Dynamic Thermal Performance of Concrete and Masonry Walls

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ABSTRACT

Modern, massive building envelope technologies (masonry and concrete systems) are gaining acceptance by builders today. All U.S. thermal building standards, including ASHRAE 90.1 and 90.2 and the Model Energy Code, are linked to the steady-state clear wall R-value. They also have separate requirements for high mass walls.

Very often, only steady-state R-value is used as a measure of the steady-state thermal performance of the wall. This value does not reflect the dynamic thermal performance of massive building envelope systems. Proper application of thermal mass in buildings can be one of the most effective ways of reducing building heating and cooling loads. However, these systems require application of dynamic thermal performance analysis.

The dynamic thermal performance of a series of wall assemblies is analyzed in this paper. Results should enable an approximate dynamic thermal performance evaluation for most popular massive walls. Also, some complex structures are analyzed. Normally, complex three-dimensional building envelope components cannot be accurately simulated using one-dimensional computer models such as DOE-2 or BLAST. Typically, thermal modelers have to use simplified one-dimensional descriptions of complex walls, which may significantly reduce the accuracy of computer modeling. The application of a newly developed equivalent wall theory enabled accurate whole building dynamic energy analysis for complex three-dimensional wall material configurations.

A new measure of the wall thermal dynamic performance is proposed in this paper—dynamic benefit for massive systems (DBMS). The thermal mass benefit is a function of the material configuration and climatic conditions. To enable wall performance comparisons, the "R-value equivalent for massive system" is used. The R-value equivalents for massive walls are obtained by comparison of the thermal performance of the massive walls and lightweight wood frame walls.

INTRODUCTION

Proper application of thermal mass in buildings can be one of the most effective ways of reducing building heating and cooling loads. Several massive modern building envelope technologies (masonry and concrete systems) have found their application in buildings in the last decade. They suffer from the lack of an accepted measure of their thermal performance. The steady-state R-value traditionally used as a wall thermal performance measure does not reflect the dynamic thermal performance of massive building envelope systems. To show the benefit of these systems, thermal performance analysis has to incorporate thermal mass effects.

A new measure of the wall thermal dynamic performance is proposed in this paper—dynamic benefit for massive systems (DBMS).The thermal mass benefit is a function of the material configuration and climatic conditions. DBMS values are obtained by comparison of the thermal performance of the massive walls and lightweight wood frame walls. The product of DBMS and steady-state R-value is called "R-value equivalent for massive systems," which enables comparisons of massive walls. It does not have a physical meaning and should be understood only as an answer to the question, "What wall R-value should a house with wood frame walls have to obtain the same space heating and cooling loads as a similar house containing massive walls?"

The dynamic thermal performances of more than 20 multilayer and homogenous wall material configurations were analyzed using thermal performance comparisons of massive walls and lightweight wood-frame walls. A one-story ranch-type house was used for these comparisons, and they were

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performed using DOE-2.1E, a whole building energy computer code.

Application of the newly developed equivalent wall theory enabled whole building dynamic energy analysis for complex three-dimensional wall material configurations. Normally, complex building envelope components cannot be accurately analyzed using one-dimensional computer models such as DOE-2. Typically, thermal modelers have to use simplified one-dimensional descriptions of complex walls. This significantly reduces the accuracy of the computer modeling because of the complicated two- and three-dimensional heat transfer that can be observed in most wall assemblies.

In this paper, response factors, heat capacity, and R-value were computed for complex walls using finite difference computer modeling. They enabled a calculation of the wall thermal structure factors and estimation of the simplified one-dimensional equivalent wall configuration. Thermal structure factors reflect the thermal mass heat storage characteristics of the wall assembly. The equivalent wall has a simple multilayer structure and the same thermal properties as the complex wall. The equivalent wall and complex wall dynamic thermal behaviors are identical. The thermal and physical properties describing the equivalent wall can be used, very simply, in whole building energy simulation programs with hourly time steps. These whole building simulation programs require simple one-dimensional descriptions of the building envelope components. In this work, DOE-2.1E was used to calculate heating and cooling loads for six U.S. climates.

THERMAL MASS BENEFIT—METHODOLOGY

Masonry or concrete walls having a mass greater than or equal to 30 lb/ft^2 (146 kg/m^2) and solid wood walls having a mass greater than or equal to 20 lb/ft^2 (98 kg/m^2) are defined by the *Model Energy Code* (CABO 1995) as massive walls. They have heat capacities equal to or exceeding 6 Btu/ft^2·°F (266 J/[m^2·K]). The same classification is used in this work.

The evaluation of the dynamic thermal performance of massive wall systems is a combination of experimental and theoretical analysis. It is based on dynamic, three-dimensional, finite difference simulations, whole building energy computer modeling, and dynamic guarded hot box tests. Dynamic hot box tests serve to calibrate computer models. However, they are not needed for all wall assemblies. For simple one-dimensional walls, theoretical analysis can be performed without compromising the accuracy when the computer model is calibrated using a similar material configuration.

General Procedure

The massive wall is typically tested in a guarded hot box under steady-state and dynamic conditions. These tests enable calibration of the computer models and estimation of the steady-state R-value as well as wall dynamic characteristics. Dynamic hot box tests performed on massive walls consist of two steady-state test periods connected by a rapid temperature change on the climate side. The finite difference computer code Heating 7.2 (Childs 1993) is applied to model the wall under dynamically changing boundary conditions (recorded during the hot box test). The Heating 7.2 computer model was validated in the past using steady-state hot box test results (Kosny 1995).

For each individual wall, a finite difference computer model is developed. The accuracy of the computer simulation is determined in several ways. The first check is to compare test and simulated R-values. The simulated steady-state R-value has to match the experimental R-value within 5% to be consistent with the accuracy of hot box measurements (Kosny and Christian 1995). Also, computer heat flow predictions are compared with the hot box measured heat flow through the 2.4 m by 2.4 m (8 ft by 8 ft) specimen exposed to dynamic boundary conditions. The computer program uses boundary conditions recorded during the test (temperatures and heat transfer coefficients). Values of heat flux on the surface of the wall generated by the computer program are compared against the values measured during the dynamic hot box test.

Response factors, heat capacity, and R-value are computed using the finite-difference computer code. They enable calculation of the wall thermal structure factors and development of the simplified one-dimensional "thermally equivalent wall" configuration (Kossecka and Kosny 1996, 1997; Kossecka 1998). Thermal structure factors reflect the thermal mass heat storage characteristics of wall systems. A thermally equivalent wall has a simple multiple-layer structure and the same thermal properties as the nominal wall. Its dynamic thermal behavior is identical to the complex wall tested in the hot box.

Development of a thermally equivalent wall enables the use of whole-building energy simulation programs with hourly time steps (DOE-2 or BLAST). These whole building simulation programs require simple one-dimensional descriptions of the building envelope components. The use of the equivalent wall concept provides a direct link from the dynamic hot box test to accurate modeling of buildings containing walls that have three-dimensional heat flow within them, such as the insulating concrete form (ICF) wall systems (Kosny et al. 1998; CABO 1995).

The DOE-2.1E computer code is utilized to simulate a single-family residence in representative U.S. climates. The space heating and cooling loads from the residence with massive walls are compared to loads for an identical building simulated with lightweight wood-frame exterior walls. Twelve lightweight wood-frame walls with R-values from 0.4 to 6.9 Km^2/W (2.3 to 39.0 h·ft^2·°F/Btu) are simulated in six U.S. climates. The heating and cooling loads generated from these building simulations are used to estimate the R-value equivalents that would be needed in conventional wood-frame construction to produce the same loads as for the house with massive walls in each of the six climates. The resulting values account for not only the steady-state R-value but also the inherent thermal mass benefit. This procedure is almost identical to that used to create the thermal mass benefits tables in the *Model Energy Code* (CABO 1995). The thermal mass benefit is a function of the climate. R-value equivalents for massive systems are obtained by comparison of the thermal performance of the massive wall and lightweight wood-frame walls, and they should be understood only as the R-value needed by a house with wood-frame walls to obtain the same space heating and cooling loads as an identical house containing massive walls. There is not a physical meaning of the term "R-value equivalent for massive system."

Dynamic Hot Box Test and Development of Finite Difference Computer Model of Wall

A dynamic hot box test takes about 200 hours. It serves mainly to calibrate the computer model of the tested wall. This time-consuming test-based calibration of the computer model is required only for complex massive wall configurations. In the case of simple one-dimensional walls, only the theoretical analysis can be performed without compromising the accuracy. A dynamic hot box test performed on massive walls consists of two steady-state test periods connected by a rapid temperature change on the climate side. In addition to calibration of the computer model, the test enables estimation of the steady-state R-value and wall dynamic characteristics.

Dynamic three-dimensional computer modeling is used to analyze the response of the complex massive walls to a triangular surface temperature pulse. This analysis enables estimation of the steady-state R-value of the wall, thermal capacity, response factors, and wall thermal structure factors. The wall thermal structure factors are used later to create the one-dimensional equivalent wall that is necessary for whole-building energy simulations.

A calibrated heat conduction, finite-difference computer code, Heating 7.2, is used for this analysis (Childs 1993). The accuracy of Heating 7.2 is validated by examining its ability to predict the dynamic process measured during the dynamic hot box test for the massive wall (Kosny et al. 1998). The computer program uses recorded test boundary conditions (temperatures and heat transfer coefficients) at one-hour time intervals.

Values of heat flux on the surface of the wall generated by the program are compared with the values measured during the dynamic test. The computer program has to reproduce the same wall thermal response as was recorded during the hot box test. Later, this calibrated computer model is used to generate the equivalent wall that enables one-dimensional whole building energy analysis.

Equivalent Wall Generated for Use in One-Dimensional Whole-Building Modeling

The dynamic thermal performance analysis for massive walls that is described here is based on whole building energy modeling results. A "real" three-dimensional description of complex walls cannot be used directly by whole-building simulations. Such walls must be simplified to a one-dimensional form to enable the dynamic whole building thermal analysis using DOE-2, BLAST, or similar computer programs. The use of the equivalent wall enables more accurate modeling of buildings containing complicated three- and two-dimensional internal structures. Very often, such complicated walls are composed of several different materials with drastically different thermal properties. In prior works by Kossecka and Kosny (1996, 1997) and Kossecka (1998), the equivalent wall concept was introduced. The equivalent wall is generated using three thermal structure factors φ_{ii}, φ_{cc} ,and φ_{ie} , steady-state R-value, and wall thermal capacity C. The thermal structure factors are calculated using the following integrals over the wall volume of dimensionless temperatures weighted by local volumetric heat capacity:

$$\varphi_{ii} = \frac{1}{C}\int_V dv\rho c(1-\theta)^2 \qquad (1)$$

$$\varphi_{ee} = \frac{1}{C}\int_V dv\rho c\theta^2 \qquad (2)$$

where subscript i denotes interior, e denotes exterior, ρ is density, v is three-dimensional region, c is specific heat, and θ is dimensionless temperature.

The thermal structure factors are normalized by the following identity:

$$\varphi_{ii} + 2 \cdot \varphi_{ie} + \varphi_{ee} = 1 \qquad (3)$$

$$\varphi_{ie} = \frac{1}{C}\int_V dv\rho c \;\; \theta(1-\theta) \qquad (4)$$

The thermal structure factors constitute, together with wall R-value and overall thermal capacity C, the basic thermal wall characteristics that can be determined experimentally. They represent the fractions of heat stored in the volume of the separated wall element, which are transferred across each of its surfaces. The quantity φ_{ii} is comparatively large if most of the thermal mass is concentrated near the interior surface of the wall and the most resistance belongs to its outer part, located near the exterior surface; the opposite holds for φ_{ee}. The upper limit of φ_{ii} and φ_{ee} is 1, the lower limit is 0. For walls with internal symmetry planes, $\varphi_{ii} = \varphi_{ee}$.

A calibrated three-dimensional computer model of the complex wall serves for calculation of response factors. For a triangular pulse that is simulated on one wall side, the dynamic finite-different computer code calculates a series of response factors. With known wall U-factor, thermal capacity C, and thermal structure factors φ_{ii}, φ_{ee}, and φ_{ie}, response factors can be calculated using the following equations:

$$\sum_{n=1}^{\infty} nH_{ii}(n\Delta) = -\frac{C}{U\Delta}\varphi_{ii} \quad (5)$$

$$\sum_{n=1}^{\infty} nH_{ee}(n\Delta) = -\frac{C}{U\Delta}\varphi_{ee} \quad (6)$$

$$\sum_{n=1}^{\infty} nH_{ie}(n\Delta) = -\frac{C}{U\Delta}\varphi_{ie} \quad (7)$$

where H_{ii}, H_{ee}, and H_{ie} are the normalized response factors, U is wall thermal transmittance, Δ is time interval.

The one-dimensional equivalent wall is generated using Equations 1 through 4. An equivalent wall has the same steady-state and dynamic thermal performance as a real, complex wall. As is shown in the works of Kossecka and Kosny (1996, 1997), even for the complex thermal bridge configuration, response factors for both walls (nominal complex wall and equivalent wall), as well as steady-state R-values and thermal structure factors, have the same values.

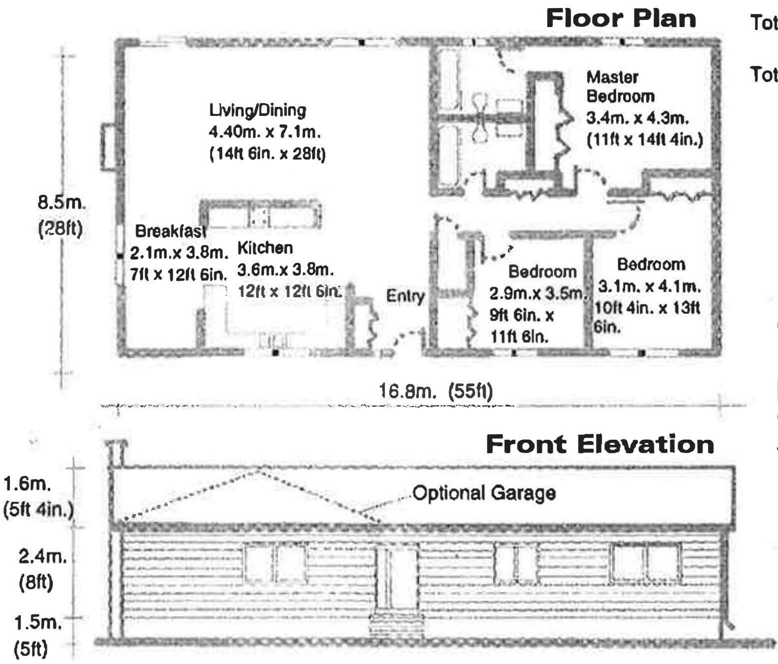
Dynamic Whole Building Modeling of a House Containing Wood-Frame Walls

Comparative analysis of the space heating and cooling loads from two identical residences, one with massive walls and a second containing lightweight wood-frame exterior walls, was introduced for the development of massive wall thermal requirements in the *Model Energy Code* (CABO 1995). This procedure was adopted by the authors. The DOE-2.1E computer code was utilized to simulate a single-family residence in six representative U.S. climates. Twelve lightweight wood-frame walls with R-values from 0.4 to 6.9 K·m²/W (2.3 to 39.0 h·ft²·°F/Btu) were simulated. The heating and cooling loads generated from these building simulations were used to estimate the R-value equivalents for massive walls. A list of the cities and climatic data is presented in Table 1.

TABLE 1
Six U.S. Climates (TMY) Used for DOE 2.1E Computer Modeling

Cities	HDD 18.3°C(65°F)	CDD 18.3°C(65°F)
Atlanta	1705 (3070)	870 (1566)
Denver	3379 (6083)	315 (567)
Miami	103 (185)	2247 (4045)
Minneapolis	4478 (8060)	429 (773)
Phoenix	768 (1382)	2026 (3647)
Washington, D.C.	2682 (4828)	602 (1083)

To normalize the calculations, a standard North American residential building is used. The standard building selected for this purpose is a single-story ranch style house that has been the subject of previous energy-efficiency modeling studies (Huang et al. 1987). All U.S. residential building thermal standards, including ANSI/ASHRAE Standard 90.2 and the *Model Energy Code*, are based on the



Dynamic Thermal Performance is Expressed as a Comparison of Thermal Performances for the Building Containing Traditional Wood-Framed Construction and the Same Building with Massive Walls

Figure 1 *One-story residential building used in thermal analysis.*

whole building energy modeling performed with the use of this house. A schematic of the house is shown in Figure 1. The house has approximately 143 m^2 (1540 ft^2) of floor area, 123 m^2 (1328 ft^2) of exterior wall elevation area, eight windows, and two doors (one door is a glass slider; its impact is included with the windows). The elevation wall area includes 106 m^2 (1146 ft^2) of opaque wall area, 14.3 m^2 (154 ft^2) of window area, and 2.6 m^2 (28 ft^2) of door area. The following building design characteristics and operating conditions are used during computer modeling:

Interior walls:
Mass: 3.57 lb/ft^2 of floor area
Specific heat: 0.26 Btu/lb°F
Furniture:
Mass: 3.30 lb/ft^2 of floor area
Specific heat: 0.30 Btu/lb°F
Thickness: 51 mm (2 in.)
Thermostat set point:
21°C (70°F) heating
26°C (78°F) cooling.
Window type:
Double-pane clear glass
Transmittance: 0.81
Reflectance: 0.15
Roof insulation:
R-value 5.3 K·m^2 / W (30 h·ft^{2}°F/Btu)

For the base-case calculation of infiltration, we used the Sherman-Grimsrud infiltration method, an option in the DOE-2.1E whole-building simulation model (Sherman and Grimsrud 1980). An average total leakage area of 0.0005, expressed as a fraction of the floor area (Dickerhoff et al. 1982; Harrje and Born 1982; Sherman and Grimsrud 1980), is assumed. This is considered average for a single-zone wood-framed residential structure. This number cannot be converted directly to average air changes per hour because it is used in an equation driven by hourly wind speed and temperature difference between the inside and ambient air data, which varies for the six climates analyzed for this study. However, for the six climates, this represents an air change per hour range that will not fall below an annual average of 0.35 ACH.

DOE-2.1E simulations for six U.S. climates are performed for lightweight wood-frame walls (50 mm by 200 mm [2 by 4 in.] construction) of R-values from 0.4 to 6.9 m^2·K/W (2 to 39 h·ft^2·°F/Btu). Steady-state R-values were computed for wood-framed walls using the Heating 7.2 finite difference computer code. The accuracy of Heating 7.2's ability to predict wall system R-values was verified by comparing simulation results with published test results for 28 masonry, wood-frame, and metal-frame walls tested at other laboratories. The average differences between laboratory test and Heating 7.2 simulation results for these walls were ±4.7% (Kosny and Desjarlais 1994). Considering that the precision of the guarded hot box method is reported to be approximately 8%, the ability of Heating 7.2 to reproduce the experimental data is within the accuracy of the test method (ASTM 1989). Because of the high accuracy of these simulations, all steady-state clear wall R-values used in this procedure are directly linked to existing thermal standards where wall thermal requirements are based on clear wall R-values.

The total space heating and cooling loads for 12 lightweight wood-frame walls were calculated using DOE-2.1E simulations. Regression analysis was performed to analyze the relation between steady-state clear wall R-values (of wood-stud walls) and the total building loads for six U.S. climates. For all six climates, there was a strong correlation (r^2 was about 0.99). Regression equation parameters are presented in Table 2.

TABLE 2
Parameters in Equation 8 Expressing the Relation Between Steady-State Clear Wall R-Values (of Wood-Stud Walls) and Total Building Loads for Six U.S. CLimates*

Cities	a (Y-Intercept)	b (Slope)
Atlanta	$1.8e^8$	−4.69
Denver	$1.65e^9$	−4.76
Miami	$2.97e^{18}$	−11.0
Minneapolis	$3.25e^{12}$	−5.95
Phoenix	$3.56e^9$	−5.27
Washington	$3.01e^9$	−5.01

* R-value range: 0.4-6.9 m^2·K/W (2-39 h·ft^2·°F/Btu).

$$R = a \cdot E^b \tag{8}$$

where E = total building load (MBtu/yr) and R = wall R-value.

Effective R-Values and Dynamic Benefits for Massive Systems (DBMS)

The heating and cooling loads generated for 12 lightweight wood-frame walls can be used to estimate the R-value equivalents for massive walls. Equation 8 yields the wall R-value that would be needed in conventional wood-frame construction to produce the same load as the house with massive walls in each of six climates. There is no physical meaning for the term "R-value equivalent for massive walls." This value accounts not only for the steady-state R-value but also the inherent thermal mass benefit. This procedure is similar to that used to create the thermal mass benefits tables in the *Model Energy Code* (CABO 1995). Thermal mass benefits are a function of the material configuration and the climate. A dimensionless measure of the wall thermal dynamic performance is proposed in this paper---dynamic benefit for massive systems (DBMS) defined by Equation 9:

$$DBMS = mR_{eqv}\ 1/R \quad (9)$$

where DBMS is dynamic benefit for massive systems, mR_{eqv} is the R-value equivalent for massive wall, and R is the steady-state R-value.

Equation 9 documents the thermal benefits of using massive wall assemblies in residential buildings regardless of the level of the wall steady-state R-value.

RESULTS

Dynamic Thermal Performance of Simple Multilayer Wall Assemblies

Simple multilayer walls without thermal bridges are accurately described by one-dimensional models. Because DOE-2 can simulate these walls without compromising the accuracy, dynamic hot-box tests were not performed on them except for one example. A wall constructed with a foam core and two equally thick concrete layers on both sides was tested in the hot box. Experimental results collected from this test were used to calibrate the computer model for simple multi-layer walls. The same material data were used for all wall configurations analyzed in this section (see Table 3).

Four series of massive walls are depicted in Figures 2 through 5. These 19 walls are grouped according to R-value:

Figure 2: R - 3.03 $m^2 \cdot K/W$ (17.2 $h \cdot ft^2 \cdot °F/Btu$),
Figure 3: R - 2.29 $m^2 \cdot K/W$ (13.0 $h \cdot ft^2 \cdot °F/Btu$),
Figure 4: R - 1.58 $m^2 \cdot K/W$ (9.0 $h \cdot ft^2 \cdot °F/Btu$), and
Figure 5: R - 0.88 $m^2 \cdot K/W$ (5.0 $h \cdot ft^2 \cdot °F/Btu$).

There are four wall material configurations within the groups:

1. Concrete on both sides of the wall, core of the wall made insulation material.
2. Insulation on both sides of the wall, core of the wall ma of concrete.
3. Concrete on the interior wall side, insulation on the exteri wall side.
4. Concrete on the exterior wall side, insulation on the interi wall side.

Based on Equations 1 and 2, DBMS values were calculated for all 19 wall material configurations. They ar presented in Tables 3 through 7. Data presented in the table show that the most effective wall assemblies are walls wit thermal mass (concrete) being in good contact with the interio of the building (walls 1, 2, and 3 in Tables 4 and 5 and als walls 1 and 3 in Tables 6 and 7). Walls where the insulatio material is concentrated on the interior side of the wall have the smallest DBMS values (wall 4 in Tables 4 and 5 and als wall 3 in Tables 6 and 7). Other wall configurations with the concrete wall core and insulation placed on both sides of the wall have higher DBMS values (walls 5 and 6 in Tables 4 and 5 and also wall 4 in Table 6).

TABLE 3
Thermal Properties of Material for Mutilayer Walls

Material	Thermal Conductivity $W/m \cdot K$ ($Btu \cdot in./h \cdot ft^2 \cdot F$)	Density kg/m^3 [lb/ft^3]	Specific Heat $kJ/kg \cdot K$ ($Btu/lb \cdot °F$)
Concrete	1.44 (10.0)	2240 (140)	0.84 (0.20)
Insulating Foam	0.036 (0.25)	25.6 (1.6)	1.21 (0.29)
Gypsum Board	0.16 (1.11)	800 (50)	1.09 (0.26)
Stucco	0.72 (5.00)	1856 (116)	0.84 (0.20)

TABLE 4
DBMS Values for R_{SI} - 3.03 (R-17.2) Walls

Wall	DBMS					
	Atlanta	Denver	Miami	Minneapolis	Phoenix	Washington
"1"	2.08	1.86	1.89	1.47	2.43	1.78
"2"	2.12	1.86	2.07	1.48	2.48	1.80
"3"	2.15	1.85	2.44	1.47	2.46	1.83
"4"	1.34	1.4	1.07	1.30	1.44	1.34
"5"	1.6	1.53	1.56	1.37	1.67	1.51
"6"	1.5	1.48	1.44	1.35	1.56	1.59

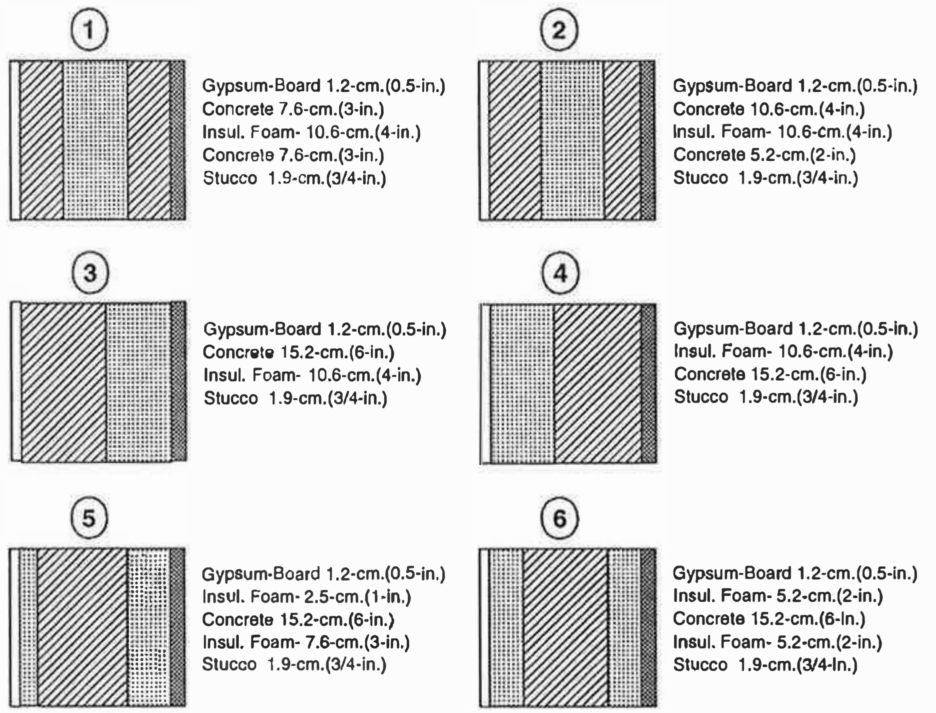


Figure 2 *Schematics of massive walls of R-3.03 $m^2 \cdot K/W$ (17.2 $h \cdot ft^2 \cdot °F/Btu$).*

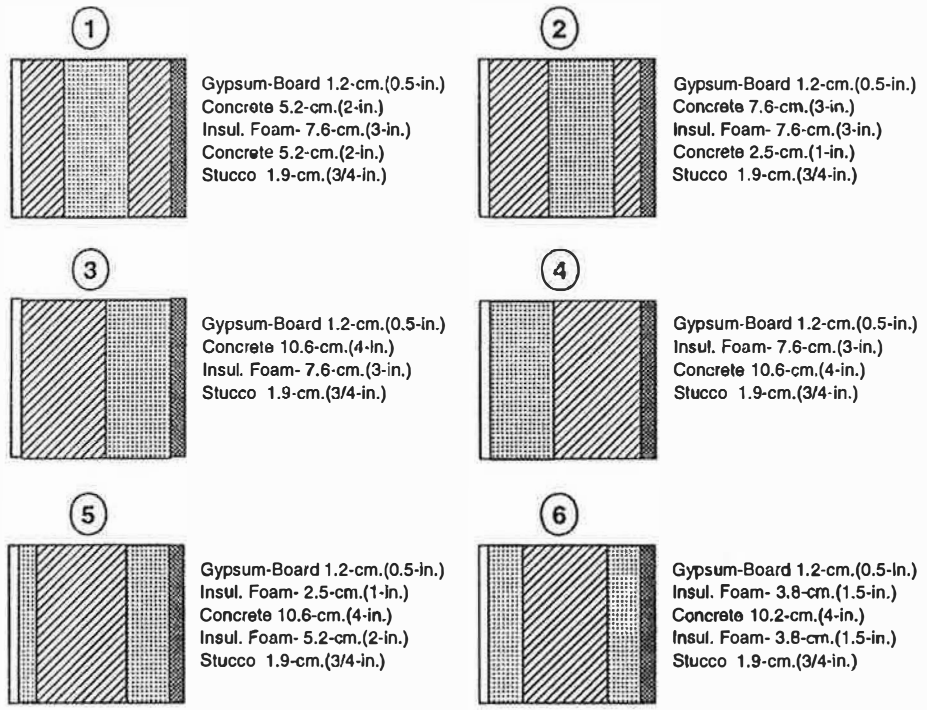


Figure 3 *Schematics of massive walls of R-2.29 $m^2 \cdot K/W$ (13.0 $h \cdot ft^2 \cdot °F/Btu$).*

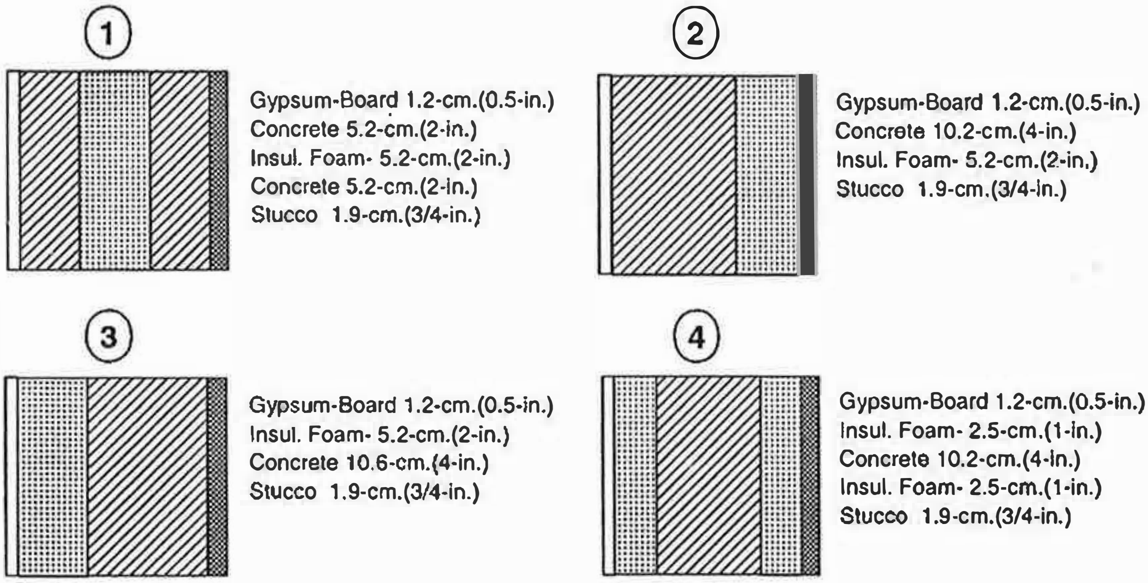


Figure 4 *Schematics of massive walls of R-1.58 $m^2 \cdot K/W$ (9.0 $h \cdot ft^2 \cdot °F/Btu$).*

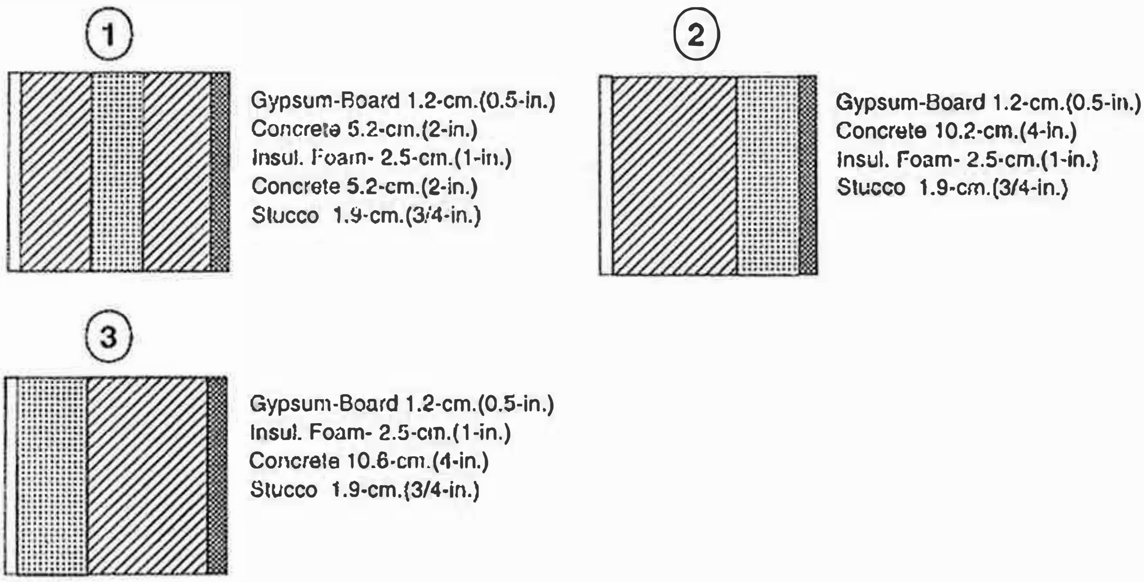


Figure 5 *Schematics of massive walls of R-0.88 $m^2 \cdot K/W$ (5.0 $h \cdot ft^2 \cdot °F/ Btu$).*

TABLE 5
DBMS Values for R_{SI} - 2.29 (R-13.0) Walls

	DBMS					
Wall	**Atlanta**	**Denver**	**Miami**	**Minneapolis**	**Phoenix**	**Washington**
"1"	1.99	1.86	1.73	1.47	2.46	1.74
"2"	2.08	1.88	2.01	1.49	2.56	1.79
"3"	2.11	1.88	2.20	1.49	2.57	1.80
"4"	1.33	1.42	1.08	1.31	1.47	1.35
"5"	1.64	1.59	1.59	1.38	1.80	1.52
"6"	1.58	1.55	1.49	1.37	1.73	1.49

TABLE 6
DBMS Values for R_{SI} - 1.58 (R-9.0) Walls

	DBMS					
Wall	**Atlanta**	**Denver**	**Miami**	**Minneapolis**	**Phoenix**	**Washington**
"1"	1.87	1.79	1.61	1.39	2.45	1.64
"2"	1.94	1.80	2.10	1.40	2.58	1.70
"3"	1.32	1.39	1.03	1.24	1.52	1.31
"4"	1.59	1.55	1.45	1.31	1.86	1.47

The most favorable climate for application of the massive wall systems is in Phoenix. The worst location for these systems is Minneapolis. As shown in Table 7, for Minneapolis and Miami, in buildings containing low R-value walls with the insulation material concentrated on the interior side of the wall, total building loads can be higher than in the case of the lightweight walls of the same steady-state R-value (DBMS lower than 1).

Different proportions in wall mass or insulation distribution (walls 1 vs. 2 and 5 vs. 6) effect significant differences in DBMS values in the same climates. This indicates that the DBMS value is sensitive to the changes in wall exterior and interior layers. Data presented in Tables 4 through 7 cannot be used to predict the dynamic thermal performance of walls with significantly different exterior or interior layers (for example, walls with brick or siding exterior finish).

For the four common wall material configurations, detailed relations between steady-state R-values and dynamic R-value equivalents are depicted in Figures 6 through 9. They can be used for estimation of the approximate dynamic benefit for walls of similar configurations. For walls with more complicated configuration, the these values have to be estimated individually.

Complex Wall Assemblies—One-Dimensional Simplifications are Not Accurate

Complex walls cannot be analyzed using simple one-dimensional tools. The methodology applied for dynamic thermal performance evaluations of complex massive wall systems needs to be able to thermally analyze complicated

TABLE 7
DBMS Values for R_{SI} - 0.88 (R-5.0) Walls

	DBMS					
Wall	**Atlanta**	**Denver**	**Miami**	**Minneapolis**	**Phoenix**	**Washington**
"1"	1.43	1.41	1.14	1.03	2.03	1.25
"2"	1.49	1.41	1.48	1.05	2.11	1.29
"3"	1.08	1.14	0.74*	0.94*	1.33	1.05

* DBMS values lower than 1.0 indicate that for the house containing massive walls of low steady-state R-value, space heating and cooling loads may be higher than for the house containing lightweight walls of the same R-value.

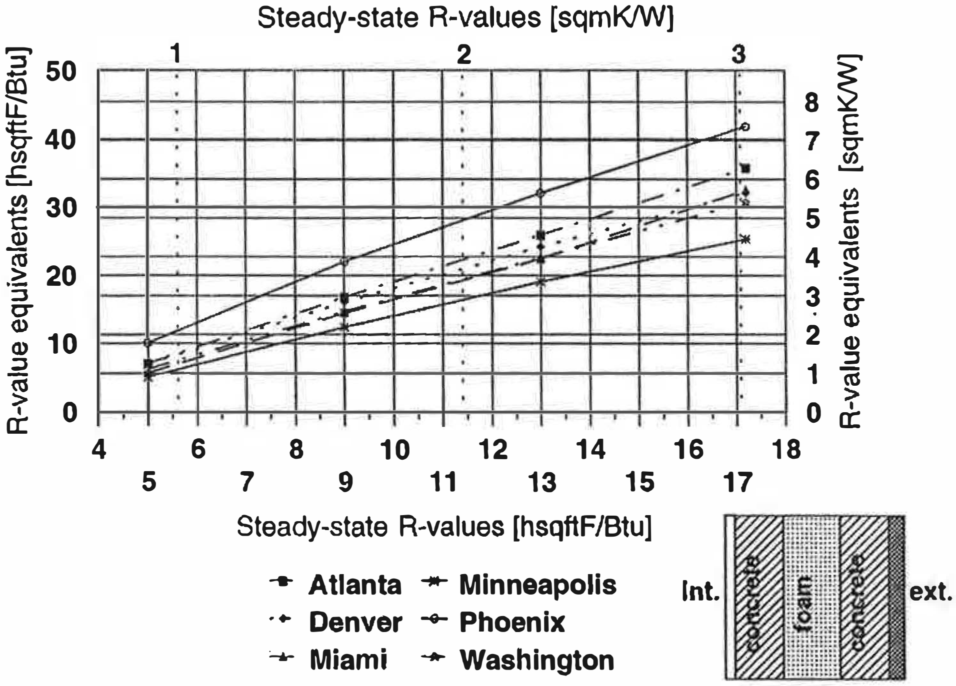


Figure 6 *R-value equivalents for massive walls with foam core and concrete layers located on both sides.*

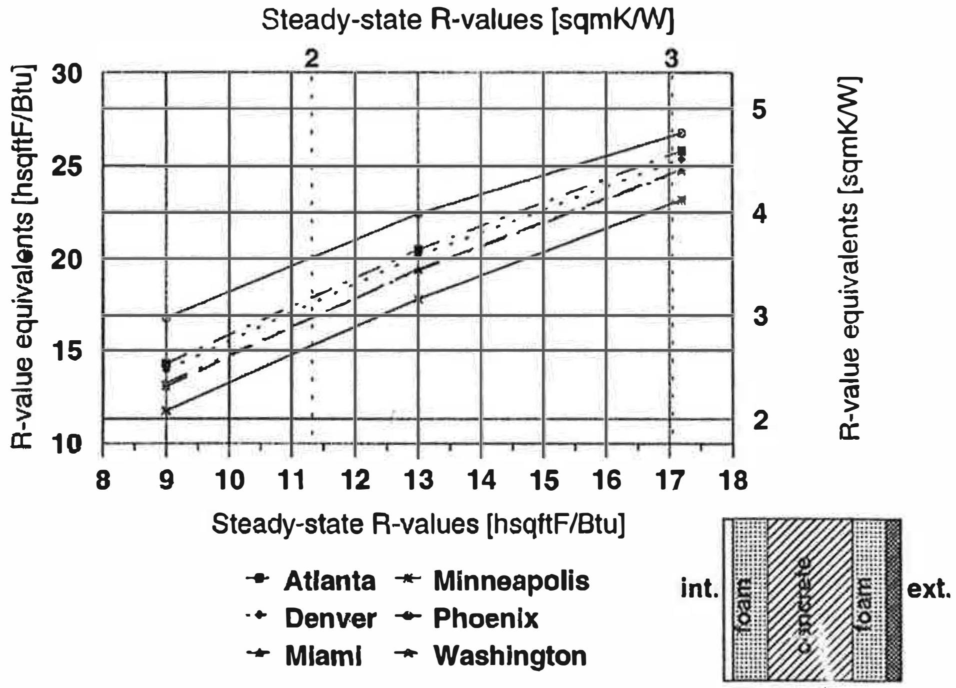


Figure 7 *R-value equivalents for massive walls with massive core and insulation located on both sides.*

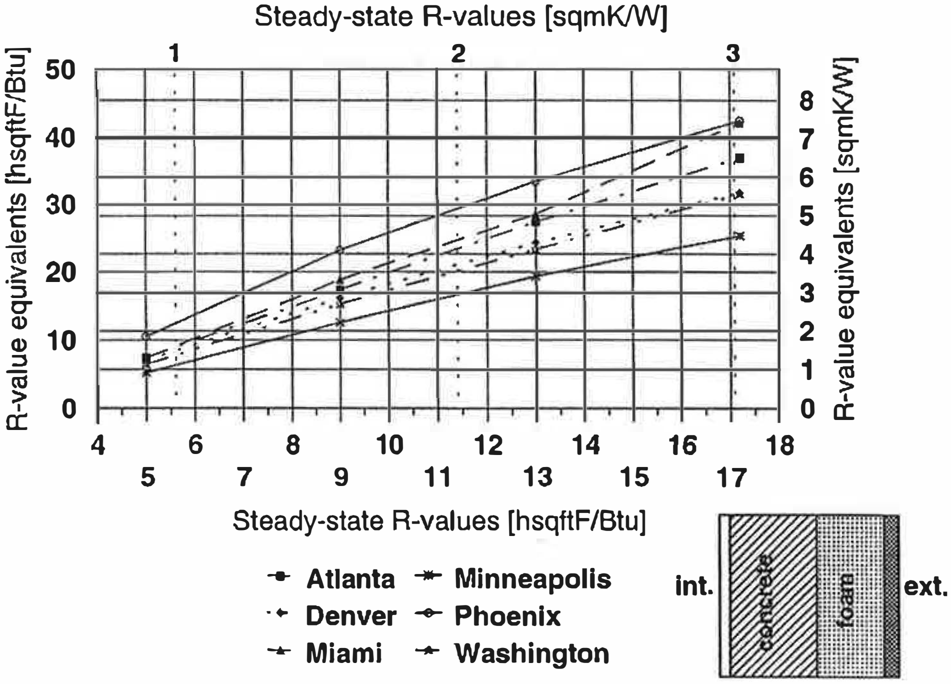


Figure 8 *R-value equivalents for massive walls with thermal mass located on the interior side and insulation on the exterior side.*

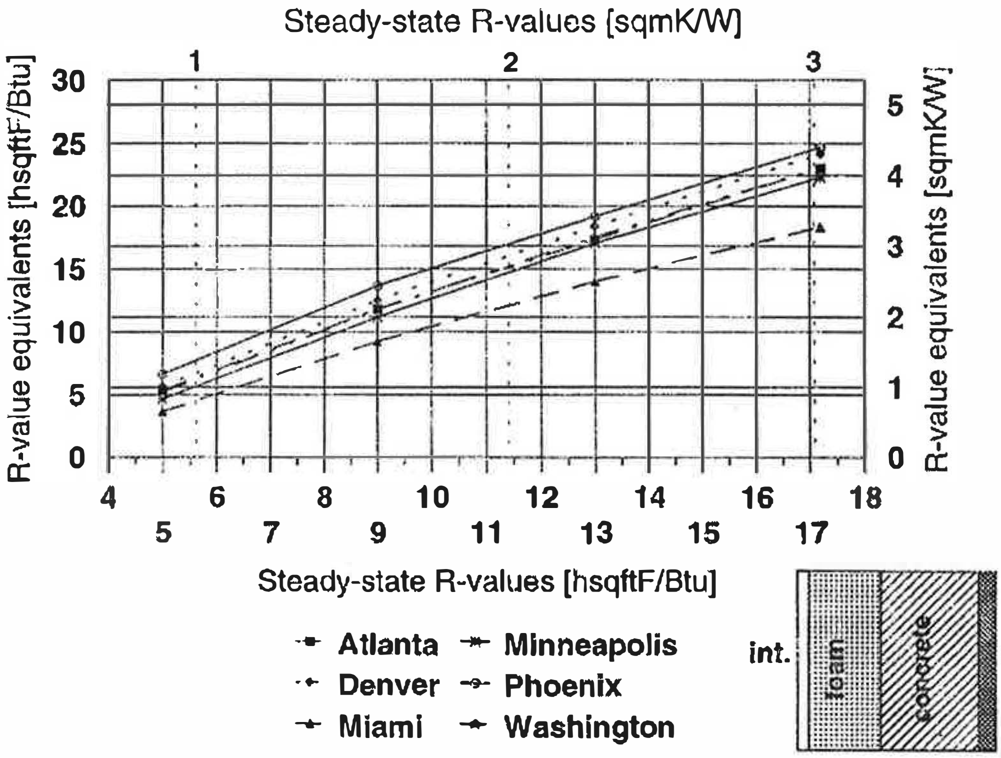


Figure 9 *R-value equivalents for massive walls with insulation located on the interior side and thermal mass on the exterior side.*

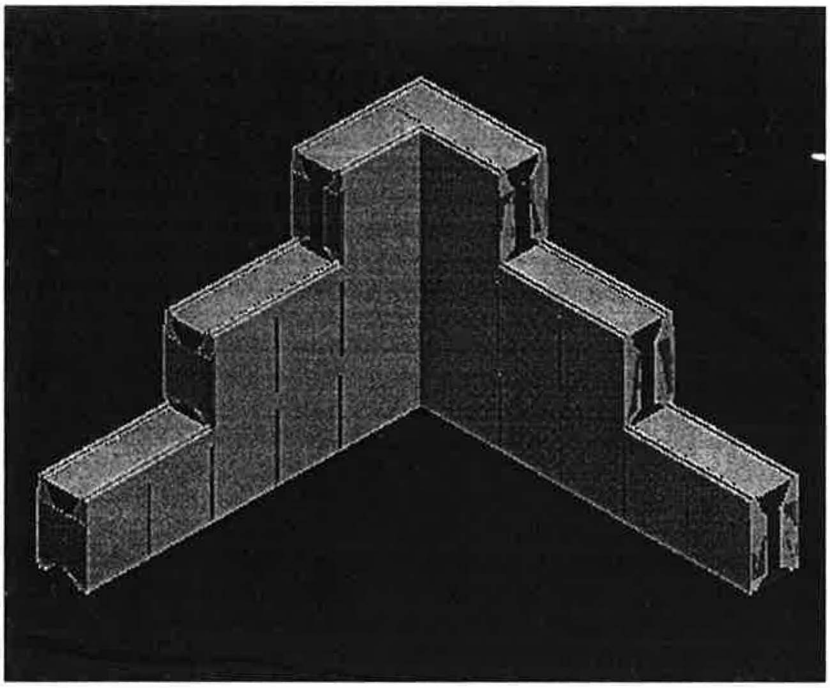


Figure 10 Rendering of the ICF wall (complex foam form-work filled with concrete).

geometries and material configurations. In this section, the ICF (insulating concrete form) wall is used as an example. Two- or three-dimensional heat transfer similar to that in this example can be observed in most masonry units and some of the ICF forms. Some experimental and theoretical results for ICF wall system are presented here.

As shown in Figure 10, the example ICF wall has a complex three-dimensional internal structure. The basic component of this wall is the 0.23 m. (9.25 in.) thick EPS foam wall form. The thickness of the exterior and interior form walls (made of foam) varies from 3.8 cm to 8.8 cm (1.5 in. to 3.5 in.). These foam components of the form are connected with the metal mesh going across the wall. There is a three-dimensional network of vertical and horizontal channels (about 15.75 cm or 6.25 in. in diameter) inside the ICF wall form. These channels have to be filled with concrete during the construction of the wall. The exterior surface of the wall is finished with a 13 mm (½ in.) thick layer of stucco, and on the interior surface 13 mm (½ in.) thick gypsum boards are installed. Reinforced high-density concrete is poured into the internal channels formed by ICF units.

Heating 7.2 was used for the dynamic three-dimensional heat transfer analysis of the ICF wall. The accuracy of Heating 7.2 was validated by examining its ability to predict the dynamic process measured during the dynamic hot-box data for this massive wall. The steady-state R-value or the computer-modeled ICF wall had to match the test-generated R-value. Then the computer program used temperatures and heat transfer coefficients recorded during the test at one-hour time intervals. Values of heat flux on the surface of the wall generated by the program were compared with the values measured during the dynamic test. This task is described in detail by Kosny et al. (1998). The general conclusion was that the computer program reproduced the test data very well. This exercise confirmed the ability of Heating 7.2 to reproduce the dynamic heat transfer process measured during the dynamic hot-box test of the actual complex massive wall.

Response factors, heat capacity, and R-value were computed using the validated computer model of the ICF wall. They enabled calculation of the wall thermal structure factors and generation of the simplified one-dimensional equivalent wall configuration. This equivalent wall had a simple six-layer structure and the same thermal response as the real wall (Kosny et al. 1998). Kossecka and Kosny (1996, 1997) and Kossecka (1998) analyzed the case of a complex thermal bridge configuration. They showed that response factors, steady-state R-values, and thermal structure factors are the same for the complex wall and equivalent wall. One-dimensional approximate models of the complex structures based only on geometrical simplifications are much less accurate.

To illustrate this fact, a simple one-dimensional model was developed for the ICF wall. It was based on the total thickness of the ICF wall, 0.23 m. (9.25 in.), and the thickness of the exterior and interior foam forms, which varied from 3.8 cm to 8.8 cm (1.5 in. to 3.5 in.). The equal thickness for the exterior and interior foam forms was assumed as 5.08 cm (2 in.). Due to the fact that computer programs such as DOE-2 or BLAST can perform only one-dimensional thermal analysis, it is likely that most DOE-2 or BLAST modelers would make similar simplifications. Comparisons of steady-state R-values and X

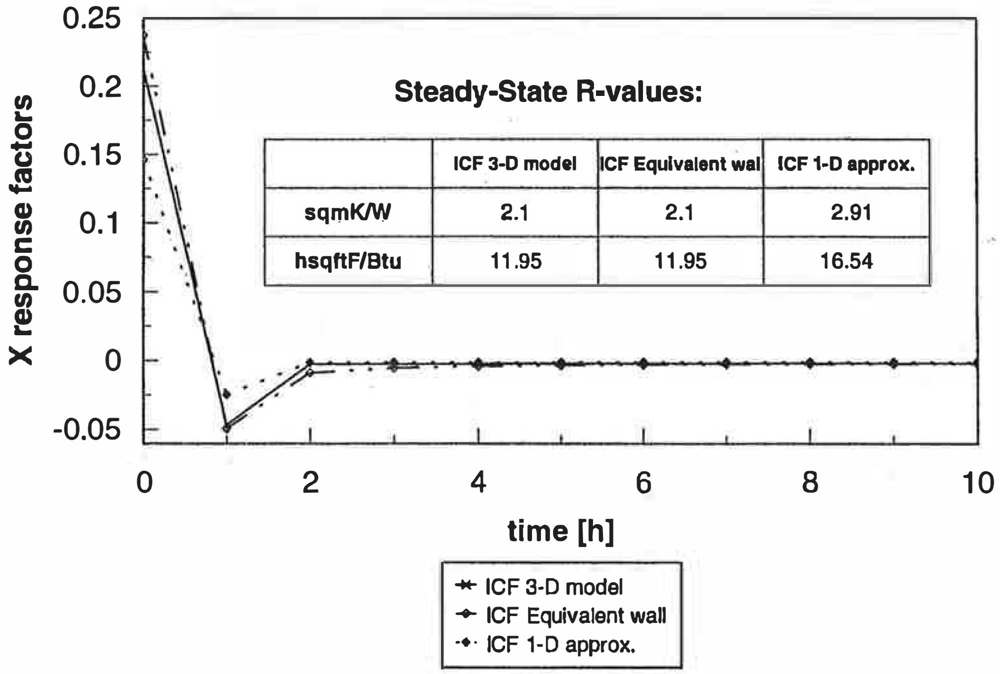


Figure 11 *Comparisons of steady-state R-values and X response factors for ICF wall, equivalent wall, and simple one-dimensional model of ICF wall.*

response factors are presented in Figure 11. It is shown that for the simple one-dimensional model, the R-value is 38% higher that the R-value calculated for the three-dimensional model of ICF wall. At the same time, R-values for the ICF wall and equivalent walls are equal. Also, the first five *X* response factors for this wall have significantly different values from the essentially equal *X* response factors calculated for the accurate three-dimensional model of ICF wall and the equivalent wall.

The equivalent wall technique is a relatively simple way to allow whole-building energy simulations (using DOE-2 or BLAST) for buildings containing complex assemblies. If the accurate equivalent wall could not be generated, the dynamic thermal performance evaluation will not be accurate because it is based on one-dimensional whole building simulations. It is possible to generate a series of response factors or transfer functions for the complex wall and modify DOE-2 source code to enable this type of wall data input. However, the equivalent wall technique represents all the thermal information about the wall by only five numbers (*R*, *C*, and three thermal structure factors). This is much simpler than the alternative use of a long series of response factors or Z-transfer function coefficients (for massive walls, 60 to sometimes 150 numbers multiplied by 3), which has to be accompanied with the troublesome modification of the program source code to enable this type of wall data input.

Low R-Value Massive Walls—Negative Impact of Thermal Mass

As shown in Table 7, for buildings located in Minneapolis and Miami containing low R-value massive walls with the insulation material concentrated on the interior side of the wall, total building loads can be higher with thermal mass than with the equivalent lightweight wall of the same steady-state R-value (DBMS lower than 1). Extrapolating the data presented in Tables 4 through 7, it can be observed that massive walls with R-values below 0.53 to 0.7 $m^2 \cdot K/W$ (3-4 $h \cdot ft^2 \cdot {}^\circ F/Btu$) have negative impacts on building loads for all considered locations except Phoenix.

Two low R-value wall material configurations were simulated to analyze this interesting finding:

- Solid 20.3 cm (8 in.) thick wall made of high-density concrete, 2240 kg/m^3 (140 lb/ft^3).
- Wall assembled with two-core 29.5 cm (11 5/8 in.) thick concrete blocks made of high-density concrete, 2240 kg/m^3 (140 lb/ft^3) insulated with 4.8 cm (1 7/8 in.) foam inserts.

Due to the three-dimensional geometry of the wall assembled with two-core concrete blocks, an equivalent wall was generated for this wall. Steady-state R-values for these two walls are presented in Table 8.

Based on results of computer modeling and Equations 1 and 2, DBMS values were calculated for these two walls and are presented in Table 9. These results show that only in the

TABLE 8
Steady-State R-Values for Solid 8 in. Wall and Two-Core 29.5 cm (11 5/8 in.) Thick Units Insulated with 4.8 cm (1 7/8 in.) Foam Inserts

Type of Wall Unit and Wall Thickness	Thermal Resistivity of Concrete m·K/W (h·ft²·°F/Btu·in.)	Steady-State R-Value m²·K/W (h·ft²·°F/Btu)	Thickness of Insulating Insert cm (in.)	Thermal Resistivity of Insert Material, m·K/W (h·ft²·°F/Btu·in.)
Solid 20.3 cm	1.39 [0.2]	0.28 [1.6]	—	—
Two-core 29.5 cm (11 5/8 in.)	1.39 [0.2]	0.40 [2.29]	4.76 [1-7/8]	29.2 [4.18]

TABLE 9
DBMS Values for Low R-Value Walls

Wall	DBMS*					
	Atlanta	Denver	Miami	Minneapolis	Phoenix	Washington
Solid	0.73	0.76	0.43	0.44	1.21	0.65
Two-core	0.89	0.91	0.62	0.57	1.46	0.78

* DBMS values lower than 1.0 indicate that for the house containing massive walls of low steady-state R-value, space heating and cooling loads may be higher than for the house containing lightweight walls of the same R-value.

special climate of Phoenix do the traditional massive systems used for foundations have benefit above grade.

CONCLUSIONS

Finite-difference computer modeling, validated by dynamic hot-box tests, was used to examine the steady-state and dynamic thermal performances of massive wall assemblies. Six U.S. locations were considered during computer dynamic modeling. Four series of multilayer massive walls were analyzed. Data for 19 walls were cataloged in four groups representing walls of the same steady-state R-value:

- R - 3.03 m^2·K/W (17.2 h·ft^2·°F/Btu),
- R - 2.29 m^2·K/W (13.0 h·ft^2·°F/Btu),
- R - 1.58 m^2·K/W (9.0 h·ft^2·°F/Btu), and
- R - 0.88 m^2·K/W (5.0 h·ft^2·°F/Btu).

All walls contained four main wall material configurations:

- Concrete on both sides of the wall, wall core made of the insulation material.
- Insulation on both sides of the wall, massive concrete core of the wall.
- Concrete on the interior wall side, insulation on the exterior wall side.
- Concrete on the exterior wall side, insulation on the interior wall side.

Two additional wall configurations were modeled as low R-value modifications of the material configurations represented by these main groups.

The results of the dynamic computer analysis show that most effective configurations are massive walls with thermal mass (concrete layer) being in good contact with the interior of the building. Walls with the insulation material concentrated on the interior side of the wall showed the least favorable dynamic thermal performance. Dynamic thermal performance of walls with either the concrete wall core or the insulation placed on both sides of the wall falls between the above two constructions.

Dynamic thermal performance of massive walls is also a function of climate. The most favorable climate for application of the massive wall systems is in Phoenix. The relatively worst location for these systems is in Minneapolis (especially for less insulating walls).

It was found that in buildings containing low R-value walls (an average R-value below 0.7 m^2·K/W [4.0 h·ft^2·°F/Btu]), the use of massive walls is ineffective in all considered locations except Phoenix. It is more efficient to use a lightweight wall of the same steady-state R-value.

Complicated three-dimensional heat transfer can be observed in most masonry units and some of the ICF forms. These assemblies have to be simplified to one-dimensional forms to be used in such whole building simulation programs as DOE-2 or BLAST.

Detailed three-dimensional thermal computer analysis proved that the application of the equivalent wall technique helps to generate accurate one-dimensional replicas of complex building envelope assemblies. An example ICF wall had a complex three-dimensional internal structure. There was a three-dimensional network of vertical and horizontal concrete channels inside the ICF wall form. Several horizontal steel components additionally complicated heat transfer in this wall. Calibrated finite-difference computer code was used to generate an equivalent wall for the complex ICF wall. It was shown that response factors, steady-state R-values, and thermal structure factors were essentially the same for the complex ICF wall and equivalent wall. A simple one-dimensional approximate model was also made for the ICF wall. The thickness of each material layer was estimated as the average thickness for the ICF wall. It was found that this one-dimensional approximate model of the complex structures, based only on geometric simplifications, was inaccurate, both in terms of R-values and the response factors.

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