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GUARDED HOT BOX MEASUREMENTS OF THE DYNAMIC HEAT TRANSMISSION CHARACTERISTICS OF SEVEN WALL SPECIMENS—PART II

W.C. Brown

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ABSTRACT

ASHRAE Research Project 515 had the goal of producing measured dynamic heat transmission characteristics of walls. The work was undertaken utilizing a guarded hot box facility. The measured dynamic heat transmission characteristics are used to confirm the data and procedures provided in the ASHRAE Handbook—Fundamentals *for predicting dynamic heat transfer. The steady-state (thermal resistance) and dynamic heat transmission characteristics of seven wall specimens were measured. The test specimens represented wall types ranging in construction from an insulated steel stud wall with stucco finish to an insulated concrete block wall with brick veneer finish.*

For all specimens, the measured frequency response compared quite well with the predicted frequency response. On the other hand, the measured thermal resistance varied from 45% to 90% of the predicted thermal resistance. It is concluded that, within the constraints imposed on the equations and data and assuming actual assembly thermal resistance, heat flux predicted using the Handbook *z-transfer function coefficients will be accurate enough for practical purposes.*

INTRODUCTION

ASHRAE Research Project 515 was undertaken to produce measured dynamic heat transmission characteristics of walls.

The first objective of the project was designed to determine whether the dynamic heat transmission characteristics of nonhomogeneous walls differ significantly from the response that would be predicted using methods from the *1989 ASHRAE Handbook—Fundamentals* (ASHRAE 1989). The second objective, which was added after the project began, was designed to demonstrate that the measurement procedure used with the seven generic walls (the original objective) provided accurate data. Both objectives are documented in the final contract report (Brown 1991).

Most procedures for estimating dynamic heat transfer through, and temperature variations of, building walls and roofs are based on the z-transfer function data and procedures that are published in the *ASHRAE Handbook.* These were developed by Stephenson and Mitalas at the National Research Council of Canada (Mitalas 1968; Stephenson and Mitalas 1971; Mitalas 1978). They pertain to walls and roofs made up of layers of homogeneous materials and have no allowance for thermal bridges, such as framing members or brackets that support cladding. The *Handbook* only gives z-transfer function coefficients that relate the heat flux component through the interior surface of the wall to the sol-air temperature on the exterior. This is sufficient to calculate the rate of heat transfer at the interior due to a change in exterior conditions, but another set of coefficients is needed when calculating the component of heat transfer at the interior due to a change in interior temperature. The latter is required for the calculation of room thermal response.

NRCC developed an experimental procedure for obtaining both sets of z-transfer function coefficients for a wall specimen. It uses test results obtained from a dynamically calibrated ASTM C-236 guarded hot box apparatus (ASTM 1991). The testing and data reduction procedures and confirmation of their validity, the second objective of RP-515, are documented in a companion paper (Brown and Stephenson 1993). This paper documents the first objective and describes the construction of the seven generic test specimens, presents the z-transfer function coefficients determined for the specimens, and comments on the implications of the results.

TEST SPECIMENS

Specifications for the seven generic test specimens were developed by the ASHRAE monitoring committee in consultation with NRCC. Test specimens were constructed using building materials that were obtained

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TABLE 1

Summary of Test Specimen Descriptions, and "Measured" Thermal Transmittance (U-Factor) and Z-Transfer Function Coefficients. Note that U-Factor and Z-Transfer Function Coefficients are Reported for 0°C (32°F) Mean Temperature.

Construction		U-value	Coefficients c_n, b_n, d_n						
No.	Description			n=0	n=1	n=2	n=3	n=4	n=5
1	89 mm [3.5"] insulated steel stud wall w/25 mm [1"]stucco	0.76 [0.134]	c	4.3823	-5.0281	1.2659			
			b	0.1032	0.4179	0.0976	0.0014		
			d	1.0000	-0.3849	0.0050			
2	25 mm [1"] extruded polystyrene on 200 mm [8"] concrete slab	1.01 [0.178]	c	3.6649	-7.3151	4.9626	-1.3787	0.1397	
			b	0.0015	0.0257	0.0371	0.0087	0.0003	
			d	1.0000	-1.2364	0.3481	-0.0405	0.0021	
3	200 mm [8"] concrete slab on 25 mm [1"] extruded polystyrene	1.02 [0.180]	c	10.1458	-16.6276	7.2687	-0.6731	-0.0711	
			b	0.0014	0.0183	0.2022	0.0029		
			d	1.0000	-1.4836	0.5981	-0.0728	0.0011	
4	89 mm [3.5"] insulated steel stud wall on 100 mm [4"] concrete slab	0.64 [0.113]	c	6.2455	-11.3309	6.5383	-1.4812	0.2302	
			b	0.0173	0.1218	0.0598	0.0029		
			d	1.0000	-0.8380	0.0404	-0.0006		
5	140 mm [6"] hollow CMU w/50 mm [2"] ext. poly. & 89 mm [3.5"] clay brick	0.43 [0.077]	c	10.6690	-28.9969	29.0165	-12.9742	2.2935	
			b	0.0002	0.0032	0.0040	0.0006		
			d	1.0000	-2.1653	1.5048	-0.3349	0.0034	
6	89 mm [3.5"] insulated steel stud wall w/89 mm [3.5"] clay brick	0.53 [0.094]	c	7.2460	-14.4387	9.9135	-2.8831	0.3485	
			b	0.0048	0.0722	0.0907	0.0179	0.0006	
			d	1.0000	-1.0340	0.2414	-0.0221	0.0009	
7	150 mm [6"] solid CMU w/100 mm [4"] ext. poly. & 25 mm [1"] granite	0.56 [0.099]	c	17.0794	-32.4576	19.6809	-4.4393	0.1829	
			b	0.0005	0.0118	0.0246	0.0088	0.0005	
			d	1.0000	-1.7326	1.0032	-0.2490	0.0252	0.0006

from local sources. All specimens were 8 ft × 8 ft (2440 mm × 2440 mm), the size required by the test apparatus. The concrete slabs of specimens #2/#3 and #4 were cast by a local precast company and delivered to the laboratory within a few days of casting. Concrete block and clay brick components of specimens were constructed in specimen test frames by a local masonry contractor. Steel stud frames were built in-house for those specimens that required them. Other finishing touches, such as the installation of gypsum board and insulation, were also performed in-house.

General descriptions of all test specimens are given in Table 1. Specific details of the test specimens are given in individual specimen reports that follow. All specimens were constructed at about the same time. The first specimen (#1) was tested after it had been left to age (cure) for a month in the laboratory. The elapsed time between construction and testing of the remaining specimens was six weeks or longer.

Twenty thermocouples were installed to monitor temperatures within the test calorimeter. A 4-by-4 grid of 16 thermocouples was mounted on the interior and exterior surfaces of specimens to measure surface temperatures at the insulated sections. Thermocouples were also mounted on the interior and exterior surfaces to measure surface temperatures at the thermal bridges. Additional thermocouples were mounted on and within the specimens to monitor temperatures at other points of interest. For example, a string of four thermocouples was mounted over one of the steel studs in those specimens that contained steel studs. This thermocouple string and a matching string on the insulation were duplicated at various interfaces through the specimen. Typically, a specimen was instrumented with more than 100 thermocouples. With these temperature measurements, it was possible to determine temperature gradients through both the insulation and the thermal bridges. Such information provided increased confidence in the accuracy of the thermal measurements.

TEST RESULTS

Test data and results for the seven test specimens are recorded in individual specimen reports that are appended below. Values of thermal resistance and z-transfer function coefficients determined for all specimens are given in Table 1.

The individual specimen reports follow a standard format. Each report contains the following information:

1. a brief description of the test specimen and a discussion of the test program and results;
2. the time constants, τ_n, and z-transfer function coefficients, d_n, b_n, and c_n, measured for the specimen;
3. the material properties that were used to predict the response of the specimen;
4. numerical and graphical presentation of measured, calculated, and predicted thermal resistance;
5. numerical and graphical presentation of measured, calculated, and predicted $1/B$ and D/B responses.

The following definitions of "measured," "calculated," and "predicted" values are used in the summary reports:

"Measured" values were determined directly from experimental data.

"Calculated" values were determined indirectly from the experimental data, e.g., R_w was not "measured" at T_m=24°C (75°F) but was "calculated" from the R_w vs. T_m relationship determined from the experimental data; $1/B$ and D/B were "calculated" from the z-transfer function coefficients that were themselves determined from the experimental data.

"Predicted" values were determined from "book" material property data and the governing equations; models of the specimens did not include thermal bridges. Z-transfer function coefficients were "predicted" by the same program that was used to generate the *Handbook* coefficients (Mitalas and Arsenault 1972) and were normalized to the "predicted" thermal resistance.

The "book" material property data for the seven generic specimens were obtained from manufacturers' information if they were available. Failing that, the data were usually available from Chapter 22 of the *Handbook*.

A comparison between "measured" and "predicted" values of specimen thermal resistance, R_S, should take the sensitivity of insulation thermal resistance to mean temperature, T_m, into account. However, while specimen R_S was "measured" at $Tm=0\pm10$°C (32 ± 18°F), "book" values of insulation thermal resistance are normally quoted for T_m=24°C (75°F). Specimen R_S can, therefore, only be "predicted" with confidence at T_m=24°C (75°F). The way around this conundrum is to determine the dependence of specimen R_S on T_m from the experimental data (a linear relationship generally serves for temperature extremes experienced by buildings) and to "calculate" specimen R_S at T_m=24°C (75°F). The individual specimen reports list values of R_S "measured" at T_m=0°C (32°F), "calculated" from experimental data, and "predicted" from "book" data for T_m=24°C (75°F).

The values of $1/B$ and D/B were determined from interior environmental conditions to exterior environmental conditions. They therefore have built into them the interior and exterior surface heat transfer coefficients that were in effect during the tests. Since the values of $1/B$ and D/B are very sensitive to the surface coefficients, it was decided that the test surface coefficients would be the "book" surface coefficients used in "predicting" values of $1/B$ and D/B.

The values of $1/B$ and D/B determined in this project were "measured" at discrete periods. Z-transfer function coefficients c_n, b_n, and d_n were then determined from these experimental data through a series of mathematical steps. The question of whether these coefficients reproduced the "measured" values is addressed by a tabulation of the "measured" and "calculated" values in the individual reports. A second question of how well these "calculated" values compared to "predicted" values is addressed by a graphical presentation of the "measured," "calculated," and "predicted" values at the discrete test periods and of the "calculated" and "predicted" frequency response for the range from steady state to the shortest test period.

CONCLUSIONS

Measurement of the dynamic heat transmission characteristics of a homogeneous wall specimen and of seven generic wall specimens has provided a number of insights into the dynamic thermal performance of "real" walls and how well that performance could be predicted from the data and procedures in the *ASHRAE Handbook—Fundamentals*. The following conclusions are drawn from this project.

1. Measured overall thermal resistance (steady-state performance) was significantly different from predicted values if thermal bridges were not accounted for in the prediction. For the seven generic wall specimens in this project, the measured thermal resistance varied from 45% of "book" value to 90% of "book" value.
2. Measured $1/B$ frequency response was in close agreement with that predicted for the specimens, even though thermal bridges were not included in the prediction. It is hypothesized that the favorable comparison between measured and predicted response is a consequence of the fast response of the thermal bridges; all were of steel.
3. Measured D/B response was of a shape similar to that predicted for the specimens. However, while the measured and predicted phase shifts were generally in good agreement, the measured and predicted amplitudes were not. The difference appears to be primarily due to the difference between measured and predicted thermal resistance.
4. Since the predicted $1/B$ frequency response was in such good agreement with the measured response, it can be concluded that the *Handbook* equation and coefficients will predict heat fluxes that are in good agreement with the "real" solution. There are two cautions that must accompany this conclusion. The first is that the good agreement was based on coefficients normalized to the corresponding thermal resistance. Hence, load and energy calculations will only be as good as the accuracy of the thermal resistance. The second caution is related to the fact that, since the *Handbook* equation assumes a constant interior temperature, the accuracy of the D/B frequency response is not important to its solution. Only under this condition is the difference between

the calculated and predicted *D/B* amplitudes not important.

5. While not directly represented by the data presented in this report, it was noted, probably not for the first time, that the dynamic response of a wall system is quite sensitive to the magnitudes of the interior and exterior film coefficients. The z-transfer function coefficients should, therefore, be used with caution when the actual film coefficients differ from the test film coefficients.

ACKNOWLEDGMENTS

John Richardson was responsible for the construction, instrumentation, and testing of all specimens. His attention to detail and constant vigilance ensured that an increasingly temperamental test apparatus continued to deliver accurate measurements of dynamic heat transmission characteristics. Gint Mitalas's depth of understanding of the issues addressed in this project and his ability to reduce the knotty questions to solvable bites contributed immeasurably to the successful completion of this project.

REFERENCES

ASHRAE. 1989. *1989 ASHRAE handbook—Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM. 1991. C236-89: Standard test method for steady state thermal performance of building assemblies by means of a guarded hot box. *Annual Book of ASTM Standards*, Volume 04.06. Philadelphia: American Society for Testing and Materials.

Brown, W.C. 1991. Final Report—ASHRAE Research Project 515-RP: Dynamic heat transmission characteristics of seven generic wall types and dynamic heat transmission characteristics of a homogeneous wall specimen. Ottawa: National Research Council Canada.

Brown, W.C., and D.G. Stephenson. 1993. ASHRAE Research Project 515-RP: Part 1—A guarded hot box procedure for determining the dynamic response of full scale specimens. To be presented at the ASHRAE winter meeting, January, Chicago.

Burch, D.M., R.R. Zarr, and B.A. Licitra. 1987. A dynamic test method for determining transfer function coefficients for a wall specimen using a calibrated hot box. *ASTM Symposium on Insulation Materials, Testing and Applications*, Bal Harbour, FL, December 6-9. ASTM Special Technical Publication 1030.

Carslaw, H.S., and J.C. Jaeger. 1959. *Conduction of heat in solids*, 2d ed. London: Oxford University Press.

Mitalas, G.P. 1968. Calculation of transient heat flow through walls and roofs. *ASHRAE Transactions* 74(II). Also reprinted as NRC 10629, National Research Council Canada.

Mitalas, G.P. 1978. Comments on the z-transfer function method for calculating heat transfer in buildings. *ASHRAE Transactions* 84(I). Also reprinted as NRCC 17235, National Research Council Canada, Ottawa.

Mitalas, G.P., and J.G. Arsenault. 1972. FORTRAN IV program to calculate z-transfer functions for the calculation of transient heat transfer through walls and roofs. DBR Computer Program No. 33. Ottawa: National Research Council Canada.

Stephenson, D.G. 1987. A procedure for determining the thermal diffusivity of materials. *Journal of Thermal Insulation*, Vol. 10, April, pp. 236-242. Reprinted as NRCC 28337, National Research Council Canada, Ottawa.

Stephenson, D.G., and G.P. Mitalas. 1971. Calculation of heat conduction transfer functions for multi-layer slabs. *ASHRAE Transactions*.

Stephenson. D.G., K. Ouyang, and W.C. Brown. 1988. A procedure for deriving thermal transfer functions for walls from hot-box test results. Internal Report No. 568, National Research Council Canada, Ottawa.

TEST SPECIMEN #1

Description

Specimen #1 consisted of a 25 mm [1"] thick stucco exterior finish mounted to an insulated, heavy gauge steel stud wall. The studs were 89 mm [3-1/2"] deep and located 406 mm [16"] on center. The insulation was *RSI*-2.1 [*R*-12] friction fit glass fiber batts. The specimen was finished on the warm side with 12 mm [1/2"] gypsum board.

Test Results

The thermal resistance, R_S, determined at T_m=24°C [75°F] was 51% of that predicted from the sum of the resistances through the insulation. This indicates that the studs were acting as a significant thermal bridge for this wall design. The frequency response was measured at periods of 24 h, 12 h and 6 h and the values of *1/B* and *D/B* were determined from these measurements. The c_n coefficients were determined from a fit to the data measured at 12 h period. The *D/B* response of this specimen was typical of that exhibited by all specimens with gypsum board interior finish.

TABLE 1-1
Time constants and z-transfer function coefficients determined from measured data. τ_n are in hours, and b_n, c_n and d_n are dimensionless and based on Δ = 1 h.

n	0	1	2	3	4	5
τ_n		1.01	0.22	0.16	0.14	0.07
d_n	1.0000	-0.3849	0.0050			
b_n	0.1032	0.4179	0.0976	0.0014		
c_n	4.3823	-5.0281	1.2659			

TABLE 1-2
Physical properties used to predict thermal response.
l - thickness - mm [in.]
λ - thermal conductivity - W/(m·K) [Btu/(h·ft·°F)]
ρ - density - kg/m³ [lb/ft³]
C_p - specific heat - kJ/(kg·K) [Btu/(lb·°F)]

Material	l	λ	ρ	C_p
Gypsum board (interior)	12 [1/2]	0.160 [0.092]	800 [50]	1.09 [0.26]
Glass fiber batt insulation	89 [3-1/2]	0.042 [0.024]	14.5 [0.9]	0.71 [0.17]
Gypsum board (exterior)	12 [1/2]	0.160 [0.092]	800 [50]	1.09 [0.26]
Stucco	25 [1]	0.720 [0.426]	1856 [116]	0.84 [0.20]

Heat transfer coefficients:
Interior - 0.078 m²·K/W [0.44 h·ft²·°F/Btu]
Exterior - 0.033 m²·K/W [0.19 h·ft²·°F/Btu]

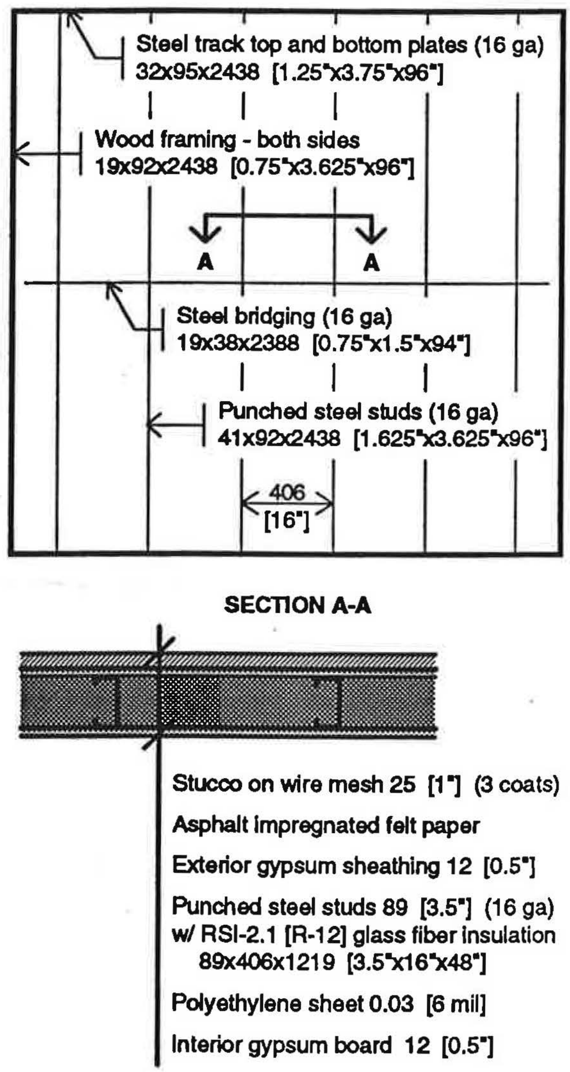
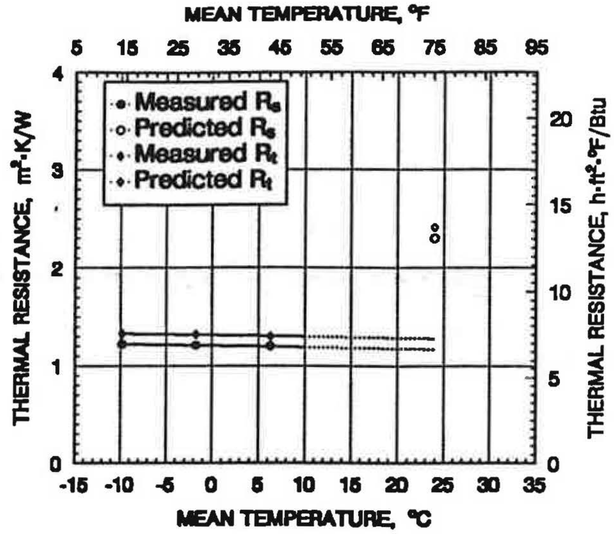


FIGURE 1-1 Elevation and cross sectional views of the specimen from the calorimeter (interior).

TEST SPECIMEN #1 (con't)

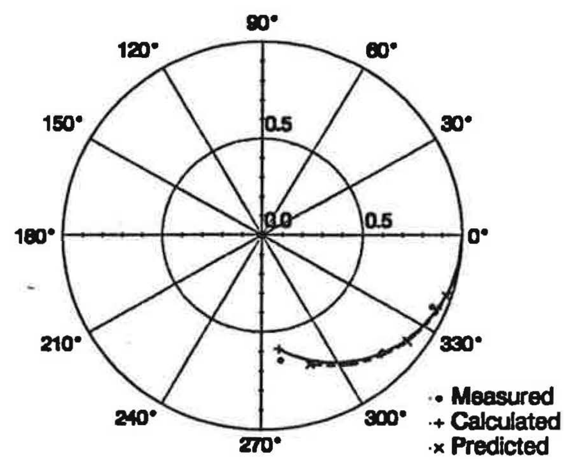
Steady State Response

		Measured	Calculated	Predicted
T_m	°C [°F]	0 [32]	24 [75]	24 [75]
R_1	m²·K/W [h·ft²·F/Btu]	0.078 [0.44]		
R_S	m²·K/W [h·ft²·F/Btu]	1.21 [6.85]	1.17 [6.66]	2.27 [13.08]
R_2	m²·K/W [h·ft²·F/Btu]	0.033 [0.19]		



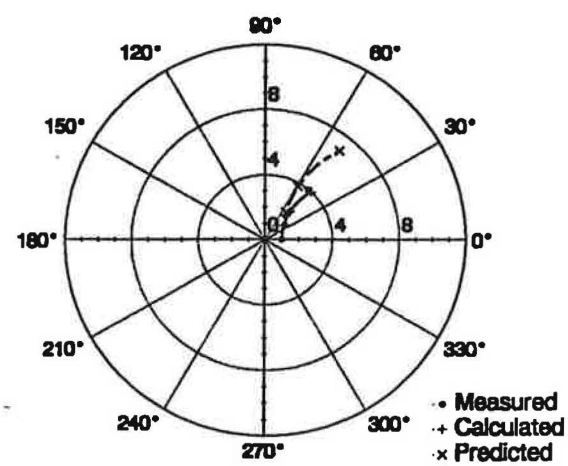
1/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48		
24	0.93∠-23°	0.96∠-24°
12	0.85∠-45°	0.85∠-46°
6	0.65∠-82°	0.60∠-82°



D/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48		
24	1.46∠37°	1.43∠38°
12	2.25∠49°	2.25∠49°
6	3.99∠50°	4.01∠47°



TEST SPECIMEN #2

Description

Specimen #2 consisted of 25 mm [1"] of extruded polystyrene insulation (*RSI*-0.7 [*R*-5]) mounted with light gauge steel furring to the warm side of an 200 mm [8"] thick precast concete slab. The furring was located 610 mm [24"] on center. The specimen was finished on the warm side with 16 mm [5/8"] gypsum board.

Test Results

The thermal resistance, R_S, determined at T_m=24°C [75°F] was 77% of that predicted from the sum of the resistances through the insulation. The frequency response was measured at periods of 48 h, 24 h, 12 h and 6 h and the values of $1/B$ and D/B were determined from these measurements. The c_n coefficients were determined from a fit to the data measured at 24 h and 6 h periods. The D/B response of this specimen was typical of that exhibited by all specimens with gypsum board interior finish.

TABLE 2-1
Time constants and z-transfer function coefficients determined from measured data. τ_n are in hours, and b_n, c_n and d_n are dimensionless and based on Δ = 1 h.

n	0	1	2	3	4	5
τ_n		9.05	0.45	0.44	0.39	0.34
d_n	1.0000	-1.2364	0.3481	-0.0405	0.0021	
b_n	0.0015	0.0257	0.0371	0.0087	0.0003	
c_n	3.6649	-7.3151	4.9626	-1.3787	0.1397	

TABLE 2-2
Physical properties used to predict thermal response.
l - thickness - mm [in.]
λ - thermal conductivity - W/(m·K) [Btu/(h·ft·°F)]
ρ - density - kg/m^3 [lb/ft^3]
C_p - specific heat - kJ/(kg·K) [Btu/(lb·°F)]

Material	l	λ	ρ	C_p
Gypsum board (interior)	16 [5/8]	0.160 [0.092]	800 [50]	1.09 [0.26]
Ext. polystyrene insulation	25 [1]	0.029 [0.018]	28.8 [1.8]	1.22 [0.29]
Reinforced concrete slab	203 [8]	1.728 [1.0]	2240 [140]	0.92 [0.22]

Heat transfer coefficients:
Interior - 0.078 m^2·K/W [0.44 h·ft^2·°F/Btu]
Exterior - 0.051 m^2·K/W [0.29 h·ft^2·°F/Btu]

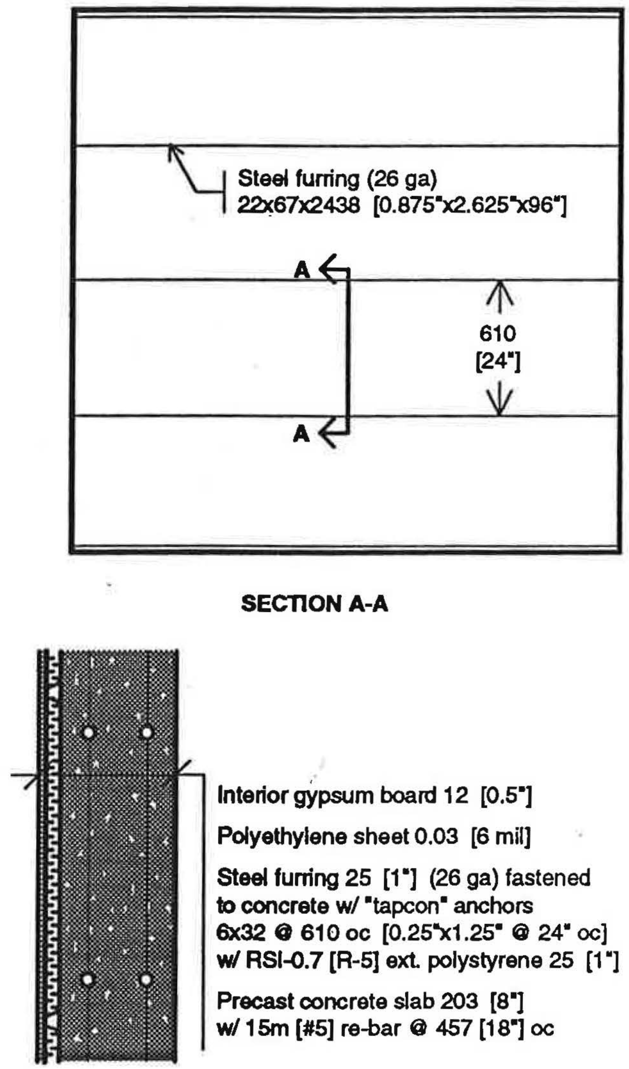
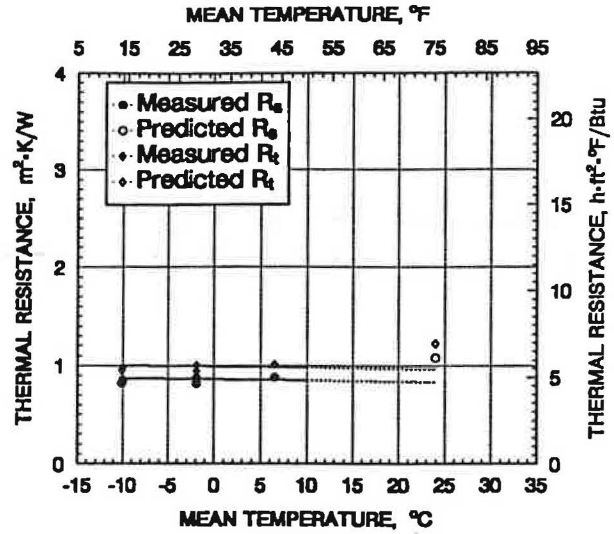


FIGURE 2-1 Elevation and cross sectional views of the specimen from the calorimeter (interior).

TEST SPECIMEN #2 (con't)

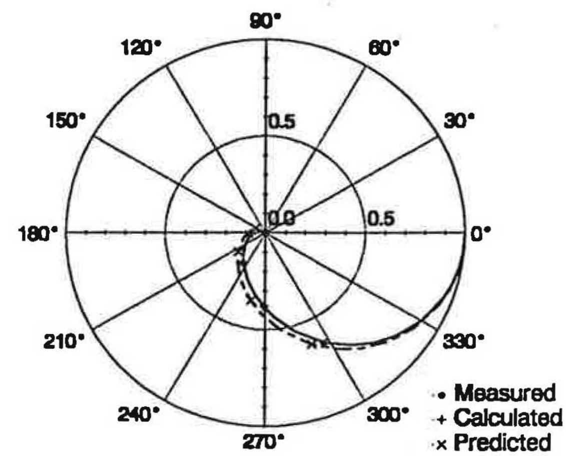
Steady State Response

		Measured	Calculated	Predicted
T_m	°C [°F]	0 [32]	24 [75]	24 [75]
R_1	m²·K/W [h·ft²·F/Btu]	0.078 [0.44]		
R_S	m²·K/W [h·ft²·F/Btu]	0.86 [4.89]	0.84 [4.74]	1.08 [6.12]
R_2	m²·K/W [h·ft²·F/Btu]	0.051 [0.29]		



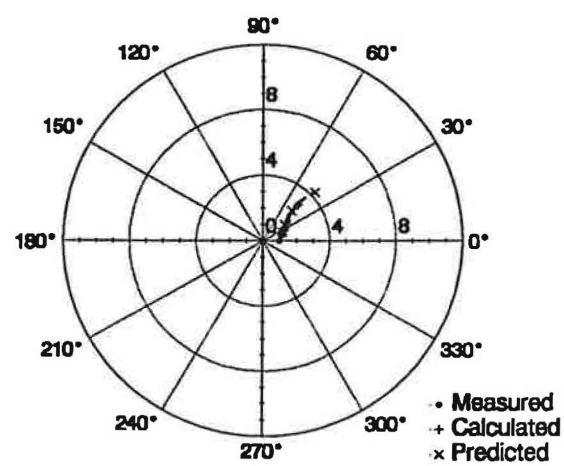
1/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48	0.64∠-63°	0.64∠-62°
24	0.38∠-91°	0.38∠-91°
12	0.19∠-127°	0.19∠-126°
6	0.08∠-177°	0.07∠-176°



D/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48	1.24∠17°	1.22∠19°
24	1.40∠27°	1.40∠27°
12	1.88∠39°	1.81∠39°
6	3.03∠46°	3.03∠46°



TEST SPECIMEN #3

Description

Specimen #3 was Specimen #2 reversed, i.e., the 200 mm [8"] concrete was located to the interior and the 19 mm [5/8"] gypsum board was located on the exterior. (Note that while the wall specimen was reversed, the surface heat transfer coefficients were not, and it cannot therefore be assumed that the same $1/B$ response will be measured for both.)

Test Results

The thermal resistance, R_S, determined at T_m=24°C [75°F] was 77% of that predicted from the sum of the resistances through the insulation. The frequency response of Specimen #3 was measured at periods of 48 h, 24 h, 12 h and 6 h and the values of $1/B$ and D/B were determined from these measurements. The c_n coefficients were determined from a fit to the data measured at the 24 h and 6 h periods. The D/B response of this specimen was of a shape typical of that exhibited by specimens with a concrete interior finish.

TABLE 3-1
Time constants and z-transfer function coefficients determined from measured data. τ_n are in hours, and b_n, c_n and d_n are dimensionless and based on Δ = 1 h.

n	0	1	2	3	4	5
τ_n		11.39	0.98	0.60	0.25	0.07
d_n	1.0000	-1.4836	0.5981	-0.0728	0.0011	
b_n	0.0014	0.0183	0.0202	0.0029		
c_n	10.1458	-16.6276	7.2687	-0.6731	-0.0711	

TABLE 3-2
Physical properties used to predict thermal response.
l - thickness - mm [in.]
λ - thermal conductivity - W/(m·K) [Btu/(h·ft·°F)]
ρ - density - kg/m³ [lb/ft³]
C_p - specific heat - kJ/(kg·K) [Btu/(lb·°F)]

Material	l	λ	ρ	C_p
Reinforced concrete slab	203 [8]	1.728 [1.0]	2240 [140]	0.92 [0.22]
Ext. polystyrene insulation	25 [1]	0.029 [0.018]	28.8 [1.8]	1.22 [0.29]
Gypsum board (interior)	16 [5/8]	0.160 [0.092]	800 [50]	1.09 [0.26]

Heat transfer coefficients:
Interior - 0.078 m²·K/W [0.44 h·ft²·°F/Btu]
Exterior - 0.043 m²·K/W [0.24 h·ft²·°F/Btu]

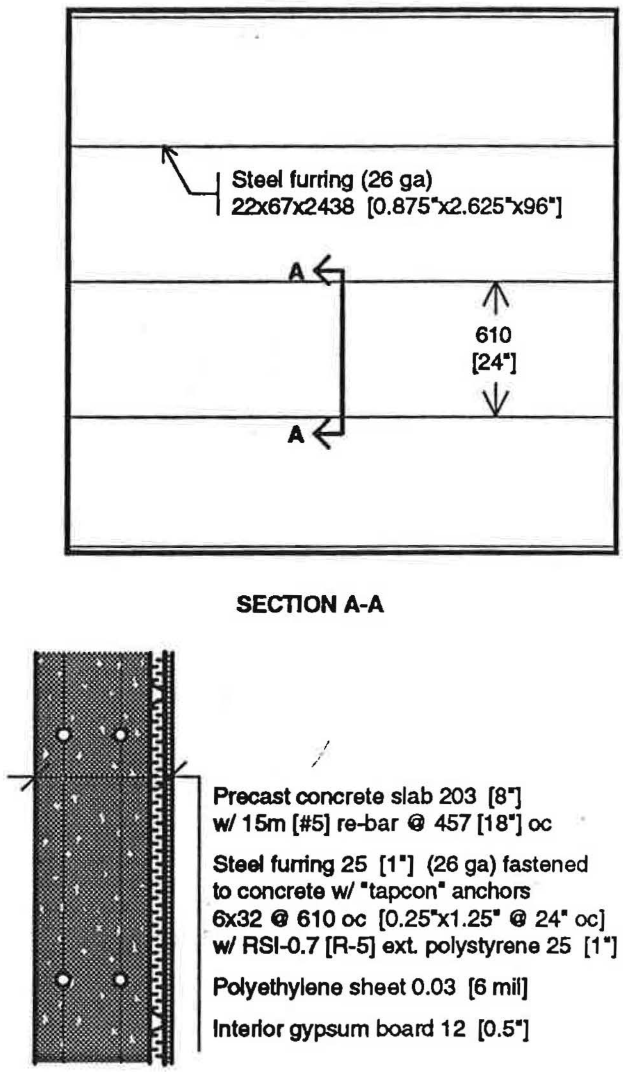
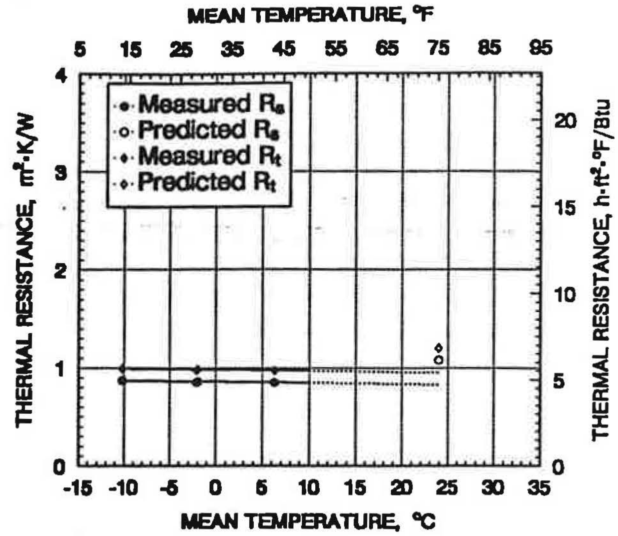


FIGURE 3-1 Elevation and cross sectional views of the specimen from the calorimeter (interior).

TEST SPECIMEN #3 (con't)

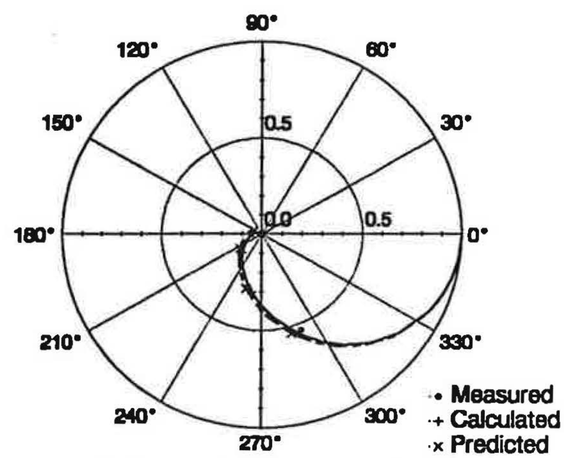
Steady State Response

		Measured	Calculated	Predicted
T_m	°C [°F]	0 [32]	24 [75]	24 [75]
R_1	m²·K/W [h·ft²·F/Btu]	0.078 [0.44]		
R_S	m²·K/W [h·ft²·F/Btu]	0.86 [4.88]	0.83 [4.73]	1.08 [6.12]
R_2	m²·K/W [h·ft²·F/Btu]	0.043 [0.24]		



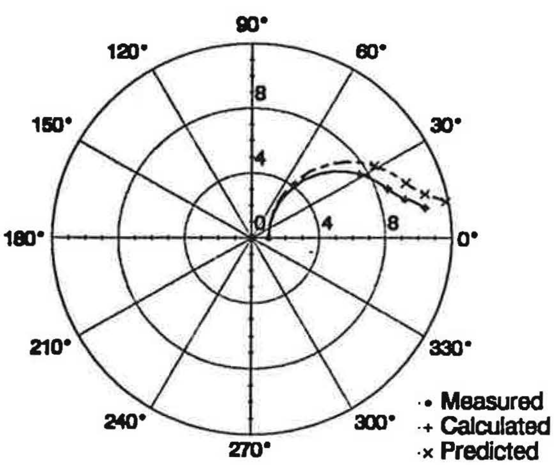
1/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48	0.53∠ -68°	0.55∠ -70°
24	0.31∠-100°	0.30∠-100°
12	0.15∠-135°	0.14∠-135°
6	0.06∠-187°	0.04∠-182°



D/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48	7.52∠31°	7.51∠32°
24	8.69∠20°	8.69∠20°
12	9.45∠14°	9.51∠15°
6	10.56∠10°	10.56∠10°



TEST SPECIMEN #4

Description

Specimen #4 consisted of an insulated steel stud wall mounted to a 100 mm [4"] thick reinforced concrete slab. The studs were 89 mm [3-1/2"] deep and located 406 mm [16"] on center. The insulation was *RSI*-2.1 [*R*-12] friction fit glass fiber batts. The specimen was finished on the interior with 16 mm[5/8"] gypsum board.

Test Results

The thermal resistance, R_S, determined at T_m=24°C [75°F] was 58% of that predicted from the sum of the resistances through the insulation. This indicates that the steel studs were acting as a significant thermal bridge for this wall design. The frequency response was measured at periods of 48 h, 24 h, 12 h and 6 h and the values of *1/B* and *D/B* were determined from these measurements. The c_n coefficients were determined from a fit to the data measured at the 24 h and 6 h periods. The *D/B* response of this specimen was of a shape typical of that exhibited by specimens with gypsum board interior finish.

TABLE 4-1
Time constants and z-transfer function coefficients determined from measured data. τ_n are in hours, and b_n, c_n and d_n are dimensionless and based on Δ = 1 h.

n	0	1	2	3	4	5
τ_n		4.19	0.26	0.25	0.22	0.08
d_n	1.0000	-0.8380	0.0404	-0.0006		
b_n	0.0173	0.1218	0.0598	0.0029		
c_n	6.2455	-11.3309	6.5383	-1.4812	-0.2302	

TABLE 4-2
Physical properties used to predict thermal response.
l - thickness - mm [in.]
λ - thermal conductivity - W/(m·K) [Btu/(h·ft·°F)]
ρ - density - kg/m^3 [lb/ft^3]
C_p - specific heat - kJ/(kg·K) [Btu/(lb·°F)]

Material	l	λ	ρ	C_p
Gypsum board (interior)	16 [5/8]	0.160 [0.092]	800 [50]	1.09 [0.26]
Glass fiber batt insulation	89 [3-1/2]	0.042 [0.024]	14.5 [0.9]	0.71 [0.17]
Reinforced concrete slab	102 [4]	1.728 [1.0]	2240 [140]	0.92 [0.22]

Heat transfer coefficients:
Interior - 0.079 m^2·K/W [0.45 h·ft^2·°F/Btu]
Exterior - 0.054 m^2·K/W [0.31 h·ft^2·°F/Btu]

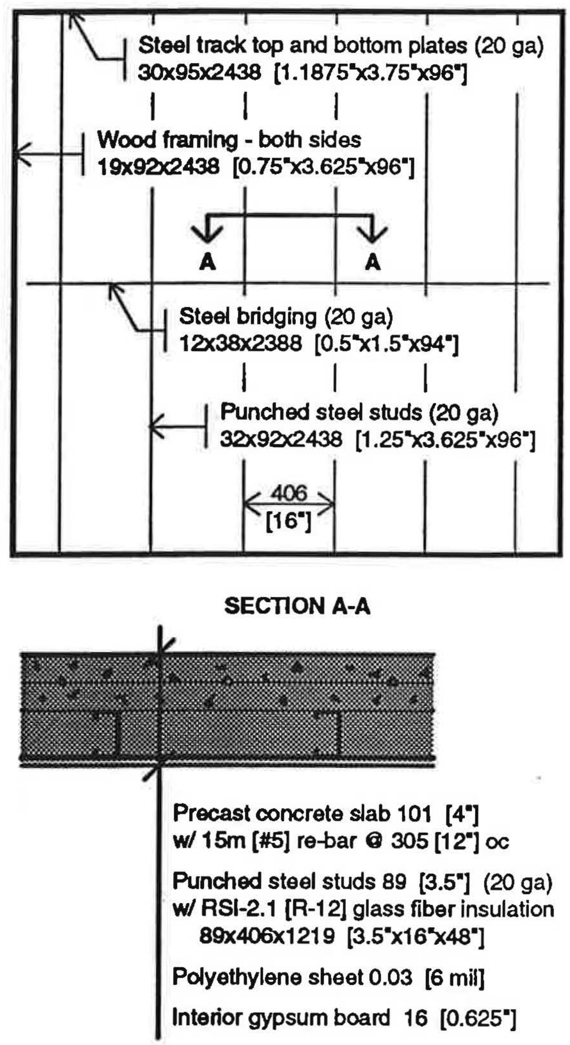
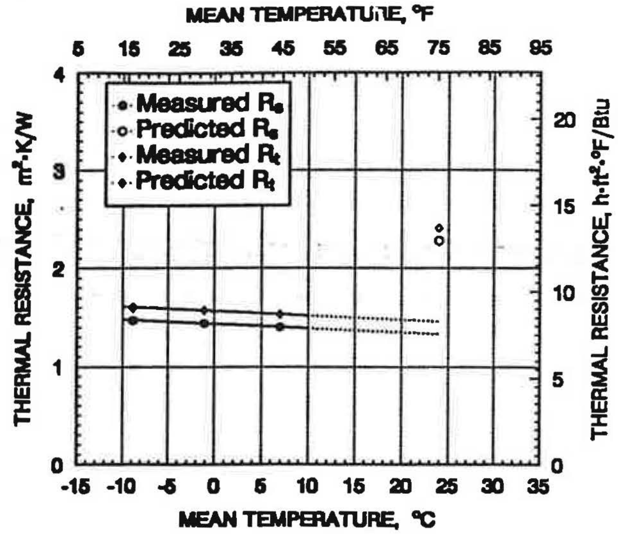


***FIGURE 4-1** Elevation and cross sectional views of the specimen from the calorimeter (interior).*

TEST SPECIMEN #4 (con't)

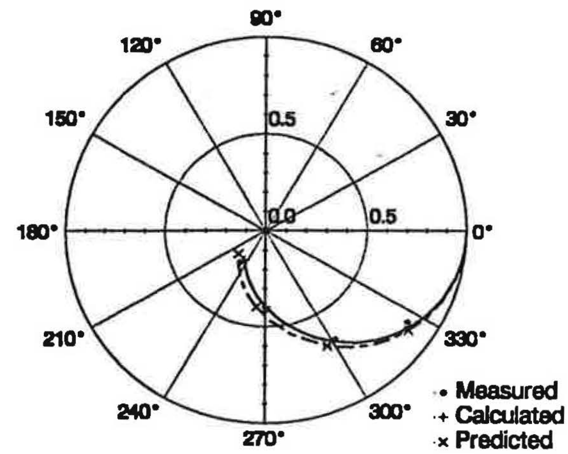
Steady State Response

		Measured	Calculated	Predicted
T_m	°C [°F]	0 [32]	24 [75]	24 [75]
R_1	m²K/W [h·ft²·F/Btu]	0.079 [0.45]		
R_S	m²K/W [h·ft²·F/Btu]	1.43 [8.13]	1.33 [7.56]	2.28 [12.93]
R_2	m²K/W [h·ft²·F/Btu]	0.054 [0.31]		



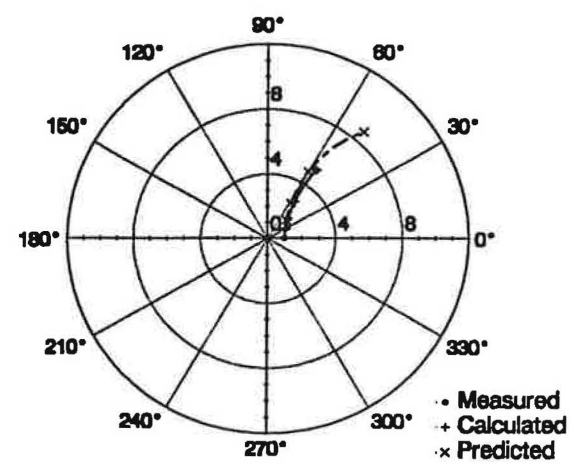
1/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48	0.85∠ -34°	0.87∠ -35°
24	0.66∠ -59°	0.67∠ -60°
12	0.41∠ -89°	0.40∠ -90°
6	0.21∠-128°	0.18∠-125°



D/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48	1.30∠30°	1.24∠31°
24	1.71∠45°	1.71∠45°
12	2.83∠56°	2.79∠55°
6	5.11∠56°	5.11∠56°



TEST SPECIMEN #5

Description

Specimen #5 consisted of a hollow concrete block wall with 51 mm [2"] extruded polystyrene attached to the exterior and a 22 mm [7/8"] furred air space to the interior. The specimen was finished on the exterior with 89 mm [3-1/2"] clay brick and on the interior with 16 mm [5/8"] gypsum board.

Test Results

The thermal resistance, R_S, determined at T_m=24°C [75°F] was 90% of that predicted from the sum of the resistances through the insulation. This indicates that the steel furring and 'truss-type' brick ties were not acting as significant thermal bridges for this wall design. The frequency response was measured at periods of 48 h, 24 h, 12 h for both z-transfer function coefficients and at the 6 h period for the *D/B* response (the *1/B* response at the 6 h period was below the sensitivity of the test apparatus). The c_n coefficients were determined from a fit to the data measured at the 24 h and 6 h periods. The *D/B* response of this specimen was similar to that exhibited by specimens with a concrete interior finish.

TABLE 5-1
Time constants and z-transfer function coefficients determined from measured data. τ_n are in hours, and b_n, c_n and d_n are dimensionless and based on Δ = 1 h.

n	0	1	2	3	4	5
τ_n		14.39	4.18	1.20	0.22	0.01
d_n	1.0000	-2.1653	1.5048	-0.3349	0.0034	
b_n	0.0002	0.0032	0.0040	0.0006		
c_n	10.6690	-28.9969	29.0165	-12.9742	2.2935	

TABLE 5-2
Physical properties used to predict thermal response.
l - thickness - mm [in.]
λ - thermal conductivity - W/(m·K) [Btu/(h·ft·°F)]
ρ - density - kg/m³ [lb/ft³]
C_p - specific heat - kJ/(kg·K) [Btu/(lb·°F)]

Material	l	λ	ρ	C_p
Gypsum board (interior)	16 [5/8]	0.160 [0.092]	800 [50]	1.09 [0.26]
Air space		RSI-0.16 [R-0.91]		
Hollow concrete masonry units	140 [5-1/2]	0.737 [0.43]	1215 [76]	0.92 [0.22]
Ext. polystyrene insulation	51 [2]	0.029 [0.018]	28.8 [1.8]	1.22 [0.29]
Burned clay brick	89 [3-1/2]	0.780 [0.45]	1920 [120]	0.79 [0.19]

Heat transfer coefficients:
Interior - 0.078 m²·K/W [0.44 h·ft²·°F/Btu]
Exterior - 0.055 m²·K/W [0.31 h·ft²·°F/Btu]

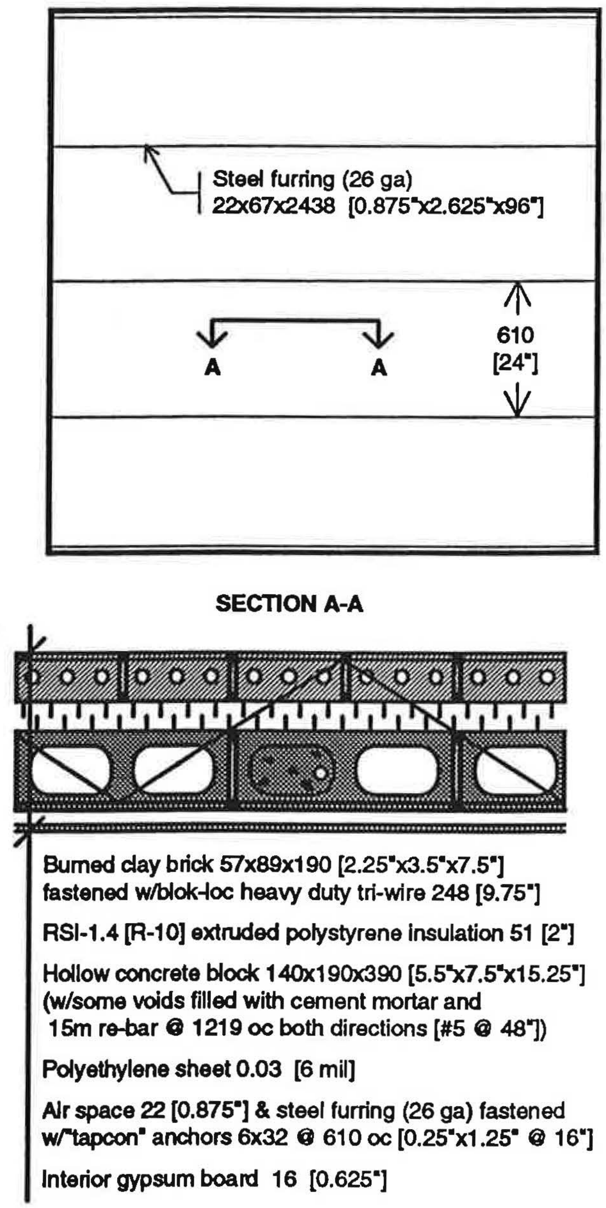
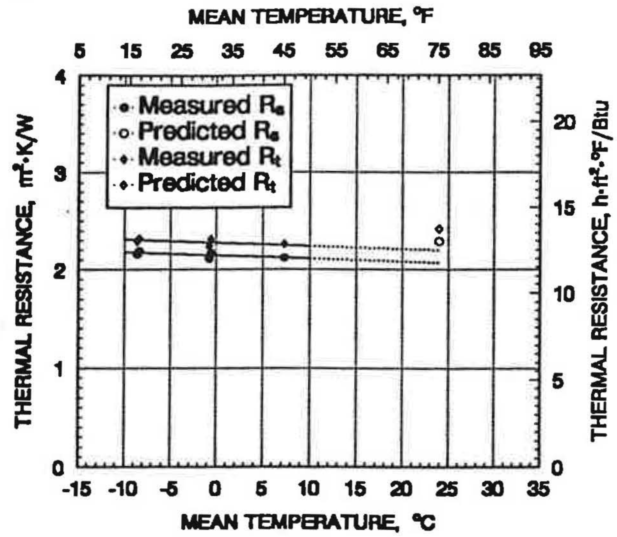


FIGURE 5-1 Elevation and cross sectional views of the specimen from the calorimeter (interior).

TEST SPECIMEN #5 (con't)

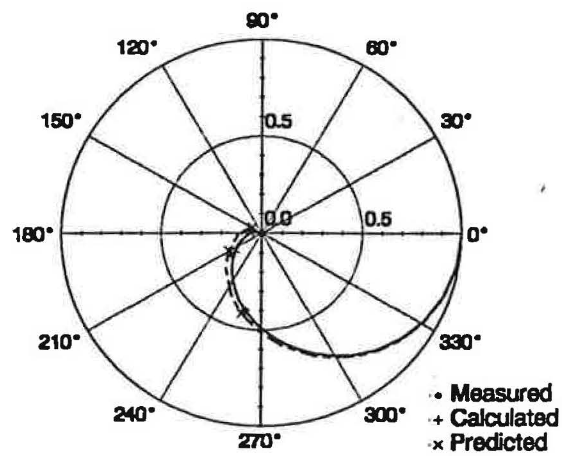
Steady State Response

		Measured	Calculated	Predicted
T_m	°C [°F]	0 [32]	24 [75]	24 [75]
R_1	m²·K/W [h·ft²·F/Btu]	0.078 [0.44]		
R_S	m²·K/W [h·ft²·F/Btu]	2.14 [12.17]	2.07 [11.73]	2.29 [12.99]
R_2	m²·K/W [h·ft²·F/Btu]	0.055 [0.31]		



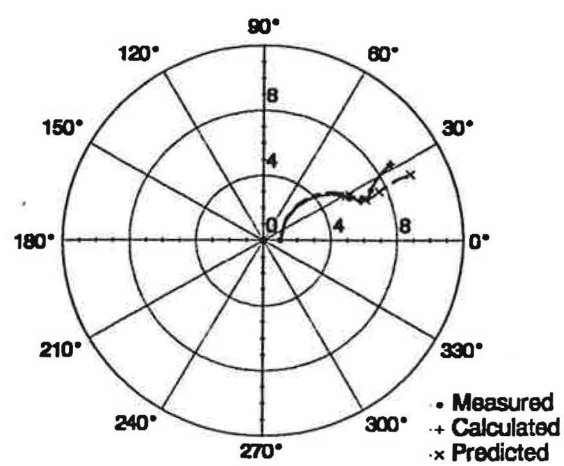
1/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48	0.41∠-101°	0.41∠-101°
24	0.19∠-145°	0.16∠-144°
12	0.06∠-198°	0.04∠-187°
6		



D/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48	5.75∠27°	5.44∠30°
24	6.28∠23°	6.28∠23°
12	7.10∠26°	6.82∠24°
6	8.91∠32°	8.91∠32°



TEST SPECIMEN #6

Description

Specimen #6 consisted of an insulated steel stud wall finished on the exterior with 89 mm [3-1/2"] burned clay brick. The studs were 89 mm [3-1/2"] deep and located 406 mm [16"] on center. The insulation was *RSI*-2.1 [*R*-12] friction fit glass fiber batts. The specimen was finished on the interior with 16 mm [5/8"] gypsum board.

Test Results

The thermal resistance, R_S, determined at T_m=24°C [75°F] was 63% of that predicted from the sum of the resistances through the insulation. This indicates that the combination of steel studs and brick ties were acting as a significant thermal bridge for this wall design. The frequency response was measured at periods of 24 h, 12 h and 6 h and the values of *1/B* and *D/B* were determined from these measurements. The c_n coefficients were determined from a fit to the data measured at the 24 h and 6 h periods. The *D/B* response of this specimen was of a shape typical of that exhibited by specimens with gypsum board interior finish.

TABLE 6-1

Time constants and z-transfer function coefficients determined from measured data. τ_n are in hours, and b_n, c_n and d_n are dimensionless and based on Δ = 1 h.

n	0	1	2	3	4	5
τ_n		3.46	0.49	0.37	0.33	0.31
d_n	1.0000	-1.0340	0.2414	-0.0221	0.0009	
b_n	0.0048	0.0722	0.0907	0.0179	0.0006	
c_n	7.2460	-14.4387	9.9135	-2.8831	0.3485	

TABLE 6-2

Physical properties used to predict thermal response.
l - thickness - mm [in.]
λ - thermal conductivity - W/(m·K) [Btu/(h·ft·°F)]
ρ - density - kg/m^3 [lb/ft^3]
C_p - specific heat - kJ/(kg·K) [Btu/(lb·°F)]

Material	l	λ	ρ	C_p
Gypsum board (interior)	16 [5/8]	0.160 [0.092]	800 [50]	1.09 [0.26]
Glass fiber batt insulation	89 [3-1/2]	0.042 [0.024]	14.5 [0.9]	0.71 [0.17]
Gypsum board (exterior)	12 [1/2]	0.160 [0.092]	800 [50]	1.09 [0.26]
Air space		RSI-0.21 [R-1.19]		
Burned clay brick	89 [3-1/2	0.780 [0.45]	1920 [120]	0.79 [0.19]

Heat transfer coefficients:
Interior - 0.078 m^2·K/W [0.44 h·ft^2·°F/Btu]
Exterior - 0.051 m^2·K/W [0.29 h·ft^2·°F/Btu]

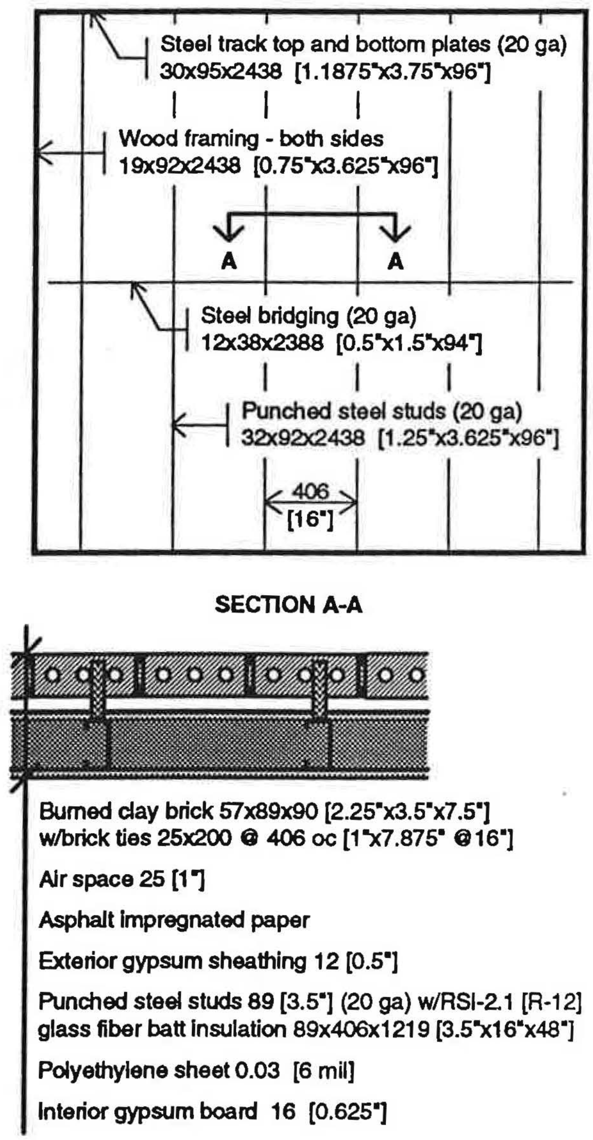
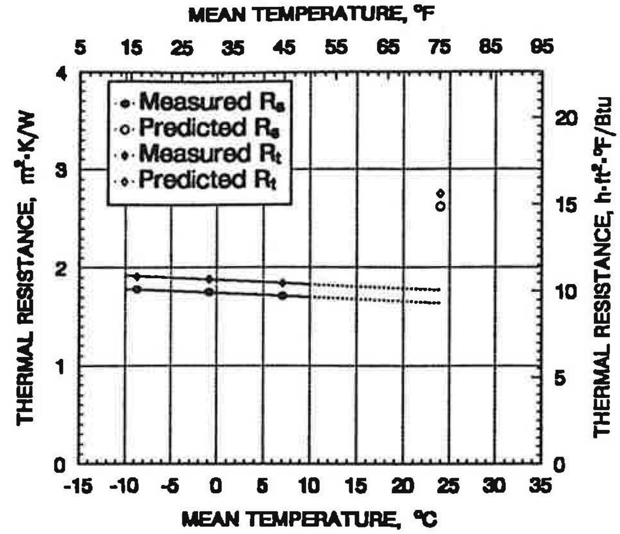


***FIGURE 6-1** Elevation and cross sectional views of the specimen from the calorimeter (interior).*

TEST SPECIMEN #6 (con't)

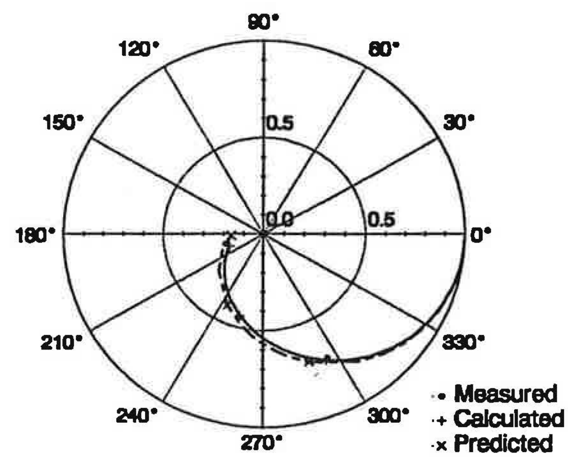
Steady State Response

		Measured	Calculated	Predicted
T_m	°C [°F]	0 [32]	24 [75]	24 [75]
R_1	m²·K/W [h·ft²·F/Btu]	0.078 [0.44]		
R_S	m²·K/W [h·ft²·F/Btu]	1.74 [9.89]	1.64 [9.31]	2.62 [14.87]
R_2	m²·K/W [h·ft²·F/Btu]	0.051 [0.29]		



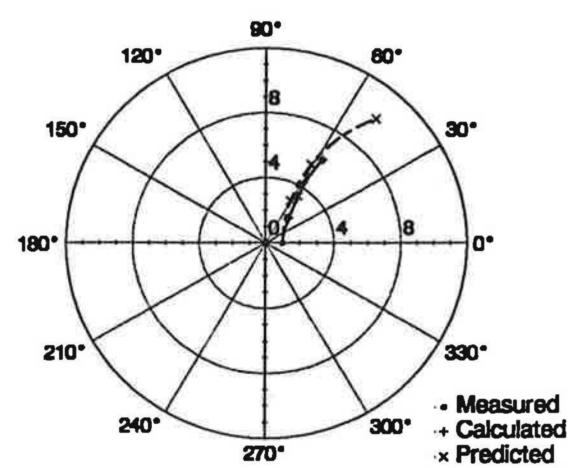
1/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48		
24	0.71∠-64°	0.72∠-65°
12	0.45∠-105°	0.44∠-105°
6	0.19∠-165°	0.18∠-160°



D/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48		
24	2.04∠48°	2.04∠48°
12	3.48∠58°	3.27∠56°
6	6.06∠57°	6.06∠57°



TEST SPECIMEN #7

Description

Specimen #7 consisted of a solid concrete block wall with 100 mm [4"] extruded polystyrene, a 46 mm [1-3/4"] air space and 27 mm [1"] granite attached to the exterior.

Test Results

The thermal resistance, R_S, determined at T_m=24°C [75°F] was 45% of that predicted from the sum of the resistances through the insulation. This indicates that the steel anchors that held the granite to the block are acting as significant thermal bridges for this wall design. The frequency response was measured at periods of 48 h, 24 h, 12 h and 6 h and the values of $1/B$ and D/B were determined from these measurements. The c_n coefficients were determined from a fit to the data measured at the 24 h and 6 h periods. The D/B response of this specimen was of a shape typical of that exhibited by specimens with a concrete interior finish. The large discrepancy between the calculated and predicted response is due in large part to the difference between measured and predicted R-value.

TABLE 7-1
Time constants and z-transfer function coefficients determined from measured data. τ_n are in hours, and b_n, c_n and d_n are dimensionless and based on Δ = 1 h.

n	0	1	2	3	4	5
τ_n		7.42	0.90	0.73	0.70	0.30
d_n	1.0000	-1.7326	1.0032	-0.2490	0.0252	-0.0006
b_n	0.0005	0.0118	0.0246	0.0088	0.0005	
c_n	17.0794	-32.4576	19.6809	-4.4393	0.1829	

TABLE 7-2
Physical properties used to predict thermal response.
l - thickness - mm [in.]
λ - thermal conductivity - W/(m·K) [Btu/(h·ft·°F)]
ρ - density - kg/m³ [lb/ft³]
C_p - specific heat - kJ/(kg·K) [Btu/(lb·°F)]

Material	l	λ	ρ	C_p
Solid concrete masonry units	140 [5-1/2]	1.728 [1.00]	2100 [131]	0.92 [0.22]
Ext. polystyrene insulation	100 [4]	0.029 [0.018]	28.8 [1.8]	1.22 [0.29]
Air space		RSI-0.22 [R-1.25]		
Exterior granite veneer	27 [1]	2.600 [1.50]	2600 [162]	0.88 [0.21]

Heat transfer coefficients:
Interior - 0.079 m²·K/W [0.45 h·ft²·°F/Btu]
Exterior - 0.043 m²·K/W [0.24 h·ft²·°F/Btu]

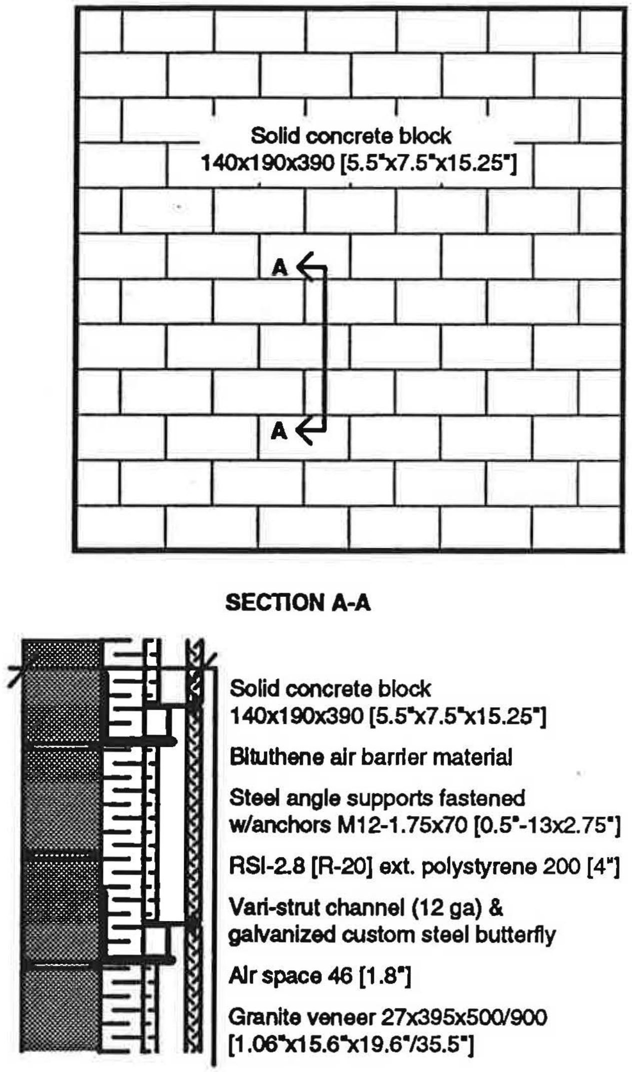
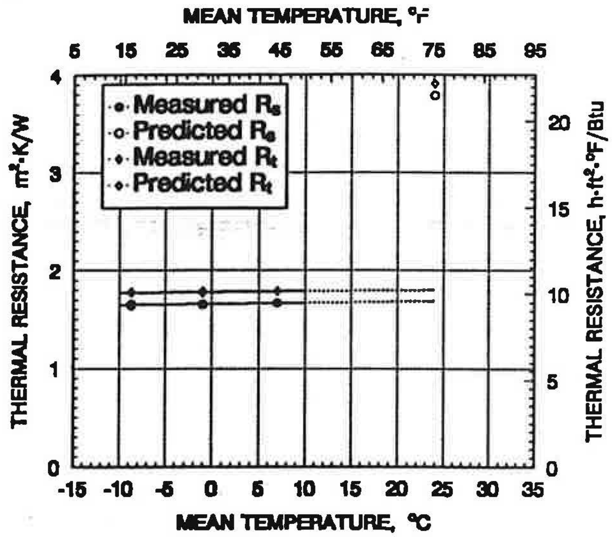


FIGURE 7-1 Elevation and cross sectional views of the specimen from the calorimeter (interior).

TEST SPECIMEN #7 (con't)

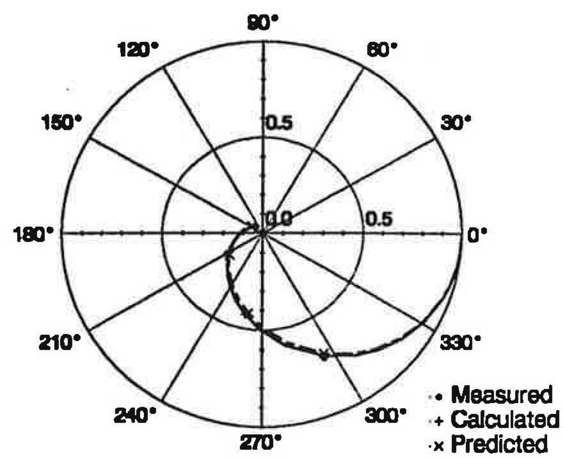
Steady State Response

	Measured	Calculated	Predicted
T_m °C [°F]	0 [32]	24 [75]	24 [75]
R_1 m²·K/W [h·ft²·F/Btu]	0.079 [0.45]		
R_S m²·K/W [h·ft²·F/Btu]	1.66 [9.93]	1.69 [9.60]	3.79 [21.54]
R_2 m²·K/W [h·ft²·F/Btu]	0.043 [0.24]		



1/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48	0.71∠-64°	0.70∠-64°
24	0.42∠-101°	0.43∠-102°
12	0.21∠-149°	0.19∠-151°
6	0.05∠-221°	0.05∠-217°



D/B Response

Period	Measured	Calculated
h	Amp∠Phase	Amp∠Phase
48	11.66∠45°	11.49∠43°
24	14.70∠27°	14.70∠27°
12	16.79∠17°	16.41∠18°
6	18.23∠11°	18.23∠11°