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THERMAL PERFORMANCE OF STEEL-FRAMED WALLS

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FINAL REPORT

Thermal Performance of Steel-Framed Walls

Prepared for

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EXECUTIVE SUMMARY

In wall construction, highly conductive members spaced along the wall, which allow higher heat transfer than that through less conductive areas, are referred to as thermal bridges. Thermal bridges in walls tend to increase heat loss and, under certain adverse conditions, can cause dust streaking ("ghosting") on interior walls over studs due to temperature differentials, as well as condensation in and on walls. Although such adverse conditions can be easily avoided by proper thermal design of wall systems, these effects have not been well understood and thermal data has been lacking. Therefore, the present study was initiated to provide (1) a better understanding of the thermal behavior of steel-framed walls, (2) a set of R-values for typical wall constructions, and (3) information that could be used to develop improved methods of predicting R-values. An improved method for estimating R-value would allow an equitable comparison of thermal performance with other construction types and materials. This would increase the number of alternative materials for walls available to designers, thus allowing them the freedom to correctly choose the optimum choice for construction. In order to arrive at an improved method, experimental data on the heat transfer characteristics of steel-framed walls was collected.

Twenty-three wall samples were tested in a calibrated hot box [ASTM C976] to measure the thermal performance of steel-framed wall systems. The tests included an array of stud frame configurations, exterior sheathing and fiberglass batt insulations. Other studies of the thermal bridging in steel-framed walls have not included the use of insulating sheathing, which reduces the extent of the thermal bridges and improves total thermal performance. The purpose of the project was to provide measured R-values for commonly used steel-framed wall configurations and to improve R-value estimating methods. Also, detailed monitoring of temperature gradients in the test walls combined with numerical analysis provided new insights into heat transfer phenomenon concerning thermal bridges.

Test results were compared to R-value estimates using the parallel path method, the isothermal planes method and the ASHRAE Zone method. The comparison showed that the known procedures do not fully account for the three-dimensional effects created by steel framing in a wall, often underestimating the wall's R-value when insulating sheathing is used. Test results showed the use of insulating sheathing increased the wall R-value by a greater amount than that expected based solely on the sheathing R-value. This suggests that the use of insulating sheathing mitigates the effects of thermal bridges, including heat loss, dust streaking on the studs, and condensation. A method for accurately predicting the thermal performance of residential steel-framed walls was developed using zone factors created by Oak Ridge National Laboratories with the ASHRAE Zone method. Alternately, a simplified graph was developed from which the R-value can be read directly for common types of wall construction.

INTRODUCTION

Light gage steel framing is enjoying increased attention throughout the United States as the cost of lumber continues to rise. However, some barriers to widespread acceptance by builders still exist, particularly where technical data is sparse. One such problem deals with the thermal performance of steel framing in walls. Steel members in wall construction form a thermal bridge that interrupts the insulation layer of a wall. This causes a higher rate of heat transfer by conduction through the wall framing than through other parts of the wall. One method to reduce the thermal bridging effect is to provide a break, such as insulating sheathing. To evaluate the effectiveness of this approach, a series of tests on steel-framed wall assemblies, both with and without insulating sheathing, were conducted for this project.

The results of the project provide insights into methods of reducing the effects of thermal bridges, and should encourage the design of systems to mitigate the effects of thermal bridges in building envelopes. A method for accurately predicting the thermal performance of residential steel-framed walls was developed using zone factors created by Oak Ridge National Laboratories (ORNL) with the ASHRAE Zone method [1]. The development of alternative steel systems should increase the pool of building materials, potentially decrease the cost of construction, and provide more versatility for engineers and designers.

Purpose

Previous work in this area has produced very little empirical data on the thermal performance of steel-framed walls. Available data is inconsistent since it was obtained by different researchers, using various measurement methods, under diverse conditions [2,3,4,5]. Furthermore, most computer modeled effects of steel framing have not been validated by actual test results, and therefore cannot be used to make generalizations for a calculating method. None of this data is sufficient for derivation of a calculation method to predict the R-value of a wall containing steel framing. Finally, current calculation methods may not properly account for the effects of insulating sheathing, which is typically recommended for providing a thermal break from the exterior. Currently, the effects of steel framing are often misunderstood by engineers, builders, and manufacturers of construction products due to the above mentioned reasons. Many code organizations do not list R-values for steel-framed walls with insulating sheathing, nor do they provide explicit and simple procedures to determine R-values for walls constructed differently from those specified in codes. The creation of an accurate method for estimating R-values would allow comparison with other construction types, and lead to the selection of the most cost-effective solution. The intent of this project is to provide a simple yet accurate approach to the collection of data and to use the resultant data to produce a simple calculation procedure for predicting R-values of walls with steel framing.

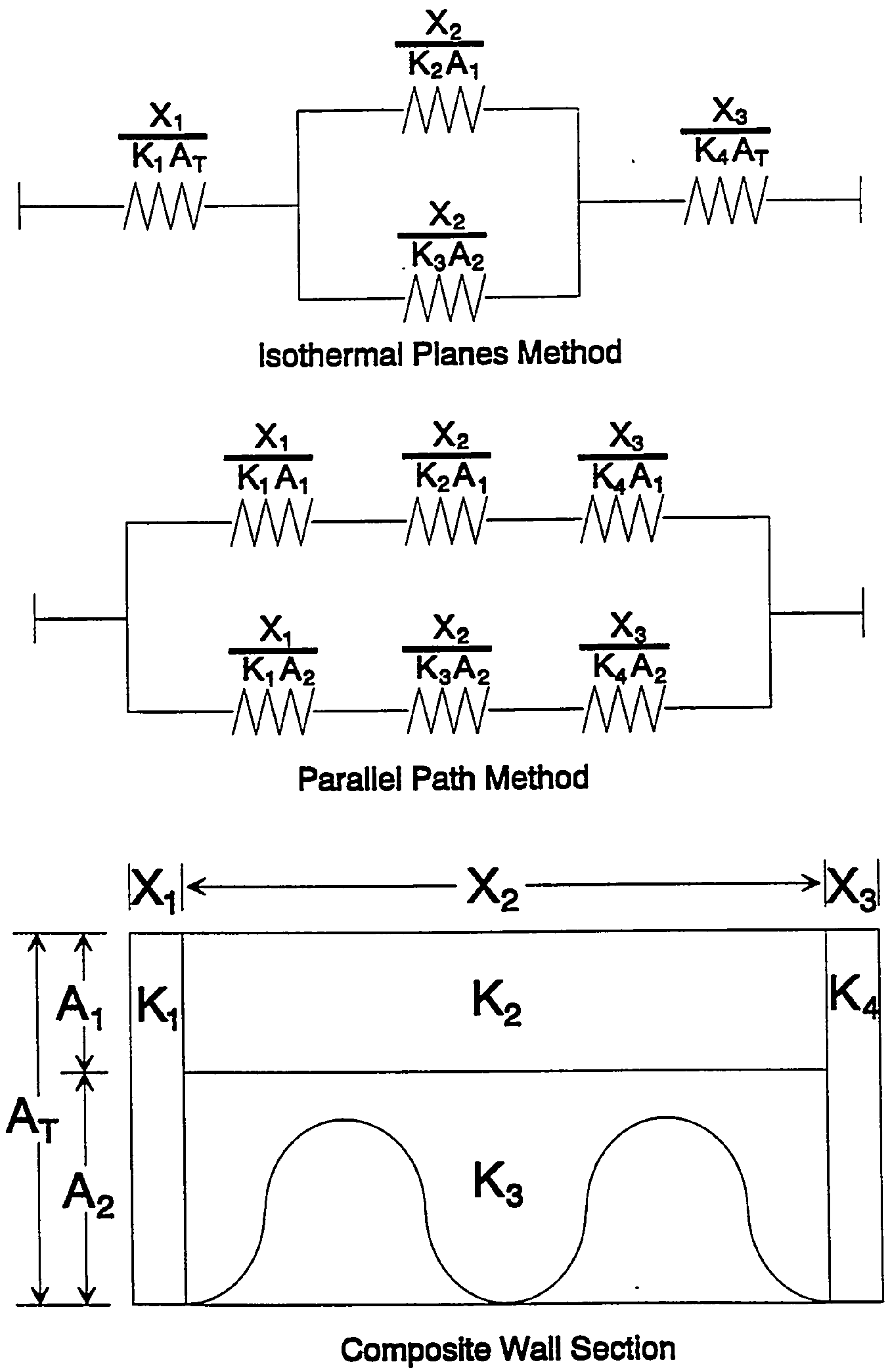
Three considerations should be addressed in an evaluation of the thermal performance of walls. The first is the determination of an R-value for the entire assembly (studs, cavity insulation, sheathing, etc.) so that energy use is predictable. The second is the potential for vapor condensation in the wall, and the third is the potential for "ghosting" or dust streaking on the interior wall opposite studs because of non-uniform interior surface temperature. This report focuses on the principal consideration, the determination of R-values for typical steel-framed wall assemblies, since the thermal conductivity of the wall often dictates the second and third considerations. The information developed provides a means to design steel-framed walls to achieve desired levels of thermal performance and avoid undesirable secondary effects.

BACKGROUND

Current Calculation Methods

Typical simple calculations for estimating the wall R-value, a property quantifying the resistance to heat flow, assume one-dimensional, steady-state heat transfer through the wall. For one-dimensional conduction in a homogeneous wall, temperature is a function of the x-coordinate only (transverse direction through the wall), and heat is transferred exclusively in this direction. For a plane wall using a single material, calculating the R-value is simple, but many walls being used today are composite walls using many materials to make up the wall. Non-homogeneous walls are often characterized by series-parallel configurations, such as those shown in Figure 1.

Figure 1
Equivalent Circuits for One-Dimensional Models



Although heat flow is two-dimensional for most areas and three-dimensional for some locations, it is often reasonably accurate to assume one-dimensional heat flow for simplification. Using this assumption, two different thermal circuits can be used to calculate the wall's R-value. The first configuration presumes that surfaces normal to the x-direction are isothermal, while the second assumes that surfaces parallel to the x-direction are adiabatic (no heat transfer occurring). Hence, these heat transfer methods are referred to as the isothermal planes method and the parallel path method.

For parallel path method calculations, a component wall can be divided into parallel heat flow paths of different conductances that extend from surface to surface. The heat flows through these paths are assumed to be independent of one another, and the thermal conductance for each path is calculated using a series relationship analogous to electrical resistance. The average resistance is found by multiplying the resistance of each path by the fraction of the total area over which the heat flow path acts.

An alternative to the parallel path method is to assume that heat can flow laterally in any component, which creates isothermal planes (isothermal planes method) parallel to the building surfaces. Resistances of adjacent components are combined in parallel, resulting in effective resistances acting in series. The thermal resistance equals the sum of these effective series. Typically, this number is smaller than that obtained using the parallel path method.

Even though these are theoretically equivalent circuits, differences in R-values obtained from the calculations will occur, and the differences will increase as the two dimensional effects of heat transfer within the wall become larger. With steel framing, the heat transfer in the y-direction (laterally in the plane of the wall normal to the x-direction) can be as significant as the heat transfer in the x-direction. As heat is transferred along the y-direction, the other materials of the non-homogeneous wall are exposed to different temperature distributions, thereby changing the heat transfer characteristics of the wall. However, the capacity of the adjacent facing materials to transmit heat to the metal is limited. Also, contact between materials limits heat transfer through contact resistance. Contact resistance is the change attributed to the temperature drop across the interface between materials, and for steel framing, can be a large factor. Most contact resistances between materials are small, but the contact resistances associated with steel framing members have a large effect on the heat transfer characteristics of the wall since in many cases, the area of metal in contact with other materials is a great deal larger than the thickness of the metal through the layer of insulation.

Both of the previous described methods assume the heat flow is perpendicular to the wall. However, if a thermal bridge, such as a steel framing member, is placed in the wall component next to a material with low thermal conductivity, then two-dimensional effects become significant at or near the thermal bridge. The ASHRAE Zone method is often used for this type of construction. It is a modification of the parallel path method. An area "weighing factor" is applied to the section of the wall with the thermal bridge, and this section is known as Zone A, the area affected by thermal bridge. The width of this zone is overstated compared to the one used in the usual parallel path calculation. The width is calculated from equation (1):

$$W = m + 2 \cdot d \tag{1}$$

where m = width of conductive element

d = distance from metal flange to wall surface

The equation is used to calculate W for each side of the wall. The larger value from this calculation is used for the width of Zone A. Zone B is the remaining area of the wall without the thermal bridge. An R-value is computed for each zone using the parallel path method. The two separate zone computations are then combined using a method similar to the isothermal planes method, and the average resistance over the entire wall area is calculated. An example of this method is located in the 1993 ASHRAE Handbook of Fundamentals, Chapter 22.

We have looked at one-dimensional numerical solutions for calculating the R-value of the composite wall. For steel framing, it frequently is necessary to account for multi-dimensional effects. One method that accounts for multi-dimensional effects is finite-difference computer solutions. In contrast to analytical solutions, which allow temperature determination at any point in the wall, the finite-difference solution allows for the determination of temperature only at discrete points. These points, or "nodes", are selected by dividing the wall into small control volumes and placing a node in the center. The node represents the average temperature of the control volume. From this selection, an appropriate energy conservation equation can be chosen for each of the nodes. The complete set of equations is then solved simultaneously for the temperature at each node. For residential steel-frame walls, the exact form of the energy conservation equation is given by:

$$(\delta^2 T/\delta x^2) + (\delta^2 T/\delta y^2) = 0 \qquad (2)$$

where T = temperature

x, y = locations, vertical and horizontal in the wall

This can be expressed as a finite-difference equation which can be solved using the method of successive overrelaxation. This is an extremely popular iterative technique to solve a system of equations, particularly those dealing with heat transfer in a wall. The temperature for each node is calculated successively until the previous temperature and the current temperature are within an acceptable range for the temperatures, or

$$\text{ABS}\ (T_{now} - T_{previous}) \leq \alpha \qquad (3)$$

where α is the uncertainty in the temperature that is considered to be acceptable. These equations are then solved using a computer, and an approximation of the actual temperature field is obtained. From these temperature fields, the total heat into the wall is known, along with the temperatures at the boundary conditions and an R-value for the entire wall section is estimated.

TESTING

John Goodrow, Holometrix, Inc.

The tests were conducted by Holometrix, Inc., located in Bedford, MA [13]. The Holometrix hot box facility is an ASTM C976 Calibrated Hot Box designed for both window and wall testing. Holometrix is accredited by National Voluntary Lab Accreditation Program (NVLAP) and National Fenestration Rating Council (NFRC). The hot box is capable of testing an 8' wide by 9' high wall. The Holometrix hot box consists of a meter chamber, climatic chamber, and a divider wall/sample holder separating the two chambers. The climatic chamber can be controlled between -10°F and +50°F. The meter chamber can be controlled between 60°F and 130°F. The box is capable of providing either parallel or perpendicular wind with wind speeds up to 15 miles per hour on the climatic chamber side. The meter chamber uses low air velocities that simulate the natural convection conditions that occur inside buildings. Temperatures were measured with Type-T copper-constant thermocouples. The facility is also capable of measuring the air leakage characteristics of a wall as installed in the facility. During a test, a tracer gas system is used to ensure that the wall is adequately sealed against air infiltration.

Before initiation of the testing program, a homogeneous wall of known R-value was run in the test facility. This wall was constructed of a 4" thick expanded polystyrene foam faced with 1/8" thick wood facers on both sides. Conductance measurements done per American Society of Testing and Materials (ASTM) Test Method C518 in a National Institute of Standards and Technology (NIST) traceable heat flow meter were compared with the conductance measurements done in the hot box at the beginning of the test program. The "tested" R-value differed from the "known" R-value by less than 1 percent.

Also, as part of the facility calibration, random individual thermocouples were calibrated by comparing their outputs to an ice reference and an NIST traceable thermometer. The differences seen were well within the manufacturer's stated accuracy for the thermocouples (±1.8 F). Actual differences were less than ±0.5 F.

Sample Descriptions

For the tests, a series of 8' by 8' walls were constructed that represented typical steel-frame construction. The materials used in building the walls are discussed below:

- Steel studs used were C-shaped members with thicknesses of 0.033" or 0.043" in three different sizes: 3 5/8" by 1 5/8", 6" by 1 5/8" and 3 5/8" by 2 1/2". Studs were spaced at 12" o.c., 24" o.c., and 48" o.c. and joined to top and bottom tracks using #6, type S-12, 5/16" pan head screws.

- Insulation used included R-11, R-13, R-15 and R-19 unfaced full width fiberglass batts. The insulation was carefully installed so that it was snug in the cavities and fit inside the stud channels.

- Exterior sheathings used included 1/2" plywood, extruded polystyrene foam (1/2", 1" and 2" thicknesses) and aluminum foil-faced polyisocyanurate foam (1" thickness). The plywood was attached to the studs using #6 bugle head screws. The insulative sheathings were attached using the same type of screws and 1 1/4" plastic washers on the cold side. Different screw lengths were chosen, depending on the sheathing thickness, so that the screw was 3/8" - 1/2" longer than the sheathing thickness.

- Each wall had 1/2" gypsum wall board over a 4 mil polyethylene vapor barrier installed on the warm side of the sample using #6 bugle head screws 1" long.

Before each test, the sample was sealed around the perimeter using tape and caulk. In addition, all holes in the exterior sheathing where screws were located were sealed as well as the joints between the individual pieces of sheathing. On the warm side, the gypsum board was sealed with paper joint tape and compound as is done in conventional construction. Each screw hole was similarly sealed along with the joint between the two sheets of gypsum board, and the sample was sealed to the frame using tape and caulk. These techniques served to minimize any air infiltration during the test. To confirm air leakage, a digital air flow meter was installed in a duct coming out of the metering chamber. If air flow was detected, the pressures on either side of the sample were balanced until the air flow was minimized.

The tests were conducted at 70°F warm side, 20°F cold side with no simulated wind except tests 1.A , Group A. Test A.3 was scheduled with 1/2" gypsum on the exterior but was eliminated during the tests to eliminate redundancy since the conductivity of gypsum and plywood samples were similar. The twenty three-different tests are described in detail below:

Group A

1 a. 1/2" Plywood sheathing
b. 3 5/8" C shaped studs (0.043" nominal thickness and 1 5/8" flange) 24" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

1.A Same as wall A.1 except that the wind speed on the cold side of the sample was 15 mph, perpendicular to the sample.

1.B Same as wall A.1, except that the mean temperature was 75°F (cold side = 50°F, warm side = 100°F)

2 a. 1" Extruded Polystyrene rigid insulative sheathing
b. 3 5/8" C-shaped studs (0.043" nominal thickness and 1 5/8" flange) 24" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

4 a. 1" Extruded Polystyrene rigid insulative sheathing installed over 1/2" Gypsum Board.
b. 3 5/8" C-shaped studs (0.043" nominal thickness and 1 5/8" flange) 24" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

5 a. 1/2" Extruded Polystyrene rigid insulative sheathing
b. 3 5/8" C-shaped studs (0.043" nominal thickness and 1 5/8" flange) 24" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

6 a. 2" Extruded Polystyrene rigid insulative sheathing
b. 3 5/8" C-shaped studs (0.043" nominal thickness and 1 5/8" flange) 24" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

7 a. 1/2" Plywood sheathing installed over horizontal ("hat" style, 7/8") metal furring on the face of the studs.
b. 3 5/8" C-shaped studs (0.043" nominal thickness and 1 5/8" flange) 24" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

8 a. 1" Extruded Polystyrene rigid insulative sheathing installed over horizontal ("hat" style, 7/8") metal furring on the face of the studs.
b. 3 5/8" C-shaped studs (0.043" nominal thickness and 1 5/8 flange) 24" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

9 a. 1/2" Plywood sheathing installed over silicone foam tape 3/4" wide by 5/16" thick on the face of the studs.
b. 3 5/8" C-shaped studs (0.043" nominal thickness and 1 5/8" flange) 24" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

Group B

1 a. 1/2" Plywood sheathing
b. 3 5/8" C-shaped studs (0.043" nominal thickness and 1 5/8" flange) 12" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

2 a. 1" Extruded Polystyrene rigid insulative sheathing
b. 3 5/8" C-shaped studs (0.043" nominal thickness and 1 5/8" flange) 12" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

Group C

1 a. 1/2" Plywood sheathing
b. 3 5/8" C-shaped studs (0.033" nominal thickness and 1 5/8" flange) 24" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

2 a. 1" Extruded Polystyrene rigid insulative sheathing
b. 3 5/8" C-shaped studs (0.033" nominal thickness and 1 5/8" flange) 24" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

3 a. 1" Extruded Polystyrene rigid insulative sheathing over 1/2" plywood
b. 3 5/8" C-shaped studs (0.033" nominal thickness and 1 5/8" flange) 24" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

4. a. 1/2" Plywood sheathing
b. 3 5/8" C-shaped studs (0.033" nominal thickness and 1 5/8" flange)
24" o.c., with R-11 full width glass fiber insulation.
7/8" air space
3 5/8" C-shaped studs (0.033" nominal thickness and 1 5/8" flange)
24" o.c., with R-11 full width glass fiber insulation.
The two walls were held together using 3 5/8" C-shaped stud pieces (0.033" nominal thickness and 1 5/8" flange) located four per stud at 32" o.c. vertically. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

Group D

1 a. 1/2" Plywood sheathing
b. 6" C-shaped studs (0.043" nominal thickness and 1 5/8" flange)
24" o.c., with R-19 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

2 a. 1" Extruded Polystyrene rigid insulative sheathing
b. 6" C-shaped studs (0.043" nominal thickness and 1 5/8" flange)
24" o.c., with R-19 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

3 a. 1" Aluminum foil-faced Polyisocyanurate Foam sheathing
b. 6" C-shaped studs (0.043" nominal thickness and 1 5/8" flange)
24" o.c., with R-19 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

4 a. 1/2" Plywood sheathing installed over Horizontal Furring on the face of the studs
b. 6" C-shaped studs (0.043" nominal thickness and 1 5/8" flange)
48" o.c., with R-19 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board installed over horizontal ("hat" style, 7/8") metal furring on the face of the studs

Group E

1 a. 1" Extruded Polystyrene rigid insulative sheathing
b. 3 5/8" C-shaped studs (0.043" nominal thickness) with 2 1/2" flange.
48" o.c., with R-11 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board.

Group F

1 a. 1" Extruded Polystyrene rigid insulative sheathing
  b. 3 5/8" C-shaped studs (0.043" nominal thickness with 1 5/8" flanges.)
  24" o.c., with R-15 full width glass fiber insulation. The construction included top and bottom tracks the same thickness as the studs.
  c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board.

2 a. 3/4" California Stucco applied over wire mesh and 1" Extruded Polystyrene rigid insulative sheathing
  b. 3 5/8" C-shaped studs (0.033" nominal thickness with 1 5/8" flanges.)
  24" o.c., with R-13 full width glass fiber insulation. The tracks were eliminated for this test.
  c. 0.0045" Poly vapor barrier and 1/2" Gypsum Board

Component Thermal Conductivities

In addition to the air and sample thermocouples used according to ASTM C976, 30 additional thermocouples (15 on each side of the sample) were installed on the surface and inside the wall at various locations to measure surface temperatures of the warm side and interior of the gypsum board, the stud surface temperatures (hot and cold), and the interior and surface temperature of the exterior sheathing. After each sample wall was constructed, pieces of the wall components were tested to verify material thermal conductivities. Samples of the glass fiber insulation were tested in a "R-Matic" heat flow meter (24" by 24" sample). Samples of the plywood, gypsum board and exterior insulative sheathings were tested in a "Rapid-k" heat flow meter (12" by 12" sample). Samples of the steel studs and steel furring strips were tested in a "laser flash" diffusivity instrument (1/2" diameter sample). Table 1 shows measured thermal conductivities for the individual wall components and the recognized ASTM methods used to obtain the measurements.

Table 1
Wall Component Thermal Conductivities

Component	Samples	ASTM Method	Density (pcf)	Nominal Thickness (inches)	Actual Thickness (inches)	Measured K	R-value
R-11 insulation	3	C518	0.53	3.5	3.5	0.309	11.33
R-13 insulation	3	C518	0.88	3.5	3.5	0.265	13.21
R-15 insulation	3	C518	1.62	3.5	3.5	0.245	14.29
R-19 insulation	2	C518	0.53	6.25	6.0	0.330	18.18
XPS Foam	1	C518	2.18	0.5	0.575	0.195	2.95
XPS Foam	2	C518	1.91	1.0	1.015	0.190	5.33
XPS Foam	1	C518	1.98	2.0	1.962	0.183	10.72
Polyisocyanurate Foam	1	C518	NA	1.0	0.95	0.140	6.79
Gypsum Board	2	C518	NA	0.5	0.489	1.208	0.40
Plywood	2	C518	NA	0.5	0.472	0.934	0.51
Steel Framing	2	E1461	NA	0.043	0.043	435.4	0.00
Steel Framing	2	E1461	NA	0.033	0.035	391.7	0.00
Steel Furring	2	E1461	NA	0.018	0.017	322.4	0.0

TEST RESULTS

The composite wall ASTM C976 test results are shown in Table 2.

Table 2
ASTM C976 Test Results

Group	Test #	R-Value	Description
A		(hr·ft^2·°F/Btu)	24" o.c. 3 5/8 x 1 5/8, 0.043" thick with R-11 insulation
	1	7.9	1/2" plywood sheathing
	1.A	7.8	1/2" plywood with 15 mph wind
	1.B	7.4	1/2" plywood at 75°F mean
	2	13.7	1" XPS
	4	13.9	1" XPS over 1/2" gypsum
	5	11.4	1/2" XPS
	6	18.9	2" XPS
	7	9.3	7/8" hat channels, 1/2" plywood
	8	14.4	7/8" hat channels, 1" XPS
	9	8.4	Foam tape on flanges
B			12" oc, 3 5/8 x 1/58, 0.043" thick with R-11 insulation
	1	6.8	1/2" plywood
	2	12.4	1" XPS
C			24" oc, 3 5/8 x 1 5/8, 0.033" thick with R-11 insulation
	1	8.3	1/2" plywood
	2	13.9	1" XPS
	3	14.5	1" XPS over 1/2" plywood
	4	13.3	Double wall
D			6" x 1 5/8, 0.043" thick with R-19 insulation
	1	10.1	1/2" plywood - studs 24" oc
	2	16.2	1" XPS - studs 24" oc
	3	17.1	1" polyisocianurate - studs 24" oc
	4	12.4	hat channels, 1/2" plywood - studs 48" oc
E			24" oc, 3 5/8" x 2 1/2", 0.043" thick with R-11 insulation
	1	13.5	XPS sheathing
F			24" oc, 3 5/8 x 1 5/8, 0.043" thick with R-15 insulation
	1	15.6	R-15 insulation, 1" XPS sheathing
	2	15.7	3/4" California stucco with 1" XPS, R-13 insulation

Changing the stud spacing from 24" o.c. to 12" o.c. showed a decrease of 1.2 hr·ft^2·°F/Btu to 1.4 hr·ft^2·°F/Btu in R-value for 1/2" plywood and 1" XPS sheathing, respectively. This indicates the added steel associated with the 12" o.c. wall produced a consistent reduction in wall R-value.

Comparing tests A1 and A2 (3 5/8" stud, R11 cavity insulation) with D1 and D2 (6" stud, R19 cavity insulation) showed that the use of increased cavity insulation R-value, 7 hr·ft^2·°F/Btu, only increased the overall wall R-value 2.2 hr·ft^2·°F/Btu to 2.5 hr·ft^2·°F/Btu for 1/2" plywood and 1" XPS sheathing, respectively. By contrast, test A2 (3 5/8" stud, R11 cavity insulation) with 1" XPS exterior sheathing was 3.6 hr·ft^2·°F/Btu larger in R-value than test D1 (6" stud, R19 cavity insulation) with 1/2" plywood sheathing. Test D1's cavity insulation was approximately 7 hr·ft^2·°F/Btu greater than A2's cavity insulation, but A2's exterior sheathing was 5 hr·ft^2·°F/Btu, compared to approximately 0.5 hr·ft^2·°F/Btu for D1's plywood sheathing. This comparison shows that insulation is much more effective on the exterior than on the interior.

Comparing test E1, larger flange size, with test A2 showed only a minimal reduction in R-value (0.2 hr·ft^2·°F/Btu) for using a wider flange. While the difference in flange size was small, 7/8", this would indicate that small differences in flange size have little effect on the overall wall R-value.

Comparison of the two tests with different wind speed on the exterior (tests A1 and A1.A) showed that although the cold side convection coefficient was significantly increased during the test with the 15 MPH wind, it did not significantly affect the R-value of the wall. This information is offered to allow comparison to previous building assembly hot box tests by other researchers.

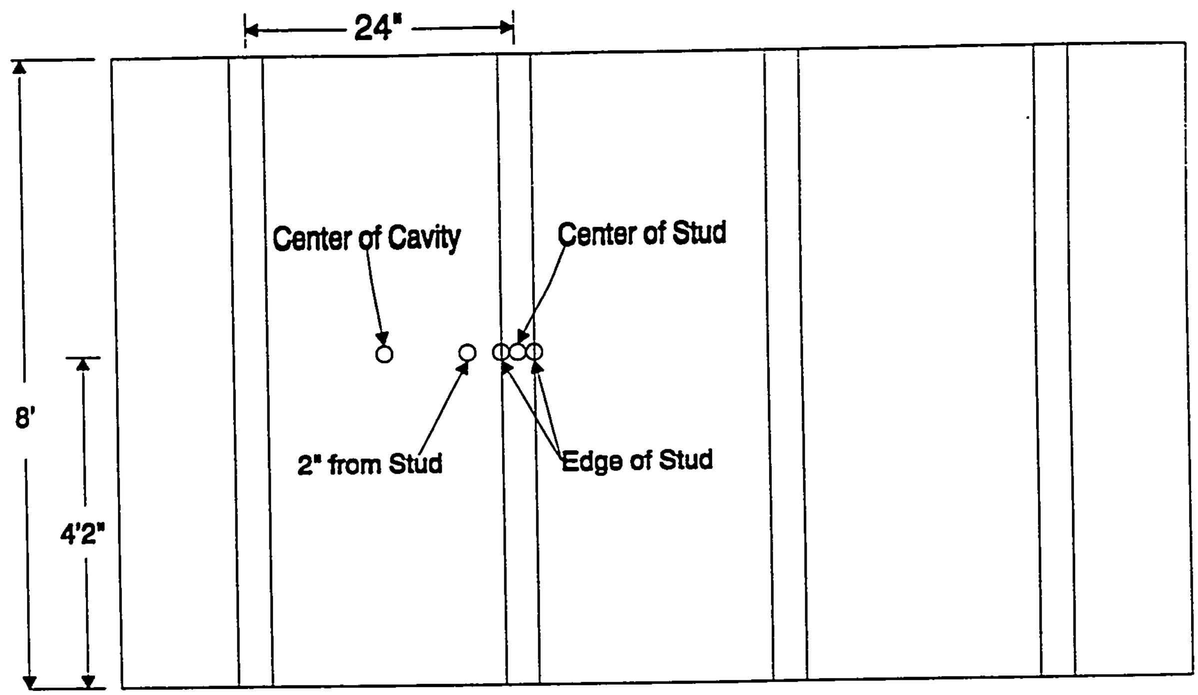
The use of steel furring channels in the walls only increased the R-value of those walls by approximately the R-value of the air gap they introduced in the wall (7/8"). This suggests that although the contact resistance is changed using the furring channels, there is little benefit other than the air gap. The R-value for the plane air space is approximately 1.1 [1, Chapter 22, Table

2]. Comparing test walls A7 with A1 and A8 with A2 shows an increase in R-value of 1.4 and 0.7, respectively.

For test group A, it was noticed at disassembly that the warm side thermocouple located in the middle of the stud was attached to the sample surface over a screw. This would account for the slightly lower temperatures shown in the temperature differentials. In subsequent wall assemblies, screw locations were noted and thermocouples were not attached near screws. This piece of data offered some insight into the effect of the screw. When analyzing the data from other tests, it seems that the surface temperatures over the faces of the studs are not dependent on the horizontal location (see Figures 3-6). The temperatures measured on the surface of the studs and on the outside surfaces over the studs did not vary considerably from the web side of the stud to the open side of the stud. This was also true for the studs with wide flanges. Presumably, this was due to the inherent high thermal conductivity of the steel and the relatively short distances involved.

Using thermocouples to measure surface temperature gradients, the difference in surface temperature over the cavity and over the center of the stud, and surface to surface temperature difference (ΔT) suggest that surface temperature gradients on the gypsum (warm side) are larger in steel-framed walls with low R-value exterior sheathing than those with high R-value sheathings. Figure 2 shows the thermocouples locations used in this analysis and Figures 3 through 6 graphically depict the surface temperature gradients for Group A. When comparing interior and surface temperatures on the warm side of the sample, the difference between the temperature over the cavity and over the stud decreases as the R-value of the sheathing increases (the temperature over the cavity being somewhat constant and the temperature over the stud increasing as sheathing R-value increases). The surface temperature difference from cavity to stud on the cold side was varied from 3°F (plywood) to 0.2°F (2" XPS), while the warm surface had much larger surface temperature differences, 10.1°F (plywood) to 2.5°F (2" XPS), as shown in Figures 4 and 6. This indicates a reduction of heat flowing through the stud for larger R-value sheathing and a reduction in possible thermal bridging effects.

Figure 2
Thermocouple Locations



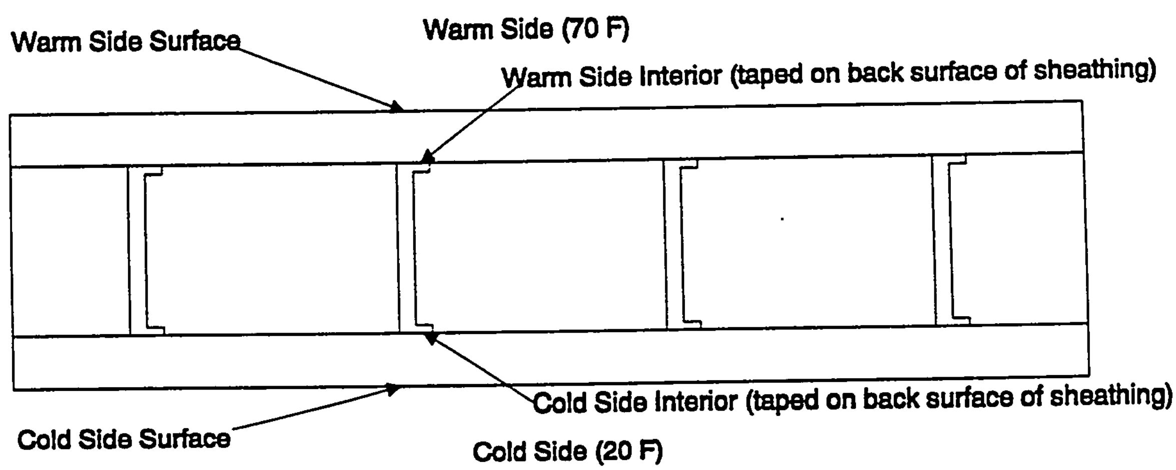


Figure 3
Warm Side Interior Temperature Distributions

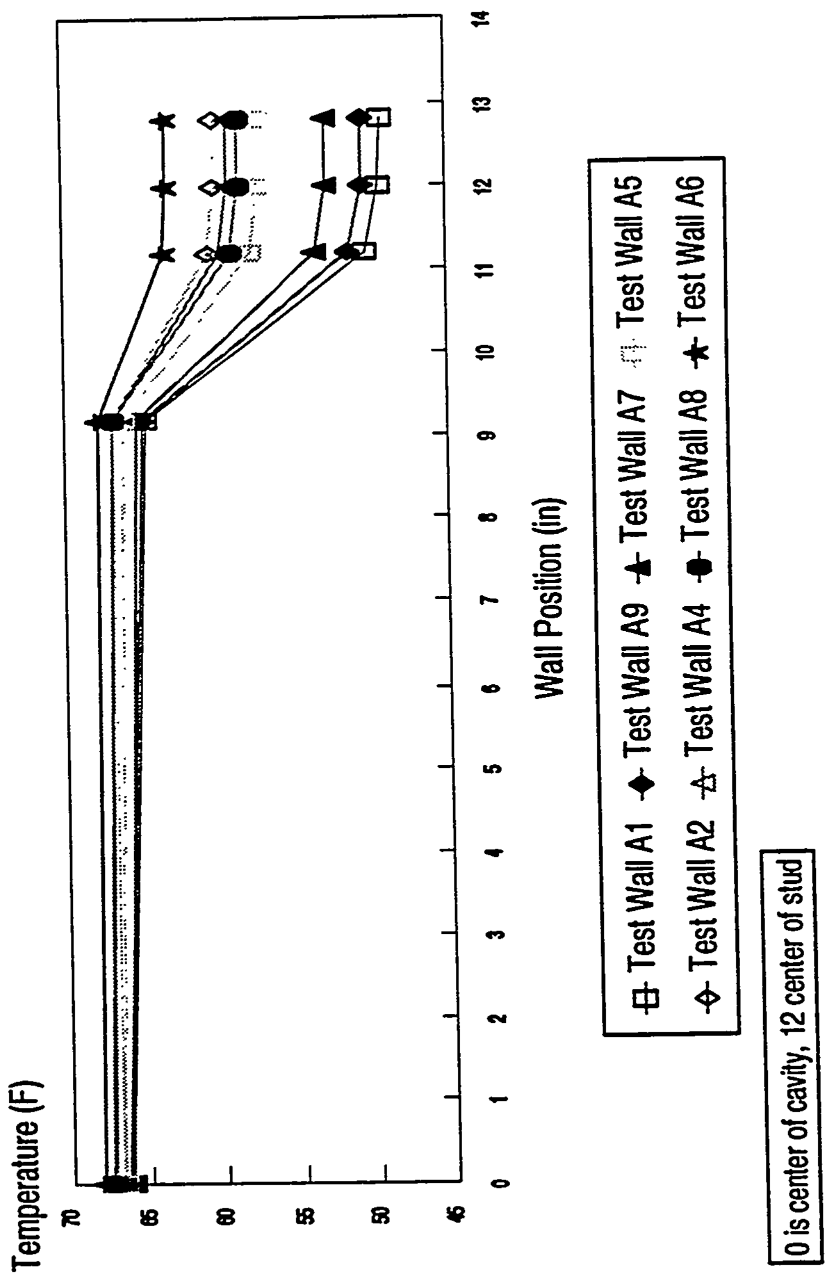


Figure 4
Warm Side Surface Temperature Distributions

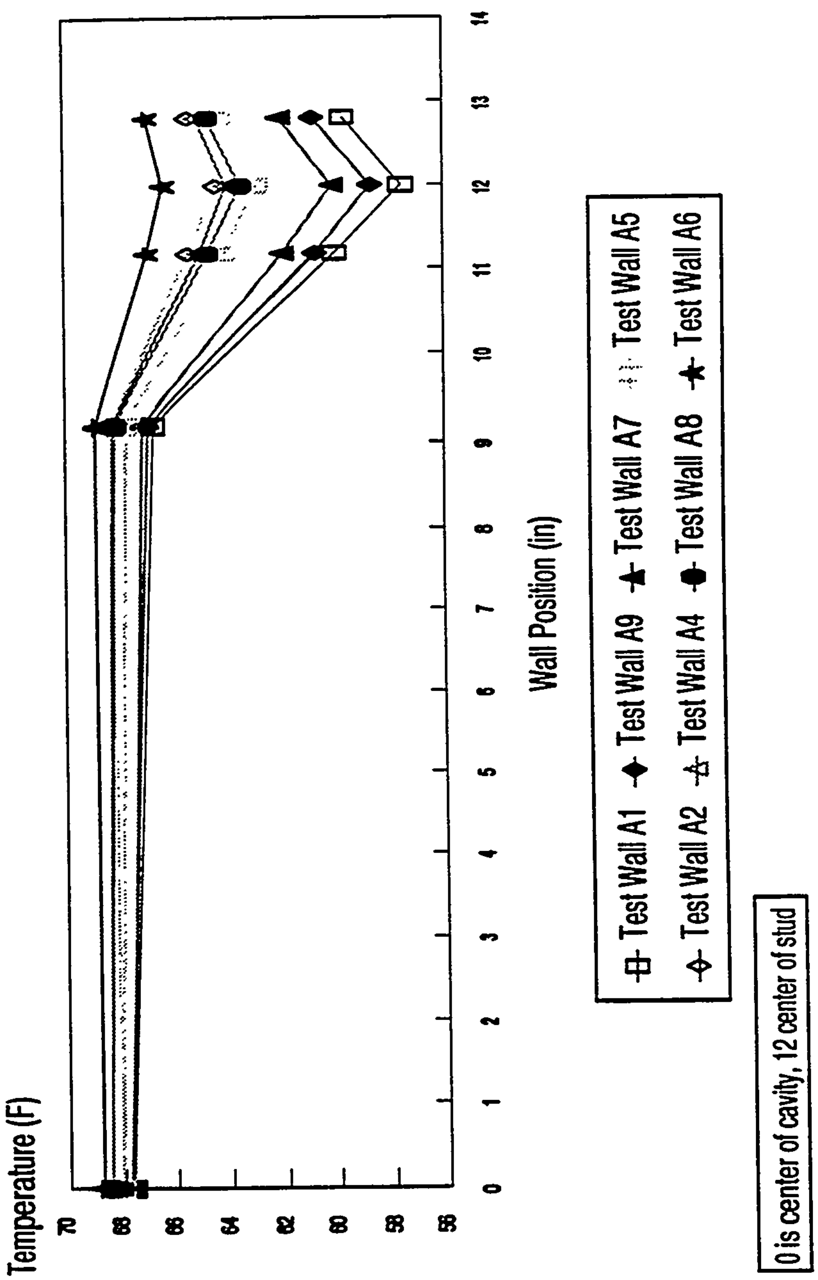


Figure 5
Cold Side Interior Temperature Distributions

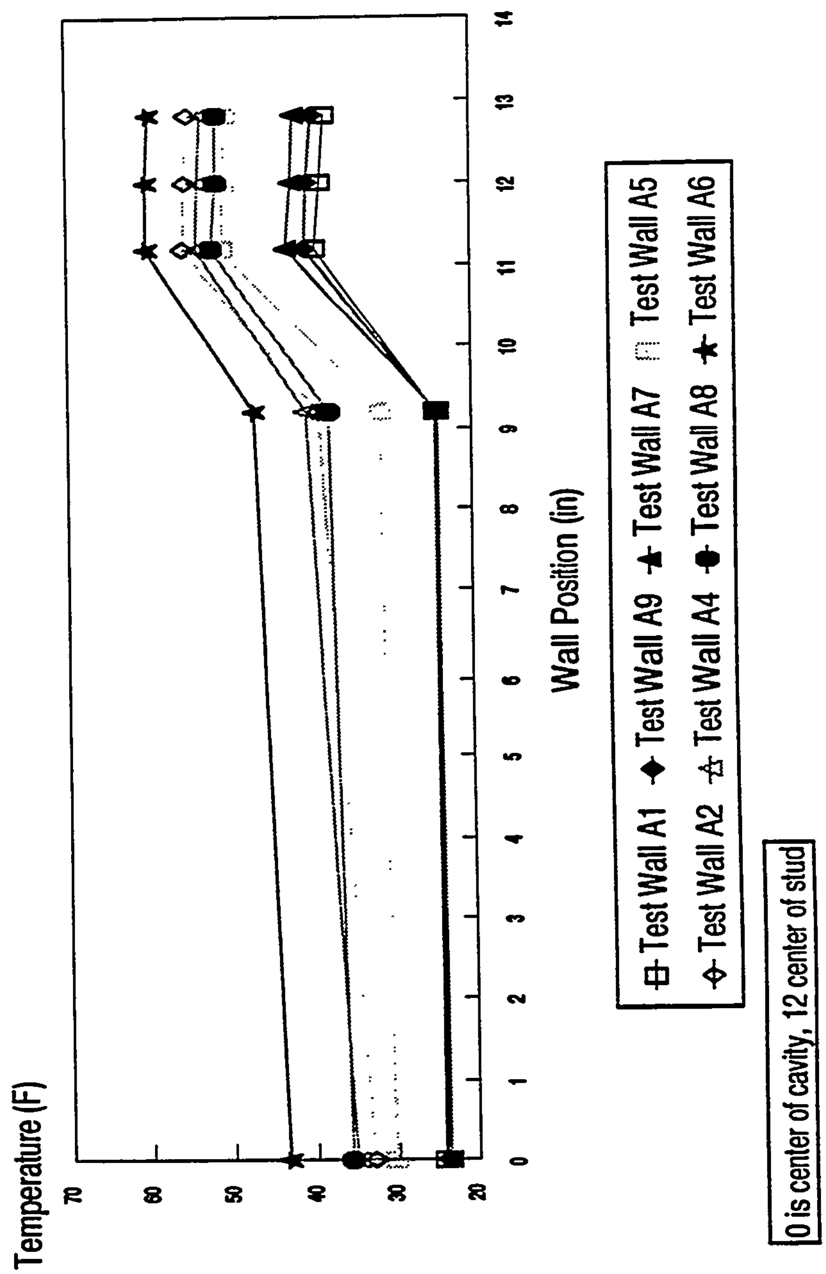
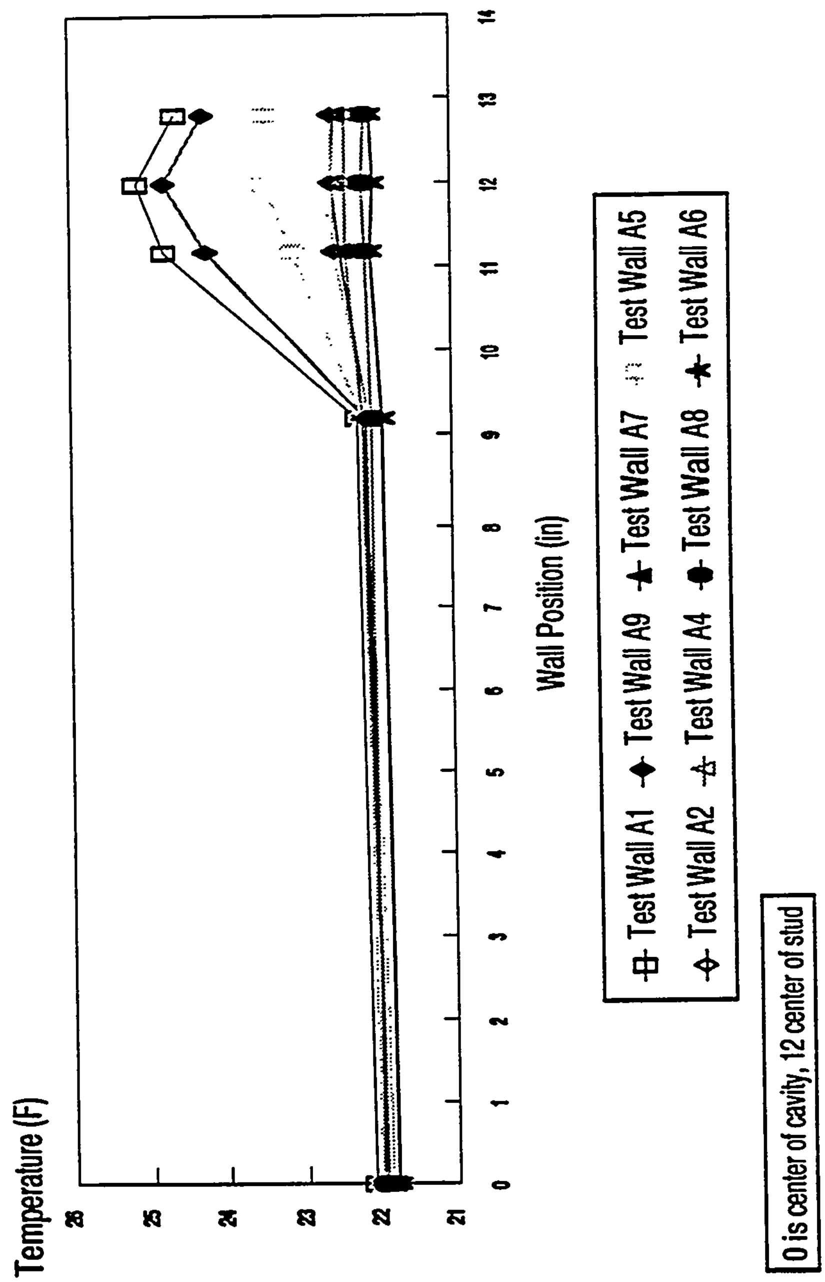


Figure 6
Cold Side Surface Temperature Distributions



This reduction in heat flow is also shown in the warm surface to cold surface ΔT for two paths through the wall (Table 3), one through the center of the cavity and the other though the center of the stud.

Table 3
Exterior Surface to Exterior Surface Temperature Difference

Wall	R-Value (hr ft² °F/Btu)	ΔT over cavity insulation (°F)	ΔT center of stud (°F)	ΔT over cavity insulation - ΔT center of stud (°F)	Cavity ΔT/Lateral ΔT
A1	7.9	45.6	32.4	13.2	4.5
A9	8.4	45.8	33.9	11.9	5.1
A7	9.3	45.8	37.6	8.2	6.1
A5	11.4	46.0	39.4	6.6	8.8
A2	13.7	46.2	41.8	4.6	12.5
A4	13.9	46.5	41.6	4.9	10.3
A8	14.4	46.5	41.3	5	9.3
A6	18.9	47.0	44.3	2.7	18.7

The reduction in heat transfer through the stud is evident in the increase in surface to surface ΔT at the center of stud, since in each test the warm side (70°F) and cold sides (20°F) were at constant temperature and the heat input to the warm side was constant (steady-state conditions). At these conditions, a smaller ΔT would indicate a faster rate of heat transfer. The cold side showed very little lateral temperature difference, so the change ΔT (Table 3, Column 4) is dependent on the warm side surface temperature. For the low R-value sheathed walls, the stud is cooling the gypsum, by as much as 10.1°F for the plywood wall (Figure 4). The reduction in this cooling effect by use of high R-value exterior sheathing is shown in the difference between the ΔT over cavity insulation and ΔT center of stud. With the plywood exterior sheathing, the difference in surface to surface ΔT from the cavity to the stud is 13.2°F (Table 3, Column 5). This difference is consistently reduced by increasing the exterior sheathing R-value until a temperature difference of 2.7°F is measured for the wall with 2" XPS sheathing (R-10).

Comparing surface to surface ΔT with the surface temperature gradient from Figure 4 for the warm side gives the ratio between the amount of heat being transferred laterally through the gypsum wallboard to the steel stud and the amount of heat being transferred perpendicularly (surface to surface) through the cavity insulation. This relationship increases from 4.5°F (plywood sheathing) to 18.7°F (2" XPS sheathing). The ΔT across the cavity is fairly constant, varying from 45.6°F (plywood sheathing) to 47.0°F (2" XPS sheathing), while the surface temperature gradient varies from 10.1°F (plywood sheathing) to 2.5°F (2" XPS). This decrease in lateral heat transfer is evident in the increase in surface to surface ΔT center of stud and Cavity ΔT/Lateral ΔT for walls with increasing exterior sheathing R-value.

Although humidity was not controlled during the tests, no condensation was noted on the warm surface of the samples during or after tests. In addition, upon removal of the wall samples at the conclusion of each test series, there was no evidence (such as stains on the gypsum board) to suggest that there was any condensation on the interior surface of the gypsum board. If any condensation did occur inside the wall on the warm side, the vapor barrier was successful at protecting the gypsum board. On the interior of the cold side of some samples, small amounts of condensation were noted on the inside surface of the sheathing upon disassembly, but this is not uncommon due to the temperatures involved and should not be interpreted as an effect of the steel framing.

For test A.9 (1/2" plywood installed over insulating tape on the studs), it was observed that after the plywood was screwed to the studs, the foam tape was compressed. The original thickness was 5/16" and when compressed (as tested) the thickness varied from approximately 1/8" (near screws) to 1/4" (away from the screws).

In terms of "ghosting", airborne dirt tends to accumulate on cool areas of a surface faster than adjacent warm areas. As a result, a pattern of dirty and clean areas, called "ghost marks", may appear on the interior surface of insulated walls, and generally outlines the framing of the building. Previous work by others [7,8] indicate that minor (acceptable) ghost marking can be expected to occur when the temperature difference between cavity and stud is about 3.3°F, and considerable (unacceptable) ghost marking will occur when the temperature differential is about 8°F (with marking appearing in under two years). The seriousness of the marks, or streaks, depends on the time necessary for a noticeable streak to appear in relation to a redecorating schedule set by the homeowner, Figure 4 graphically displays the interior wall surface temperature differential for the Group A series of tests. It is evident that ghosting would be expected in houses in northern climates in walls A.1, A.9, and A.7. All of these walls are sheathed with plywood, a low-R-value sheathing. No ghosting problems would be expected in the remaining walls in Group A.

COMPARISON OF TEST AND MODEL RESULTS

To arrive at an accurate estimation procedure, current methods of estimation were evaluated for accuracy. The parallel path method, isothermal planes method, and the ASHRAE Zone method were used to produce estimates of the wall R-value using a one-dimensional heat flow path. For each of these three methods, a framing factor is used to account for the top and bottom tracks. The framing factor is the area of framing material/area of wall. The use of framing factors for the parallel method and isothermal planes method are discussed in the ASHRAE Handbook of Fundamentals [1]. For the ASHRAE Zone method, the framing factor is used to calculate an apparent spacing between framing members and an apparent wall area. These are then used in the method discussed previously.

For steel framing, it may be necessary to account for multi-dimensional effects. One method to solve for this is to use finite-difference solutions incorporating a computer. In contrast to analytical solutions, which allow temperature determination at any point in the wall, the finite-difference solution allows for the determination of temperature at discrete points. These points, or "nodes", are selected by dividing the wall into small control volumes and placing a node in the center. The node represents the average temperature of the control volume. From this selection, an appropriate energy conservation equation can be chosen for each of the nodes. The complete set of equations is then solved simultaneously for the temperature at each node. For walls, the exact form of the energy conservation equation is given by:

$$(\delta^2 T/\delta x^2) + (\delta^2 T/\delta y^2) = 0 \qquad (2)$$

where T = temperature

x, y = locations, vertical and horizontal in the wall

This can be expressed as a finite-difference equation which can be solved using iteration where the temperature for each node is calculated successively until the previous temperature and the current temperature are within an acceptable range for the temperatures, or

$$ABS(T_{now} - T_{previous}) \leq \alpha \quad (3)$$

where α is the acceptable uncertainty in the temperature. The equations are solved using a personal computer, and an approximation of the actual temperature field is obtained. From these temperature fields, the total heat into the wall is known, along with the temperatures at the boundary conditions and an R-value for the entire wall section is estimated. The results of the finite-difference modeling using TABA finite difference program [14] and the various calculation procedures for R-values are shown in Table 4 and compared to the experimental results. An α of 0.05 was used for the finite-difference modeling, (Since these methods typically have assumptions based on the use of tracks, test construction F.2 was not used in the comparison.)

Table 4
Hot Box Test and Estimation Results

Wall Section	Experimental R-Value	Zone Est. R-Value	Par. Path R-Value	Iso Planes R-Value	F-D Model R-Value	Difference Zone to Experimental	Difference Model to Experimental
A.1	7.9	8.5	13.2	3.7	7.2	-7.6%	8.9%
A.2	13.7	13.6	18.2	8.5	13.6	1.0%	1.0%
A.4	13.9	13.3	18.5	8.8	13.3	2.2%	2.2%
A.5	11.4	10.9	15.2	5.6	11.0	4.4%	3.5%
A.6	18.9	18.4	23.8	14.3	17.8	2.6%	5.8%
A.7	9.3	9.1	13.9	5.0	9.2	2.1%	1.1%
A.8	14.4	14.7	18.8	8.7	14.2	-2.1%	1.4%
A.9	8.4	7.1	13.4	4.4	8.1	15.5%	3.6%
B.1	6.8	6.2	13.0	2.9	5.7	8.8%	16.2%
B.2	12.4	11.0	17.9	7.7	11.9	11.3%	4.0%
C.1	8.3	8.5	13.3	3.8	8.1	-2.4%	2.4%
C.2	13.9	13.6	18.2	8.6	13.7	2.2%	1.4%
C.3	14.5	14.2	18.9	8.8	14.6	2.1%	-0.7%
C.4	13.3	14.2	18.5	8.7	13.0	-6.8%	2.3%
D.1	10.1	10.9	15.2	6.1	9.7	-8.0%	4.0%
D.2	16.2	16.7	24.4	9.8	15.4	-3.1%	4.9%
D.3	17.1	18.6	26.3	11.6	16.1	-8.8%	5.8%
D.4	12.4	14.8	19.1	7.7		-19.4%	
E.1	13.5	13.0	17.9	8.4	13.2	3.7%	2.2%
F.1	15.6	14.9	20.4	9.7		4.5%	

Use of insulative sheathing or decreasing the amount of steel in the wall section produced estimations by the finite-difference model closer to the test results. The errors associated with the parallel path and isothermal planes method were too large for even a rudimentary comparison and thus were eliminated from consideration. However, due to nature of these calculation procedures, actual R-values for steel-framed walls fall between the estimates from the parallel path and isothermal planes method. The differences in the ASHRAE Zone, parallel path, and isothermal planes estimations relative to each other and the test results can be attributed to the two-dimensional effects of the wall assembly.

Since the ASHRAE Zone method proved to be the most simplistic, a comparison was made between the calculated Zone method R-values (Table 4, Column 3) and test results. Fifty-seven percent of the ASHRAE Zone estimations within 5 percent of the test R-values, and 86 percent of the estimations within 10 percent of the test R-values. The ASHRAE Zone R-values for walls B2, A9 and D4 were greater/smaller than 10 percent of the test R-values, with D4 being 19.4 percent greater than the test results.

The B series of walls, tests of 12" o.c. framed walls, also produced test R-values 8.8 to 11.3 percent more than the ASHRAE Zone R-values, indicating that smaller spacing of highly conductive materials adversely affects zone estimations. This is to be expected, since the ASHRAE Zone method is for widely spaced members. The ASHRAE Zone method is a parallel path method that uses a weighing factor to arrive at a zone of influence for the highly conductive member [1]. The ASHRAE Zone method defines a zone of influence as the region as a distance from the closest surface, not the relative thermal conductivity of the material(s) to the surface. This is done to isolate the two dimensional effects of the steel framing and, since the R-value of the sheathing considers the area transmittance of both zones, a reasonable estimate is obtained. The only flaw comes in the area of influence changes based on the temperature of the steel stud, which is dependent on the sheathing used, as evident in the surface to surface temperature distributions and the surface temperatures. This results in the zone of influence for low R-value exterior sheathing to be underestimated, producing ASHRAE Zone method R-values for 24" o.c. steel-frame walls 2.1 to 7.6 percent larger than test results. On the other hand, the use of insulating sheathing results in the zone of influence being over estimated, as evidence in test results larger by as much as 15.5 percent than ASHRAE Zone R-values for 24" o.c. steel-framed walls.

Comparison of Parallel Path Correction Factors

Another method for calculating the R-value of steel-framed walls provides correction factors for the parallel path method. Correction factors are applied to the cavity insulations R-value to obtain an effective R-value. This R-value is then added to the wall sheathings R-values to arrive at a total R-value. ASHRAE Standard 90.1 [10] lists parallel path correction factors for steel-framed walls. The method only lists correction factors for 3 5/8" studs, 16" o.c. and 24" o.c., or 6" studs, 16" o.c. and 24" o.c.. Groups A and D were chosen for comparison of actual correction factors using the test results. The correction factor is defined as:

$$R_T = R_i + R_e \qquad (4)$$

where R_T = R-value of wall
R_i = sum of series element R-values (typically any sheathings)
R_e = correction factor x insulation R-value

For 3 5/8" framed walls, 24" o.c., the ASHRAE correction factor is 0.60. For 6" framed walls, 24" o.c., the ASHRAE correction factor is 0.45. The actual correction factors based on the test results were calculated using:

$$CF = \frac{R_T - R_i}{\text{Rinsulation}} \qquad (5)$$

The comparison of correction factors obtained from the test data and the factors given in Standard 90.1 is shown in Table 5. The added R-value is the apparent added R-value for that particular wall based on tests A.1 and D.1 unsheathed R-values. The net added R-value is the difference between the apparent added and the actual sheathing R-value.

Table 5
Comparison of Parallel Path Correction Factors

Wall Section	Test Total R-Value	Unsheathed R-Value	Sheathing R-Value	Added R-Value	Net Added R-Value	Percentage Difference Net Added	Calculated Correction Factor	ASHRAE CF	ASHRAE CF R-Value	Difference Test - ASHRAE
A.1	7.9	7.0	0.9				0.6	0.6	7.5	5%
A.2	13.7	8.0	5.7	6.7	1.0	15%	0.7	0.6	12.3	10.2%
A.4	13.9	7.7	6.1	6.9	0.80	10%	0.7	0.6	12.7	8.6%
A.5	11.4	8.0	3.4	4.4	1.0	23%	0.7	0.6	10.0	12.3%
A.6	18.9	7.8	11.1	11.9	0.8	6%	0.7	0.6	17.7	6.3%
A.7	9.3	8.4	0.9	2.3	1.4	60%	0.7	0.6	7.5	19.4%
A.8	14.4	8.7	5.7	7.4	1.7	22%	0.8	0.6	12.3	14.6%
A.9	8.4	7.5	0.9	1.4	0.5	31%	0.7	0.6	7.5	10.7%
D.1	10.1	9.2	0.9				0.5	0.45	9.5	5.9%
D.2	16.2	10.5	5.7	7.0	1.3	19%	0.6	0.45	14.3	11.7%
D.3	17.1	9.9	7.2	7.9	0.7	9%	0.5	0.45	15.8	7.6%

A correction factor of 1.0 would indicate that the framing member had no effect on the insulation R-value. All of the calculated correction factors were larger (up to 22 percent) than the ASHRAE factors, which indicates the steel framing had a smaller effect than would be predicted from the ASHRAE factors. It appears that the wall sections with higher R-value sheathing are penalized, by as much as 10 percent, when using the correction factors given in ASHRAE 90.1 to calculate the wall R-value. The ASHRAE correction factors were developed from a testing program sheathed with plywood only, and our tests on the wall with plywood validates that correction factor (Test A.1). However, when looking at the tests with insulating sheathing for walls with 3 5/8" studs 24" oc, the factor increases from 0.60 to about 0.70 (Tests A.2 through A.6). The correction factor for walls with 6" studs, 24" o.c., is also larger by 11 percent or more (Tests D.1 through D.3) than the 0.45 stated in ASHRAE 90.1. Using the ASHRAE correction factors to calculate the R-value of the wall resulted in R-values 5 percent to 19.4 percent less than the test R-values (Table 5, Column 11).

Another result from this analysis was the increase in apparent added R-value over the actual sheathing R-value for walls with insulating sheathing. By taking the total R-value for the wall and subtracting the individual sheathing R-values, the unsheathed R-value for the wall is obtained. Comparing this unsheathed R-value for each wall with the unsheathed value for test A1 (plywood), the apparent R-value added can be evaluated. The use of insulating sheathings added approximate 1 hr•ft^2•°F/Btu over the expected R-value obtained by adding the sheathing R-values to unsheathed cavity R-value from test A1. This increase ranged from 6 percent to 23 percent increase in apparent R-value for the insulating exterior sheathings.

MODIFIED ZONE FACTORS - METHOD OF CLEAR WALL R-VALUE CALCULATIONS FOR STEEL-FRAMED WALLS

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The thermal resistance of building walls is typically predicted based on one of the procedures recommended in the ASHRAE Handbook of Fundamentals [1 pp. 22.5-22.11]. For metal-framed walls, two methods are in common use: Zone Method and modified Parallel Path Method. These methods are based on parallel path calculations. The only dissimilarity between them is the method of estimating the area of the wall that is thermally affected by thermal bridging. Several authors report the accuracy of above methods as unsatisfactory [9]. A series of over 1000 two-dimensional computer simulations was conducted for clear wall area of the metal-frame wall systems. The phrase "clear wall" was defined by J. Kosny and A.O. Desjarlais [15] as the flat part of the wall system, that is free of thermal anomalies due to building envelope subsystems such as corners, door and window openings, and structural joints with roofs, floors, ceilings and other walls. The Heating 7.2 finite difference computer code was used to model walls [16]. The Heating 7.2 model was validated by comparing simulation results against the test results of 9 metal stud walls reported by W.C. Brown [3], W.R. Strzepek [9], and several being reported in present study. The ability of Heating 7.2 to reproduce the experimental data is within the accuracy of the test method. The following seven wall design parameters were considered during modeling: stud spacing, stud depth, stud flange size, stud metal thickness, thickness of sheathing, thermal conductivity of exterior sheathing and thermal conductivity of cavity insulation. Isotherms showing the temperature distribution in walls simulated with a temperature difference across the wall were used as an aid to estimate areas affected by the thermal bridges and to calculate the overall metal-frame wall R-values. This parameter analysis of the major design variables found in typical metal-frame walls, helped us identify that only four of these variables significantly affected the precision of the R-value calculations.

Clear wall R-values calculated by the ASHRAE Zone Method were compared with the results of the simulation. The comparison showed that the differences in the thermal calculations are caused by the estimation of the metal stud zone area. For most wall configurations, the thermal bridge distortion area recommended for ASHRAE Zone Method calculations is too large while thermal bridge distortion area for Parallel Path Method is too small. The effects of all wall design parameters were estimated by means of parametric analysis.

A new more precise mathematical algorithm for Zone Method R-value calculations was developed. The authors found that this algorithm, thanks to its clarity, reduces chance of errors during calculations.

This technique has been customized for estimating zones of thermal anomalies caused by metal studs for metal-frame walls. The authors validated this method by comparison with simulating results from a detailed 3-D finite difference code (Heating 7.2) of over 700 cases of metal-frame walls with cavity insulation. For all considered configurations of wall with cavity insulation the discrepancies between results were within the range of ±2 percent. This is compared with the ASHRAE Zone Method range of error ±15 percent.

Method of Thermal Analysis

Two and three-dimensional computer modeling was used for all metal-frame wall configurations. A heat conduction, finite difference computer code Heating 7.2, was used for thermal analysis of metal-frame walls [16]. The resultant isotherm maps were used to calculate average heat fluxes, and then wall system R-values. The accuracy of Heating 7.2's ability to predict wall system R-values was verified by comparing simulation results with published test results for twenty-eight masonry, wood-frame, and metal-frame walls. Ten empty and eight filled masonry 2-core 12-in .(30-cm.) masonry units reported by Valore [17], Van Geem [18], and James [19] were modeled with accuracy better than ±4 and ±6 percent, respectively [15]. 2x4 wood-frame wall reported by James was modeled with accuracy better than ±2 percent. The differences between laboratory test and Heating 7.2 simulation results for nine metal stud walls described by Brown [3], Strzepek [9], and several measured as a part of this project are presented in Table 6.

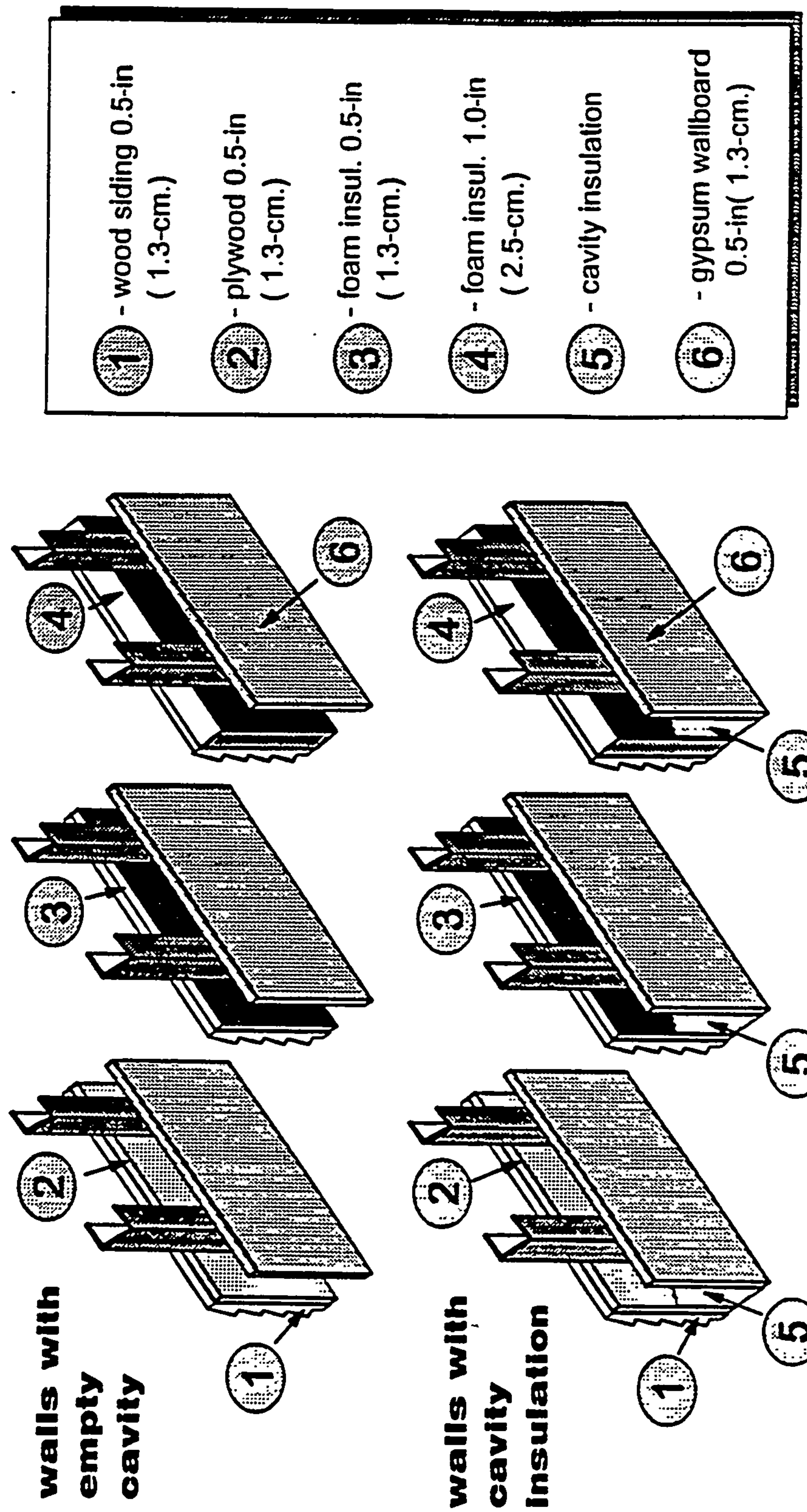
Table 6
Accuracy of Heating 7.2 R-Value Modeling for Metal-Frame Walls

Wall Description	Author	Difference Between Results (Rtest-Rsim)/Rtest x 100%
stucco, no sheathing insulation, mineral fiber as cavity insulation - 3.5-in. (8.9-cm.) studs, 16-in. (40-cm.) o.c.	W.C. Brown	-3.5
precast concrete slab -4-in. (20-cm.), mineral fiber as cavity insulation - 3.5-in. studs, 16-in. o.c.	W.C. Brown	+5.1
stucco,wood fiber board, no cavity insulation - 3-5/8-in. (9.2-cm.) studs, 16-in. (40-cm.) o.c.	W.R. Strzepek	+6.4
stucco, wood fiber board, mineral fiber as cavity insulation - 3-5/8-in. studs, 16-in. o.c.	W.R. Strzepek	-5.8
0.5-in. (1.3-cm.) plywood sheathing, glass fiber as cavity insulation, studs -3-5/8-in. (9.2-cm.), 24-in. (60-cm.) o.c.	present report wall A1	+8.0
1.0-in. XPS sheathing, glass fiber as cavity insulation, studs -3-5/8-in. 24-in. o.c.	present report wall A4	+1.2
1.0-in. XPS sheathing, glass fiber as cavity insulation, studs -3-5/8-in. 12-in. o.c.	present report wall B2	+5.4
0.5-in. (1.3-cm.) plywood sheathing, glass fiber as cavity insulation, studs -6-in. (15.2-cm.), 24-in. (122-cm.) o.c.	present report wall D1	+5.1
1.0-in. XPS sheathing, glass fiber as cavity insulation, studs -6-in. 24-in. o.c.	present report wall D2	-2.2

Considering that the precision of the guarded hot box method is reported to be approximately 8 percent [20], the ability of Heating 7.2 to reproduce the experimental data is within the accuracy of the test method.

Figure 7 depicts the base wall configurations used for computer modeling. The following six metal-frame wall configuration variations (3x4x3x4x3x2 = 864 walls) were selected for detailed analysis:

Figure 7
Wall Constructions Used for Computer Modeling



- Stud depth - 3.5-in. (8.9-cm.), 4.0-in. (10.1-cm.), 6.0-in. (15.2-cm.);
- Stud flange size - 1.0-in. (2.5-cm.), 1.5-in. (3.8-cm.), 2.0-in. (5.1-cm.), 2.5-in. (6.4-cm.);
- Stud metal thickness 14 GA (1.9-mm.), 16 GA (1.5-mm.), 18 GA (1.2-mm.);
- Stud spacing 16-in. (40-cm.) o.c., 24-in. (60-cm.) o.c., 40-in. (100-cm.), 60-in. (152-cm.) o.c.;
- Sheathing insulation - 6.5 hft^2F/Btu per in (45mK/W), of thickness 0-in., 0.5-in (1.3-cm.), or 1.0-in. (2.5-cm.); and
- Empty cavity, or insulated cavity 3.45 hft^2F/Btu per in (23.9 mK/W).

In addition, as it is shown in Table 7, several levels of insulation material were considered, to estimate the effect of different insulating techniques, and insulation material thermal properties on the precision of the Zone Method R-value calculations. There were 294 additional wall configuration variations:

Table 7
Metal Stud Wall Configurations With
Variable Thermal Properties of Insulating Materials

stud depth [in]	stud spacing [in]	stud flange size [in]	thickness of sheathing [in]	number of sheathing resistivities	number of cavity insul. resistivities	stud metal thickness
3-1/2	16	1-1/2	1/2	7	3	16 G.A.
4	16	1-1/2	1/2	7	3	16 G.A.
6	16	1-1/2	1/2	7	3	16 G.A
3-1/2	16	1-1/2	1	7	3	16 G.A
4	16	1-1/2	1	7	3	16 G.A.
6	16	1-1/2	1	7	3	16 G.A.
3-1/2	16	1-1/2	1/2	7	3	14 G.A.
3 -1/2	16	1-1/2	1/2	7	3	18 G.A.
3-1/2	24	1-1/2	1/2	7	3	16 G.A.
3-1/2	16	2	1/2	7	3	16 G.A.
3-1/2	16	1-1/2	1/2	7	empty	16 G.A.
3-1/2	16	1-1/2	1	7	empty	16 G.A.
3-1/2	16	1	1/2	7	5	14 G.A.
3-1/2	16	1	1	7	5	14 G.A.

- Seven levels of thermal resistivity for sheathing insulation material 1.0 to 7.0 hft^2F/Btu per in. (7.0 to 49 mK/W) and
- Three, or sometimes five, levels of thermal resistivity for cavity insulation material were considered during modeling:

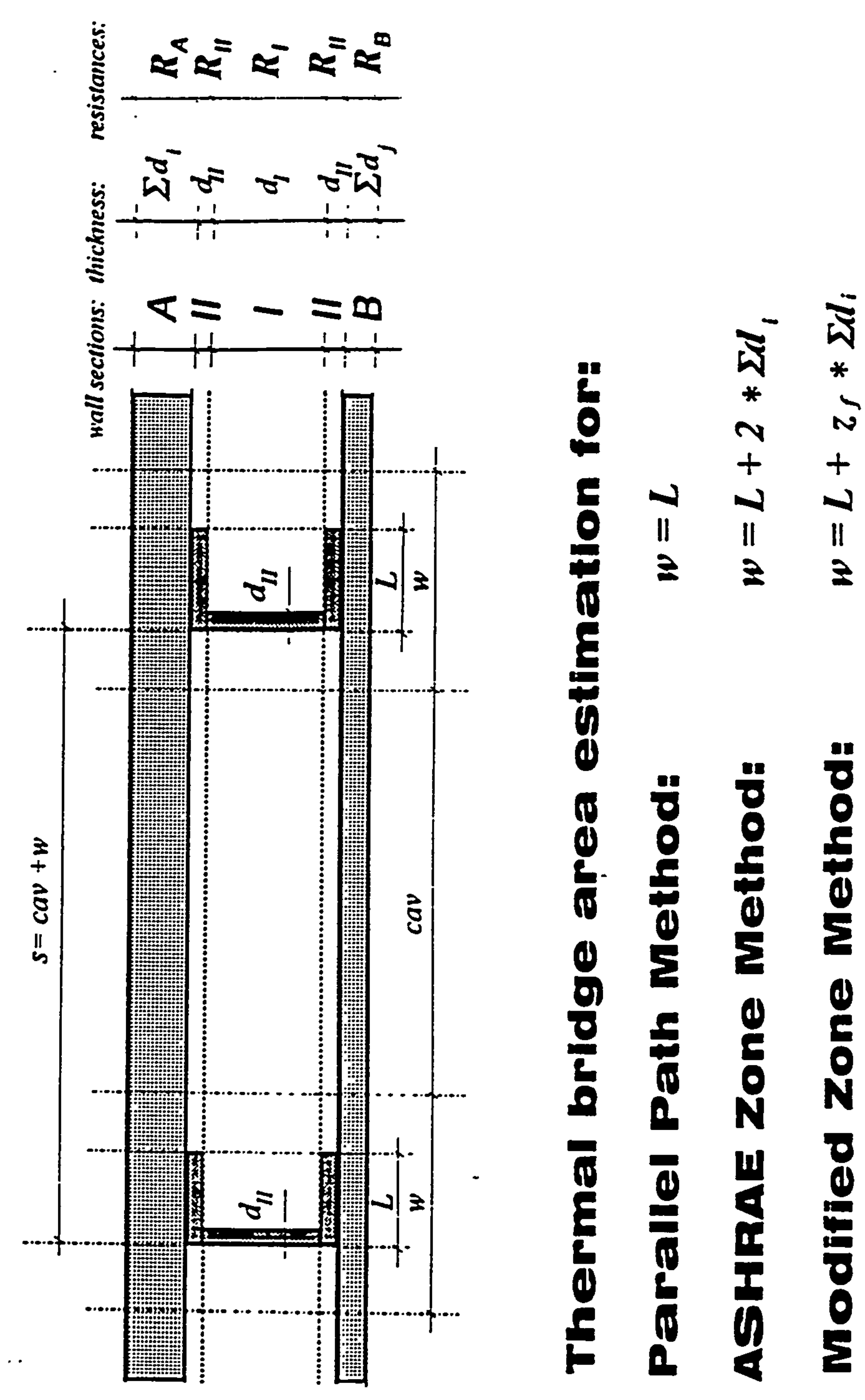
  - 2.0, 3.0, and 4.0 hft^2F/Btu per in. (14.0, 21.0, and 28.0 mK/W), and
  - 2.0, 2.5, 3.0, 3.5, and 4.0 hft^2F/Btu per in. (14.0, 17.5, 21.0, 24.5, and 28.0 mK/W).

For each metal-frame wall case, the simulated R-value was compared with the R-value calculated by means of the ASHRAE Zone Method. This allowed an estimation of errors associated with ASHRAE Zone Method R-value calculations. Then the zone factor was used as a variable parameter to minimize (to less than 0.05 percent) discrepancy between simulated and Zone Method calculated R-values. Using this procedure, it was possible to estimate "accurate" zone factors for all considered metal-frame wall configurations. Then, regression analysis was employed to determine the importance of the design parameters. It was found that changes of stud size, thermal resistivity of sheathing, thermal resistivity of the cavity insulation, and change of thickness of sheathing material were parameters capable of affecting the precision of Zone Method R-value calculations by more than 1.5 percent.

Methods of Clear Wall R-Value Calculations Recommended by ASHRAE for Metal-Frame Walls

There are two methods of clear wall R-value calculations described in Chapter 22 of the ASHRAE Handbook of Fundamentals [1] for structures containing metal elements: Parallel Path Method, and ASHRAE Zone Method. Both methods are based on parallel-path calculations. The only difference between the two methods is the way metal stud thermal bridge area of influence is estimated. Figure 8 shows the width of the zone of thermal anomalies around metal stud - w. This zone can be assumed as equal to the length of the stud flange - L (Parallel Path Method), or can be calculated as a sum of the length of stud flange and a distance double that from wall surface to metal - $\sum d_i$ (ASHRAE Zone Method).

Figure 8
Calculation Model for Metal-Frame Wall



For the purpose of the parametric analysis, the following mathematical procedure was developed. It was found to be much simpler than the procedure described by ASHRAE Handbook of Fundamentals [1]. Also, this technique is less prone to user errors, because only R-values are used rather than a mix of conductivity, R-values, and partial areas of wall sections. For the wall materials, as marked in Figure 8, the area of the wall horizontal intersection was divided into two zones: the zone of thermal anomalies around metal stud - *w* and the cavity zone - *cav*. Vertical layers of wall materials were grouped in two exterior and interior surface sections *A* (sheathing, siding) and *B* (wall-board), and interstitial sections *I* and *II* (cavity insulation, metal stud flange).

Let us assume that the layers or layer of wall materials in wall section *A* are thicker than those in wall section *B*, that can be described as follows:

$$\sum_{i=1}^{n} d_i \geq \sum_{j=1}^{m} d_j \qquad (6)$$

where for the section "*A*," *n* is the number of the layer of material (of thickness d_i) between metal stud flange and the wall surface, and *m* is the number of the layer of material (of thickness d_j) for the section "*B*", respectively.

Then, the width of the zone of thermal anomalies around the metal stud - *w* can be estimated by the following equation:

$$w = L + z_f * \sum_{i=1}^{n} d_i \qquad (7)$$

where L - stud flange size,

d_i - thickness of material layer in section "*A*", and

z_f - zone factor (for ASHRAE Zone Method $z_f = 2$).

For the zones of thermal anomalies around metal stud - *w*, and - *cav*, and for sections of the wall material marked as in Figure 8, partial resistances R_A, R_B, R_I, and R_{II} can be calculated as follows:

- for the section "*A*":

$$R_A = \sum_{i=1}^{n} (r_i * d_i) \qquad (8)$$

where r_i - thermal resistivity of layer of material of thickness d_i in the section "*A*"

- for the section "*B*":

$$R_B = \sum_{j=1}^{m} (r_j * d_j) \qquad (9)$$

where r_j - thermal resistivity of the layer of material of thickness d_j in the section "*B*"

- for the section "*I*" (thickness d_I):

$$\frac{1}{R_I} = \frac{d_{II}}{w*R^I_{met}} + \frac{w-d_{II}}{w*R^I_{ins}} \qquad (10)$$

that gives:

$$R_I = \frac{R^I_{met}*R^I_{ins}*w}{d_{II}*(R^I_{ins}-R^I_{met})+w*R^I_{met}} \qquad (11)$$

where d_{II} - thickness of the section "*II*" (also stud metal thickness), and:

$$R^I_{ins} = r_{ins} * d_I \qquad (12)$$

$$R^I_{met} = r_{met} * d_I \qquad (13)$$

for:

r_{met} - thermal resistivity of metal stud,

r_{ins} - thermal resistivity of insulation in cavity between studs, and

d_I - thickness of the section "*I*".

- for the section "*II*" (representing flange layers of thickness d_{II}):

$$\frac{1}{R_{II}} = \frac{L}{w*R^{II}_{met}} + \frac{w-L}{w*R^{II}_{ins}} \tag{14}$$

that gives

$$R_{II} = \frac{R^{II}_{met}*R^{II}_{ins}*w}{L*(R^{II}_{ins}-R^{II}_{met})+w*R^{II}_{met}} \tag{15}$$

where

$$R^{II}_{met} = r_{met}* d_{II} \tag{16}$$

and

$$R^{II}_{ins} = r_{ins}* d_{II} \tag{17}$$

The total clear wall R-value is calculated as a "parallel sum" of resistances from zones "*w*" and "*cav*." It is given by the following formula:

$$\frac{1}{R_{tot}} = \frac{\frac{w}{\sum R_w} + \frac{cav}{\sum R_{cav}}}{s} \tag{18}$$

but, from the Figure 8, the width of the zone "*cav*" can be estimated as follows:

$$cav = s - w \tag{19}$$

where s - distance between studs.

So, after a set of transformations:

$$R_{tot} = \frac{\sum R_w * \sum R_{cav} * s}{w*(\sum R_{cav} - \sum R_w) + s*\sum R_w} \tag{20}$$

where

$$\sum R_{cav} = R_A + R_B + R^I_{ins} + 2*R^{II}_{ins} \tag{21}$$

$$\sum R_w = R_A + R_B + R_I + 2*R_{II} \tag{22}$$

In case of the metal-frame wall without cavity insulation, the thermal resistances R_{II} can be omitted, and in expressions (10, 11, and 12), the thermal resistance R^I_{ins} should be replaced by the resistance R_{air} of a plane airspace [1 pp. 22.2-22.3], where thickness is equal the stud depth. However, the authors do not recommend the usage of the ASHRAE Zone Method for walls with empty cavities between metal studs.

Accuracy of ASHRAE Zone Method of Clear Wall
R-Value Calculations for Metal-Frame Walls

The zone method for calculating R-values for envelopes containing metal elements [1] is based on the simple, and well-known, Parallel Path Method of summing series and parallel thermal resistances. However, the description is ambiguous and several people can produce different results from the Zone Method calculations on the same wall [21]. Such misinterpretations result in errors in ASHRAE Zone Method calculations. It was found that the usage of the simple, mathematical algorithm developed for this project can reduce many of operations necessary for R-value calculation.

A second source of errors of ASHRAE Zone Method calculations for R-value is the incorrect assumption that the width of the zone of thermal anomalies caused by the metal stud depends only on geometrical dimensions of the stud flange and layers of material between metal and wall surface. The authors believe the description and proposed modification to the ASHRAE Zone Method in this report should reduce both of these sources of errors.

In reality, there are additional parameters affecting the size of this zone. The authors examined the errors generated by the following wall parameters:

- ratio of resistivity of the sheathing material and resistivity of the cavity insulation,

- thickness of sheathing insulation,
- stud depth,
- stud spacing,
- stud flange size, and
- stud thickness (gauge).

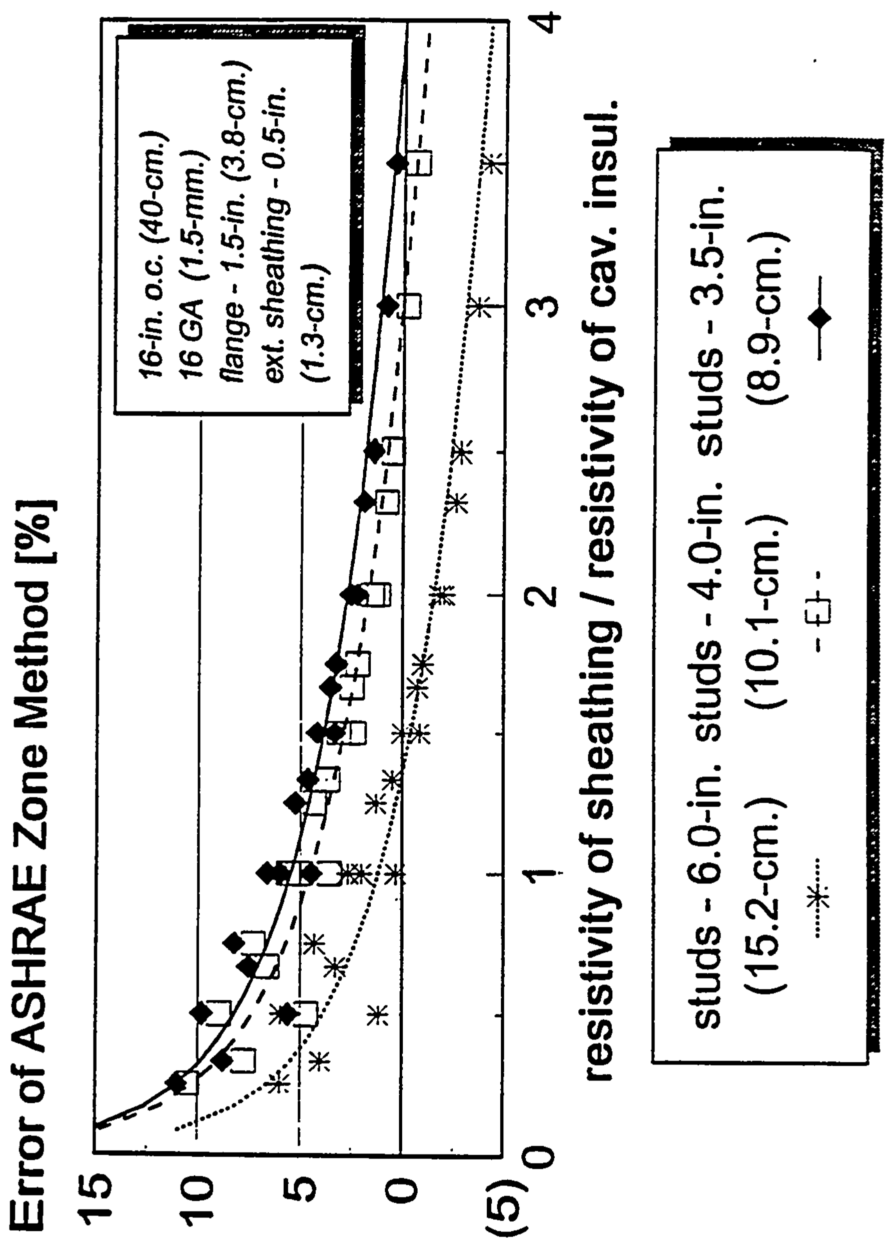
The ASHRAE Zone Method of estimating the thermal bridge area around the metal stud (as shown in Figure 8) results in different errors in the R-value calculations for different wall configurations. Heating 7.2 simulation results were compared against ASHRAE Zone Method R-values for over 1000 metal-frame wall configurations. The errors of ASHRAE Zone Method calculations were estimated by the following formula:

$$\varepsilon = \frac{R_{simul} - R_{zone}}{R_{simul}} * 100\% \qquad (23)$$

where R_{simul} is the Heating 7.2 simulated R-value, and R_{zone} is the R-value calculated by the use of the ASHRAE Zone Method.

In Figure 9, the errors of the ASHRAE Zone Method are depicted as a function of the ratio between sheathing material thermal resistivity and cavity insulation thermal resistivity. It is seen that for 3-1/2 and 4-in. (8.9 and 10.1-cm.) studs the ASHRAE Zone Method underestimates wall R-values up to 15 percent. For the wall configuration of 3-1/2-in. (8.9-cm.) stud, 16 GA (1.5-mm.), 16-in. (40-cm.) o.c. stud spacing, 1.5-in (3.8-cm.) flange, R-12 (2.1-m^2K/W) mineral fiber cavity insulation and 1/2-in. (1.3-cm.) EPS sheathing insulation of R-4 per in. (27.7-mK/W), (ratio of resistivity of sheathing and resistivity of cavity insulation ≈1.2), the ASHRAE Zone Method R-values are only 5 percent lower than results of computer simulation. For 6-in. (actual 5.5-in.) studs R-19 (3.3-m^2K/W) mineral fiber cavity insulation and 1/2-in. (1.3-cm.) EPS sheathing insulation of R-4 per in. (27.7-mK/W), (ratio of resistivity of sheathing and resistivity of cavity insulation ≈1.2) the ASHRAE Zone Method error is less than 1 percent.

Figure 9
Error of ASHRAE Zone Method



In Figure 10, a comparison of the ASHRAE Zone Method errors is shown for 0.5-in (1.3-cm.), and 1.0-in. (2.5-cm.) thick sheathing. Errors are up to four percent higher for walls with 1.0-in. sheathing than for 0.5 in. sheathing. In all but a few cases the ASHRAE Zone Method underestimates the R-value of the metal-frame wall. For the case of 3-1/2-in. (8.9-cm.) stud, 16 GA (1.5-mm.), 16-in. (40-cm.) o.c., 1.5-in (3.8-cm.) flange, R-12 (2.1-m^2K/W) mineral fiber cavity insulation and 1/2-in. (1.3-cm.) plywood sheathing of R-1.2 per in. (8.3-mK/W), (ratio of resistivity of sheathing and resistivity of cavity insulation ≈0.35), the ASHRAE Zone Method error is around 7 percent.

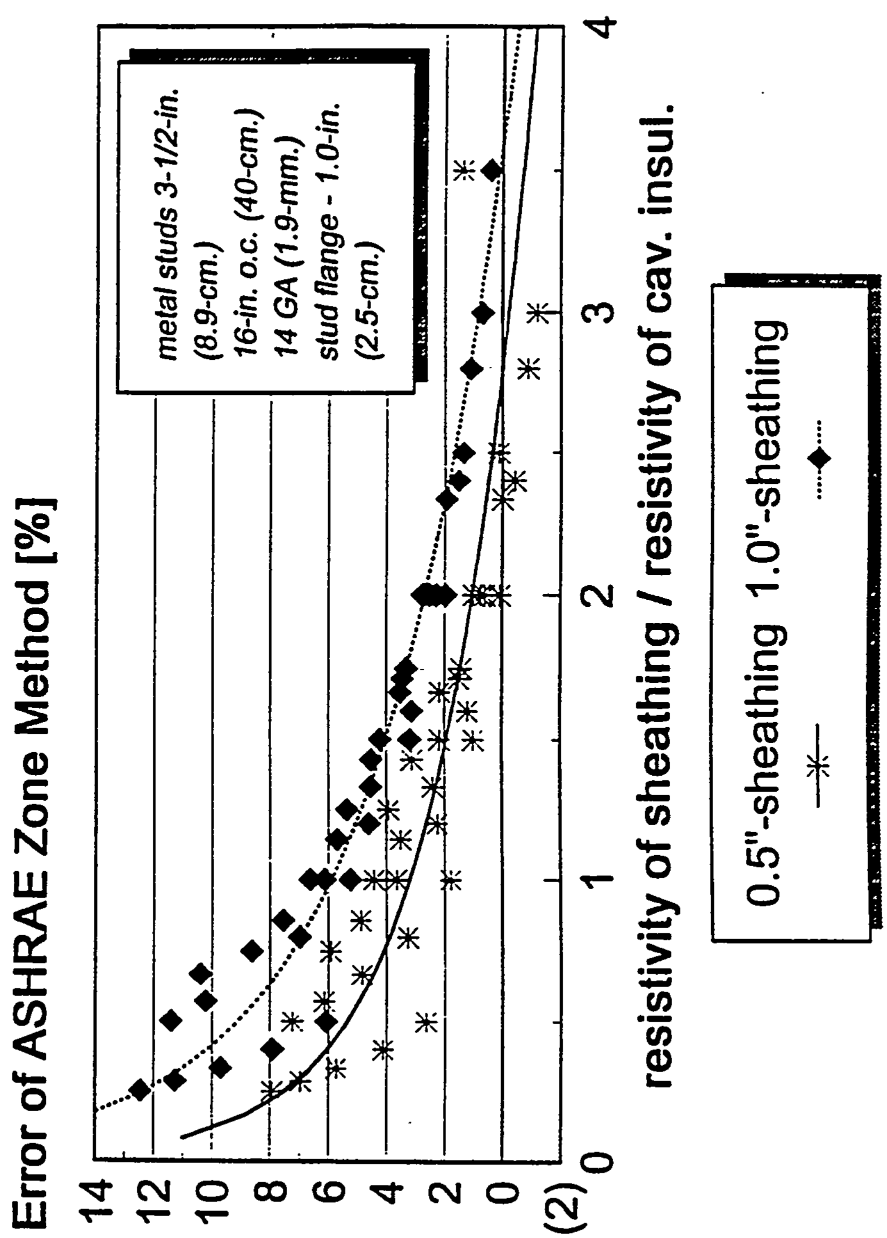
For metal stud walls with empty cavities, the accuracy of Zone Method R-value calculations is not sensitive to changes of the area of thermal bridge zone. For these walls the ASHRAE Zone Method overestimates R-values by +4 to +14 percent. Even greater errors were obtained for walls without exterior sheathing insulation. The authors suggest, that the application of the ASHRAE Zone Method should be limited to cases of metal-frame walls containing cavity filling.

In summary, the differences between ASHRAE Zone Method and Heating 7.2 estimated R-values were within ±15 percent for more than 1000 metal-frame walls configurations. The highest errors were observed for walls without sheathing insulation.

Modified Way of Estimating the Area of Thermal Bridge Caused by Metal Stud for Zone Method Calculations of Clear Wall R-value

Clear wall R-values computed by the ASHRAE Zone Method can vary considerably from those predicted by Heating 7.2 modeling. These differences are caused mostly by the errors in estimating the area influenced by the metal stud thermal bridge. For most wall configurations, the thermal bridge area recommended for ASHRAE Zone Method calculations is too large (as illustrated by the positive errors shown in Figures 9 and 10), while thermal bridge area for Parallel Path Method is too small. The effects of several wall design parameters on the precision of ASHRAE Zone Method R-value calculation were estimated by means of parametric analysis where thermal bridge area was computed by means of the formula (7). Then, the zone factor z_f was used as a variable parameter in reducing the discrepancy between computer simulation generated R-values and ASHRAE Zone Method R-values. The improved values of zone factor z

Figure 10
Error of ASHRAE Zone Method, Dependence



were estimated for error range of ±0.05 percent, for metal-frame wall configurations containing cavity insulation.

In Figure 11, modified zone factors were plotted against the ratio of thermal resistivity of sheathing material to that of the resistivity of the cavity insulation for 3-1/2-in. (8.9-cm.) studs, and for three different stud flange sizes. It is seen that stud flange size does not affect the value of zone factor. This means that the modified Zone Method does not need to be sensitive to the stud flange size.

The influence of stud thickness on the value of the modified zone factor is depicted in Figure 12. For three popular stud metal thicknesses - 14 GA (1.9-mm.), 16 GA (1.5-mm.), and 18 GA (1.2-mm.) the maximum differences between zone factors for the same wall configurations are negligible. A change of stud metal thickness from 14 GA to 18 GA causes an increase of the zone factor of about 0.05. This means that the modified Zone Method does not need to be sensitive to the stud metal thickness.

Figure 13 shows that a change of the distance between studs does not affect the value of zone factor for stud spacing - 16-in. (40-cm.), and 24-in. (60-cm.), with the same wall material configurations (selected form Table 7). This indicates that the modified Zone Method does not need to be sensitive to the stud spacing.

Figure 14 shows how much the inaccurate estimating of a zone factor can result in an error of R-value calculations. It is seen that difference of ±0.1 from the correct value of a zone factor can cause errors within 1.5 percent in the R-value. Therefore, factors such as stud flange size, stud metal thickness, and stud spacing can safely be neglected during estimation of the modified zone factor without significantly reducing the precision of the modified Zone Method R-value computations.

Elimination of the three above mentioned design parameters helped establish a new, simple way of estimating zones of thermal anomalies caused by metal studs for metal-frame walls. The authors have found that, the zone factor is mostly affected by:

Figure 11
Modified Zone Factors for Several Stud Flange Sizes

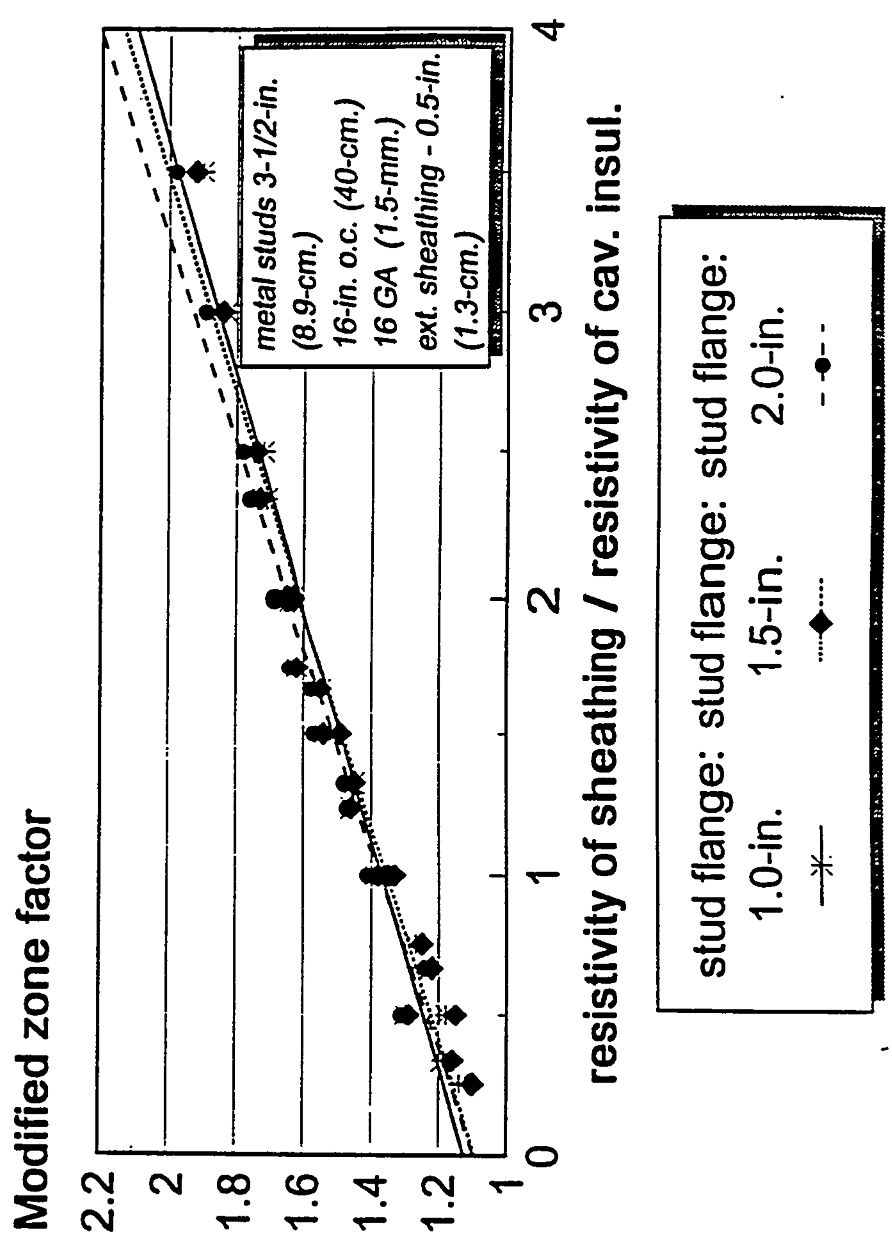


Figure 12
Modified Zone Factors for Metal Thicknesses

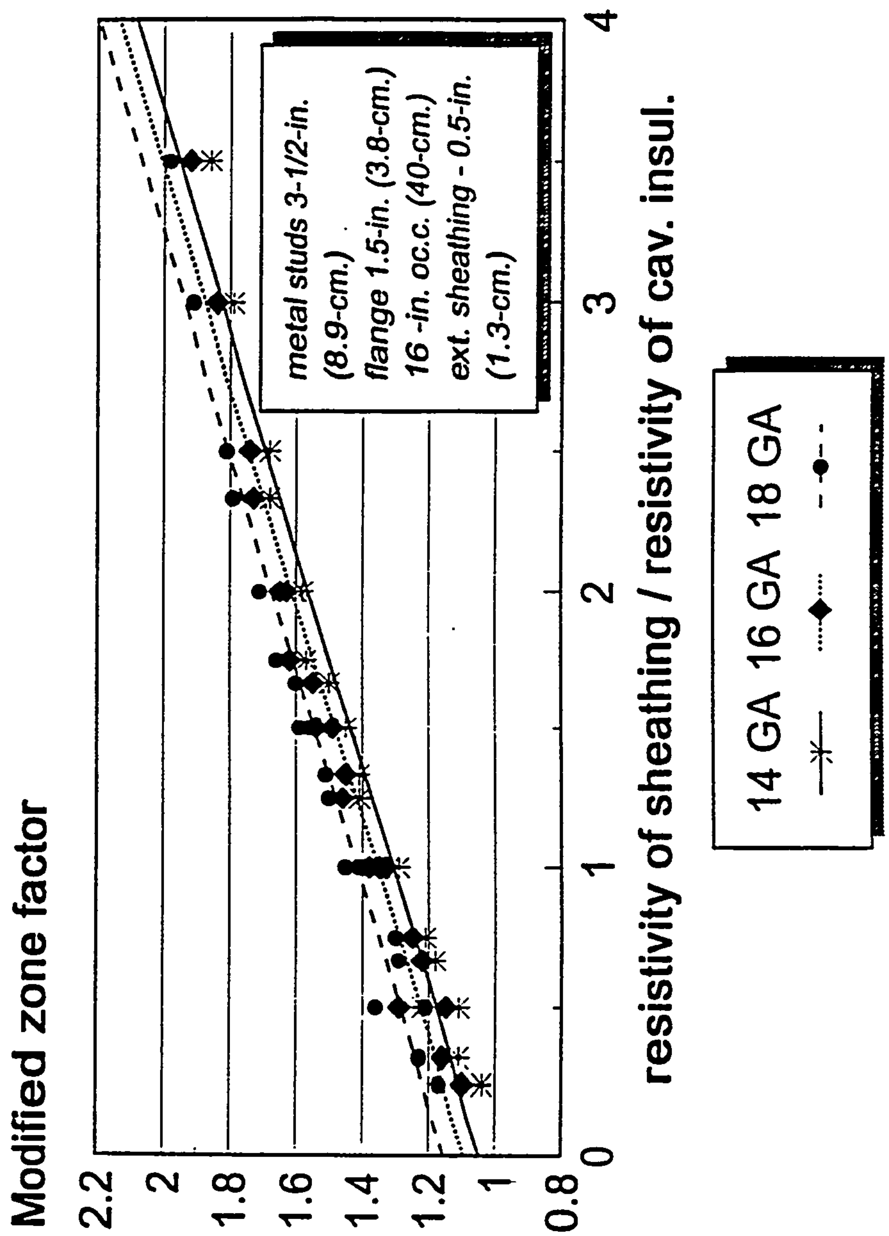


Figure 13
Effect of Stud Spacing on Zone Factors

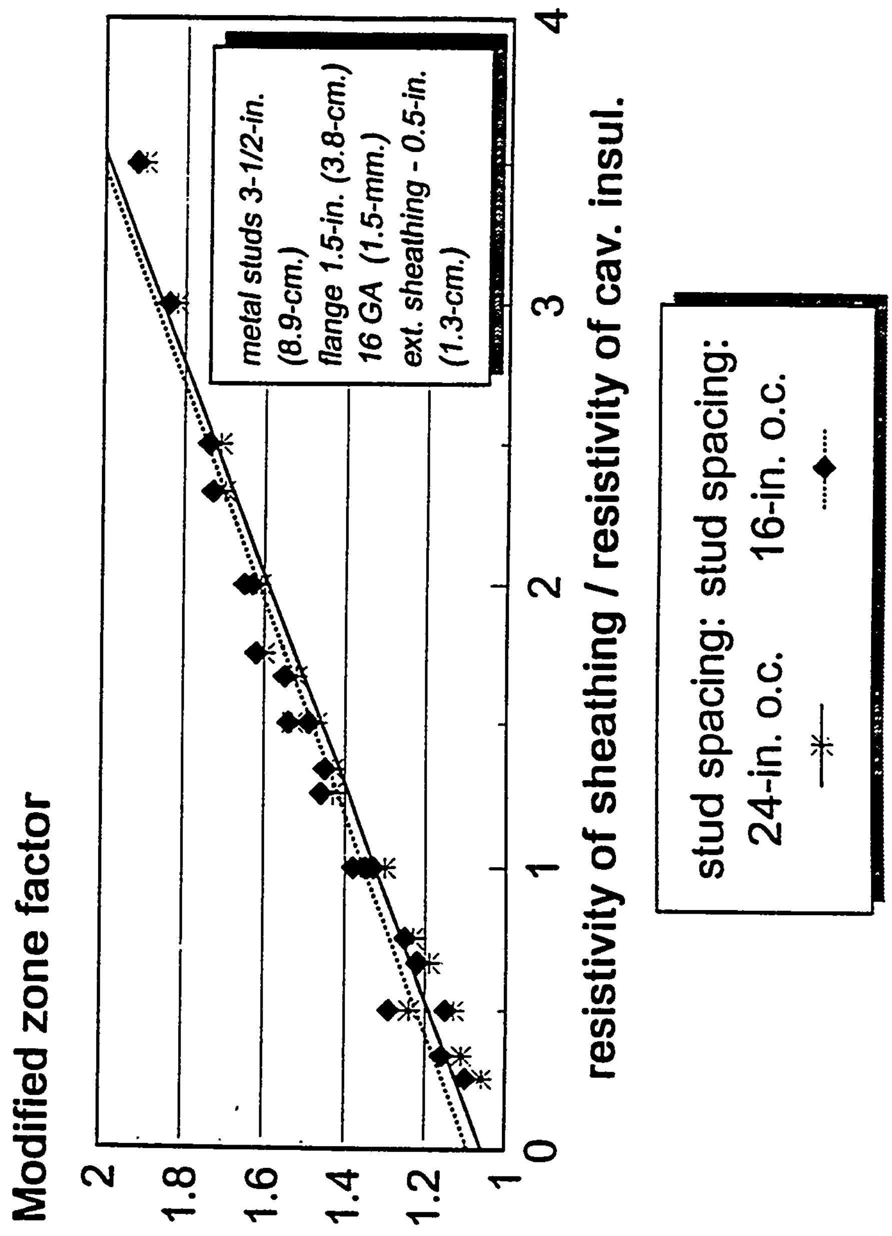
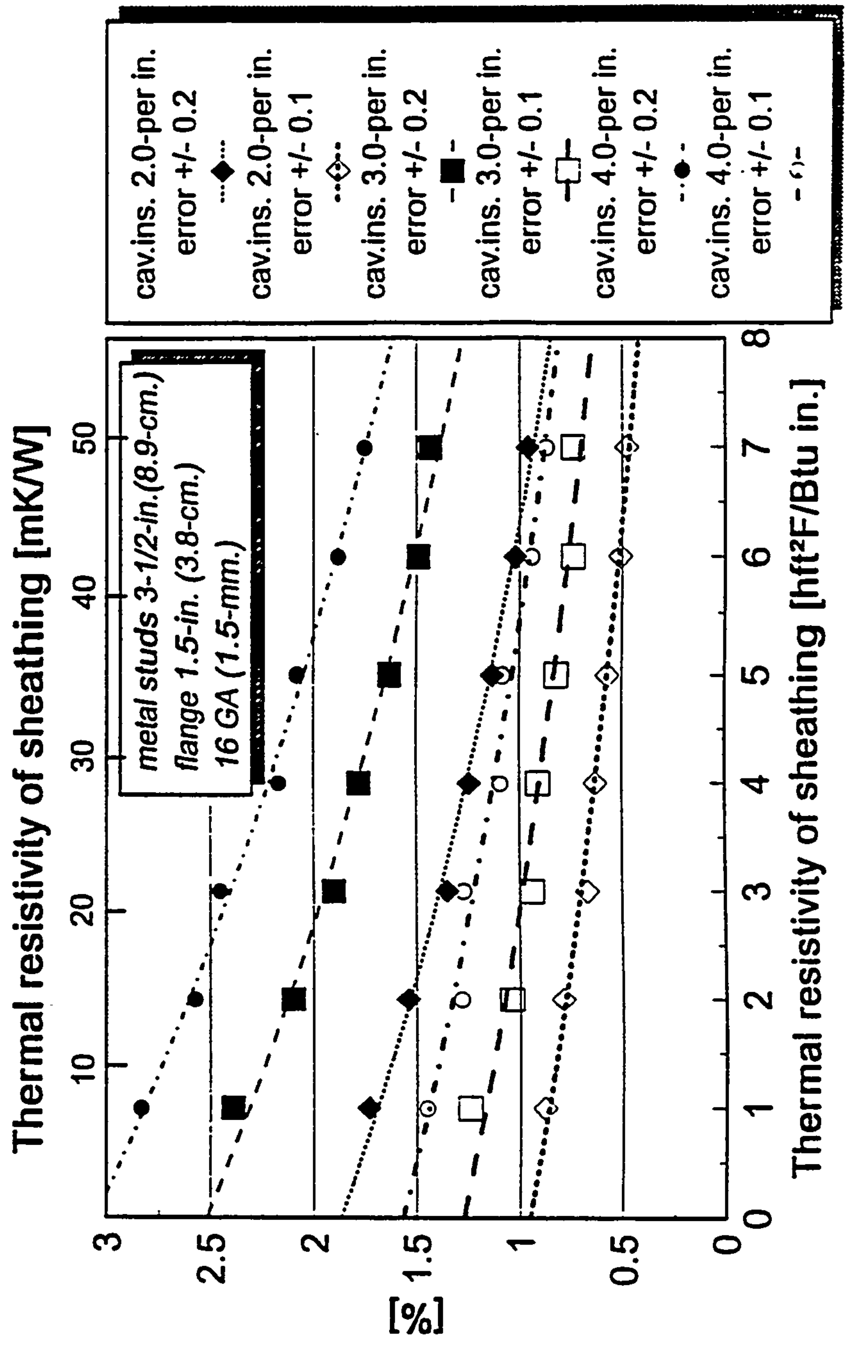


Figure 14
Inaccuracy of Zone Method Due to Zone Factor Estimation



- ratio of thermal resistivity of sheathing material to resistivity of cavity insulation,
- stud depth, and
- sheathing thickness.

Improved values of zone factors for three stud sizes - 3-1/2-in. (8.9-cm.), 4-in. (10.1-cm.), 6-in. (15.2-cm.), and for two sheathing thicknesses - 0.5-in. (1.3-cm.), and 1.0-in. (2.5-cm.) are plotted in Figure 15. It is seen that for very common combinations of materials containing mineral fiber as a cavity insulation - R-3.45 per in. (23.9-mK/W) and EPS sheathing - R-4.0 per in. (27.7-mK/W), (ratio of resistivity of sheathing and resistivity of cavity insulation ≈1.16), the value of zone factor is contained between 1.4 to 1.9 for 0.5-in. (1.3-cm.) thick sheathing, and 1.2 to 1.7 for 1.0-in. (2.5-cm.) thick sheathing.

Figure 15 can also be used to estimate modified zone factors. A thermal bridge area for metal-frame walls with insulated cavities can be computed by means of equation (7) and then parallel path calculations applied according to equations (8), (9), (11), (15), and (20) can serve for determining metal-frame wall R-values. A calculating form for Modified Zone Method R-value computations is presented in Figure 16. It should improve R-value calculations for metal stud walls providing user with a simple step-by-step procedure. An example of R-value calculations, based on modified ASHRAE Zone Method, for metal stud wall is described in Figure 17.

The authors verified the accuracy of the above method of R-value calculations for 712 cases of metal-frame walls with insulated cavities (864 base cases - 432 walls with empty cavities +294 cases from Table 7 - 14 walls with empty cavities = 712). The following set of design parameters was considered:

- Stud depth - 3.5-in. (8.9-cm.), 4.0-in. (10.1-cm.), 6.0-in. (15.2-cm.),
- Stud flange - 1.0-in. (2.5-cm.), 1.5-in. (3.8-cm.), 2.0-in. (5.1-cm.), 2.5-in. (6.4-cm.),
- Stud metal thickness - 14 GA (1.9-mm.), 16 GA (1.5-mm.), 18 GA (1.2-mm.),
- Stud spacing - 16-in. (40-cm.) o.c., 24-in. (60-cm.) o.c., 60-in. (152-cm.) o.c.,
- Plywood or insulation sheathing thickness - 0.5-in (1.3-cm.), 1.0-in. (2.5-cm.).

Figure 15
Modified Zone Factor for R-Value Calculations

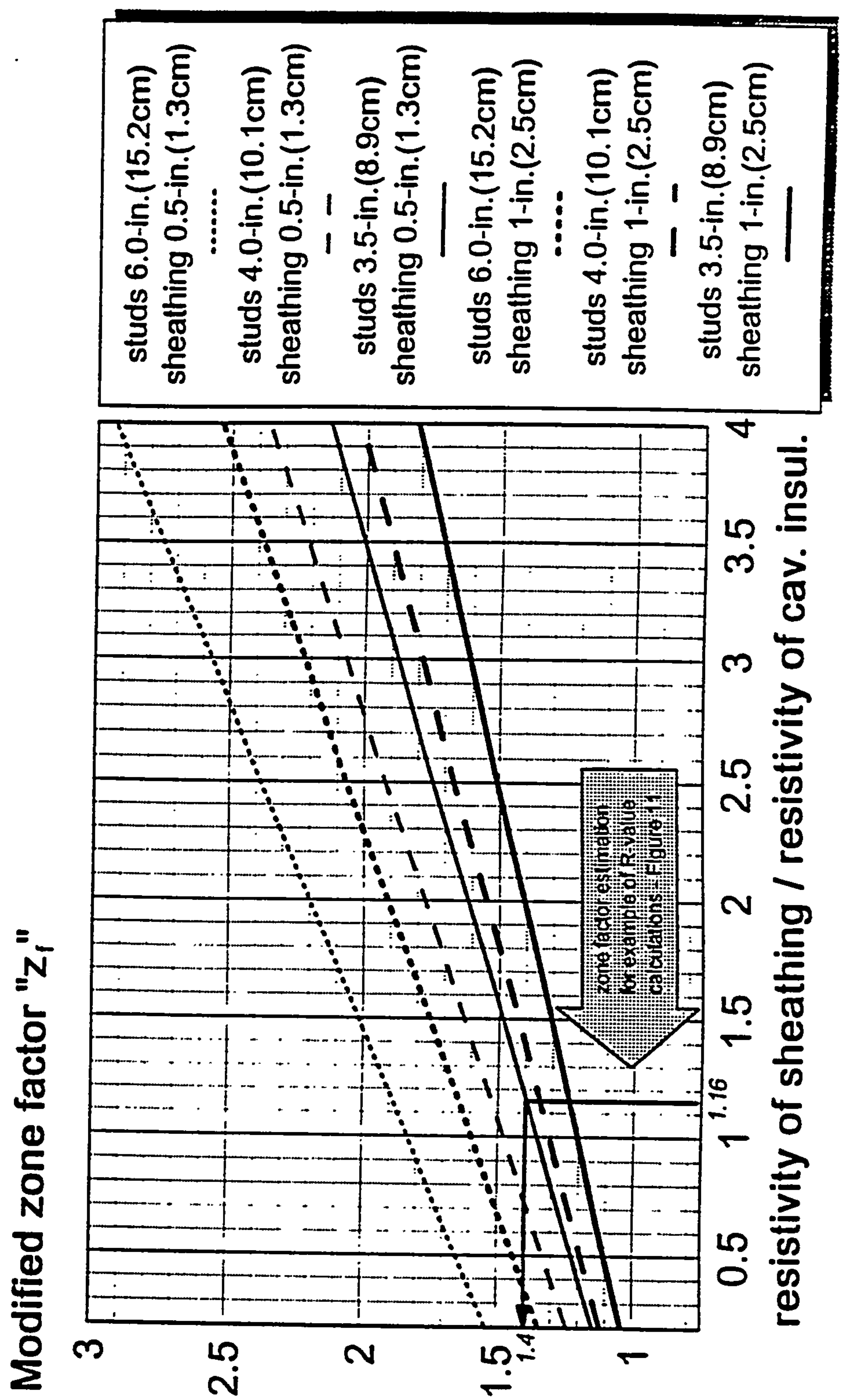
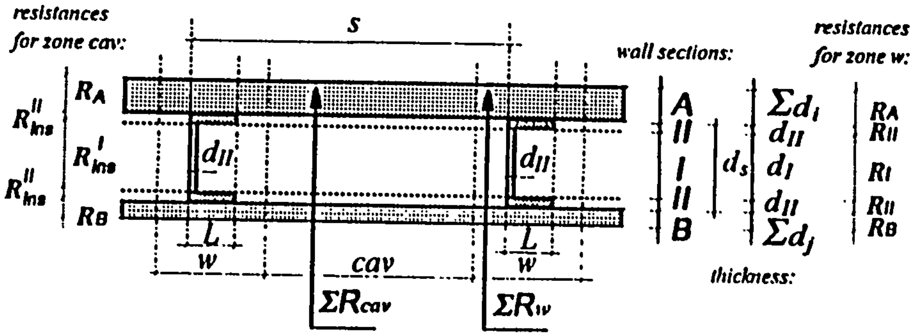


Figure 16
Modified Zone Method R-Value Calculation Form



wall section	material	thickness [in.]	resistivity [hft²F/Btu-in]
A		$d_{i1}=$	$r_{i1}=$
A		$d_{i2}=$	$r_{i2}=$
A		$d_{i3}=$	$r_{i3}=$
B		$d_{j1}=$	$r_{j1}=$
I&II	metal	$d_{II}=$	$r_{met}=$
I&II	cavity insul.	$d_s=$	$r_{ins}=$

s= ; $d_I = d_s - 2 \times d_{II} =$

$\frac{\text{resistivity of sheathing}}{\text{resistivity of cav. insul.}} =$

z_I (*from Zone Factor Chart*) =

$w = L + z_I \times \Sigma d_i =$

$R_A = \Sigma(r_i \times d_i) =$

$R_B = \Sigma(r_j \times d_j) =$

$R'_{ins} = r_{ins} \times d_I =$

$R''_{ins} = r_{ins} \times d_{II} =$

$R'_{met} = r_{met} \times d_I =$

$R''_{met} = r_{met} \times d_I =$

$$R_I = \frac{R'_{met} \times R'_{ins} \times w}{d_{II} \times (R'_{ins} - R'_{met}) + w \times R'_{met}} = \text{\_\_\_\_\_\_\_\_} =$$

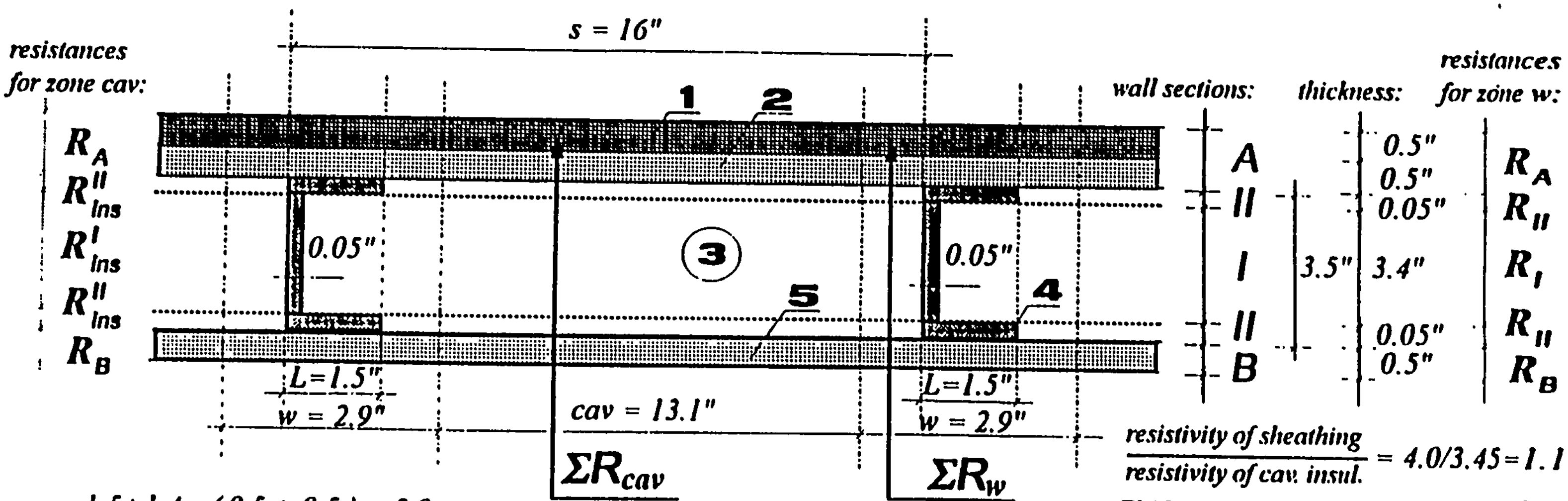
$$R_{II} = \frac{R''_{met} \times R''_{ins} \times w}{L \times (R''_{ins} - R''_{met}) + w \times R''_{met}} = \text{\_\_\_\_\_\_\_\_} =$$

$\Sigma R_{cav} = R_A + R_B + R'_{ins} + 2 \times R''_{ins} =$

$\Sigma R_w = R_A + R_B + R_I + 2 \times R_{II} =$

$$R_{tot} = \frac{\Sigma R_w \times \Sigma R_{cav} \times s}{w \times (\Sigma R_{cav} - \Sigma R_w) + s \times \Sigma R_w} = \text{\_\_\_\_\_\_\_\_} = \boxed{\quad [hft^2F/Btu]}$$

Figure 17
Example of Modified Zone Method R-Value Calculation



$\frac{\text{resistivity of sheathing}}{\text{resistivity of cav. insul.}} = 4.0/3.45 = 1.16$

Zf (from Zone Factor Chart - Fig.9) = 1.4

$w = 1.5 + 1.4 \times (0.5 + 0.5) = 2.9$

$cav = 16 - 2.9 = 13.1$

1 - plywood $r = 1.2$ hft²F/Btu-in.
2 - EPS $r = 4.0$ - " -
3 - fiber-glass $r = 3.45$ - " -
4 - metal $r = 0.003$ - " -
5 - dry-wall $r = 0.9$ - " -

$R_A = 0.5 \times 4.0 + 0.5 \times 1.2 = 2.6$ hft²F/Btu
$R_B = 0.5 \times 0.9 = 0.45$ - " -
$R^{I}_{ins} = 3.4 \times 3.45 = 11.73$ - " -
$R^{II}_{ins} = 0.05 \times 3.45 = 0.173$ - " -
$R^{I}_{met} = 3.4 \times 0.003 = 0.0102$ - " -
$R^{II}_{met} = 0.05 \times 0.003 = 0.00015$ - " -

$$R_I = \frac{0.0102 \times 11.73 \times 2.9}{0.05 \times (11.73 - 0.0102) + 2.9 \times 0.0102} = 0.56 \text{ hft}^2\text{F/Btu}$$

$$R_{II} = \frac{0.00015 \times 0.173 \times 2.9}{1.5 \times (0.173 - 0.00015) + 2.9 \times 0.00015} = 0.00029 \text{ hft}^2\text{F/Btu}$$

$$\Sigma R_{cav} = 2.6 + 0.45 + 11.73 + 2 \times 0.173 = 15.126 \text{ hft}^2\text{F/Btu}$$

$$\Sigma R_w = 2.6 + 0.45 + 0.56 + 2 \times 0.00029 = 3.61 \text{ hft}^2\text{F/Btu}$$

$$R_{tot} = \frac{3.61 \times 15.126 \times 16}{2.9 \times (15.126 - 3.61) + 16 \times 3.61} = 9.58 \text{ hft}^2\text{F/Btu}$$

The R-values of all these cases, obtained using the proposed modified Zone Method, were compared against Heating 7.2 simulation results. They were within the range of ±2 percent of the Heating 7.2 simulation results.

Summary

This chapter introduces a new, improved method for estimating the clear wall R-value of the metal-frame wall systems. This Modified Zone Method is accurate within ±2 percent of error if compare to a validated computer model. This Modified Zone Method makes three major improvements to the ASHRAE Zone Method; the best available simple calculation procedure prior to this work:

- It provides a more accurate estimate of the zone factor input to the calculation which is more sensitive to common metal stud wall variations.
- The calculation technique is much simpler and less prone to user errors. There are fewer computational steps and only R-values are used rather than a mix of thermal conductivities, R-values and partial areas of the wall section (a one-page easy to use form is provided in Figure 16).
- The description of this method, example of R-value calculation - Figure 17, and step-by-step calculating form illustrated within this chapter are far superior to the frequently misinterpreted explanations found in the ASHRAE 1993 Handbook of Fundamentals.

A validated computer model has been used to analyze the accuracy of the ASHRAE Zone Method of clear wall R-value calculations for walls containing metal studs. Over 1000 metal-frame walls were simulated using a finite difference computer code. This work has lead to the following major conclusions useful in the design and thermal performance characterization of metal-frame wall systems.

1. The accuracy of the ASHRAE Zone Method of R-value calculations for metal-frame walls is about ±15 percent. The less accurate results of R-values were observed for walls with no exterior sheathing insulation.

2. The main reason of inaccuracy of the ASHRAE Zone Method at R-value computations of metal-frame walls with insulated cavities is the assumption of the uniform zone factor for all wall geometries and material configurations.

3. For metal stud walls with empty cavities the ASHRAE Zone Method overestimates clear wall R-values up to 15 percent. For metal stud walls with empty cavities the accuracy of Zone Method R-value calculations is not sensitive to changes of zone factors. Due to this fact, we could not find the way of increasing accuracy of Zone Method R-value calculations for metal stud walls with empty cavities by using more accurate, modified zone factors. So, we suggest limited application of Zone Method only for cases of metal stud walls containing cavity insulation.

4. For walls with cavity insulation, the accuracy of Zone Method R-value computations strongly depends on the thermal bridge area, that is assumed in the parallel path calculations.

5. An application of the modified zone factors can reduce errors of Zone Method R-value calculations to ±2 percent or less for metal-frame walls with insulated cavities.

6. This simple method does not account for the other thermal shorts found in metal-frame walls, such as corners, door and window openings, and structural joints with roofs, floors, ceilings and other walls. For such more general analysis, we suggest the application of a simple method developed by J. Kosny and A.O. Desjarlais including the impacts of these wall details on the total overall wall thermal resistance [15]. This would generate an overall wall R-value for metal-frame walls.

APPLICATIONS - HOW TO CALCULATE R-VALUE FOR STEEL-FRAMED WALLS

As discussed earlier, the width for the thermal bridge area is calculated using the equation:

$$W = m + 2*d \tag{1}$$

If the constant 2 is allowed to become a variable, designated the zone factor Z, and then used to reduce the discrepancy between the computer simulation results and the ASHRAE Zone method R-values the above equation becomes:

$$W = m + Z*d \tag{24}$$

where W = thermal bridge width
m = width of stud (often flange width)
Z = zone factor
d = distance from wall exterior surface to flange of steel stud

The researchers concluded through the parametric study that the zone factor was mostly affected by the ratio of thermal resistivity of sheathing to cavity insulation, size of the stud and thickness of sheathing material. Correct values of zone factors for 3.5" and 6" studs with two sheathing thicknesses, 0.5" and 1.0", are shown in Figure 15. These factors can be used to calculate the correct width for the thermal bridge, which can then be used to calculate the wall's R-value. The researchers verified the accuracy of the above method of R-value calculations for over 200 cases of steel-frame walls with insulated cavities.

Below is an example calculation of how to calculate the R-value of a steel-frame wall:

Example of R-Value Calculation

Problem: Using the ORNL zone factor and the ASHRAE Zone method, calculate the wall R-value for a house with nominal 3.5" by 1.25", 0.04" thick steel studs at 24" o.c., with R-11 fiberglass insulation. The inside finish is 0.5" gypsum wallboard; the outside finish is 1" extruded polystyrene (R-5) with 0.5" hardboard siding.

Solution: For a home with 24" o.c. construction, framing will typically account for 12 percent (framing percentage) of the thermal transmission area. This 12 percent accounts for studs, tracks, and extra framing around windows. This percentage may change depending on the design, and the accurate framing percentage may need to be calculated. The remaining 88 percent will be insulated cavity. The R-values and thermal conductivities for the various building materials can be obtained from manufacturers and publications such as The ASHRAE Handbook of Fundamentals [1].

Step 1: Determine thermal conductivities (k (Btu·in/hr f^2 °F)) and conductances (C (Btu·in/hr f^2 °F)) for the materials:

Steel	314.4 Btu·in/hr·ft^2·°F
Gypsum	2.22 Btu/hr·ft^2·°F
Insulating sheathing (XPS)	0.2 Btu·in/hr·ft^2·°F
Hardboard siding	1.5 Btu/hr·ft^2·°F
Cavity insulation	0.318 Btu·in/hr·ft^2·°F

Step 2: Calculate adjusted spacing between two studs

The first computation is to calculate the adjusted spacing between the two studs. This is the apparent spacing between two members using the framing percentage above, and is used to calculate the basic area. The basic area is the area of transmittance used to calculate the R-value of the wall:

Adjusted section width = 2 * flange width/framing percentage = 2 * 1.25"/0.12 = 20.8"
Adjusted spacing = adjusted section width/2 = 20.8"/2 = 10.4"

This defines the width of area to be evaluated for the R-value and takes into account the tracks, studs, and extra framing around windows. For the ASHRAE Zone method, this is the representative area of the wall with one stud in the center of adjusted section width.

Step 3: Calculate Basic Area of Transmittance

The basic area is calculated using the adjusted spacing above to arrive at the area to be evaluated. Since the framing percentage has already been taken into account in calculating the width of basic area, a height of 12", or 1', is assumed to simplify the calculations.

Basic Area = (10.4"/12") * 1' = 0.87 ft^2

This area is then divided into two zones, one with a steel element (Zone A) and one without (Zone B), and the representative UA values are calculated for the parallel path through each Zone.

Step 4: Calculate area of Zone A and Zone B

Using Equation (26) to calculate the width, first determine the zone factor. Resistivity is the inverse of conductivity, or 1/k.

Resistivity of exterior sheathing/Resistivity of insulation = (1/0.2 Btu·in/hr·ft^2·°F)/(1/0.318 Btu·in/hr·ft^2·°F) = 1.59. From Figure 16, the zone factor, Z, is 1.3.

The width of Zone A is determined using Equation (26).

Inside $W = m + Z*d = 1.25'' + 1.3*0.5'' = 1.9''$

Outside $W = m + Z*d = 1.25'' + 1.3*(1.0''+0.5'') = 3.2''$

Using the larger value of W, the area of Zone A is $(3.2''/12'')*1' = 0.27$ ft^2. The area of Zone B is 0.87 ft^2 - 0.27ft^2 = 0.6 ft^2

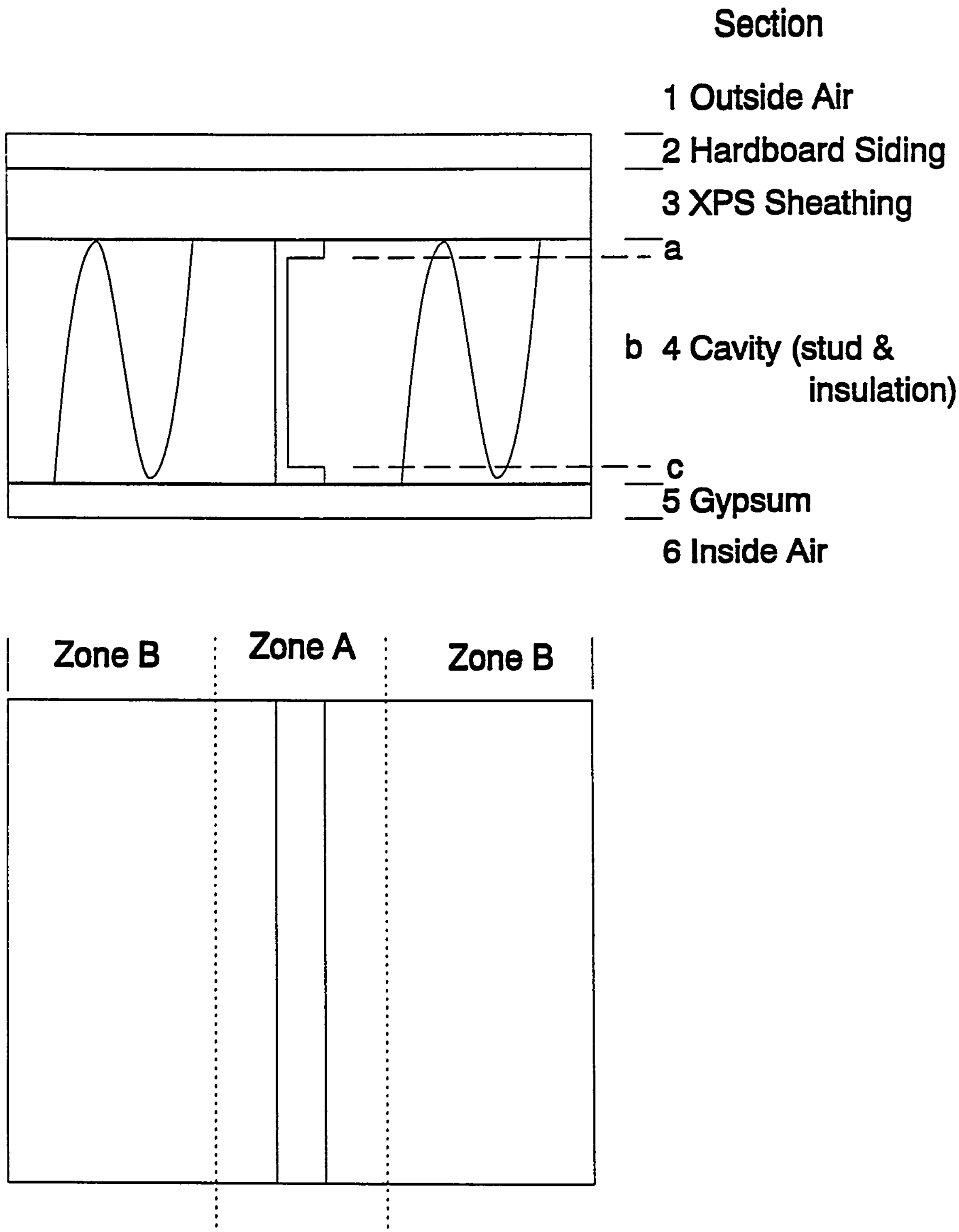
Step 5: Determine area transmittance (UA) for Zone A

Using the method outlined in the ASHRAE Handbook of Fundamentals, the wall is divided into parallel sections from inside to outside, and the area conductance of each section is calculated by adding the area conductances of its metal and nonmetal paths. These are converted to area resistances R/A and added to obtain the total resistance of Zone A. Figure 18 shows the wall with sections and zones outlined.

Table 8
Zone A Area Transmittance

Section	Area x Conductance = CA	1/CA = R/A
No. 1 Air (outside, 15 mph)	0.27 ft^2 x 6 Btu/hr·ft^2·°F = 1.62	0.62
No. 2 0.5" hardboard siding	0.27 ft^2 x 1.5 Btu/hr·ft^2·°F = 0.41	2.44
No. 3 1" XPS	0.27 ft^2 x 0.2 Btu·in/hr·ft^2·°F / 1" = .05	20
No. 4a Steel flange	0.1 ft^2 x 314 Btu·in/hr·ft^2·°F /0.04" = 785	1/(785 + 1.35) = 0.0013
No. 4a Insulation	0.17 ft^2 x 0.318 Btu·in/hr·ft^2·°F /0.04" = 1.35	
No. 4b Steel web	0.003 ft^2 x 314 Btu·in/hr·ft^2·°F /3.42" = 0.275	1/(0.275 + .025) = 3.33
No. 4b Insulation	0.267 ft^2 x 0.318 Btu·in/hr·ft^2·°F /3.42" = 0.025	
No. 4c Steel flange	0.1 ft^2 x 314 Btu·in/hr·ft^2·°F /0.04" = 785	1/(785 + 1.35) = 0.0013
No. 4c Insulation	0.17 ft^2 x 0.318 Btu·in/hr·ft^2·°F/0.04" = 1.35	
No. 5 Gypsum	0.27 ft^2 x 2.22 Btu/hr·ft^2·°F = 0.45	1.66
No. 6 Air (inside)	0.27 ft^2 x 1.63 Btu·in/hr·ft^2·°F = 0.44	2.27
	Total R/A	30.32
	UA	0.033

Figure 18
Example Wall for Modified Zone Method of Calculation



For Zone B, the unit resistances are added and then converted to area transmittance:

Table 9
Zone B Area Transmittance

Section	Unit Resistance, R (hr·ft²·°F/Btu)
No. 1 Air (outside, 15 mph)	0.17
No. 2 Hardboard siding	0.67
No. 3 XPS	5
No. 4 Insulation	11
No. 5 gypsum	0.45
No. 6 Air (inside)	0.61
Total R	17.9
UA	(1/17.9)*0.6 ft² = 0.034

Step 6: Calculate R-value: Add UA from each of the Zones to obtain an area transmittance for the basic area = 0.033+0.034 = 0.067

The effective R-value is the basic area divided by the total UA from above.

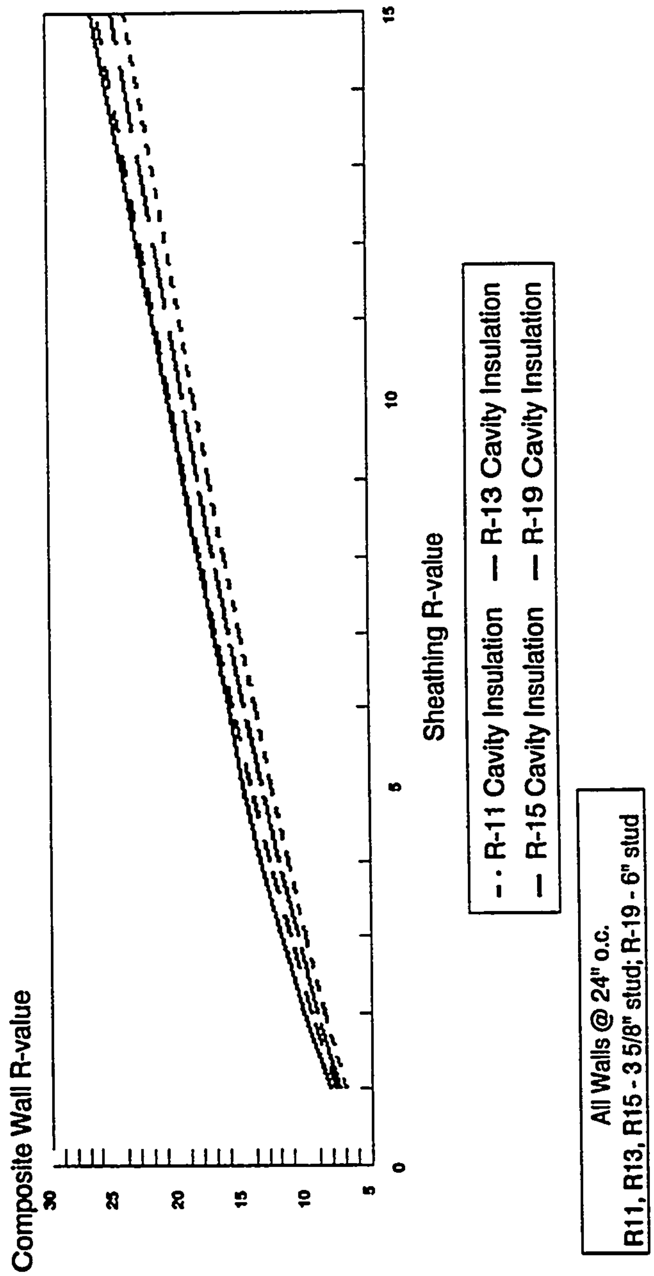
Solution: R-value = 0.87/0.067 = 13.0 hr·ft² °F/Btu.

The above method can be used to calculate the R-value of walls with 3.5" and 6" studs, any thickness, with any exterior sheathing using the ORNL zone factor with the ASHRAE Zone method.

Simplified Graph For Wall R-Values

Figure 19 shows a linear estimation for the R-value of a steel-framed wall based on (1) total sheathing with the R-value indicated on the abscissa, and (2) cavity insulation R-value indicated for the plotted lines. Using 24" o.c. walls, the graph was created from a parametric study using the TABA finite-difference model and varying the sheathing R-values. Results using the graph were found to be within 5 percent of the test results. The graph offers a simplified method for quickly estimating the R-value, without any lengthy and time consuming computations. The graph could be used by builders and building officials to provide a reasonably accurate estimation for the R-value for the wall, with calculations using the method outlined previously available if needed.

Figure 19
Simplified Graph for Estimating Wall R-Value



CONCLUSIONS

The results of these tests showed how typical residential steel-frame walls perform with different steel stud types, cavity insulations and several exterior sheathings. The data obtained not only provide a database for the study of thermal bridges but also provide a means for validating calculation methods.

An important conclusion gained from this testing is that the use of insulative sheathing can decrease the effects of the thermal bridging by the steel framing. Moreover, the "Parallel Path Correction Factors" for wall sections with metal studs presented in ASHRAE 90.1 appear to be accurate only for wall sections with low R-value sheathing. The correction factors for ASHRAE were reasonably reproduced in this testing program for walls sheathed with plywood only, but the data show that adding insulative sheathing to the exterior of the walls effectively increases the correction factors for these walls.

The test results suggest that surface temperature gradients, the difference in surface temperature over the cavity and that over the center of the stud, on the gypsum (warm side) are larger in steel-framed walls with low R-value exterior sheathing. By using a higher R-value sheathing, this surface temperature gradient is reduced. Analysis of the surface temperature gradients near the studs on the warm side of the sample illustrates this point. When comparing interior and surface temperatures on the warm side of the sample, the apparent difference between the temperature over the stud cavity and over the stud decreases as the R-value of the sheathing increases (the temperature over the cavity being somewhat constant and the temperature over the stud increasing as sheathing R-value increases). This indicates a reduction of heat flowing through the stud for larger R-value sheathing and a reduction in thermal bridging effects.

The finite-difference model produced accurate R-values for the walls modeled. Although this method is not available or simple enough for everyday use, results help to define the stud's region of influence. The region of influence for a steel stud was found dependent on the R-value of sheathing used for the walls. The ASHRAE Zone method defines the region as a distance from the closest surface, not the relative thermal conductivity of the material(s) to the surface.

This is done to isolate the two dimensional effects of the steel framing and, since the R-value of the sheathing considers the area transmittance of both zones, a reasonable estimate is obtained. The only flaw comes in the area of influence changes based on the temperature of the steel stud, which is dependent on the sheathing used, as evident in the surface to surface temperature distributions and surface temperatures. Compared to experimental results, the walls without insulative sheathing had higher ASHRAE Zone method R-values, and the walls with insulative sheathing had lower ASHRAE Zone method R-values. By using the zone factor with the ASHRAE Zone method, and not a uniform zone factor, the accuracy of the ASHRAE Zone method can be increased to ± 2 percent for steel-framed walls with cavity insulation.

In conclusion, the test results showed the use of insulating sheathing increased the walls R-value by a greater amount than that expected based solely on the sheathing R-value. Comparing the test results to R-value estimates using the parallel path method, the isothermal planes method and the ASHRAE Zone method showed that the known procedures do not fully account for the two-dimensional effects created by steel framing in a wall, often underestimating the walls R-value when insulating sheathing is used. This suggests that the use of insulating sheathing in wall constructions mitigates the effects of thermal bridges, including heat loss, streaking on the studs, and condensation.

REFERENCES

1. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook of Fundamentals, 1993.

2. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Manual of Heat Transmission Coefficients for Walls, Roofs, Ceilings, and Floors, 1993.

3. Brown, W.C., D.G Stephenson, Guarded Hot Box Measurements of the Dynamic Heat Transmission Characteristics of Seven Wall Specimens: Part II. ASHRAE Transactions. volume 99, part 1, 1993

4. Staelens, P.G., Thermal Bridges and Standardization, ASHRAE Transactions, volume 94, part 2, 1988.

5. Trethowen, H.A., Thermal Insulation and Contact Resistance in Metal-Framed Panels, ASHRAE Transactions, volume 94, part 2, 1988.

6. Farouk, B. and Larson, D.C., Thermal Performance of Insulated Wall Systems with Metal Studs, Intersociety Energy Conversion Engineering Conference, August 1983.

7. Ratliff, G.D. and Roeder, G.M., Thermal and Structural Behavior of Walls Made with Steel Studs with Slit Webs. United States Steel Report 57.019-052(5), December 1971.

8. Crise, D.J., Thermal Performance of Walls Framed with Steel Studs with Slit Webs. United States Steel Report 48.019-005(3), November 1972.

9. Strzepek W.R., Thermal Resistances of Metal-Frame Wall Constructions Incorporating Various Combinations of Insulating Materials, Insulation Materials, Testing and Applications, ASTM/STP 1030, 1990.

10. American Society of Testing and Materials, ASTM C 518 - 91, Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of Heat Flow Apparatus, Annual Book of ASTM Standards, Vol 04.06.

11. American Society of Testing and Materials, ASTM C 976 - 90, Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box, Annual Book of ASTM Standards, Vol 04.06.

12. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings, ASHRAE/IES 90.1-1989.

13. The Thermal Performance of Steel Stud Framed Walls with Different Stud Cavity Insulations and Exterior Sheathings. Holometrix Report NAH-1 for American Iron and Steel Institute. February 1994.

14. James, T.B. and W.P. Goss, User's Manual for Program TABA (Thermal Analysis of Building Assemblies), American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1993.

15. Kosny J., Desjarlais A.O. "Influence of Architectural Details on the Overall Thermal Performance of Residential Wall Systems." - Journal of Thermal Insulation and Building Envelope, April 1994.

16. K.W. Childs, "HEATING 7.2 User's Manual," Oak Ridge National Laboratory Report ORNL/TM-12262, February 1993.

17. R.C. Valore, "Thermophysical Properties of Masonry and it's Constituents - Part II: Thermal Transmittance of Masonry," International Masonry Institute, Washington, DC. 1988.

18. M.G. Van Geem, "Thermal Transmittance of Concrete Block Walls with Core Insulation," Journal of Thermal Insulation, Vol. 9, January 1986.

19. T.B. James, "Manual of Heat Transmission Coefficients for Building Components," - Final Draft. Dept. of Mechanical Engineering, University of Massachusetts, Amherst, MA, Nov. 1990.

20. ASTM C 236-89, Standard Test Method for "Steady-State Thermal Performance of Building Assemblies by Means of Guarded Hot Box," Vol 04.06, pp. 53-63.

21. "Foam Sheathing Over Steel Framing - Does It "Fix" Thermal Bridging?" Energy Design Update, July 1993, pp. 6 - 9.