Hotbox wall tests are used to validate and calibrate three-dimensional computer simulations. A steady-state whole-wall R-value is derived for each system. To account for thermal mass benefits, if any, customized tables and figures are generated. This information may be needed to demonstrate compliance or to modify the Council of American Building Officials' Model Energy Code (MEC) (CABO 1995) and ASHRAE/BSR Standard 90.2-1993 (ASHRAE 1993b).

PROCEDURES TO EVALUATE WALL PERFORMANCE

Whole Wall R-value

A calculation procedure and ASTM C236 or ASTM C 976 (ASTM 1989) test are proposed as a starting point for a consensus methodology for estimating whole-wall R-value, independent of construction type. A clear wall section, 8 ft by 8 ft (2.4m x 2.4m), is tested in a guarded hot box. Experimental results are compared with three-dimensional heat conduction model predictions, based on finite-difference methods. The comparison leads to a calibrated model. After the model of the test wall is calibrated, simulations are made of the "clear wall" area with insulation and structural elements and eight wall interface details: corner, wall/roof, wall/foundation, window header, window sill, door jamb, door header, and window jamb which 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 and compared with simplified calculation procedures and results from other wall systems. A reference wall elevation is defined by the user to weigh the impacts 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, door jamb, window jamb, window sill, and door header) must be available to the user. The detail descriptions should include drawings, with all physical dimensions, and thermal property data for all material components contained in the details. If critical material component thermal conductivities are not available, it may be desirable to measure individual material conductivities, particularly if the clear wall hotbox data do not agree with the computer-model predictions.

Although not necessary for every wall system, calibration of the model by hotbox measurement of clear wall test section families enhances credibility. The clear wall comparison of the experimental measurements and the model predictions minimizes the likelihood of systemic modeling errors throughout the wall detail simulations. The procedure requires 1.) Building a test wall in a hotbox frame; 2.) Instrumenting the test wall; 3.) Testing at steady state conditions; 4.) Preparing a laboratory test data summary report, which includes a comparison to results of an un-calibrated model of the clear wall;. 5.) Calibrating the model with "clear wall" hotbox results. 6.) Modeling the eight details making up a typical residential wall elevation and determine the area of influence of each detail; 7.) Calculating whole-wall R-value; 8.) Conducting parametric thermal analysis to improve details and whole-wall R-value; 9.) Preparing a paper report and an electronic report for the advanced wall database.

Thermal Mass Benefit

Wall systems with significant thermal mass, have the potential to reduce building annual heating and cooling energy requirements, depending on the climate, below that required by standard wood-frame construction with similar steady-state R-value. A procedure has been developed to measure and generate metrics that reflect this thermal mass benefit by providing an MEC-formatted table (Christian 1991). The procedure is as follows:

1. Conduct a dynamic hotbox test to determine dynamic response factors.
2. Run the three-dimensional model and compare it to dynamic hotbox test results from Step 1 and generate response factors.
3. Run an "equivalent wall " program, which generates a simplified uniform layer wall that has the same dynamic thermal behavior as the actual complex wall tested in step 1. This task will generate a list of thermo physical properties for each uniform layer (R-value, thermal capacitance and thickness).
4. Compare response factors for the three-dimensional wall generated in step 2 to the response factors of the simplified, one-dimensional wall generated in step 3. If there is an acceptable match, a set of envelope system thermo physical properties that can be used directly in whole-building simulation models is now available to define the energy-savings benefits of the thermal mass in different climates and building types compared to standard wood-frame walls.
5. A whole-building simulation program such as DOE2 will be run for the "equivalent wall" and standard code-compliant wood-frame wall on a standard building in six U.S. Climates. The mass effect will be determined by comparing the annual energy consumption from a standard house (using the "equivalent wall") to that resulting from the identical house with wood-frame walls.
6. A report is prepared containing (a) a set of uniform-layer thermo physical properties for use in whole building simulation and (b) code-compliance tables and figures: Council of American Building Officials (CABO) MEC thermal transmittance tables for this specific wall system will be derived using the hot-box-validated measurements described above. The same procedure will be used to develop the generic tables found in the MEC for all thermal mass walls with more than 6.0 Btu/ ft (19/W/m^2) of wall thermal capacitance (CABO 1995). This customized table can be used to show code officials' compliance with the prescriptive Uw requirements in the MEC that are based

on wood-frame constructions. Finally, a figure compliant with ASHRAE Standard 90.2, customized to replace the applicable figure in the prescriptive portion of this code will be developed.

Air tightness

A combination of ASTM Standards (C236 or C976 [ASTM 1989]) or E1424 and E283 (ASTM 1995) will be used to measure the air leakage and heat loss through wall assemblies under simulated wind conditions ranging from 0 to 15 mph (24 kph). Varying the differential pressures from 0 to 25-50 Pa should simulate the extremes to which a wall is exposed in a real building. However, because many of the leakage paths through an exterior wall of a residential building occur at the wall connections and not through the typical clear wall, which comprises the 8-ft by 8-ft (2.4-m x 2.4-m) test section, the test specimen will be modified to contain one light switch and one duplex outlet connected with 14-gauge wiring and possibly other details. With heat loss in a building reaching as high as 40% due to infiltration (NAIMA 1994), including this performance parameter would be important, but the workmanship quality on the construction site compared to a laboratory specimen must be considered. A second complicating factor is that, over time, materials may shrink, crack, etc., and this will change the leakage over time. We will never completely predict the impact of all variables on the energy loss of buildings (e.g., workmanship). What is important is to establish a uniform baseline for all wall systems.

Moisture Tolerance

The wall moisture behavior, like the benefit of thermal mass, is a function of climate and building operation. The likelihood of annual moisture accumulation due to vapor diffusion of a particular wall system can be estimated by computer simulation. Moisture accumulation due to airflow into the wall is more difficult. One important feature to have in a long- lasting wall assembly is the ability for the wall to dry itself out if it should be built wet or pick up moisture due to a leak in the course of its in-service life. The drying rate can be modeled and measured in the laboratory. The potential for moisture accumulation (an undesirable characteristic) over specific full annual climatic cycles also can be modeled by heat and mass transfer codes such as MOIST and MATCH (Desjarlais et al. 1994).

Examples of Whole Wall R-values

Eighteen system whole-wall R-values have been estimated by a finite-difference computer model (Childs 1993). For all eighteen of the systems, the procedure described above for calculating whole-wall R-value has been followed. The model used is a generalized three-dimensional heat conduction code to analyze building envelopes (Childs 1993).

The accuracy of the modeling was validated using 28 test results of masonry, wood-frame, and metal stud walls (Kosny and Christian 1995b). Considering that the precision of the guarded hot box is reported to be approximately 8% (ASTM C236 [ASTM 1989]), the ability of the model to reproduce the experimental data was found to be within the accuracy of the test method.

The rotatable guarded hot box (RGHB) is an envelope testing apparatus that is designed in accordance with ASTM C 236 (ASTM 1989). The RGHB accepts test specimens that are up to 13 ft by 10 ft (4m x 3m) with a metering chamber that is approximately 8 ft by 8 ft (2.4m x 2.4m). The RGHB can accommodate assemblies up to 24 in. (61 cm) thick, (2) and b used to conduct dynamic guarded hotbox tests on high-thermal mass wall systems.

The RGHB climate chamber temperature can be controlled from -10F to 140F (-23C to 60C) and the air velocity from 0 mph to 15 mph (24 kph). The RGHB metering chamber temperature can be controlled from 70F to 140F (21C to 60C) and air velocity from 0 to 1 mph (1.6 kph). The instrumentation inventory available consists of 200 type-T thermocouple-temperature sensors, 10 thermopile-type heat flux transducers, two air velocity meters, two pressure transducers, and eight other voltage output-type sensors. The test apparatus is fully automated: the chamber temperatures and air velocities are computer controlled at steady conditions or in 200-step cycles. Data collection and processing are performed in real time. The system was designed for a precision of better than 3% and a bias of less than 5%. Estimates of the error bands are generated with all test results.

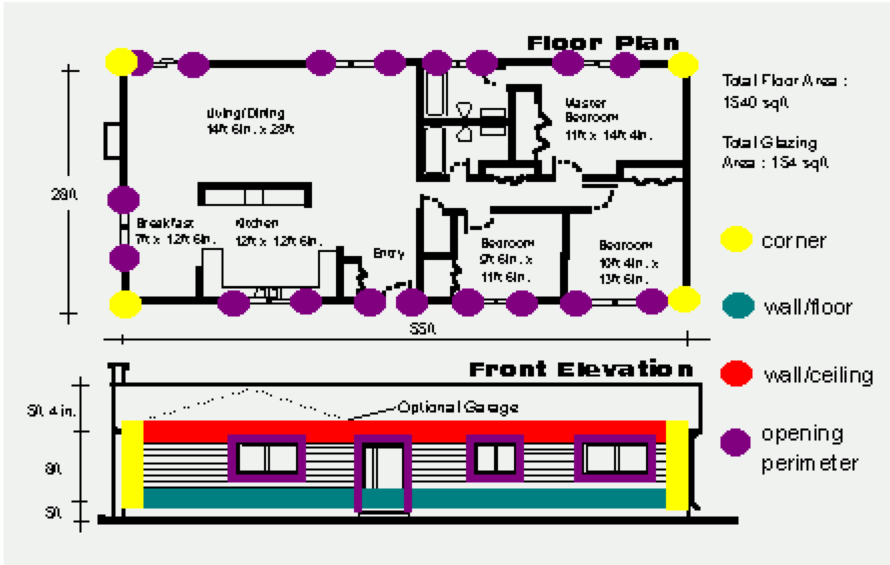

Figure 1: Floor plan and elevation for a one-story ranch house

The whole-wall R-value was estimated for 18 wall systems listed in Table 1 along with the clear whole wall R-value. A reference building show in Fig. 1 was used to establish the location and area weighing of all the interface details. The comparison of these two values gives one a good overall perspective of the importance of wall interface details for both conventional wood, metal, masonry, and several high-performance wall systems. Frequently, the opaque wall thermal performance is simply described at the point of sale as the "clear wall" value. This means that the whole-wall R-value could be overstated from -3.3% to 26.5%, as shown by the last column in Table 1 "(R_{ww}/R_{cw}) x 100%." Recognize that these differences can change by selecting different interface details with varying degrees of thermal shorts.

Interesting comparisons can be made using the data in Table 1 to illustrate the importance of using a whole-wall R-value (R_{ww}) to select the most energy-efficient wall system. The difference between the clear wall and whole-wall R-value could be argued to be representative of the energy-savings potential of adopting the rating procedure proposed in this paper. With most building owners assuming they have the higher clear wall value rather than the more representative of reality, whole R-value.

Systems 5 and 6 show two different high-performance masonry units. If one uses the clear-wall R-value to choose the one with highest R-value one would pick system 5, the low- density concrete multicore insulation unit, because its R-value is 19.2hft^{2}F/Btu (3.38 m^{2}K/W) compared to 15.22 hft^{2}F/Btu (2.68 m^{2}K/W) for system 6, EPS block-forms. However, if one uses the whole-wall R-value as the criterion for choosing the most efficient system, one would choose just the opposite because system 6 has the higher value [15.72 hft^2F/Btu .77 m^2K/W)] compared to 14.69 hft^2F/Btu (2.59 m^2K/W). Another observation is that the whole-wall R-value of the foam-form system actually is higher than the clear wall values 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 impact the whole-wall R-value more for 2x6 walls than for 2x4 walls. The ratio of R_{ww}/R_{cw} is about 90% for the 2x4 walls and 84% for the 2x6 wall.

Comparing System 11, the 6-in (15 cm) stress-skin-panel wall, to system 9, the conventional 2x6 wood-frame wall, shows that the stress-skin-panel clear-wall R-value [25 hft^2F/Btu, (4.35 m^2K/W)] is 51% higher than that of the 2x6 wall [16 hft2F/Btu, (2.88m^2K/W)]. **When details are included in the whole-wall R-value, the percentage improvement is even greater (-58%),** 21.59 hft^2F/Btu (3.8m^2K/W) to 13.69 hft^2F/Btu (2.41m^2K/W). This is an example of how advanced systems will generally benefit from a performance criteria that reflects whole-wall rather than the commonly used simplified clear-wall values.

Systems 12 through 18 listed in Table 1 are all metal. On average, the whole-wall R-value for these seven systems is 22% less than the clear-wall values. 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 when the whole-wall R-value is used as the reference compared to all other systems displayed in Table 1. For example, if one is considering either system 6 (EPS block forms) or System 12 (a 4 in. metal stud wall), the clear-wall R-value is about the same, 15 hft^2F/Btu (2.64 m^2K/W); however, if the comparison is made using the whole-wall R-value, the EPS foam-block system has a 45% higher value, 15.72 hft^2F/Btu (2.77 m^2K/W) to 10.86 hft^2F/Btu (1.91 m^2K/W).

A detailed example showing all the details for the metal frame system 15 can be found in the proceedings of the December 1995 ASHRAE Envelopes VI conference.21 In general, ASHRAE Handbook material properties and recommended details by the wall system manufacturer were selected. In the case of the metal frame systems, the details come from the American Iron and Steel Institute[17] and other common sources[18, 19].

Table 1 Whole wall R-value database

No	System description:	Clear wall R-value		Whole wall R-value		(R_{ww}/R_{cw}) x 100%
		hft²F/Btu	m²K/W	hft²F/Btu	m²K/W	
1.	12-in. (30-cm.) Two-core insul. units - concrete 120lb/ft³ (1920 kg/m³), EPS inserts - 1-7/8-in. (4.8-cm.) thick, grout fillings 24-in.(60-cm.) o.c.	3.7	0.64	3.6	0.63	97.3
2.	12-in. (30-cm.) Two-core insul units -wood concrete 40lb/ft³ (640 kg/m³), EPS inserts - 1-7/8-in. (4.8-cm.) thick, grout fillings 24-in.(60-cm.) o.c.	9.4	1.65	8.6	1.52	91.7
3.	12-in. (30-cm.) Cut-web insul. units - concrete 120lb/ft³ (1920 kg/m³), EPS inserts - 2-1/2-in. (6.4-cm.) thick, grout fillings 16-in.(40-cm.) o.c.	4.7	0.82	4.1	0.73	88.2
Updated	8” two-core concrete masonry blocks. Refer to Whole-wall thermal performance calculator web address at top of report	1.6		1.8		
Updated	10” CIF with 4” EPS. Refer to Updated ORNL Report	12.0		10.3		
Updated	5.5” Tilt-up Concrete w/o insulation. Refer to Updated ORNL Report			0.6		
4.	12-in. (30-cm.) Cut-web insul. units -wood concrete 40lb/ft³ (640 kg/m³), EPS inserts - 2-1/2-in. (6.4-cm.) thick, grout fillings 16-in.(40-cm.) o.c.	10.7	1.88	9.2	1.61	85.6

5.	12-in. (30-cm.) Multicore insul. units - polystyrene beads concrete 30lb/ft3 (480 kg/m3), EPS inserts in all cores.	19.2	3.38	14.7	2.59	76.6
6.	EPS block-forms poured in place with concrete, block walls 1-7/8-in. (4.8-cm.) thick.	15.2	2.68	15.7	2.77	103.3
7.	2x4 wood stud wall 16-in.(40-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior., -in.(1.3-cm.) gypsum board -interior..	10.6	1.86	9.6	1.69	90.9
8.	2x4 wood stud wall 24-in.(60-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior., -in.(1.3-cm.) gypsum board -interior..	10.8	1.91	9.9	1.74	91.2
9.	2x6 wood stud wall 24-in.(60-cm.) o.c., R-19 batts, -in.(1.3-cm.) plywood -exterior., -in.(1.3-cm.) gypsum board -interior..	16.4	2.88	13.7	2.41	83.7
10.	Larsen Truss walls - 2x4 wood stud wall 16-in.(40-cm.) o.c., R-11 batts, + 8-in.(20-c) thick Larsen trusses insulated by 8-in.(20-cm.) thick batts, -in.(1.3-cm.) plywood -exterior., -in.(1.3-cm.) gypsum board -interior..	40.4	7.12	38.5	6.78	95.3
11.	Stress Skin Panel Wall, 6-in. (15-cm.) thick foam core + -in. (1.3-cm.) OSB boards, -in.(1.3-cm.) plywood -exterior., -in.(1.3-cm.) gypsum board -interior..	24.7	4.35	21.6	3.80	87.5
12.	4-in. (10-cm.) Metal stud wall, 24-in. (60-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior., + 1-in.(2.5-cm) EPS sheathing + -in. (1.3-cm.) wood siding, -in.(1.3-cm.) gypsum board -interior. NAHB Energy Consv. House Details.	14.8	2.60	10.9	1.91	73.5
13.	3-1/2-in. (8.9-cm.) Metal stud wall, 16-in. (40-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior.,. + -in. (1.3-cm.) wood siding, -in.(1.3-cm.) gypsum board -interior	7.4	1.31	6.1	1.08	82.6
14.	3-1/2-in. (8.9-cm.) Metal stud wall, 16-in. (40-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior.,+ -in.(1.3-cm) EPS sheathing + -in. (1.3-cm.) wood siding, -in.(1.3-cm.) gypsum board -interior. AISI	9.9	1.74	8.0	1.42	81.3

	Manual Details.					
15.	3-1/2-in. (8.9-cm.) Metal stud wall, 16-in. (40-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior.,+ 1-in.(2.5-cm) EPS sheathing + -in. (1.3-cm.) wood siding, -in.(1.3-cm.) gypsum board -interior. AISI Manual Details.	11.8	2.07	9.5	1.67	80.5
16.	3-1/2-in. (8.9-cm.) Metal stud wall, 24-in. (60-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior.,+ -in. (1.3-cm.) wood siding, -in.(1.3-cm.) gypsum board -interior. AISI Manual Details.	9.4	1.66	7.1	1.24	74.8
17.	3-1/2-in. (8.9-cm.) Metal stud wall, 24-in. (60-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior., + -in.(1.3-cm) EPS sheathing + -in. (1.3-cm.) wood siding, -in.(1.3-cm.) gypsum board -interior. AISI Manual Details.	11.8	2.08	8.9	1.57	75.6
18.	3-1/2-in. (8.9-cm.) Metal stud wall, 24-in. (60-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior., + 1-in.(2.5-cm) EPS sheathing + -in. (1.3-cm.) wood siding, -in.(1.3-cm.) gypsum board -interior. AISI Manual Details.	13.3	2.35	10.2	1.80	76.5

Table 2 shows a comparison of the center-of-cavity R-values instead of the clear wall R-values. This suggests that when the realtor responds to a potential homebuyer by stating the R-value of insulation across the cavity, the whole-wall R-value actually may be overstated by 26.6 to 58.1%. If one is comparing the thermal performance differences between metal (system 13) and wood (system 7) frames using center-of-cavity R-values, one would conclude there is no difference because both have center-of-cavity R-values of about 14 hft^2F/Btu, (2.5 m^2K/W). However, when the whole-wall R-value is used as the criterion for comparison, the 2x4 wood wall system is 56% better [9.58 hft^2F/Btu (1.69 m^2K/W)], compared to 6.14 hft^2F/Btu (1.08 m^2K/W) for the metal system.

These comparisons are not meant to imply 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 intent of making these sample comparisons is simply to point out the importance of having the whole-wall R-value available in the marketplace for guiding wall designers, manufacturers, and buyers to more energy-efficient systems.

Table 2 Whole wall R-value compared to In-cavity R-value.

No	System description:	In-cavity R-value		Whole wall R-value		(R_{ww}/R_{cav}) x 100%
		hft^2F/Btu	m^2K/W	hft^2F/Btu	m^2K/W	
7.	2x4 wood stud wall 16-in.(40-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior., -in.(1.3-cm.) gypsum board -interior..	13.6	2.40	9.6	1.69	70.2
8.	2x4 wood stud wall 24-in.(60-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior., -in.(1.3-cm.) gypsum board -interior..	13.6	2.40	9.9	1.74	73.4
12.	4-in. (10-cm.) Metal stud wall, 24-in. (60-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior., + 1-in.(2.5-cm) EPS sheathing + -in. (1.3-cm.) wood siding, -in.(1.3-cm.) gypsum board -interior. NAHB Energy Consv. House Details.	19.6	3.46	10.9	1.91	55.3
13.	3-1/2-in. (8.9-cm.) Metal stud wall, 16-in. (40-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior.,. + -in. (1.3-cm.) wood siding, -in.(1.3-cm.) gypsum board -interior. AISI Manual Details.	14.6	2.58	6.1	1.08	41.9
15.	3-1/2-in. (8.9-cm.) Metal stud wall, 16-in. (40-cm.) o.c., R-11 batts, -in.(1.3-cm.) plywood -exterior.,+ 1-in.(2.5-cm) EPS sheathing + -in. (1.3-cm.) wood siding, -in.(1.3-cm.) gypsum board -interior. AISI Manual Details.	18.6	3.28	9.5	1.67	50.8

Conclusion

A new procedure is proposed for comparing the thermal performance differences between diverse types of wall systems. This procedure will ultimately will include four elements: whole-wall R-value, thermal mass benefits, air tightness, and moisture tolerance. The whole-wall R-value procedure described in this report should be considered for adoption in the ASHRAE Standard 90.2 (ASHRAE 1993b), MEC (CABO (1995), and HERS (Home Energy Rating System) (DOE 1995). In addition, many of the code compliance documents that are available to show builders how to comply with applicable codes, standards and energy-efficiency incentive programs would benefit by using this whole-wall R-value comparison procedure. The database of advanced wall systems is being assembled on the Internet, (http://www.cad.ornl.gov/kch/demo.html).

The whole-wall R-value is a better criterion than the center-of-wall and much better than the center-of-cavity R-value methods used to compare most types of wall systems. The value includes the effect of the wall interface details used to connect the wall to other walls, windows, doors, ceilings and foundations.

For builders and building owners to appreciate the added thermal benefits of many of the alternatives to conventional wood-frame wall construction, it is necessary to use a whole-wall R-value. The market focus on clear-wall or even worse center-of-cavity R-value, is misleading and inhibiting the market penetration of high-performance wall systems into the residential construction industry. The use of a whole-wall R-value could guide decision makers to select wall systems that have whole-wall R-values 25%-50% higher than for wall systems that have significant thermal shorting (high misleading center-of-cavity and clear-wall R-values compared to whole-wall R-value).

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Building Envelope Research

Oak Ridge National Laboratory

For more information, contact the program manager for Building Envelope Research:

Andre O. Desjarlais

Oak Ridge National Laboratory

P. O. Box 2008, MS 6070

Oak Ridge, TN 37831-6070

Voice (423)574-0022; Fax (423) 574-9338

E-mail desjarlaisa@ornl.gov

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