Chapter 11

Properties of Walls Using Lightweight Concrete and Lightweight Concrete Masonry Units

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Chapter 11 Properties of Walls Using Lightweight Concrete and Lightweight Concrete Masonry Units

11.1.0 Introduction

Wall enclosure of buildings must provide long lasting protection against the forces of nature heat/cold, wet/dry and in some areas frost or integrity against the penetration of rain and high winds. Investigations of ancient civilizations have amply demonstrated that masonry and concrete type walls have centuries of proven performance. Additionally, the protection against the destruction caused by fire has further separated concrete and masonry walls from the heavy losses incurred with temporary type construction using wood framing and organic products. In addition, our current civilization has placed many demands on buildings that include high structural strength, resistance to sound transmission, excessive air penetration and impact forces. Because masonry and concrete wall systems have successfully provide all of these necessary virtues, they have become the global material of choice for building enclosures.

Although this Chapter is presented in four sections; thermal, fire, sound and environmental resistance, it is clearly recognized that because some physical properties (e.g. thermal conductivity), there will be some overlap. A serious attempt was made to balance the amount of critical information provided against a thorough analysis of the issues, by supplying documents in the appendix as well as offering footnotes to additional references.

A considerable part of the contents of this chapter are directly excerpted from or heavily drawn upon from ACI 122 "*Guide to the Thermal Properties of Concrete and Masonry Systems"* which provides thermal-property data and design techniques that are useful in designing concrete and masonry building envelopes for energy code compliance. The 122 Guide is intended for use by owners, architects, engineers, building inspectors, code-enforcement officials, and all those interested in the advancing energy-efficient design of concrete and masonry buildings.

To reduce the use of non-recoverable energy sources, almost all authorities have now adopted energy-conservation building codes and standards, as for example the International Energy Conservation Code, IECC 2004 that applies to the design and construction of buildings. The design of energy-conserving buildings now requires comprehensive documentation of the thermal properties of the materials that comprise the envelope system.

Due to its inherent functionality and the availability of raw materials used in its production, concrete and masonry are the world's most widely used building materials. Many civilizations have built structures with concrete and masonry walls that provide uniform and comfortable indoor temperatures despite all types of climatic conditions. Cathedrals composed of massive masonry walls produce an indoor climate with little temperature variation during the entire year despite the absence of a heating system. Even primitive housing in the desert areas of North America used thick masonry walls that produced acceptable interior temperatures despite outside temperatures that had a high daily peak.

Exterior wall systems made with concrete products provide efficient load-bearing masonry wall systems as well as resistance to weather, temperature changes, fire, and noise. Many of these wall systems are made with lightweight concrete to enhance thermal characteristics, static and dynamic resistance.

In addition to structural requirements, a building envelope should be designed to control the flow of air, heat, sunlight, radiant energy, and water vapor, and to avoid the entry of rain and snow. It should also provide the many other attributes generally associated with enclosure materials, including fire and noise control, structural adequacy, durability, aesthetic quality, and economy. Any analysis of building enclosure materials should account for their multifunctional purpose.

11.1.1 Thermal Resistance and Energy Conservation with Structural Lightweight Concrete and Lightweight Concrete Masonry

Thermal Conductivity

Thermal conductivity is a specific property of a gas, liquid, or solid. The coefficient of thermal conductivity *k* is a measure of the rate at which heat (energy) passes perpendicularly through a unit area of homogeneous material of unit thickness for a temperature difference of one degree; *k* is expressed as Btu • in./(h • ft^2 • ºF)[W/(m^2K)].

The thermal resistance of a layer of material can be calculated as the thickness of the layer divided by the thermal conductivity of the material. If a wall is made up of uniform layers of different materials in contact with each other, or separated by continuous air spaces of uniform thickness, the resistances of each are combined by a simple addition. Surface-air-film resistances should be included to yield the wall's total thermal resistance (*R*-value). If any air spaces are present between layers, the thermal resistances of these air spaces are also included.

The thermal conductivity of a material, such as concrete or insulation, is usually determined by measuring in accordance with ASTM C 177 or ASTM C 236. Several methods for calculating concrete thermal conductivity have been developed and are discussed. These calculated estimates are useful if test data are not available.

Basic testing programs conducted by Technical Institutions demonstrate that, in general, the coefficient of thermal conductivity for concrete k_c, is dependent on the aggregate types used in the concrete mixture. For simplicity, these data are often correlated to concrete density *d*. Valore (1980) plotted oven-dry density of concrete as a function of the logarithm of k_c, developing a straight line that can be expressed by the equation

$$k_c = 0.5e^{0.02d} \text{ (inch-pound units)}$$
$$k_c = 0.072e^{0.00125d} \text{ (S.I. units)} \tag{11-1}$$

where d = oven-dry density in lb/ft³ [kg/m³].

Thermal conductivity values for concretes with the same density made with different aggregates can differ from the relationship expressed by Eq. (11-1) and may significantly underestimate k_c for normalweight concretes and for lightweight concretes containing normalweight supplemental aggregates (Valore 1980, 1988). This is due to differences in the thermal properties of specific mineral types in the aggregates. Thermal conductivity values obtained using Eq. (11-1) for concrete with densities from 20 lb/ft³ to 100 lb/ft³ [320 to 1600 kg/m³] correlate better to test data than for concretes outside this density range (Valore 1980).

Thermal Conductivity of Natural Minerals and Aggregates

Oven-dry thermal-conductivity values for natural minerals and aggregates are shown in Table 11.1.1.

Table 11.1.1 – Thermal Conductivity of some natural minerals

Mineral	Thermal Conductivity
Quartz (single crystal)	87, 47
Quartz	40
Quartzite	22 to 37
Hornblende-quartz-gneiss	20
Quartz-monzonite	18
Sandstone	9 to 16
Granite	13 to 28
Marble	14 to 21
Limestone	6 to 22
Chalk	6
Diorite (dolerite)	15.6
Basalt (trap rock)	9.6 to 15
Slate	13.6
Lightweight Aggregate	3.3*

*From “Thermo-Structural Stability of Concrete Masonry Walls”, Holm & Bremner 1987

Influence of Moisture

In normal use, concrete is not in moisture-free or oven-dry conditions; thus, concrete conductivity should be corrected for moisture effects.

A more accurate value to determine moisture effects may be estimated by increasing the value of k_c by 6% for each 1% of moisture by weight (Valore 1980, 1988).

$$k_c(corrected) = k_c\left[1+\frac{(6d_m-d_o}{d_o}\right] \qquad (11\text{-}2)$$

where d_m and d_o are densities of concrete in moist and oven-dry conditions, respectively.

For most concrete walls, a single factor of 1.2 can be applied to oven-dry k_c values (Valore 1980). It then becomes necessary only to change the constant in Eq. (11-2) from 0.5 [0.072] to 0.6 [0.0865] to provide for a 20% increase in k_c for air-dry, in-service, concrete, or concrete masonry:

$$k_c = 0.6 \bullet e^{0.02d} \text{ (inch-pound units)}$$

$$k_c = 0.0865 \bullet e^{0.00125d} \text{ (S.I. units)} \qquad (11\text{-}3)$$

Thermal Conductivity of Concrete Used in Concrete Masonry Units

Concrete Masonry Units (CMU) consists of approximately 65 to 70% aggregate by volume. The remaining volume consists of voids between aggregate particles, entrapped air, and cement paste. The typical air-void content of concrete used to make lightweight CMU's, for example, has been found to be about 8-12% by volume. Expressed as a percentage of the cement paste, void volumes are approximately 25 to 40%. For a typical lightweight CMU having a net w/c of 0.6 and an average cement-paste air-void content of 40%, the thermal conductivity would be in the range of 1.5 to 1.8 Btu • in./h • ft^2 • ºF [0.22 to 0.26 W/(m^{2}K)]. Such values are considerably lower than those in Eq. (11-1) or Eq. (11-2) for typical lightweight aggregate, concrete (void-free) (Valore 1980) because the air spaces found in the zero slump CMU lightweight concrete provide additional heat flow resistance, thus lowering the conductivity.

Thermal Conductivity Calculations Using the Cubic Model

The cubic model can be used to calculate k_c as a function of cement paste conductivity, aggregate conductivity, and aggregate volume. The cubic model (Fig. 11.1.1) is a unit volume cube of concrete consisting of a cube of aggregate of volume V_a encased on all sides by a layer of cement past of unit thickness, $(1 - V_a^{1/3})/2$. The cubic model also accounts for the fact that concrete is a thermally and physically heterogeneous material and may contain highly conductive aggregates that serve as thermal bridges or shunts. Thermal bridges are highly conductive materials surrounded by relatively low conductive materials that greatly increase the composite system's conductivity. In the case of concrete, highly conductive aggregates are the thermal bridges and they are surrounded by the lower conductive cement paste and/or and fine aggregate matrix. To use the cubic model, Eq. (11-4), thermal-conductivity values for cement paste k_p, aggregate k_a, and aggregate volume V_a are required for estimating the thermal conductivity of concrete.

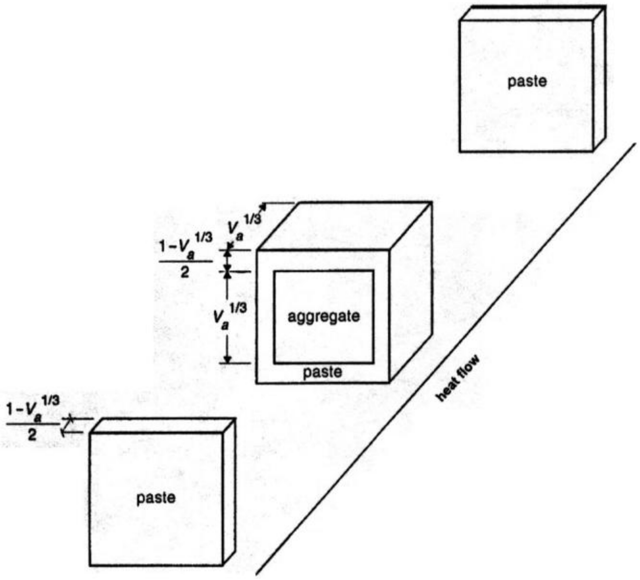

Figure 11.1.1 ***Cubic model for calculating thermal conductivity k_c of concrete as a function of conductive k_p and k_a of cement paste and aggregate, and volume fraction V_a of aggregate.***

$$k_c = k_p \left[\frac{V_a^{2/3}}{V_a^{2/3} - V_a + \left(\frac{V_a}{\left(\frac{k_a V_a^{2/3}}{k_p} \right) + 1 - V_a^{2/3}} \right)} \right] \quad \textbf{(11-4)}$$

When fine and coarse aggregate k_a values differ, k_c is calculated for the paste/fine aggregate mortar first and the calculation is then repeated for the paste/coarse aggregate combination using the appropriate V_a value in each step. For concretes weighing 120 lb/ft^3 [1920 kg/m^3] or less, thermal conductivities determined using Eq. (11-2) show good agreement with the thermal conductivity determined using the simpler conductivity/density relationship of Eq. (11-1). For normalweight concretes with densities greater than 120 lb/ft^3 [1920 kg/m^3], Eq. (11-4), yields more accurate k_c values than Eq. (11-1).

The cubic model shows that the thermal conductivity of a discrete two-phase system, such as concrete, can also be calculated by knowing the volume fractions and the thermal conductivity values of the cement pastes and aggregates (Fig. 11.1). For lightweight aggregate concretes, Eq. (11-1) yields k_c values similar to those calculated by using the cubic-model equation, Eq. (11-4). Equation (11-1) is not always accurate over a wide range of concrete densities (Valore 1980), particularly above 100 lb/ft^3 [1600 kg/m^3], because aggregate mineralogical characteristics cause a wide range of aggregate thermal conductivities. The cubic-model equation is also appropriate for calculating thermal conductivities of concrete above 100 lb/ft^3 [1600 kg/m^3]. The cubic-model equation demonstrates how the factors that influence concrete thermal conductivity k_c impose a ceiling limit on k_c even for concretes containing hypothetical aggregates with infinitely high thermal conductivities. The insulative effect of the cement paste matrix on k_c is determined by its quantity and quality of the paste volume fraction and density. **The cubic model also explains how normalweight aggregates produce disproportionately high conductivity values when added to lightweight-aggregate concrete.**

Practical Thermal Conductivity

Practical thermal conductivity design values for normalweight and lightweight concrete, solid clay brick, cement mortar, and gypsum materials are shown in Table 11.1.2, (ACI 122).

Table 11.1.2 – Suggested practical thermal conductivity design values*

Thermal conductivity, Btu/h • ft^2 •(°F/in.), at oven-dry density in lb/ft^{3†}																
			Density													
Group	Material or type or aggregate	Exposure type	20	30	40	50	60	70	80	90	100	110	120	130	140	150
Matrix Insul.	Neat cement paste	Pr	0.8	1.1	1.4	1.7	2.1	2.5	3.0	3.5	4.1	4.7	5.4	--	--	--
Insul. Struct	Autoclaved aerated (cellular)	Pr	0.7	1.0	1.3	1.6	2.0	2.5	--	--	--	--	--	--	--	--
Insul	Expanded polystyrene beads, perlite, vermiculite	Pr	0.8	1.1	1.5	1.9	2.4	--	--	--	--	--	--	--	--	--
Blocks Struct.	ASTM C 330 aggregates	Pr Un	-- --	-- --	-- --	1.7 1.8	2.4 2.6	2.7 3.0	3.0 3.2	3.6 3.8	4.9 5.3	5.0 5.4	6.4 6.8	-- --	-- --	-- --
Blocks Struct.	ASTM C 330 LW aggregates with ASTM C 33 sand	Pr Un	-- --	-- --	-- --	1.9 2.1	2.5 2.7	3.2 3.5	4.1 4.4	5.1 5.5	6.2 6.8	7.6 8.2	9.1 9.9	-- --	-- --	-- --
Blocks Struct.	Limestone	Pr Un	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	5.5 5.85	6.6 7.0	7.9 8.3	9.4 10.0	11.1 11.7	13.8 13.75
Blocks Struct.	Sand gravel < 50%quartz or quartzite	Pr Un	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	10.0 10.7	13.8 14.6	18.5 19.6
Blocks struct.	Sand gravel > 50% quartz or quartzite	Pr Un	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	11.0 11.8	15.3 16.5	20.5 22.0
Insul. Struct. Masonry	Cement-sand mortar; sanded foam concrete solid clay bricks	Pr Un Pr Un	-- -- -- --	-- -- -- --	-- -- -- --	-- -- -- --	2.8 3.1 -- --	3.6 3.9 2.5 3.1	4.5 4.8 3.0 3.7	5.5 6.0 3.6 4.3	6.7 7.3 4.2 5.1	8.1 8.7 4.9 5.9	9.7 10.5 5.6 6.8	11.5 12.4 6.4 7.8	13.5 14.7 7.4 9.0	-- -- 8.4 10.2

***For normalweight and lightweight concretes, solid clay bricks, and cement mortars.**

†Multiply Btu/h • ft^2 (°F/in.) values by 0.1442 to convert to W/m •K. Multiple lb/ft^3 values by 16 to convert to kg/m^3

Pr= protected exposure; mean relative humidity in wall up to 60%. Exterior wall surface coated with stucco, cement-based paint, or continuous coating of latex paint; or inner wither of composite wall with a full collar joint, or inner wythe of cavity wall.

Un=unprotected exposure; mean relative humidity in wall up to 80%. Exterior wall surface uncoated or treated with a water repellent or clear sealer only.

Densities above 100 lb/ft^3 do not apply to pumice or expanded clay or shale concretes.

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Thermal Resistance of Concrete Masonry Units

Thermal resistance of CMU's is affected by many variables, including unit shape and size, concrete density, insulation types, aggregate type(s), aggregate grading, aggregate mineralogy, cementitious binder, and moisture content. It simply is not feasible to test all of the possible variations. More than 100 CMU walls, however, have been tested and reported on by Valore 1980. These tests provide a basis for comparison of various calculation methods. Two calculation methods have been widely used and accepted: the parallel-path method and the series-parallel method (also know as isothermal planes). Both methods are described in the following paragraphs.

The parallel-path method was considered acceptable practice until insulated CMU's appeared in the marketplace. The parallel-path method assumes that heat flows in straight parallel lines through a CMU. If a hollow CMU has 20% web area and 80% core area, this method assumes that 20% of the heat flow occurs through the web and 80% occurs through the core (Fig. 11.2). This method is reasonably accurate for un-insulated hollow CMU's.

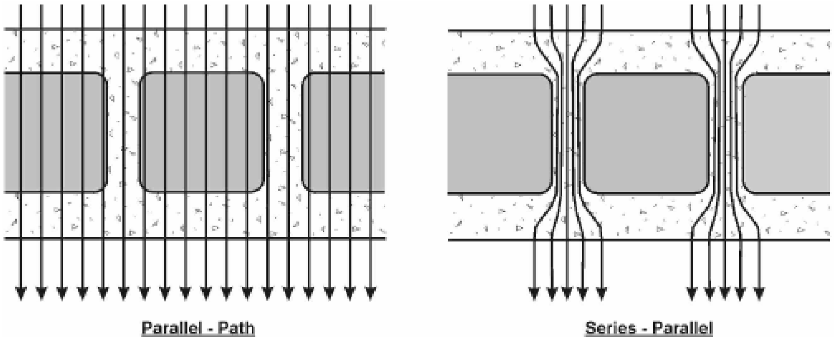


Figure 11.1.2. ***Parallel and series parallel heat flow schematics.***

The series-parallel (also known as isothermal planes) method is the current practice and provides good agreement with test data for both un-insulated and insulated CMU's. As with fluid flow and electrical currents, the series-parallel method considers that heat flow follows the path of least resistance. It accounts for lateral heat flows in CMU face shells and heat bypassing areas of relatively high thermal resistance, either air space or insulation in the hollow cores. Therefore CMU cross webs are a thermal bridge. As shown in Fig. 11.2, heat flow is mostly concentrated in webs.

The basic equation for the series-parallel method is

$$R_T = R_f + \frac{1}{\left(\frac{a_{np}}{R_{np}} + \frac{a_{np}}{R_{np}}\right)} + \ldots + \frac{1}{\left(\frac{a_{np}}{R_{np}} + \frac{a_{np}}{R_{np}}\right)} \tag{11-5}$$

where

a_{np} = fractional area of heat flow path number p of thermal layer number n;

R_{np} = thermal resistance of heat flow path number p of thermal layer number n, h • ft² • ºF/Btu (m²K/W);

R_f = surface-air-film resistances, equal to 0.85 h • ft² • ºF/Btu (0.149 m² K/W); and

R_T = total CMU thermal resistance including surface-air-film resistance, h • ft² • ºF/Btu (m²K/W).

Using this method, the masonry unit is divided into thermal layers. Thermal layers occur at all changes in unit geometry and at all interfaces between adjacent materials. For example, a hollow un-insulated CMU will have three thermal layers:

1. The interior face shell and mortar joint;
2. The hollow core air space and cross web; and
3. The exterior face shell and mortar joint.

A hollow CMU with and insulation insert placed over reduced cross webs in the middle of the CMU has five thermal layers:

1. The exterior face shell and mortar joint;
2. The full height concrete webs and hollow core air space;
3. The reduced height concrete webs combined with the insulating insert and air space;
4. The same as layer 2; and
5. The same as layer 1.

These five layers are shown in Fig. 11.1.3.

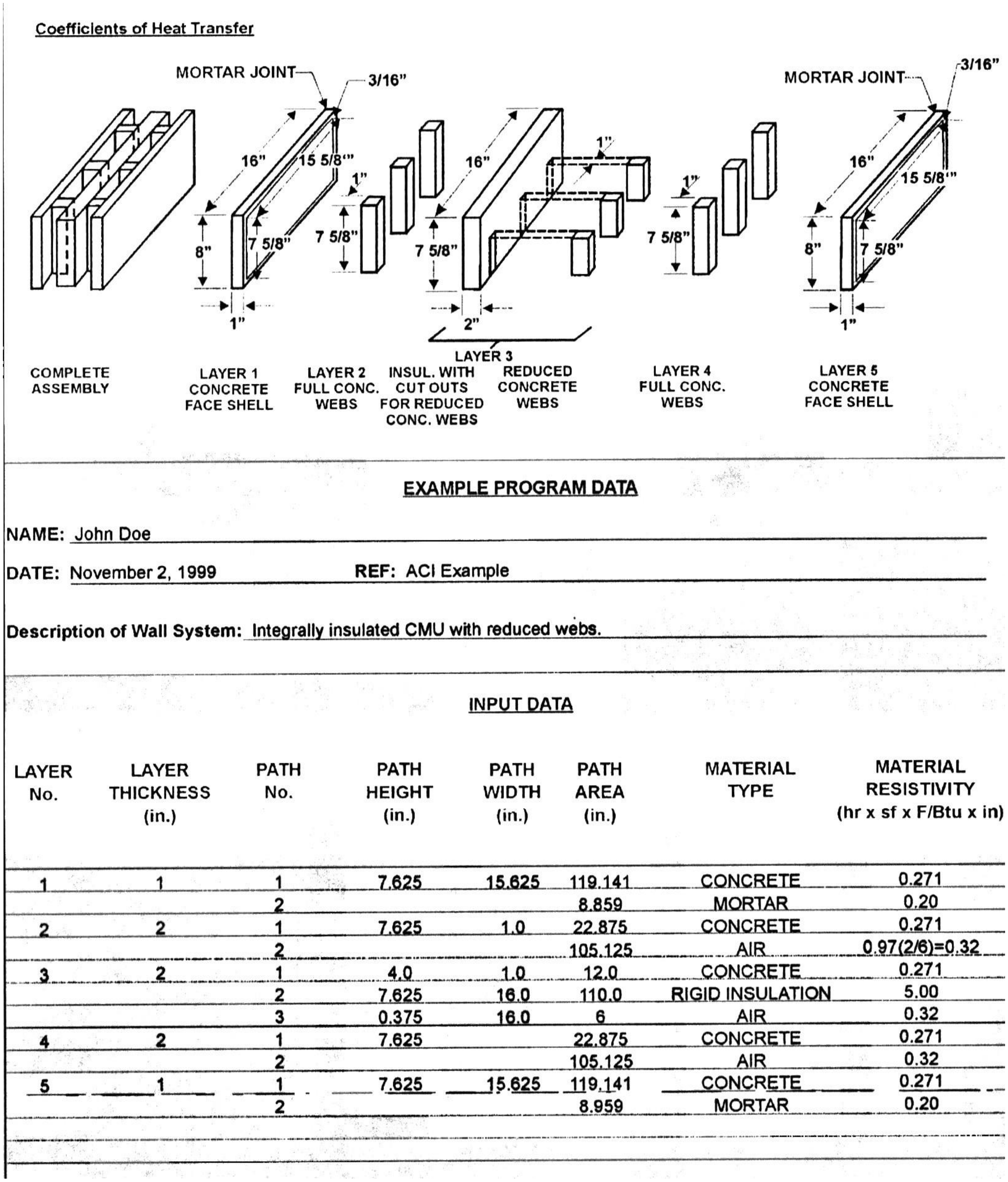
The series-parallel method also dictates that thermal layers be further divided into heat flow paths corresponding to the materials in each layer: for example, the reduced-cross-web insulated CMU. Layer one has two heat flow paths: the face shell concrete and the mortar joint mortar. Layer three has three heat flow paths: the reduced cross web concrete, the insulating insert insulation, and the air space. As is the case in most commercially available insulated CMU's, the insulating insert does not completely wrap the unit's webs (that is, it does not cover the mortar joint area and it does not have a 8 x 16 in. [200 x 400 mm] profile to fully cover a typical CMU's area) and that is why layer three must have three heat flow paths. If the insulating insert does in fact have an 8 x 16 in. [200 x 400 mm] profile, then the layer has only two heat flow paths: the reduced cross web and the insulating insert. Table 11.1.3. lists standard CMU dimensions.

Table 11.1.3 – Dimensions of plain-end two-core concrete blocks, in inches (meters) for calculating *U*-values.

Thickness		Actual length	Average face shell thickness x2	Average web thickness x3	Fractional web face area	Fractional core face area	Average core thickness or web length[*]
Nominal	Actual						
	Lb	A	fs	w	a_w (w/A)	a_c $(1 - a_w)$	Lf or L_w $(Lb - fs)$
4 (0.10	3.625(0.092)	15.62 (0.397	2.36 (0.06)	3.42 (0.087	0.22	0.78	1.265(0.032)
6 (0.15	5.625(0.143)	15.62 (0.397	2.38 (0.06)	3.45 (0.088	0.22	0.78	3.245(0.082)
8 (0.20	7.625(0.194)	15.62 (0.397	3.04(0.078	3.48 (0.088	0.22	0.78	4.585(0.116)
10 (0.25	9.625(0.244)	15.62 (0.397	3.46(0.088	3.81 (0.097	0.24	0.76	6.165(0.157)
12 (0.30	11.62 (0.295)	15.62 (0.397	3.46(0.088	4.17 (0.106	0.27	0.73	8.165(0.207)

[*] In direction of heat flow for Method 2 only; for Methods 1 and 3, web length is direction of heat flow in actual thickness *Lb.*

Reprinted from "Calculation of U-*Values of Hollow Concrete Masonry," R. C. Valore, Jr.,* Concrete International, *V. 2, No. 2, Feb. 1980*



Coefficients of Heat Transfer

EXAMPLE PROGRAM DATA

NAME: John Doe

DATE: November 2, 1999 **REF:** ACI Example

Description of Wall System: Integrally insulated CMU with reduced webs.

INPUT DATA

LAYER No.	LAYER THICKNESS (in.)	PATH No.	PATH HEIGHT (in.)	PATH WIDTH (in.)	PATH AREA (in.)	MATERIAL TYPE	MATERIAL RESISTIVITY (hr x sf x F/Btu x in)
1	1	1	7.625	15.625	119.141	CONCRETE	0.271
		2			8.859	MORTAR	0.20
2	2	1	7.625	1.0	22.875	CONCRETE	0.271
		2			105.125	AIR	0.97(2/6)=0.32
3	2	1	4.0	1.0	12.0	CONCRETE	0.271
		2	7.625	16.0	110.0	RIGID INSULATION	5.00
		3	0.375	16.0	6	AIR	0.32
4	2	1	7.625		22.875	CONCRETE	0.271
		2			105.125	AIR	0.32
5	1	1	7.625	15.625	119.141	CONCRETE	0.271
		2			8.959	MORTAR	0.20

Figure 11.1.3. ***Five layers of an insulated hollow CMU.***

Calculation Methods for Steady-State Thermal Resistance of Wall Systems

Thermal resistance, or *R*-value as it is commonly known, is the most widely used and recognized thermal property. Building codes generally prescribe requirements for minimum *R*-value or maximum thermal transmittance, *U*-value, for elements of a building envelope. Thermal resistance *R* is the reciprocal of thermal conductance 1/*C* and does not include surface-air-film resistances. Thermal conductance *C* is the coefficient of heat transfer for a wall and does not include surface-air-film resistances. Thermal transmittance *U* is the overall coefficient of heat transfer and does include the interior and exterior surface-air-film resistances plus the wall's thermal resistance. The total thermal resistance of a wall (R_T) is the reciprocal of *U*; $R_T = 1/U$ h • ft² • ºF/Btu [m²K/W]. Units for *U*-value and *C* are Btu/h • ºF [W/(m²K)].

Maximum *R* Value That Can Be Achieved With Insulated CMU'S

In keeping with well known natural laws, the movement of heat, water, electricity…is determined by the path of least resistance. For example an electrical network have parallel resistance paths (Fig. 11.1.4) where one resistance R_1 *is extremely large in comparison to the other resistance* R_2, the current flow in the high resistance path will approach zero and virtually all current flows will pass through the low resistance path…a "shunt" is developed.

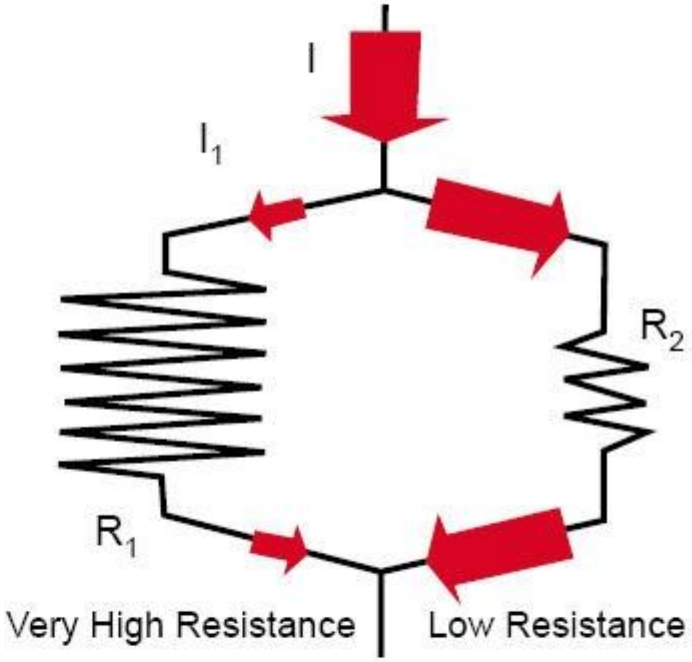


Figure 11.1.4. ***Current flow in an electric network***

This situation is replicated in a standard commercially available ASTM C 90 concrete masonry unit with full depth webs Fig. 11.1.5 when **all core spaces are filled with a totally nonconducting, super-insulating material with a thermal resistivity approaching infinity ($r_{fill} \longrightarrow \infty$).**

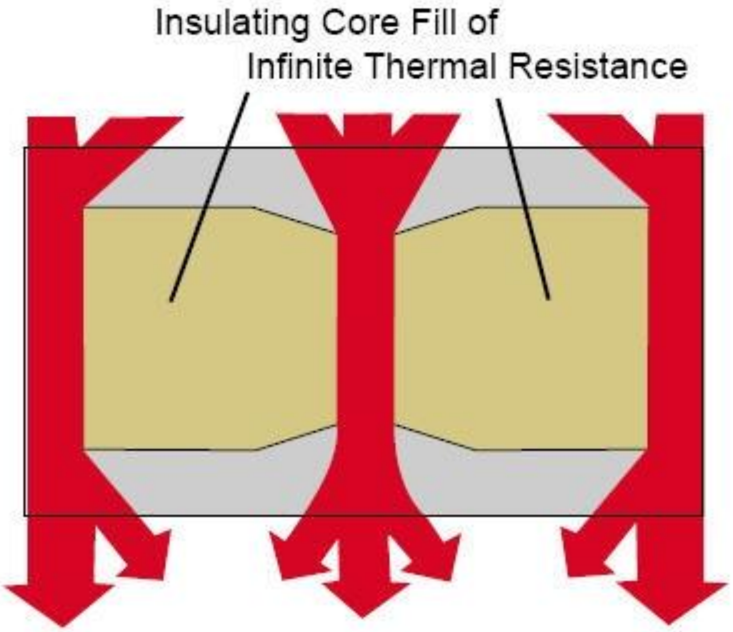


Figure 11.1.5. ***Heat Flow in an insulated Concrete Masonry Unit***

In this case (Fig. 11.1.5) virtually all heat flow is through the webs and the rate of flow is decisively determined by the thermal resistivity of the block concrete.

Using standard series-parallel (Isothermal Planes) calculations methods as mandated by ASHRAE 90.1 and simple arithmetic concepts, the "limiting" thermal resistance of standard concrete masonry units may be approximated as follows:

LAYER	**THERMAL RESISTANCE**
1. Thermal Resistance of Surface Films	(.18 + .67)
2. Thermal Resistance of Two Face Shells	(2 X 1.5" X r_C)
	+
3. The equivalent thermal resistance of the parallel paths through the webs and the highly insulated cores is approximated by:	$\left[\dfrac{1}{\dfrac{.27}{8.2r_C}+\dfrac{.73}{8.2r_f}}\right]$

For a standard 12” CMU, 8.2” is the width of the core and webs; .27 and .73 are the percentage face areas of the webs and cores; and r_C and r_f are the resistivities of the block concrete and core insulating materials.

As the resistivity of the insulating material in the example approaches infinity $(r_{fill} \longrightarrow \infty)$; a totally nonconducting, perfect insulator, then the expression

$$\frac{.73}{8.2r_f}$$

will reduce to zero. From a physical perspective this suggests that all the heat in the face shells will converge on and concentrate in a path through the webs. With the use of a perfect insulating material, the equivalent path thermal resistance expression will reduce to $\frac{1}{\frac{.27}{8.2r_C}}$ or $30\,r_C$

Then the total resistance (R) of a standard commercial 12” ASTM C90 CMU will be approximately as follows:

Total Resistance = Film Resistance + Face Shell Resistance + Equivalent Web and Face Shell Resistance

$$R_{12"}^{Max} = .85 + 3r_c + 30r_c = 33r_c + .85$$

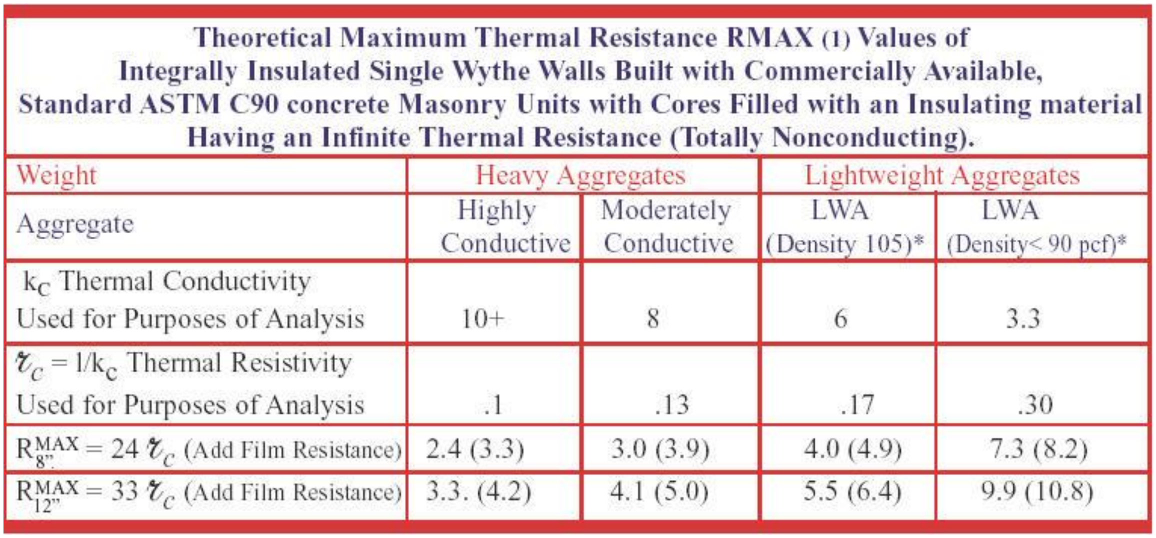
When the surface film thermal resistances are not included then the limiting thermal resistance of a standard 12” wide concrete masonry unit filled with totally non-conducting core insulation may be approximated by $33r_C$

In similar fashion, an 8” wide CMU would be approximated as follows.

$$R_{8"}^{Max} = (2x1.3r_C) + \frac{1}{.22X(4.6r_C)} = 24r_C$$

Then computation of the theoretical thermal resistance ceiling of integrally insulated concrete masonry requires inputting the value of the thermal resistivity of the block concrete. Thermal resistivity is best obtained by a guarded hot plate laboratory measurement in accordance with the procedures of ASTM C 177. An alternative is to use an estimated resistivity obtained from Chapter 22 of the *1993 ASHRAE Handbook of Fundamentals.* For Comparative analytical purposes, theoretical maximum thermal resistance R^{MAX} values of integrally insulated single wythe walls built with commercially available standard ASTM C 90 concrete masonry units with the cores filled with an insulating material having an infinite thermal resistance (totally non-conducting) is shown in the following table:

Table 11.1.4



Theoretical Maximum Thermal Resistance RMAX (1) Values of Integrally Insulated Single Wythe Walls Built with Commercially Available, Standard ASTM C90 concrete Masonry Units with Cores Filled with an Insulating material Having an Infinite Thermal Resistance (Totally Nonconducting).

Weight	Heavy Aggregates		Lightweight Aggregates	
Aggregate	Highly Conductive	Moderately Conductive	LWA (Density 105)*	LWA (Density< 90 pcf)*
k_C Thermal Conductivity Used for Purposes of Analysis	10+	8	6	3.3
$\tau_c = 1/k_C$ Thermal Resistivity Used for Purposes of Analysis	.1	.13	.17	.30
$R^{MAX}_{8"} = 24\ \tau_c$ (Add Film Resistance)	2.4 (3.3)	3.0 (3.9)	4.0 (4.9)	7.3 (8.2)
$R^{MAX}_{12"} = 33\ \tau_c$ (Add Film Resistance)	3.3. (4.2)	4.1 (5.0)	5.5 (6.4)	9.9 (10.8)

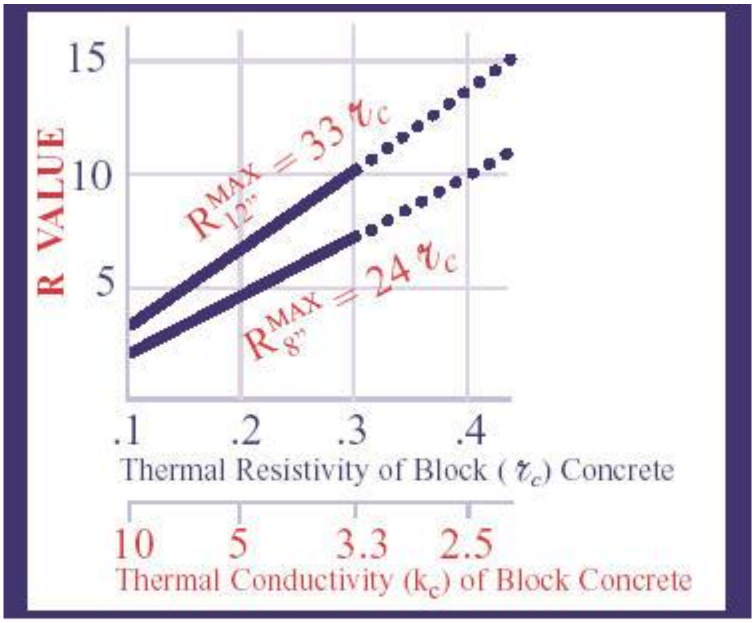


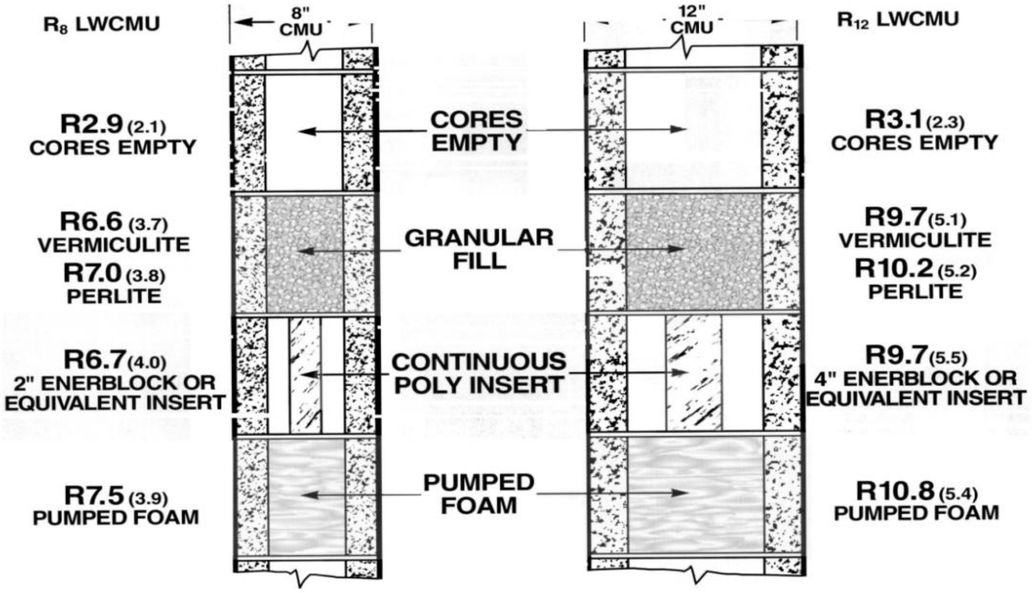
Figure 11.1.6. ***Thermal Resistance "R" Values of Single Wythe Concrete Masonry Wall (No Surface Films Added)***

It becomes clear that any strategy to increase the thermal resistance ***R*** of concrete masonry units must recognize the decisive influence of the thermal resistivity of the web block concrete and the thermal bridging effects within a standard commercial unit. One alternate strategy would be to reduce web dimensions while maintaining all of the physical requirements called for in ASTM C 90, such configurations are commercially available where the molded polystyrene inserts fit into the cut-down webs. Another strategy is to extend the effective web length by multi-core arrangements.

When thermal conductivity of the block concrete and insulating fills are known from measurements, the thermal resistance of the system may be computed using known series-parallel (Isothermal Planes) methods. Thermal conductivity of dry block concrete may be estimated for lightweight aggregate concrete up to a density of 100 pcf using the Valore equation $k=.5e^{0.02d}$ and then correcting for in-service moisture content. The thermal conductivity of concrete masonry units with densities above 100 pcf cannot be accurately estimated (without using cubic model) because of the extremely wide range of thermal conductivities of ordinary aggregates that is determined by mineral composition and crystal structure. If, for example the thermal conductivity of block concrete composed entirely of lightweight aggregates (85 pcf) were measured (ASTM C 177) to be 3.15 Btu in/sf ºF (Resisitivity of 1/3.15=.32), then the practical limiting thermal resistance of a 12" commercially available CMU made from this block concrete mix would be approximately, 33 X .32 = 10.6. With surface films added (the usual method of reporting in manufacturers literature) the $R^{MAX\ 12"}$ limit of the wall would be approximately 11.5.

Full scale wall tests sponsored by the Expanded Shale, Clay and Slate Institute using concrete masonry units composed entirely of rotary kiln produced expanded shale with cores filled with perlite produced a thermal resistance of 10. The value is less than the computed limiting R^{MAX} value of 11.5 and fully understandable by comparing the thermal resistance of perlite granular fill insulation to that of the infinite thermal resistivity $(r_{fill} \rightarrow \infty)$ used in the theoretical derivation.

R values for the walls shown (Fig. 11.1.7) include the standard interior and exterior air film resistances (+.85). When estimating R values of insulated concrete masonry units, calculations should be in accordance with the isothermal planes (series-parallel) method recommended by the National Concrete Masonry Association (NCMA) publication, "*Standard Procedure for Calculating the Overall Coefficient of Heat Transfer of Concrete Masonry".* The series parallel method is recommended by the American Society of Heating, Refrigeration and Air Conditioning (ASHRAE) "Handbook of Fundamentals" and mandated by the U.S. Department of Energy. Thermal conductivity values (k_C) for the block concrete and masonry unit dimensions may be obtained from R. Valore's paper "*Calculation of U-Values of Hollow Concrete Masonry",* American Concrete Institute CONCRETE INTERNATIONAL, February 1980 and reproduced here in Table 11.4. Thermal resistances shown are excerpted from published data and should be considered for guidance only. Where possible these values should be replaced by R test values determined from standard ASTM tests.



r

Figure 11.1.7 ***Thermal Resistance of Masonry Walls Built With Lightweight Aggregate Concrete Masonry Units and Integral Insulation***
(Normalweight concretes in parenthesis)

The above schematic is based upon the following reports:

> "Heat Transfer Observations of Lightweight Concrete Block Walls Before and After Filling the Cores with Lightweight Aggregate", Tests sponsored by the Expanded Shale, Clay & Slate Institute, conducted at Institute for Building Research at the Pennsylvania State University, June 15, 1967.
>
> ESCSI Information Sheet #311. "Energy Efficient Buildings with Lightweight Concrete Masonry". Numbers in parentheses ( ) are R values for HWCMU.
>
> Grace Construction Products brochure, MI-277C 8/85, "Zonolite Masonry Insulation".
>
> Tests conducted at the Institute for Building Research at Pennsylvania State University, Sponsored by the Perlite Institute, September 28, 1964.
>
> EnerBlock® brochure, "Insulated Concrete Masonry Wall", West Materials, Inc. 12/92.

Thermal Resistance of Other Concrete Wall Systems

The series-parallel method can also be used to calculate the thermal resistance of other concrete wall systems, such as tilt-up walls, precast walls, insulated sandwich panels, and cast-in-place walls. Wall-shear connectors and solid-concrete perimeters in sandwich panels can have relatively high thermal conductivities and will act as thermal bridges in the same manner as webs do in CMU's. When these wall types do not contain thermal bridges, the series-parallel equation can be simplified to a series equation that is, adding the resistances of each layer because each layer has only one path.

Thermal Inertia – Thermal Mass

The terms thermal inertia or thermal mass describe the reluctance to change temperature and the absorption and storage of significant amounts of heat in a building or in walls of a building. Concrete and masonry change temperature slower than many other building materials. This thermal inertia delays and reduces heat transfer through a concrete or masonry wall, resulting in a reduction in total heat loss or gain through the building envelope. With concrete or masonry walls more heat is stored in the element and later released back into the environment or room. Outdoor daily temperature cycles have a lesser effect on the temperature inside a thermally massive building because massive materials reduce heat transfer and moderate the indoor temperature.

Concrete and masonry walls often perform better than indicated by *R*-values because *R*-values are determined under steady-state temperature conditions. Thus, a thermally massive building will generally use less energy than a wood or metal frame building insulated by materials of the same *R*-value. Laboratory tests or computer simulations can be used to quantify the energy savings. These methods have permitted building codes to allow lower *R*-values for mass walls than for frame walls to achieve the same thermal performance.

Thermal diffusivity- Thermal diffusivity α indicates how quickly a material changes temperature. It is calculated by

$\alpha = k/dc_p$ = thermal diffusivity (in • ft^3/h • ºF) [JW/m^4] (12-6)

where

k = thermal conductivity (Btu • in./(h • ft^2 • ºF) [$W/(m/m^2K)$];
d = density (lb/ft^3) [kg/m^3]; and
c_p = specific heat (Btu/lb • ft^2) [J/kg • K].

A high thermal diffusivity indicates that heat transfer through a material will be fast. Materials as for example metals, with a high thermal diffusivity respond quickly to changes in temperature. Low thermal diffusivity means a slower rate of heat transfer and a larger amount of heat storage. Materials with low thermal diffusivity respond slowly to an imposed temperature difference. Materials with low thermal diffusivities, such as concrete and masonry, are effective thermal mass elements in a building.

Heat Capacity- Heat capacity is another indicator of thermal mass, one that is often used in energy codes. Concrete and masonry, because they absorb heat slowly, will generally have higher heat capacities than other materials. Heat capacity is defined as the amount of heat necessary to raise the temperature of a given mass one degree. More simply, it is the product of a mass and its specific heat. In concrete or concrete masonry, the heat capacity of walls is determined by multiplying the wall mass per area (lb/ft^2) [kg/m^2] by the specific heat (Btu/(lb • ºF) [J/(kg • K] of the wall material. For example, a single-wythe masonry wall weighing 34 lb/ft^2 (166 kg/m^2) with a specific heat of 0.21 Btu(lb • ºF) [880 J/kg •K] has a heat capacity of 7.14 Btu/(ft^2 • ºF) [46,080 J/(m^2K)]. The total wall heat capacity is simply the sum of the heat capacities of each wall component. Table 11.1.5 lists specific heat capacity values for concrete masonry materials.

Table 11.1.5 - Heat capacity of un-grouted hollow single wythe walls (Btu/ft^2 • ºF)

Size of CMU and % solid		Density of concrete in CMU, lb/ft^3*						
		80	90	100	110	120	130	140
4 in.*	65	3.40	3.78	4.17	4.55	4.93	5.56	5.96
	78	4.01	4.47	4.94	5.40	5.86	6.60	7.08
	100	5.05	5.64	6.23	6.82	7.41	8.37	8.99
6 in. *	55	4.36	4.87	5.37	5.87	6.38	7.19	7.72
	78	6.04	6.76	7.47	8.18	6.90	10.05	10.80
8 in.*	52	5.57	6.23	6.88	7.52	8.17	9.21	9.89
	78	8.17	9.14	10.11	11.08	12.04	13.61	14.63
10 in.*	48	6.50	7.25	8.01	8.76	9.51	10.60	11.38
	78	10.26	11.48	12.71	13.93	15.15	17.13	18.41
12 in.*	48	7.75	8.66	9.57	10.48	11.39	12.86	13.81
	78	12.30	13.77	15.25	16.37	18.20	20.59	22.14

*****Multiply Btu/h • ft^2 • ºF values by 5.68 to convert to W/m^2K; multiply lb/ft^3 values by 16 to convert to kg/m^3; multiply in. values by 25.4 to convert to mm.

Note: Face shell bedding (density of mortar = 120 lb/ft^3; specific heat of mortar = 0.20 [Btu/lb • ºF]

From NCMA TEK 6-16, National Concrete Masonry Association, 1989.

Insulation – The physical location of wall insulation relative to wall mass also significantly affects thermal performance. In concrete masonry walls, insulation can be placed on the interior of the wall, integral with the masonry, or on the exterior. For maximum benefit the exterior wall thermal mass should be in direct contact with the conditioned air. Because insulation on the interior of the mass thermally isolates the mass from the conditioned space, exterior insulation strategies are usually recommended. For example, rigid board insulation applied on the wall exterior, with a finish applied over the insulation, is more energy efficient than furring out the interior of a mass wall and installing batt insulation. Integral insulation strategies include insulating the cores of a masonry unit, using an insulated concrete sandwich panel, or insulating the cavity of a double-wythe masonry wall. In these cases, mass is on both sides of the insulation. Integral insulation allows greater thermal mass benefits than interior insulation but not as much as exterior insulation.

Daily temperature changes – A structure can be designed for energy savings by using the thermal mass effect to introduce thermal lag, which delays and reduces peak temperatures. Figure 9a illustrates the thermal lag for an 8 in. (20mm) concrete wall. When outdoor temperatures are at their peak, the indoor air remains relatively unaffected because the outdoor heat has not had time to penetrate the mass. By nightfall, when outside temperatures are falling, the exterior wall mass begins to release the heat stored during the day, moderating its effect on the interior conditioned space. Temperature amplitudes are reduced and never reach the extremes of the outdoor temperatures. Figure 9b represents an ideal climate condition for thermal mass in which large outdoor daily temperature swings do not create uncomfortable indoor temperatures due to the mass wall's ability to moderate heat flow into the building. Thermal mass benefits are greater in seasons having large daily temperature swings, as can occur during the spring and fall. In cold climates, the thermal mass effect can be used to collect and store solar energy and internal heat gains generated by office and mechanical equipment. These thermal gains are later reradiated into the conditioned space, thus reducing the heating load. During the cooling season, these same solar and internal gains can be dissipated using night-ventilation strategies (circulating cooler outdoor air over the thermal mass materials or walls). The night venting cools the thermal mass, allowing the interior of the building to remain cool well into the day, reducing the cooling loads and to shifting peak loads.

Building design – Building design and use can impact thermal mass because different buildings use energy in different ways. In low-rise residential construction, heating and cooling are influenced by the thermal performance of the building envelope. These buildings are said to have skin-dominated thermal loads, and the effects of exterior thermal mass for low-rise residential buildings are influenced primarily by climate and wall construction.

On the other hand, the thermal mass of commercial and high-rise residential buildings is significantly affected by internal heat gains in addition to the climate and wall construction. Large internal heat gains from lighting, equipment, occupants, and solar transmission through windows create a greater need for interior thermal mass to absorb heat and delay heat flow. Also, commercial buildings generally have peak cooling loads in the afternoon and have low or no occupancy in the evening. Therefore, delaying the peak load from the afternoon to the evening saves substantial energy because the peak then occurs when the building is unoccupied and sensors can be shifted to a nighttime setting. The benefits of thermal mass in commercial buildings are generally greater than for low-rise residential buildings.

Physical testing and computer simulations may be used to estimate the dynamic thermal performance of concrete and masonry walls and buildings. The calibrated hot box (ASTM C 976) can be used to determine the dynamic thermal performance of concrete and masonry wall sections. These tests are usually limited to 8 ft² (0.74 m²) sections of the opaque wall. A computer is needed to simulate the complex interactions of all building envelope components under constantly varying climatic conditions.

Calibrated hot-box facilities – Calibrated hot-box test facilities are used to determine the static and dynamic response of wall specimens to indoor and outdoor temperatures. The hot box consists of two highly insulated chambers clamped tightly together to surround the test wall. Air in each chamber is conditioned by heating and cooling equipment to obtain desired temperatures on each side of the test wall.

The outdoor (climatic) chamber is cycled between various temperatures. These temperature cycles can be programmed to simulate outdoor daily temperature swings. The indoor (metering) chamber is typically maintained at a constant temperature between 65 and 80 ºF (18 and 27 ºC) to simulate indoor room conditions.

The chambers and test specimens are instrumented to monitor air and surface temperatures on both sides of the test wall and heating energy input to the indoor chamber. Instruments monitor the energy required to maintain a constant indoor temperature while the outdoor temperature is varied. This energy, when corrected for small thermal losses through the frame, provides a measure of transient heat flow through the test wall.

The calibrated hot box is used to quantify the time lag between outdoor and indoor peak temperatures and the reduction in peak temperatures from outside to inside. The time lag shows the response time of a mass wall to outdoor temperature fluctuations. A long time lag and amplitude reduction relieve excessive cycling of the heating, ventilating, and air conditioning (HVAC) equipment and increase system efficiency. Additional cost savings can result where utility companies offer reduced off-peak energy rates. With a reduction in peak temperatures, less cooling capacity is needed, and the cooling capacity of the HVAC system can frequently be reduced. Similar savings occur for heating. Thermal lag depends on the *R*-value as well as the heat capacity because both of these factors influence the rate of heat flow through a wall.

Two methods of measuring thermal lag use the calibrated hot box. In one method, denoted t_o versus t_i, lag is calculated as the time required for the maximum (or minimum) indoor surface temperature t_i to be reached after the maximum (or minimum) outdoor air temperature t_o *is* attained (Fig. 9). In the second method, denoted q_{ss} versus q_w, lag is calculated as the time required for the maximum (or minimum) heat flow rate q_w to be reached after the maximum (or minimum) heat flow rate based on steady-state predictions q_{ss} is attained. The reduction in amplitude due to thermal mass is defined as the percent reduction in peak heat flow from calibrated hot-box tests when compared with peak heat flow predicted by steady-state analysis. Reduction in amplitude, like thermal lag, is dependent on both the heat-storage capacity and the thermal resistance of the wall. Depending on climate and other factors amplitude reduction for concrete and masonry walls varies between 20 and 50%.

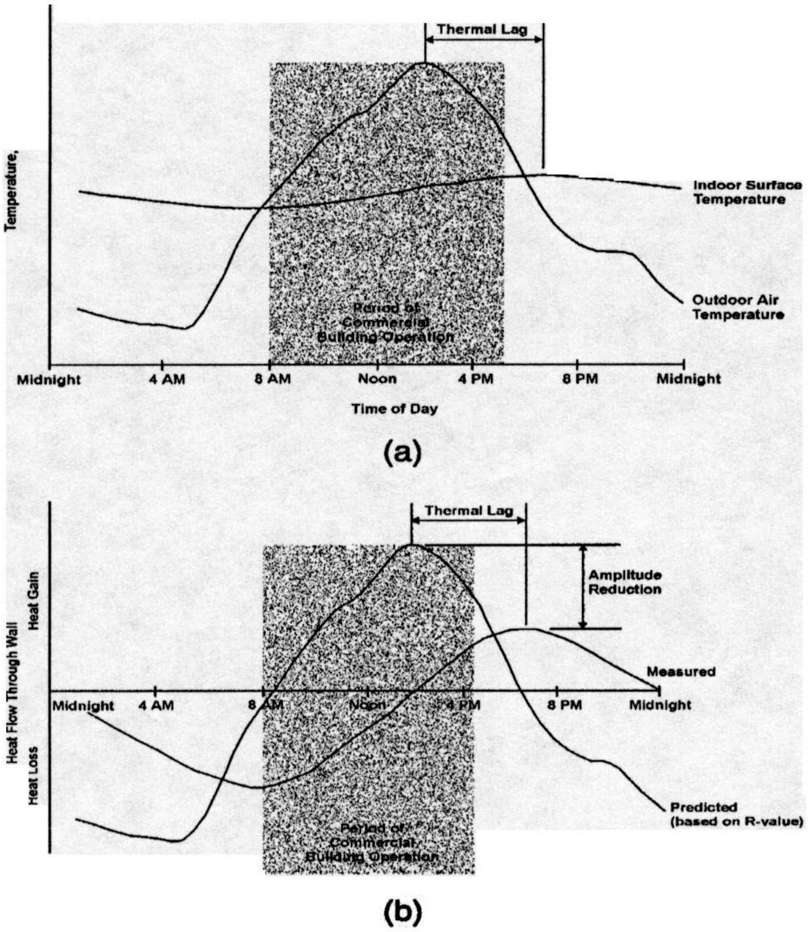


Figure 11.1.8 ***(a) Thermal lag for 8 in. concrete wall; and (b) thermal lag and amplitude reduction for 8 in. concrete wall.***

Table 11.1.6 shows values of thermal lag and amplitude reduction for various walls when cycled through a specific outside temperature cycle. Other temperature cycles may give different results.

Table 11.1.6- Thermal lag and amplitude reduction measurements from calibrated hot box tests

Wall No.	Thermal lag, h	Amplitude reduction, %
1. 8 x 8x 16 (200 x 200 x 400 mm) masonry	3.0	18
2. 8 x 8 x 16 (200 x 200 x 400 mm) masonry, with insulated cores.	3.5	28
3. 4-2-4 masonry cavity wall	4.5	40
4. 4-2-4 insulated masonry cavity wall	6.0	38
5. Finished 8 x 8 x 16 (200 x 200 x 400 mm) masonry wall	3.0	51
6. Finished 8 x 8 x 16 (200 x 200 x 400 mm) masonry wall with interior insulation	4.5	31
7. Finished 6 x 8 x 16 (150 x 200 x 400 mm) masonry wall with interior insulation	3.5	10
8. Finished 8 x 4 x 16 (200 x 100 x 400 mm) masonry wall with interior insulation	4.5	27
9. Structural concrete wall	4.0	45
10. STRUCTURAL LIGHTWEIGHT CONCRETE WALL (ESCSI)	5.5	53
11. Low-density concrete wall	8.5	61
12. Finished, insulated 2 x 4 (38 x 89 mm) wood frame wall	2.5	-6
13. Finished, insulated 2 x 4 (38 x 89 mm) wood frame wall	1.5	7.5
14. Finished, insulated 2 x 4 (38 x 89 mm) wood frame wall	1.5	-4
15. Insulated 2 x 4 (38 x 89 mm) wood frame wall with a masonry veneer	4.0	-6

Computer simulations of buildings – Computer programs have been developed to simulate the thermal performance of buildings and to predict heating and cooling loads. These programs account for material properties of the building components and the buildings' geometry, orientation, solar gains, internal gains, and temperature-control strategy. Calculations can be performed on an hourly basis using a full year of weather data for a given location. Three such programs currently in use are DOE2, BLAST, and CALPAS3, which are public domain software available through the U.S. Department of Energy (DOE). These computer simulation programs have been well documented and validated through comparisons with monitored results from test cells and full-scale buildings. Although results of such computer analyses will probably not agree completely with actual building performance, relative values between computer-modeled buildings and the corresponding actual buildings are in good agreement.

Interior Thermal Mass - Up to this point, most of the information presented in this chapter has focused on the effects of thermal mass in the exterior envelopes of buildings. Concrete and masonry can also help improve building occupant comfort and save additional energy when used in building interiors. When designing interior mass components, *R*-values are not important because there is no significant heat transfer through an interior wall or floor. Instead, heat is absorbed from the room into the mass then re-released back into the room. In other words, the interior mass acts as a storage facility for energy. A concrete floor in a sunroom absorbs solar energy during the day, then releases the stored warmth during the cooler nighttime hours.

Interior thermal mass acts to balance temperature fluctuations within a building that occur from day to night or from clouds intermittently blocking sunlight. Because of this flywheel effect, the temperature inside a building changes slowly. This keeps the building from cooling to fast at night during the heating season or heating to quickly during the day in the cooling season.

To use interior thermal mass effectively, carefully choose the heat capacity and properly locate the concrete and masonry components. Concrete or masonry as thin as 3 in. (75 mm) is sufficient to moderate the interior temperature because surface area is more important than thickness for interior thermal mass. A large surface area in contact with conditioned air tends to stabilize interior temperatures. Concrete or masonry distributed in a thin layer over the walls and floors of interior rooms is more effective than the same amount of mass placed in one thick, solid thermal mass wall. Other designs may require different placements of thermal mass. For passive solar applications, the mass should be in direct contact with the sunlight for maximum effectiveness.

Thermal Properties for Passive Solar Design

Passive solar buildings use three basic components: glazing, thermal mass, and ventilation. South-facing glass is used as the heat collector. Glass in other parts of the building is minimized to reduce heat loss or unwanted heat gain. Thermal mass is used to store heat gained through the glass and to maintain interior comfort. The building ventilation system distributes air warmed by solar gains throughout the building.

Passive solar buildings require a thermal mass to adequately store solar gains and maintain comfort in both heating and cooling seasons. The heat-storage capacity of concrete and masonry materials is determined by a variety of thermal properties, such as absorbtivity, conductivity, specific heat, diffusivity and emissivity. This section describes these properties, discusses their impact on passive solar buildings, and provides design values. These data allow designers to more accurately predict the performance of thermal storage mass and to choose appropriate materials for a particular design.

Thermal properties of the storage mass must be known to size HVAC equipment, maintain comfort in the building, and determine the optimal amount and arrangement of the thermal mass. For most passive solar applications, heat energy absorbed during the day is preferably released at night, as opposed to the next day. Therefore, the thermal mass storage effectiveness depends on the heat-storage capacity of the mass and rate of heat flow through the mass.

Conductivity, defined earlier, indicates how quickly or easily heat flows through a material. In passive solar applications, conductivity allows the solar heat to be transferred beyond the surface of the mass for more effective storage. Materials with very high conductivity values, however, should be avoided because high conductivity can shorten the time lag for heat delivery.

The amount of heat absorbed by a wall depends on its absorbtivity and the solar radiation incident on the wall. Absorbtivity is a measure of the efficiency of receiving radiated heat and is the fraction of incident solar radiation that is absorbed by a given material, as opposed to being reflected or transmitted. For opaque materials, such as concrete and masonry, solar radiation not absorbed by the wall is reflected away from it. Absorbtivity is a relative value; and absorbtivity of 1.0 indicates that a material absorbs all incident radiated heat and reflects none.

The absorbtivity of nonmetallic materials is a surface effect largely dependent on surface color. Dark surfaces have higher absorbtivities than light surfaces because they absorb more heat, while light surfaces reflect more heat than they absorb.

Sunlit thermal-mass floors should be relatively dark in color to absorb and store heat more efficiently. Robinson (1980) concludes that reds, browns, blues, and blacks will perform adequately for passive solar storage. Nonmass walls and ceilings should be light in color to reflect solar radiation to the thermal storage mass and to help distribute light more evenly.

Rough-textured surfaces, such as split-faced block or stucco, provide more surface area for collection of solar energy than smooth surfaces, but this advantage in solar energy collection has not been thoroughly investigated. Solar absorbtivity is usually determined using ASTM E 434. This test subjects a specimen to simulated solar radiation. Radiant energy absorbed by a specimen and emitted to the surroundings causes the specimen to reach an equilibrium temperature that is dependent on the ratio of absorbtivity to emissivity. Solar absorbtivity is then determined from the known emissivity.

Emissivity, sometimes called emittance, describes how efficiently a material transfers energy by radiation heat transfer or how efficiently a material emits energy. Like absorbtivity, emissivity is a unitless value defined as the fraction of energy emitted or released from a material, relative to the radiation of a perfect emitter or blackbody. For thermal storage, high-emissivity materials are used to effectively release stored solar heat into the living areas.

The ability of a material to emit energy increases as the temperature of the material increases. Therefore, emissivity is a function of temperature and increases with increasing temperature. For the purposes of passive solar building design, emissivity values at room temperature are used. Mazria (1979) and other researchers frequently assume an emissivity value of 0.90 for all nonmetallic building materials.

Emissivity is determined using either emitter or receiver methods. An emitter method involves measuring the amount of energy required to heat a specimen and the temperature of the specimen. A receiver method such as ASTM E 408 measures emitted radiation directed into a sensor.

Specific heat defined earlier, is a material property that describes the ability of a material to store heat. Specific heat is the ratio of the amount of heat required to raise the temperature of a given mass of material by one degree to the amount of heat required to raise the temperature of an equal mass of water by one degree. Materials with high specific heat values are effectively used for thermal storage in passive solar designs. Values of specific heat for concrete and masonry materials vary between 0.19 and 0.22 Btu/lb • ºF (0.79 and 0.92 kl/kg • K) (ACI 122) (Table 11..1.7).

Some heat-capacity defined earlier, storage is present in all buildings in the framing, gypsum board, furnishings, and floors. Home furnishings typically have a heat capacity of approximately 0.18 Btu/(h • ºF). A larger amount of thermal mass, however, is required in passive solar buildings. Walls and floors with high heat capacities are desirable for passive solar storage applications.

In addition to heat capacity, another property that is often used in passive solar design references is thermal diffusivity. Thermal diffusivity is a measure of heat transport relative to energy storage and is defined earlier. Materials with high thermal diffusivities are more effective at heat transfer than heat storage. Therefore, materials with low thermal diffusivities are desirable for storing solar energy.

Table 11.1.7 Thermal Properties of Various Building Materials Thermal Resistance (R), and Heat Capacity (HC)

Building material R-values are from 1989 ASHRAE Handbook of Fundamentals, chapter 22. HC-values are calculated from Density and Specific Heat from the same source, except as noted other wise.

		PER THICKNESS LISTED		
MATERIAL DESCRIPTION	THICKNESS (in.)	R VALUE (h•ft^2•°F / Btu)	HC VALUE (Btu / ft^2 • °F)	WEIGHT (pounds / ft^2)
BUILDING BOARD				
Gypsum Wallboard	0.5	0.45	0.54	2.1
Plywood (Douglas Fir)	0.5	0.62	0.41	1.4
Fiber board sheathing, regular density	0.5	1.32	0.23	0.8
Hardboard, medium density	0.5	0.69	0.65	2.1
Particleboard, medium density	0.5	0.53	0.65	2.1
INSULATING MATERIALS				
Mineral Fiber With Metal Stud Framing[1]				
R-11, 2x4 @ 16" (R-11 x .50 correction factor)		5.50	0.30	1.7
R-11, 2x4 @ 24" (R-11 x .60 correction factor)		6.60	0.27	1.4
R-19, 2x6 @ 16" (R-19 x .40 correction factor)		7.60	0.44	2.4
R-19, 2x6 @ 24" (R-19 x .45 correction factor)		8.55	0.39	1.9
Mineral Fiber With Wood Framing[2] (with lapped siding, 1/2" sheathing, and 1/2" gypsum board)				
R-11, 2x4 @ 16" on center		12.44	2.01	6.1
R-19, 2x6 @ 24" on center		19.11	2.13	6.5
Board, Slabs, and Loose Fill				
Cellular glass	1	2.86	0.13	0.7
Expanded polystyrene, extruded	1	5.00	0.08	0.3
Expanded polystyrene, molded beads[3]	1	4.00	0.03	0.1
Perlite[3]	1	3.13	0.11	0.4
Polyurethane	1	6.25	0.05	0.5
UF Foam[4]	1	4.35	0.02	0.1
Vermiculite[3]	1	2.44	0.13	0.4
Expanded Shale, Clay & Slate LWA[5]				
30# / CF Dry loose weight	1	1.21	0.53	2.5
40# / CF Dry loose weight	1	1.02	0.70	3.3
50# / CF Dry loose weight	1	0.88	0.88	4.2
Mortar[3], Plaster & Misc. Masonry				
Clay brick masonry	3.63	0.40	8.16	40.8
Stucco and cement plaster, sand aggregate	1	0.20	1.93	9.7
Gypsum plaster, perlite aggregate	1	0.67	1.20	3.8
Mortar	1	0.20	2.00	10.0
CONCRETE[3] (cast in place, precast)				
60 pcf	1	0.60	1.05	5.0
70 pcf	1	0.49	1.23	5.8
80 pcf	1	0.40	1.40	6.7
90 pcf	1	0.33	1.58	7.5
100 pcf	1	0.27	1.75	8.3
110 pcf	1	0.22	1.93	9.2
120 pcf	1	0.18	2.10	10.0
135 pcf	1	0.13	2.48	11.3
150 pcf	1	0.10	2.75	12.5
WOODS				
Southern Pine	1	1.00-0.89	1.16-1.34	3.0-3.4
California Redwood	1	1.35-1.22	0.80-0.91	2.0-2.3

1. R-Value corrected per ASHRAE / IES 90.1-1989 8C2; HC from vendors' data
2. Calculated per ASHRAE 1989 FUNDAMENTALS, Chapter 22
3. NCMA TEK 164 and NCMA "Concrete Masonry R-Value Program"
4. NBS Tech Note 946
5. R-Values from Thermophysical Properties of Masonry and its Constituents", Part I, by Rudolph Valore, Jr.

Incorporating Mass into Passive Solar Designs - In addition to the material properties discussed here, location of thermal mass materials is also important in passive solar applications. For most materials, the effectiveness of thermal mass in the floor or interior wall increases proportionally with a thickness up to approximately 3 to 4 inch (75 to 100 mm). Beyond that, the effectiveness does not increase as significantly. A 4 in. (100 mm) thick mass floor is about 30% more effective at storing direct sunlight than a 2 in. (50 mm) thick mass floor. A 6 in. (150 mm) thick mass floor, however, will only perform about 8% better than the 4 in. (100 mm) floor. For most applications, 3 to 4 inc. (75 to 100 mm) thick mass walls and floors maximize the amount of storage per unit of wall or floor material, unless thicker elements are required for structural or other considerations. Distributing thermal mass evenly around a room stores heat more efficiently and improves comfort by reducing localized hot or cold spots.

Location of thermal mass within a passive solar building is also important in determining a building’s efficiency and comfort. Mass located in the space where solar energy is collected is about four times more effective than mass located outside the collection area. If the mass is located away from the sunlit area, it is considered to be convectively coupled. Convectively coupled mass provides a mechanism for storing heat away from the collection area through natural convection and improves comfort by damping indoor temperature swings.

Covering mass walls and floors with materials having R-values larger than approximately 0.5 h • ft^2 • ºF/Btu (0.09 m^2K/W) and low thermal diffusivities will reduce the daily heat-storage capacity. Coverings such as surface bonding, thin plaster coats, stuccos, and wallpapers do not significantly reduce the storage capacity. Materials such as cork, paneling with furring and sound boards are best avoided. Direct attachment of gypsum board is acceptable if it is firmly adhered to the block or brick wall surface (no air space between gypsum board and masonry). Exterior mass walls should be insulated on the exterior or witin the cores of concrete block to maximize the effectiveness of the thermal mass. Thermal mass can easily be incorporated into the floors. If mass is used in floors, it will be much more effective if sunlight falls directly on it. Effective materials for floors include painted, colored, or vinyl-covered concrete; brick or concrete pavers; quarry tile; and dark-colored ceramic tile.

As more south-facing glass is used, more thermal mass should be provided to store heat gains and prevent the building from overheating. Although the concept is simple, in practice the relationship between the amount of glazing and the amount of mass is complicated by many factors. From a comfort standpoint, it would be difficult to add too much mass. Thermal mass will hold solar gains longer in winter and keep buildings cooler in summer. Thermal mass has a cost, however, so adding too much can be uneconomical. Design guidance on passive solar buildings is beyond the scope of this reference manual.

Summary- -Passive solar buildings represent a specialized application of thermal mass for solar heat storage, retention and re-radiation. To accomplish these tasks, the storage medium should have certain thermal characteristics. Thermal conductivity should be high enough to allow the heat to penetrate into the storage material but not so high that the storage time or thermal lag is shortened. Solar absorbtivity should be high, especially for mass floors, to maximize the amount of solar energy that can be stored.

Thermal storage materials should have high-emissivity characteristics to efficiently reradiate the stored energy back into the occupied space. Specific heat and heat capacity should be high to maximize the amount of energy that can be stored in a given amount of material.

Concrete and masonry materials fulfill all of these requirements for effective thermal storage. These materials have been used with great success in passive solar buildings to store the collected solar energy, prevent overheating, and reradiate energy to the interior space when needed.

Condensation Control

Moisture condensation on the interior surfaces of a building envelope is unsightly and can cause damage to the building or its contents. Moisture condensation within a building wall or ceiling assembly can be even more undesirable because it may not be noticed until damage has occurred. In addition increased moisture trapped in the wall lowers the thermal resistance considerably.

Air contains water vapor, and warm air carries more water vapor than cold air. Moisture, in the form of water vapor, is added to the air by respiration, perspiration, bathing, cooking, laundering, humidifiers, and industrial processes. When the air contacts cold surfaces, the air may be cooled below its dew point, permitting condensation to occur. Dew point is the temperature at which water vapor condenses.

Once condensation occurs, the relative humidity of the interior space of a building cannot be increased because any additional water vapor will simply condense on the cold surface. The inside wall surface temperature of a building assembly effectively limits the relative humidity of air contained in an interior space.

Prevention of Condensation on Wall Surfaces Under Steady-State Analysis - Condensation on interior surfaces can be prevented by using materials with high thermal resistance such that the surface temperature will not fall below the dew point temperature of the air in the room. The amount of thermal resistance that should be provided to avoid condensation can be determined from the following relationship.

$$R_1 = R_{ft} \frac{(t_t - t_o)}{(t_i - t_s)}$$

R_t = thermal resistance of wall assembly $h \cdot ft^2 \cdot {}^\circ F/Btu\,(m^2K/W)$;

R_{ft} = thermal resistance of interior surface air film $h \cdot ft^2 \cdot {}^\circ F/Btu\,(m^2K/W)$;

t_i = indoor air temperature °F (°C);

t_o = outdoor air temperature °F (°C); and

t_s = saturation, or dew poing temperature °F (°C).

Due to lag time associated with the thermal mass effect, the steady-state analysis of condensation is conservative for masonry walls. Dew point temperatures to the nearest degree Fahrenheit for various values of t_i and relative humidity are shown in Table 11.1.8.

For example, R_t is to be determined when the room temperature and relative humidity are 70 °F (21 °C) and 40% respectively, and t_o during the heating season is -10 °F (-24 °C). From Table 11.6, the dew point temperature t_s is 45 °F (7 °C) and because the resistance of the interior air film f_i is 0.68 h • ft² • °F/Btu (0.12 m²K/W)

$$R_{ft} = 0.68 h \cdot ft^2 \cdot {}^\circ F/Btu\,[0.12 m^2K/W]$$

$$R_t = \frac{0.68\,[70-(-10)]}{[70-45]} = 2.18 h \cdot ft^2 \cdot {}^\circ F/Btu\,[0.38 m^2K/W]$$

Prevention of Condensation within Wall Constructions - Water vapor in air is a gas and it diffuses through building materials at rates that depend on vapor permeabilities of materials and vapor-pressure differentials. Colder outside air temperatures increase the water-vapor-pressure differential with the warm inside air; this increases the driving force moving the inside air to the outside.

Leakage of moisture-laden air into an assembly through small cracks can be a greater problem than vapor diffusion. The passage of water vapor through a material is, in itself, generally not harmful. It becomes of consequence when, at some point along the vapor flow path, vapors fall below the dew point temperature and condense.

Water-vapor permeability and permeances of some building materials are shown in Table 11.1.9. Water-vapor permeability μ (gr/h•ft² •(in.Hg)/in.)(ng/s•m•Pa) is defined as the rate of water-vapor transmission per unit area of a body between two specified parallel surfaces induced by a unit vapor-pressure difference between the two surfaces. When properly used, low-permeability materials keep moisture from entering a wall or roof assembly, whereas high permeability materials allow moisture to escape. Water-vapor permeance M is defined as the water-vapor permeability for a thickness other than the unit thickness to which μ refers. Hence, $M = \mu/l$ where l is the flow path, or material, thickness (gr/(h • ft² - [in.Hg])(ng/s •m²•Pa).

When material such as plaster or gypsum board has a permeance too high for the intended use, one or two coats of paint are often enough to lower the permeance to an acceptable level. Alternatively, a vapor retarder can be used directly behind such products.

Polyethylene sheet, aluminum foil, and roofing materials are commonly used as vapor retarders. Proprietary vapor retarders, usually combinations of foil, polyethylene, and asphalt, are frequently used in freezer and cold-storage construction. Concrete is a relatively good vapor retarder. Permeance is a function of the w/c of the concrete. A low w/c results in concrete with low permeance.

Where climatic conditions demand insulation, a vapor retarder is generally needed to prevent condensation. Closed-cell insulation, if properly applied, will serve as its own vapor retarder but should be taped at all joints to be effective. For other insulation materials, a vapor retarder should be applied to the warm side of the insulation for the season representing the most serious condensation potential that is, on the interior in cold climate and on the exterior in hot and humid climates. Low-permeance materials on both sides of insulation, creating a double vapor retarder, can trap moisture within an assembly and should be avoided.

Table 11.1.8 Dew-Point Temperatures t_s * *ºF (ºC)*

Dry Bulb or Room Temperature	**Relative Humidity, %**									
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
40 (4)	**-7**	**6**	**14**	**19**	**24**	**28**	**31**	**34**	**37**	**40**
45 (7)	**-3**	**9**	**18**	**23**	**28**	**32**	**36**	**39**	**42**	**45**
50 (10)	**-1**	**13**	**21**	**27**	**32**	**37**	**41**	**44**	**47**	**50**
55 (13)	**5**	**17**	**26**	**32**	**37**	**41**	**45**	**49**	**52**	**55**
60 (16)	**7**	**21**	**30**	**36**	**42**	**46**	**50**	**54**	**57**	**60**
65 (18)	**11**	**24**	**33**	**40**	**46**	**51**	**55**	**59**	**62**	**65**
70 (21)	**14**	**27**	**38**	**45**	**51**	**56**	**60**	**63**	**67**	**70**
75 (24)	**17**	**32**	**42**	**49**	**55**	**60**	**64**	**69**	**72**	**75**
80 (27)	**21**	**36**	**46**	**54**	**60**	**65**	**69**	**73**	**77**	**80**
85 (29)	**23**	**40**	**50**	**58**	**64**	**70**	**74**	**78**	**82**	**85**
90 (32)	**27**	**44**	**55**	**63**	**69**	**74**	**79**	**83**	**85**	**90**

***Temperatures are based on barometric pressure of 29.92 in. Hg^2 (101.3 KPa).**

Table 11.1.9 Typical Permeance (*M*) and Permeability (μ) Values.

Material	*M*** perm	M**perm-in.
Concrete (1:2:4 mixture)**		**3.2**
Wood (sugar pine)	**---**	**0.4 to 5.4**
Expanded polystyrene (extruded)	**---**	**1.2**
Paint-two coats		
Asphalt paint on plywood	**0.4**	**---**
Enamels on smooth plaster	**0.5 to 1.5**	**---**
Various primers plus one coat flat oil paint on plaster	**1.6 to 3.0**	**---**
Expanded polystyrene (bead)	**---**	**2.0 to 5.8**
Plaster on gypsum lath (with studs)	**20.00**	**---**
Gypsum wallboard, 0.375 in. (9.5 mm)	**50.00**	**---**
Polyethylene, 2 mil (0.05 mm)	**0.16**	**---**
Aluminum foil, 0.35 mil (0.009 mm)	**0.05**	**---**
Aluminum foil, 1 mil (0.03 mm)	**0.00**	**---**
Built-up roofing (hot mopped)	**0.00**	**---**
Duplex sheet, asphalt laminated aluminum foil one side	**0.002**	**---**

11.2 Fire Resistance of Lightweight Concrete and Masonry

Definition of Terms

Fire Endurance - A measure of the elapsed time during which a material or assembly continues to exhibit fire resistance under specified conditions of test and performance. As applied to elements of buildings, fire endurance shall be measured by the methods and to the criteria defined by ASTM Methods E 119, "*Standard Methods of Fire Tests of Building Construction and Materials.*" (Fire endurance is a technical term).

Fire Resistance - The property of a material or assembly to withstand fire or give protection from it. As applied to elements of buildings, fire resistance is characterized by the ability to confine a fire or to continue to perform a given structural function, or both. (Fire resistance is a descriptive term.)

Fire Rating - A time required, usually expressed in hours, for an element in a building to maintain its particular fire-resistant properties. Model codes establish the required fire ratings for various building elements. (Fire rating or fire-resistance rating is a legal term.)

Standard Fire Tests

Fire-endurance periods for building components are normally determined by physical tests conducted according to ASTM E 119, *"Standard Methods of Fire Tests of Building Construction and Materials."* Provisions of the ASTM E 119 test require that specimens be subjected to a fire which follows the standard time-temperature curve shown in Fig. 11.2.1.

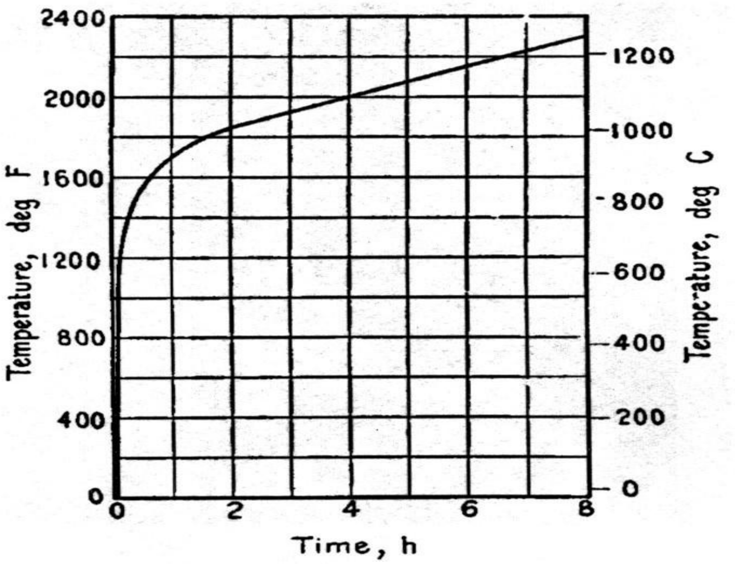


Figure 11.2.1 ***ASTM Standard E 119 Time-Temperature Curve.***

Under the E 119 standard, the fire endurance of a member or assembly is determined by the time required to reach the first of any of the following three end points:

1. Ignition of cotton waste due to passage of flame through cracks or fissures.
2. A temperature rise of 325ºF (single point) or 250ºF (average) on the unexposed surface of the member or assembly. This is known as the heat transmission end point.
3. Inability to carry the applied design load, that is, structural collapse.

Additional rating criteria for the fire endurance of a member or assembly include:

1. Concrete structural members: in some cases the average temperature of the tension steel at any section must not exceed 800ºF for cold-drawn prestressing steel or 1100ºF for reinforcing bars. Tests show that the respective steels retain approximately 50% of their original yield strength at these temperatures.
2. For wall sections: the ability to resist the impact, erosion, and cooling effects of a specific size hose stream.

Table 11.2.1 presents a listing of ASTM E 119 end-point criteria and test conditions and outlines applicable end points of various concrete and masonry members and assemblies.

ASTM E 119 classifies beams, floors, and roofs as either restrained or unrestrained. A restrained member is one in which the thermal expansion is restricted. Reinforced concrete assemblies are generally classified as restrained if they have continuity at interior supports or are restricted from lateral movement as exterior supports. Table 11.2.2 should be referenced when determining the presence of thermal restraint.

The model code requires fire testing in accordance with ASTM E 119 or analytical calculation based on ASTM E 119 test data to satisfy all fire-resistance ratings required by the codes. These recently approved analytical methods present significant cost savings when compared to actual ASTM E 119 fire testing.

End-Point Criteria and Analytical Methods - To analytically calculate the fire endurance of a given member it is useful to understand which end-point criteria will govern design of that member. As previously discussed, the first end point reached during the E 119 fire tests establishes the fire endurance period of the member. To further aid in understanding applicability of various end-point criteria see Table 11.2.1.

Walls - Concrete and masonry walls nearly always fail the heat transmission end point before allowing passage of flame or failing structurally. By examining heat transmission through various thicknesses of concrete, made with various types of aggregates, from E 119 fire tests it is possible to determine a given thickness or equivalent thickness of concrete, masonry, or brick to limit the temperature rise to below 250ºF (average) or to 325ºF (single point) as specified in ASTM E 119.

Beams - Prestressed and normally reinforced concrete beams cannot be so easily categorized. The ability of a beam to carry a design load is the primary end point and is dependent on several factors which are accounted for in rational design methods.

Floors and Roofs - Calculation of fire endurance of reinforced and prestressed concrete roof and floor slabs is based on both analyses of heat transmission and of load-carrying capacity at elevated temperatures. The heat transmission end point can be analyzed similarly to walls. As with beams, the ability of roofs and floors to carry load is influenced by several factors in design. Tabulated values for concrete cover, similar to those for beams, exist for roof and floor slabs and are shown in Table 11.2.1.

Table 11.2.1-Applicable End-Point Criteria and Test Conditions for Concrete and Masonry Members and Assemblies (Based on ASTM E 119 Standard Fire Tests)

End point Member		250 F average temperature rise or 325 F point temp. rise on unexposed surface	Flame impingement through cracks or fissures sufficient to ignite cotton waste	Carry applied load	Steel temperature end point	Restrained during testing	Hose stream test
Walls	**Bearing**	**Yes**	**Yes**	**Yes**	**Not considered**	**No**[1]	**Yes**[2]
	Nonbearing	**Yes**	**Yes**	**No load applied**	**Not considered**	**Yes**[1]	**Yes**[2]
Floors and roofs	**Restrained**	**Yes**	**Yes**	**Yes**	**No**[3]	**Yes**	**No**
	Unrestrained	**Yes**	**Yes**	**Yes**	**No**	**No**	**No**
Columns		**No**	**No**	**Yes**	**No**	**Restraint not imposed: test specifies simulation of end connection**	**No**
Individual beams-restrained: prestressed or reinforced		**No**	**No**	**Yes**	**Yes**[4]	**Yes**	**No**
Individual beams-unrestrained: prestressed or reinforced		**No**	**No**	**Yes**	**No**	**No**	**No**

[1] Non-load-bearing walls are restrained but not loaded during tests. Bearing walls are loaded but not restrained.

[2] Hose stream tests apply only to those walls required to have a one-hour rating or greater.

[3] Restrained floor and roof slabs utilizing concrete beams spaced greater than 4′ center-to-center must not exceed steel temperature limits of 1100°F (reinforcing steel) and 800°F (prestressed steel) for one-half the rating period or 1 hour, whichever is greater.*

[4] Reinforcing steel I concrete beams or joists spaced greater than 4′ center-to-center and cast monolithically with floors and columns must be maintained below 800°F (prestressing) and 1100°F (reinforcing) for 1 hours or one-half the desired rating period, whichever is greater.

***ESCSI Note:** The fact that ASTM E 119 permits the acceptance of fire resisting walls for ratings greater than one hour without exposing the same wall to a hose stream test should be pointed out to design professionals. The following addition to usual masonry specifications should be suggested "*Hose steam testing shall be conducted at, or in excess of, the fire endurance rating time specified*".

Columns - The structural fire endurance of concrete columns is influenced primarily by the column size and the concrete density. The bases at present for column fire endurance design are tabulated minimum cover and column size requirements based on past ASTM E 119 tests which were run to the structural failure end point.

Factors Influencing Endurance of Concrete and Masonry Units

Three principal factors influence the fire endurance of concrete and masonry. These factors, thickness and concrete density and aggregate type, thermal restraint conditions, and temperature distribution through members.

Effect of Structural Slab Thickness, Concrete Density and Aggregate Type on Fire Endurance - The factors which determine the fire endurance of concrete members or assemblies subject to the heat transmission end point criteria (walls, floors, roofs) are the thickness and the aggregate type of concrete used.

This can be seen clearly in Table 11.2.2, which shows that for a given aggregate type the length of time to reach a 250ºF temperature rise on the unexposed surface increases as the thickness of the concrete increases.

Table 11.2.2-Fire Endurances of Naturally Dried Specimens[1]

Slab Thickness, in.	Fire endurance, hr:min. Siliceous Aggregate	Carbonate Aggregate	Sanded expanded shale aggregate[2]
1 ½	0:18	0:18	0:24
2 ½	0:35	0:41	0:54
4	1:18	1:27	2:18
5	2:01	2:17	3:00
6	2:50	3:16	4:55
7	3:57	4:31	----

[1] Times shown are times required to reach 250ºF average temperature on unexposed surface.
[2] With sand from Elgin, Illinois, replacing 60% (by absolute volume) of the fines.

Examination of Table 11.2.2 shows that lightweight aggregate concrete transmits heat more slowly than normalweight concrete, resulting in longer fire endurances. As density, determined is reduced, resistance to heat transmission increases.

Structural lightweight concretes use aggregate such as expanded shale, clay, and slate and have densities ranging from 100 to 120 lbs per cu ft. Normalweight concretes have densities ranging from 135 to 155 lbs cu ft. Normalweight concretes utilize siliceous aggregates obtained from natural sand and gravel or carbonate aggregates such as limestone. Lightweight insulating concretes with unit weights of as low as 30 lb per cu ft are also available.

In a similar fashion the fire endurance of CMU walls is determined by unit geometry and the thermal properties of the block concrete. In the paper "*Design of Concrete Masonry Walls for Fire Endurance",* T.Z. Harmathy, former chairman of ACI Committee 216, presented empirical and semi-empirical formulae for calculating the fire endurance of CMU walls based upon a knowledge of the geometry of the units and the thermal properties (i.e. conductivity and diffusivity based upon density). The following information is taken directly from the paper:

"THERMAL PROPERTIES"
"The thermal conductivity and apparent specific heat of concrete have been the subject of extensive theoretical and experimental study (1,2,3). Generally speaking, thermal conductivity depends primarily on the mineralogical composition and microstructure of the aggregates, and apparent specific heat on the degree of chemical stability of all concretes made with highly crystalline aggregates is relatively high at room temperature and decreases with rise of temperature. Concretes made with fire-grained rocks and those with amorphous characteristics (e.g. anorthosite, basalt) exhibit low conductivities at room temperature and slowly increasing conductivities as temperature rises.

Among the common natural stones, quartz has the highest conductivity. The thermal conductivity of concretes made with quartz aggregates may be as high as 1.5 Btu/hr ft F (0.0062 cal/cm s C) at room temperature (in oven-dry condition). The lower limit for the conductivity of normalweight concretes made with natural aggregates is about 0.7 Btu/hr ft F (0.0029 cal/cm s C). As temperature rises the differences diminish, and at temperatures over 1400 F (760 C) all normalweight concretes exhibit conductivities in the range 0.6 to 0.8 Btu/hr ft F (0.0025 to 0.0033 cal/cm s C).

Lightweight aggregates are predominantly amorphous materials. In addition, their porosity is generally very high, so that the thermal conductivity of concretes made with lightweight aggregates is low, typically 0.2 to 0.4 Btu/hr ft F (0.0008 to 0.0017 cal/cm s C). Again, the differences diminish at elevated temperatures, and at temperature above 1400 F (760 C) 0.35 Btu/hr ft F (0.0015 cal/cm s C) is a typical value.

Figure 11.2.2 shows the temperature dependence of the thermal conductivity of concretes. The four solid lines delineate two regimes arrived at by combined theoretical-experimental analysis for structural Normalweight (lines 1 & 2) and lightweight concretes (lines 3 & 4), respectively. The points represent measured values for three normalweight masonry units and 13 lightweight units.

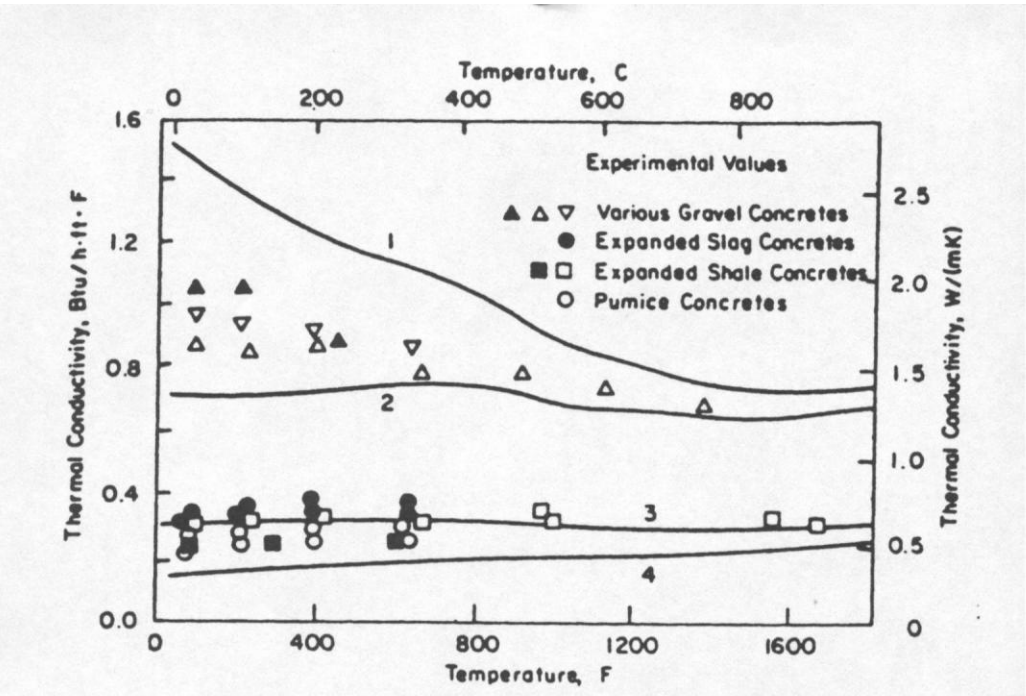


Figure 11.2.2. ***Thermal conductivity of concrete***

Effect of Restraint on Member During Fire Loading

Most cast-in-place reinforced concrete members are considered restrained. Precast or prestressed concrete members are more difficult to classify, and conditions which affect thermal restraint should be carefully examined in every case involving a beam, floor, or roof assembly. The tabular methods contained within the model codes consider either fully restrained or fully unrestrained members subjected to ASTM E 119 fire tests. In most castes the presence of restraint will enhance fire endurance.

Temperature Distribution Within Concrete and Masonry Members and Assemblies - In concrete and masonry, several factors influence temperature distribution through a member: they are the shape or thickness of the member and the concrete density and aggregate type. Temperature distribution through or within the member during ASTM E 119 fire testing is important in determining heat transmission rates in walls and floors and roofs and in determining steel and concrete temperatures in beams, floors and roofs, and columns.

Heat Transmission End Point

Solid Concrete Walls, Floors, and Roofs

When considering flat, single-wythe concrete or masonry walls, floors, or roofs, heat transmission endurance periods are based on the actual or equivalent thickness of the assembly in accordance with Fig. 11.2.3.

When the building component in questions is ribbed, tapered, undulating, or has hollow cores, an equivalent *solid thickness* must be determined. *Equivalent thickness* is the thickness obtained by considering *the gross* cross-sectional area of a wall minus the area of voids or undulations in hollow or ribbed sections, all divided by the width of the member. Calculation of equivalent thickness is outlined for several common concrete and masonry building components, in Figs. 11.2.3, 11.2.4, and 11.2.5 and elsewhere within the text.

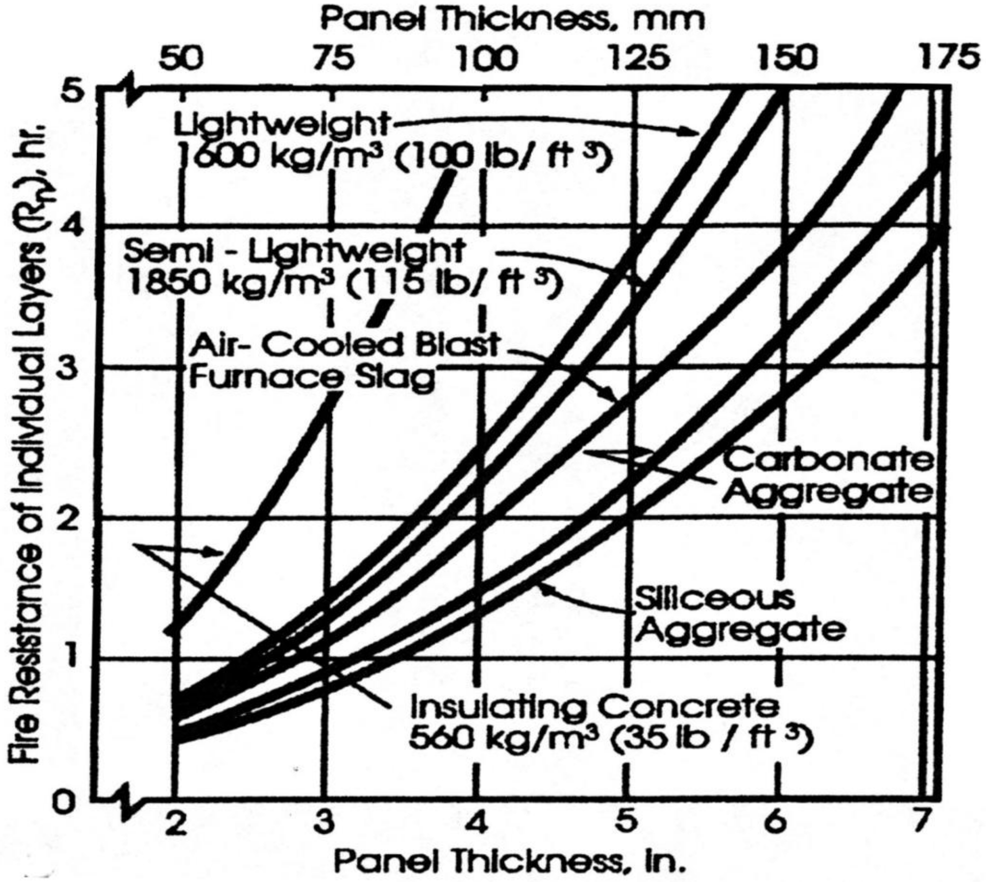


Figure 11.2.3 ***Effect of slab thickness and aggregate type on fire resistance of concrete slabs based on 250 deg F (139 deg C) rise in temperature of unexposed surface (ACI 216.1)***

Performance of Lightweight Concrete Slabs in Actual Fires - While standardized fire testing following the procedures of ASTM E 119 are valuable in establishing building code requirements, there is a great deal to be accomplished by corroborating these values with the performance in actual fires. The following is a report on a seven hour fire in a high school constructed with structural lightweight concrete (From Concrete Facts, Vol. 12 No. 1, ESCSI 1967).

Excellence in Design Provides Added Benefits - When Fire Strikes

The fire that raged undiscovered for nearly seven hours through three rooms of the James B. Conant High School on Sunday, November 27, 1966 failed to damage the prestressed lightweight concrete cored slabs selected for the building prior to its construction two years earlier. Coins left lying in desks melted, metal door locks buckled, electric wiring fused, and ductwork was ruined.

"The lightweight concrete cored . . . members were a significant factor in containing the fire within a three-room area," according to William Jarvis, chief construction superintendent for the architects who designed the Hoffman Estates, Illinois, school. "If less fire-resistant material had been used," he continued, "much more widespread damage — and subsequent costly repairs — would have resulted. No costs were involved here for structural repairs."

The construction expert emphasized that "the prestressed concrete cored beams, serving as second-story floor members directly within the fire area, suffered absolutely no structural damage — even though they were subjected to temperatures far exceeding the intensity and duration for which they are rated."

Mr. Jarvis added that the school had been constructed completely of noncombustible materials, including prestressed concrete cored slabs and beams, glass fiberboard ceiling tiles, and ceramic structural glazed tile walls. "Such construction can save untold lives, as well as millions of dollars," he stated.

Although the metal deck form between the lightweight concrete cored members was disfigured by heat, the beams prevented the fire from reaching the floor directly above. The fire did not pass through the walls at any point.

Only one school day was lost for clean-up; students were back at their desks in the undamaged part of the building on Tuesday morning.

Meanwhile, completion is slated this fall for a $1.5 million addition to the school, which will add two complete wings and bring the capacity to 2800. The precast lightweight concrete cored beams have already been installed. "These 50-foot long members speed up construction and allow for large columnless spans," stated Jack Keys, architectural superintendent for the project.

Prestressed lightweight cored members were initially selected for the school building because of their long spans (allowing for flexibility in room arrangement), heavy load capacity, economy, and fire resistance. Sixty and 48-foot precast cored members, carrying a U.L. three-hour fire rating on this project, were supplied in 20-inch depths.

The school is known for its outstanding and thorough design. It has been editorialized by the *American School Board Journal,* and the building was featured in the annual photographic exhibit at the 1965 national meeting of the American Association of School Administrators. Completely air conditioned, the original 212,000 sq. ft. plant was erected at a cost of only $12.89 per sq. ft.

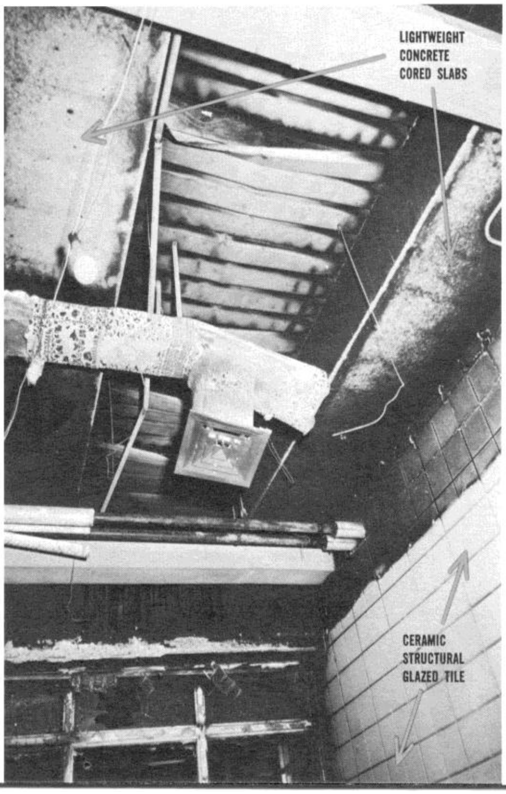
Architect: Fridstein & Fitch, Chicago

Engineer: (original construction) George A. Kennedy & Associates, Inc., Chicago; (building addition) J. W. Sih & Associates, Chicago

General Contractor: Tonyan Construction Co., McHenry, Illinois.

Dynacore prestressed concrete cored slabs and Lin Tee beams manufactured of Materialite structural lightweight concretes; all produced and supplied by Material Service, division of General Dynamics Corporation, Chicago.

Underside of prestressed concrete cored slabs, though scorched, needed only a cleaning for reuse. Corrugated steel forms between prestressed cored members, buckled by intense heat, were removed — without necessitating replacement, since poured concrete topping above for second story floor was unharmed. Ceramic structural glazed tile walls also required only cleanup work.



Tapered Flanges - Equivalent thickness for a concrete T-beam with tapered flanges is taken as the actual thickness of the flange measured at a distance of twice the minimum thickness or 6" from the end of the flange (whichever is less). This is shown in Fig. 4.

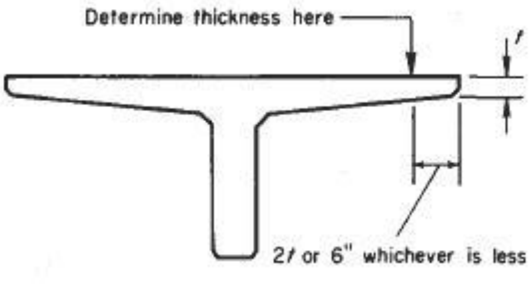


Figure 11.2.4. ***Equivalent thickness of a taper member.***

Ribbed Concrete Members - For ribbed or undulating surfaces. Calculation of equivalent thickness is based on the spacing of the stem components and minimum thickness of the flange. Calculation of the equivalent thickness is determined based on the provisions shown in Fig. 11.2.5.

$$\text{For } s \geq 4t, \text{ the thickness to be used shall be } t$$

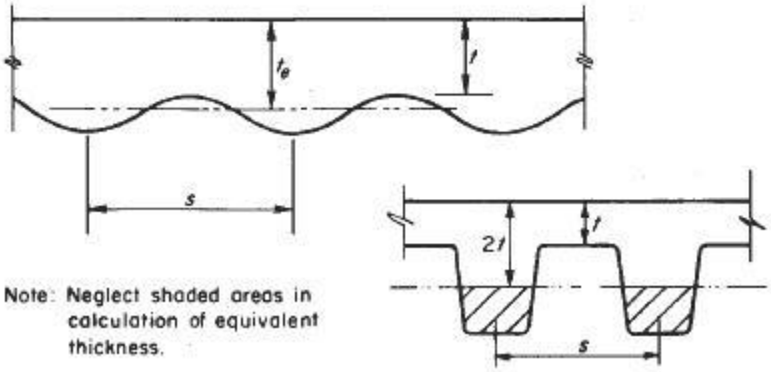
$$\text{For } s \leq 2t, \text{ the thickness to be used shall be } t_e$$

$$\text{For } 4t > s > 2t \text{ the thickness shall be } t + \left(\frac{4t}{s} - 1\right)\left(t_e - t\right)$$

s = spacing of ribs or undulations

t = minimum thickness

t_e = equivalent thickness of the panel calculated as the net cross-sectional area of the panel divided by the width; not to exceed $2t$



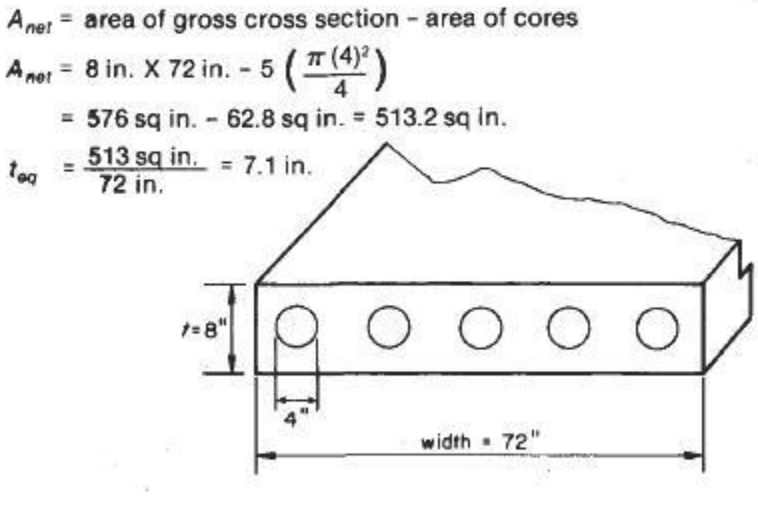
Note: Neglect shaded areas in calculation of equivalent thickness.

Figure 11.2.5 *Equivalent thickness of a ribbed or undulating section*

Hollow-Core Concrete Planks - The equivalent thickness (t_{eq}) of hollow-core planks is obtained by the equation

$$t_{eq} = \frac{A_{net}}{width}$$

where A_{net} is the gross cross section (thickness X width) minus the area of cores. This is shown in Fig 11.2.6.



A_{net} = area of gross cross section − area of cores

$A_{net} = 8 \text{ in.} \times 72 \text{ in.} - 5 \left(\frac{\pi (4)^2}{4}\right)$

$= 576 \text{ sq in.} - 62.8 \text{ sq in.} = 513.2 \text{ sq in.}$

$t_{eq} = \frac{513 \text{ sq in.}}{72 \text{ in.}} = 7.1 \text{ in.}$

Figure 11.2.6 *Typical hollow-core concrete plank*

Structural End Point

Fire Resistance of Prestressed Concrete Floor Slab - As previously discussed the fire endurance of floor and roof slabs is based on either the heat transmission or structural failure end point. It is for this reason that code approved empirical methods require both a minimum slab thickness to limit heat transmission and a minimum amount of concrete cover to limit steel temperatures. As discussed earlier, the fire endurance of reinforced or prestressed concrete slabs is dependent upon several factors, such as type of aggregate in the concrete, concrete cover, and restraint of thermal expansion.

The values for slabs shown in Table 11.2.3 represent minimum required slab thickness and concrete cover requirements for reinforced or prestressed slabs for various aggregate type concretes in restrained or unrestrained conditions. The tabular fire endurances listed are based on examination of past ASTM E 119 test results of slabs with similar cover, restraint conditions, and concrete aggregate type. The specified cover for unrestrained assemblies will maintain steel temperatures below the specified limits of 800 ºF for prestressing and 1100 ºF for reinforcing steel.

Table 11.2.3. Minimum Slab and Concrete Cover in Inches for Listed Fire Resistance of Reinforced Concrete Floors and Roofs[1]

A. Minimum Slab Thickness for Concrete Floors or Roofs[2]

Concrete aggregate type	Minimum slab thickness (inches) For fire-resistance rating				
	1 hr	1 ½ hr	2 hr	3 hr	4 hr
Siceous	3.5	4.3	5.0	6.2	7.0
Carbonate	3.2	4.0	4.6	5.7	6.6
Sand-lightweight	2.7	3.3	3.8	4.6	5.4
Lightweight	2.5	3.1	3.6	4.4	5.1

B. Cover Thickness for Reinforced Concrete Floor or Roof Slabs[3]

Concrete aggregate type	Thickness of cover (inches) for fire-resistance rating							
	Restrained[3]				Unrestraind[3]			
	1 hr	1 ½ hr	2 hr	3 hr	1 hr	1 ½ hr	2 hr.	3 hr.
Siliceous	3/4	3/4	3/4	3/4	3/4	3/4	1	1 ¼
Carbonate	3/4	3/4	3/4	3/4	3/4	3/4	3/4	1 ¼
Sand-lightweight	3/4	3/4	3/4	3/4	3/4	3/4	3/4	1 ¼
Lightweight	3/4	3/4	3/4	3/4	3/4	3/4	3/4	1 ¼

C. Cover Thickness for Prestressed Concrete Floor or Roof Slabs[3]

Concrete aggregate type	Thickness of cover (inches) for fire-resistance rating							
	Restrained[3]				Unrestraind[3]			
	1 hr	1 ½ hr	2 hr	3 hr	1 hr	1 ½ hr	2 hr.	3 hr.
Siliceous	3/4	3/4	3/4	3/4	1 1/3	1 ½	1 ¾	2 3/8
Carbonate	3/4	3/4	3/4	3/4	1	1/ ¾	1 3/8	2 ½
Sand-lightweight	3/4	3/4	3/4	3/4	1	1 ¾	1 ½	2
Lightweight	3/4	3/4	3/4	3/4	1	1 ¾	1 ½	2

Thermal Expansion During Fires - The coefficient of thermal expansion is used to predict thermally induced loads and curvatures in a structure. Thermal expansion of concrete was measured at elevated temperatures (Fig. 11.2.7).

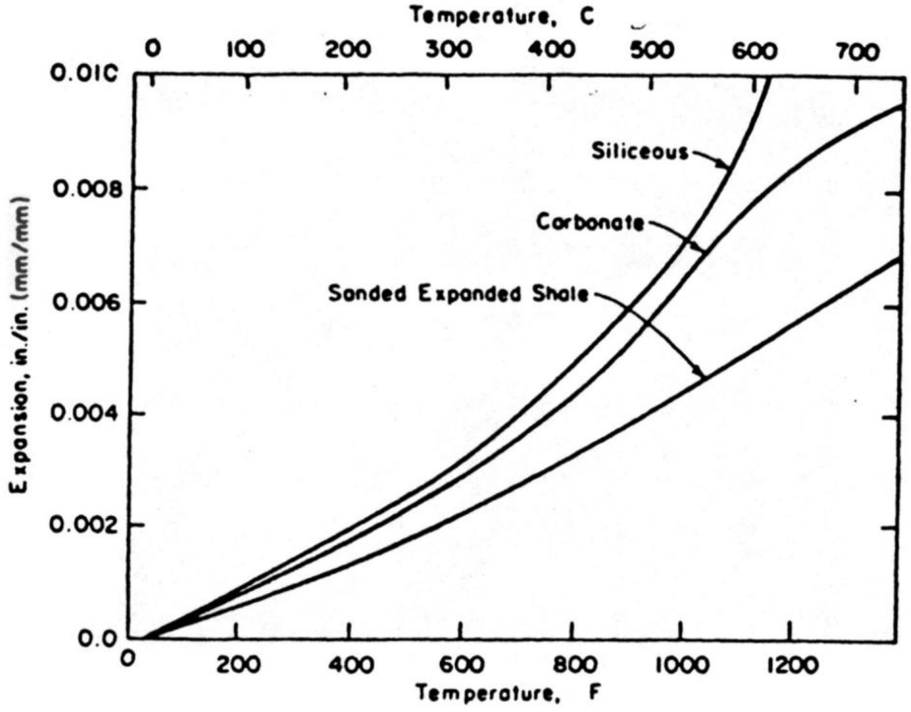


Figure 11.2.7. ***Thermal Expansion of Concrete (ACI 216, 1994)***

During actual fires members may expand against restraining structure and may cause structural damage. The influence of concrete properties on thrust fold is based on experimental research by Issen, Gustaferro and Carlson (1970). The experimental program consisted of 40 standard fire resistance test conducted by the Portland Cement Association (PCA).

The following is from the "*Best Practice Guidelines for Structural Fire Resistance Design of Concrete and Steel Buildings"* (Multihazard Mitigation Council-National Institute of Building Sciences, March 8, 2005):

"The first 25 tests were conducted to provide a set of reference tests that could be used to obtain data to examine the accuracy of predictions from the analytical method. The 25 tests included 13 normalweight (carbonate) and 12 lightweight Double-T slabs that were 16 ft long. The specimens were both prestressed and reinforced concrete designs. The expansion permitted in the tests ranged from 0.04 – 1.40 in. A diagram of a reference specimen is provided in Figure 11.2.8.

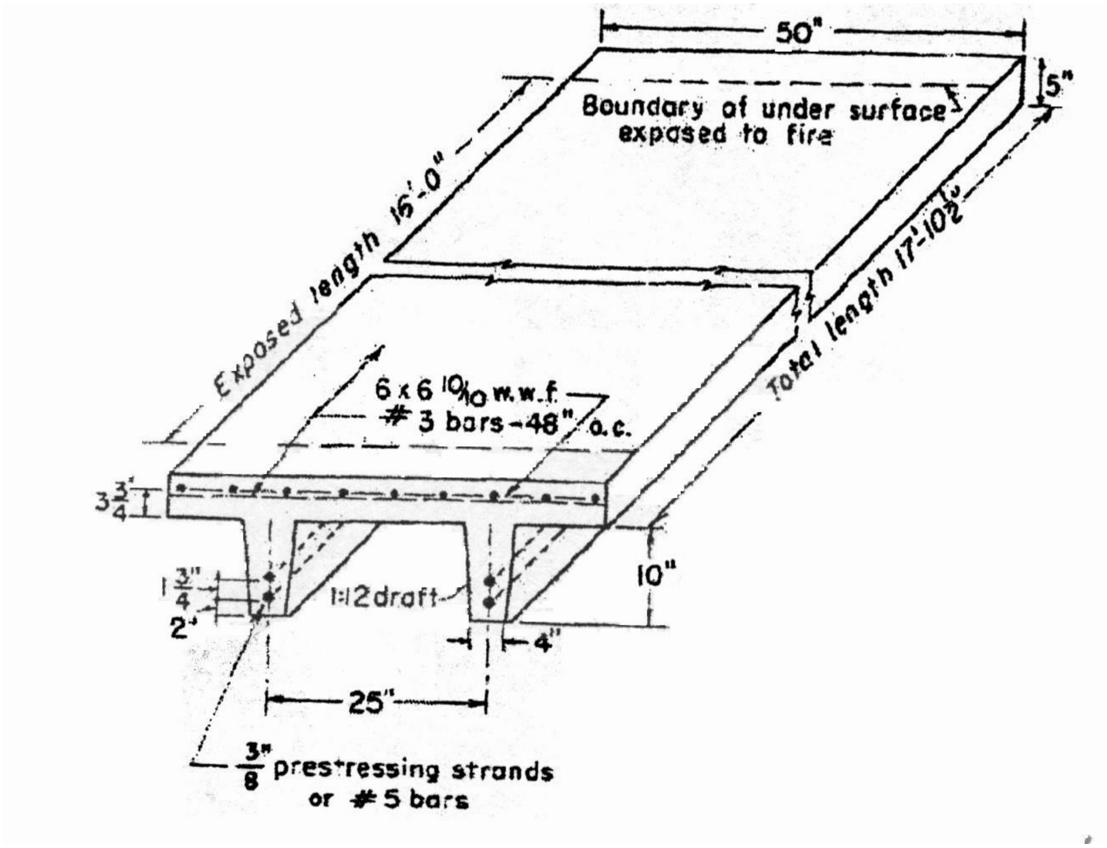


Figure 11.2.8. ***Reference Specimen (CRSI, 1980)***

The maximum thrust measured from the reference specimens is plotted in the graph in Figure 9. As expected, the thrust increased with a decrease in the amount of expansion permitted.

In the next phase of the experimental program, 15 tests were conducted with “correlation specimens”. These specimens used different geometries and aggregates to observe differences in behavior. The analytical method developed from the reference specimens was adapted with the data from the correlation specimens for increased applicability.

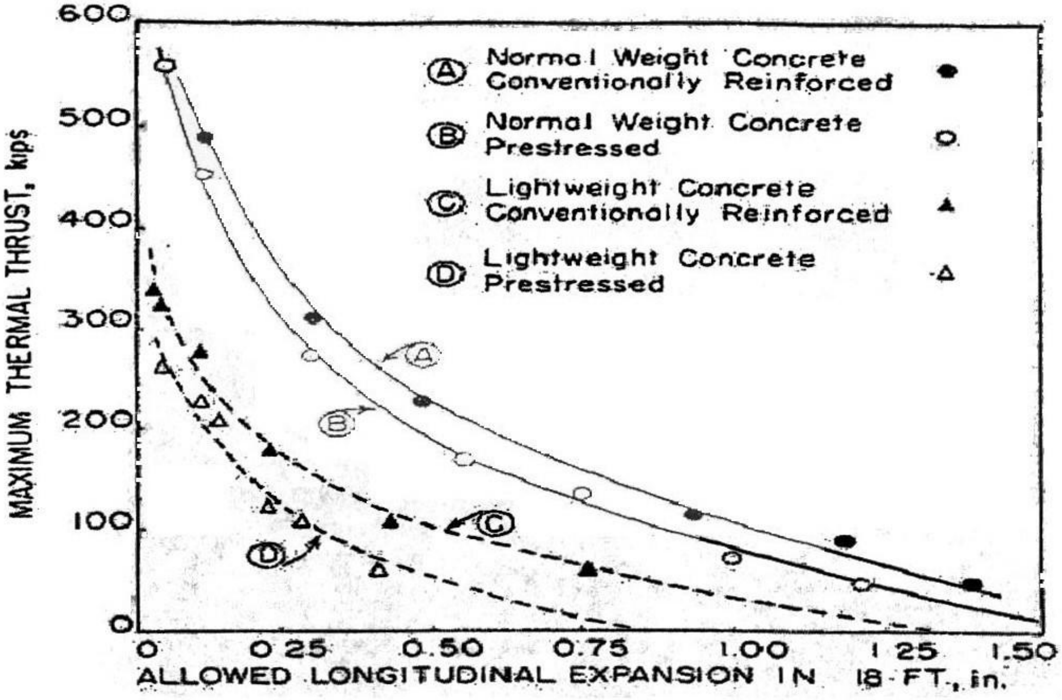


Figure 11.2.9. ***Maximum Thrust: Reference Specimens (CRSI, 1980)***

Because of the lower coefficient of thermal expansion, and slower increase in temperature (Due to lower diffusivity) it may be observed that structural lightweight concrete members tend to reduce the destructive forces caused by restraining adjacent structural assemblies.

Multi-Wythe Walls

A multi-wythe wall (that is, a wall with more than one layer of material) has a greater fire-endurance periods of the various layers. An equation for determining estimated fire endurance of multi-wythe walls based on the heat transmission end point is

$$R = (R_1^{0.59} + R_2^{0.59} \ldots + R_n^{0.59})^{1.7}$$

where

R = total fire-endurance rating in minutes
R_1, etc. = fire endurance in minutes of each individual wythe (or component lamina)

For example, two wythes – each rated at 1 hour 3.2 in. carbonate aggregate and 2.7 in. lightweight aggregate concretes) – will give

$$R = ((60)^{0.59} + (60)^{0.59})^{1.7} = 197 \text{ minutes (3 hours, 17 minutes)}$$

The equation is not applicable in all cases and must be used keeping the following conditions in mind.

1. The fire endurances (determined in accordance with ASTM E 119) of each wythe must be known.
2. The equation does not account for orientation of layering. It is known that if the more fire-resistant material is on the fire-exposed surface, a higher total rating would be obtained during actual testing than if the wythes were reversed.
3. The exponent 1.7 and its reciprocal 0.59 are average values which vary from material to material.

The equation is generally accurate within ten percent

Table 11.2.4 shows values for $R^{0.59}$ to be used in the multi-wythe equation. Note that concrete masonry block and brick are not included. $R^{0.59}$ values may be obtained for any wall tested per ASTM E 119 by simply raising the resistance, in minutes, to the 0.59 power.

Table 11.2.4. $R_n^{0.59}$ Values for Various Thicknesses of Concrete Floors, Roofs, and Walls; Various Aggregate Types[1]

Type of material	**Values of $R_n^{0.59}$ for use in Eq. 1**											
	1 ½ in	**2 in**	**2 ½ in**	**3 in**	**3 ½ in**	**4 in**	**4 ½ in**	**5 in**	**5 ½ in**	**6 in**	**6 ½ in**	**7 in**
Siliceous aggregate concrete	**5.3**	**6.5**	**8.1**	**9.5**	**11.3**	**13.0**	**14.9**	**16.9**	**18.8**	**20.7**	**22.8**	**25.1**
Carbonate aggregate concrete	**5.5**	**7.1**	**8.9**	**10.4**	**12.0**	**14.0**	**16.2**	**18.1**	**20.3**	**21.9**	**24.7**	**27.2(4)**
Sand-lightweight concrete	**6.5**	**8.2**	**10.5**	**12.8**	**15.5**	**18.1**	**20.7**	**23.3**	**26.0(4)**	**(4)**	**(4)**	**(4)**
Lightweight concrete	**6.6**	**8.8**	**11.2**	**13.7**	**16.5**	**19.1**	**21.9**	**24.7**	**27.8(4)**	**(4)**	**(4)**	**(4)**
Insulating concrete(2)	**9.3**	**13.3**	**16.6**	**18.3**	**23.1**	**26.5(4)**	**(4)**	**(4)**	**(4)**	**(4)**	**(4)**	**(4)**
Air Space(3)	---	---	----	---	---	---	----	----	----	----	----	----

(1) All model codes recognize the use of the listed $R_n^{0.59}$ values for concrete. To be used when calculating total resistance in minutes.

(2) Dry unit weight 35 pcf or less and consisting of cellular, perlite, or vermiculite concrete.

(3) The $R_n^{0.59}$ value for one ½ - to 3 ½ -inch air space is 3.3. The $R_n^{0.59}$ value for two ½ - to 3 ½ -inch air spaces is 6.7.

(4) The fire-resistance rating for this thickness exceeds 4 hours.

Fire Resistance of Concrete Masonry Walls

Concrete masonry units are available in nominal thicknesses of 2, 3, 4, 6, 8, 10 and 12 inch with varying percentages of solid area. The equivalent thickness for hollow block can be calculated using a procedure similar to that for hollow-core slabs. The percent of solids in any given masonry unit can be obtained from the manufacturer or calculated. Once equivalent thickness is known, the fire resistance rating of masonry walls can be determined. If 100% solid flat-sided concrete masonry units are used, the equivalent thickness is the actual thickness.

The equivalent thickness of concrete masonry assemblies (Fig. 10), T_{eq} shall be computed as the sum of the equivalent thickness of the concrete masonry unit, T_e as determined by T_{ef}, plus the equivalent thickness of finishes, T_{ef}, determined in accordance with:

$$T_{ea} = T_e + T_{e\backslash f}$$

$T_e = V_n / LH =$ equivalent thickness of concrete masonry unit, in. where
$V_n =$ net volume of masonry unit, $in.^3$
$L=$ specified length of masonry unit, in.
$H=$ specified height of masonry unit, in.

Ungrouted or partially grouted construction - T_e shall be the value obtained for the concrete masonry unit determined in accordance with ASTM C 140.
Solid grouted construction – The equivalent thickness, T_e of solid grouted concrete masonry units is the actual thickness of the unit.

Air spaces and cells filled with loose fill material – The equivalent thickness of completely filled hollow concrete masonry is the actual thickness of the unit when loose ordinary fill materials that meet ASTM C 33 requirements; lightweight aggregates that comply with ASTM C 331; or perlite or vermiculite meeting the requirements of ASTM C 549 and C 516, respectively.

The minimum equivalent thickness of various types of plain or reinforced concrete masonry bearing or nonbearing walls required to provide fire resistance ratings of 1 to 4 hour shall conform to Table 11.2.4. For examples of the fire resistance ratings of typical lightweight aggregate CMU's see Table 11.2.4.

"Equivalent Solid Thickness" is the average thickness of the solid material in the unit, and is used as a criteria for fire resistance. We can compute Equivalent Solid Thickness by this formula. If Ps equals percent solid volume, T equals actual width of unit, then equivalent thickness,

$$EQ.TH. = \frac{TxPs}{100}$$

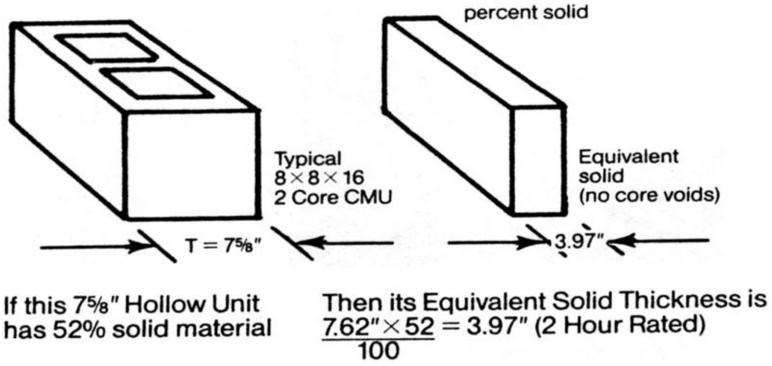


Figure 11.2.10. *Equivalent Solid Thickness*

The percent of solids in any given masonry unit can be obtained from the manufacturer, or measured in the laboratory according to the procedures of ASTM C 140. Once equivalent thickness is known, the fire-resistance rating of masonry walls can be determined from Table 11.2.4. If 100% solid flat-sided concrete masonry units are used, the equivalent thickness is the actual thickness.

Table 11.2.4. Fire Resistance Rating of Concrete Masonry Assemblies (ACI 216)

Aggregate Type	**Minimum required equivalent thickness for fire Resistance rating, in.** ^{A,B}				
	1 hr.	**1 1/2 hr.**	**2 hr.**	**3 hr.**	**4 hr.**
Calcareous or Siliceous gravel (other than limestone)	**2.8**	**3.6**	**4.2**	**5.3**	**6.2**
Limestone, cinders, Or air-cooled slag	**2.7**	**3.4**	**4.0**	**5.0**	**5.9**
Expanded clay, expanded shale or expanded slate	**2.6**	**3.3**	**3.6**	**4.4**	**5.1**
Expanded slag or pumice	**2.1**	**2.7**	**3.2**	**4.0**	**4.7**

A. Fire resistance ratings between the hourly fire resistance rating periods listed shall be determined by linear interpolation based on the equivalent thickness value of the concrete masonry assembly.

B. Minimum required equivalent thickness corresponding to the fire resistance rating for units made with a combination of aggregates shall be determined by linear interpolation based on the percent by dry rodded volume of each aggregate used in the manufacture.

Analysis of the Validity of the Fire Resistance Ratings Contained in Table 11.2.4 - A significant number of the required equivalent thickness values shown in Table 11.2.4 are fundamentally incorrect. To a large degree the ratings are based upon the tests conducted in the 1930's, wherein the walls tested were not in keeping with the requirements of ASTM E 119. Lack of conformance with the procedure of ASTM E 119 included:

- Some walls were tested too early with units that contained excessive moisture approximately 2 months old and therefore having relative humidity's greater than the maximum allowed by E 119. Because water boils at 212ºF, the temperature on the unexposed side will not rise above 212ºF until all the moisture is boiled off. As shown in Fig. 11 this process significantly extends the "steaming zone" allowing the wall to have unsupportable long fire endurance in violations of the standard procedures of E 119.

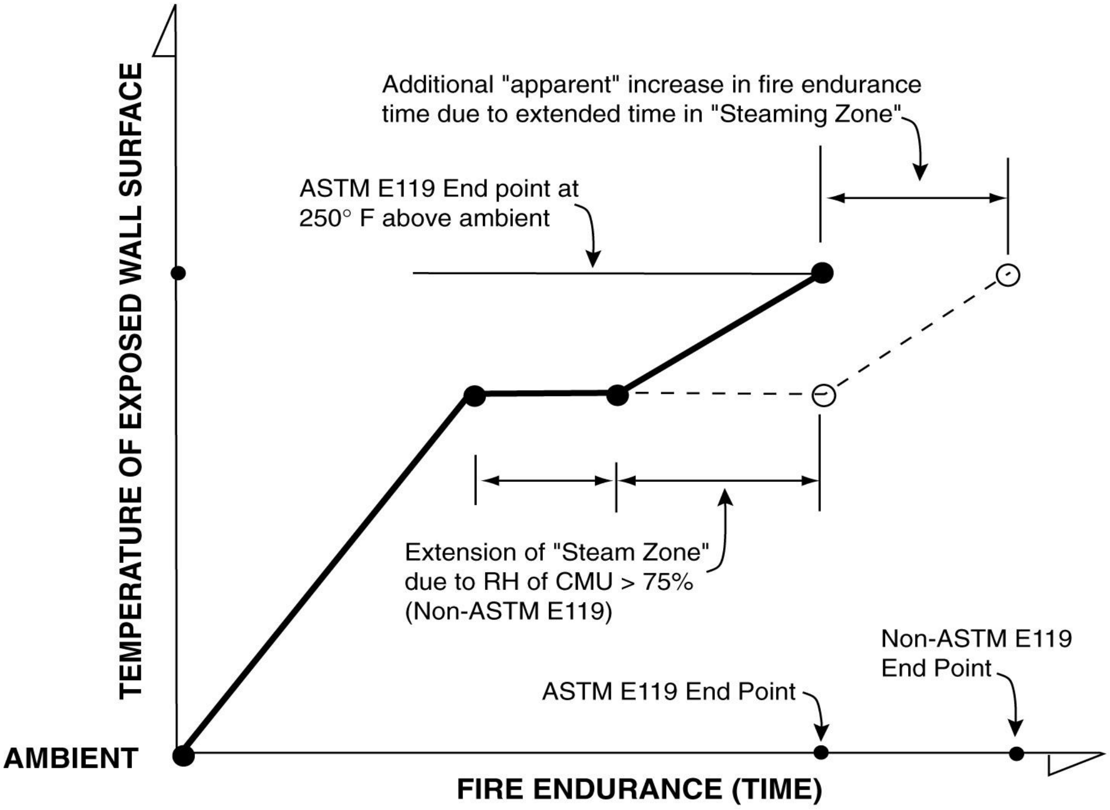


Figure 11.2.11 ***Effect of extension of fire endurance due to extension of "steaming zone" due to CMU RH > 75% (Nov. ASTM E 119)***

Table 11.2.5. Estimate Rating – Expanded Slag

Rating Hours	**American Insurance Association**		**ACI 216.1* Table 3.1**	**NCMA Sponsored Tests ASTM E 119 Omega point 1990**
	Estimated ratings* not tested in accordance to ASTM E 119	**Tested in accordance with ASTM E 119**		
4	**4.7**	**5.3**	**4.7**	**5.7**
3	**4.0**	**4.78**	**4.0**	**-----**
2	**3.2**	**4.13**	**3.2**	**3.8**
1	**2.1**	**-----**	**2.1**	**----**

***Tests not in compliance with ASTM E 119, CMU's not in compliance with ASTM C 90 (AIA Ref 42).**

Additionally all the walls tested did not meet the size requirements of ASTM E 119. Finally, many of the walls tested were composed of CMU's that did not meet the requirements of ASTM C 90 "*Standard Specification for Load Bearing Concrete Masonry Units".*

Consider for example the Tables 11.2.6 and 11.2.7 shown that were part of the fire endurance ratings data produced by the American Insurance Association and widely used in the past by the designer. Note that comparison between the "Estimated Ratings Table" and the table based upon full scale ASTM E 119 for CMU's based on an aggregate type that includes expanded slag or pumice.

Table 6 comparing the results of tests sponsored by NCMA in 1990 with the fire ratings value in Table 3.1 of ACI 216 further demonstrates the inadequacies of table 3.1. In all other sections of ACI 216 (Fire resistance of slabs, column protected by CMU and brick masonry) the protection is related to the density of the concrete, CMU's and brick Table 3.1 divides protective material resistance by aggregate type only, a technically unsupported procedure.

FULL SCALE ASTM E 119 FIRE TESTS ON CMU'S - Shown in Table 11.2.7 are the results of tests on CMU's made with ESCS aggregate.

Table 11.2.6. Fire Resistance Rating – Typical Lightweight Aggregate Masonry Units using ESCS aggregate.

Size	Type	% Solid	Equivalen Thickness	Fire Resistance Rating Hours
4x8x16	2 core	65	2.36	1
4x8x16	Solid	100	3.63	2
6x8x16	2 core	49	2.76	1
6x8x16	3 core	69	3.87	2
6x8x16	3 core	89	5.01	4
8x8x16	2 core	52	3.97	2
8x8x16	75% solid	75	5.72	4
8x8x16	2 core	58	4.40	3
12x8x16	2 core	49	5.70	4
12x8x16	75% solid	75	8.72	4
6" Backup	61% solid, unplastered faced with 2 1/4" brick			4

Equivalent thickness shown are representative of typical commercial units. Wear of mold parts, or differing geometry may result in small variation. Note: 8", 10", and 12" units shown conform to UL 618, 4" and 6" units conform to National Bureau of Standards and National Research Council full scale fire tests. The reports of these wall tests are available from the Expanded Shale, Clay and Slate Institute (ESCSI).

Table 11.2.7 compares fire resistance rating of CMU as reported in ACI 216.1, NCMA Omega Point test and UL 618.

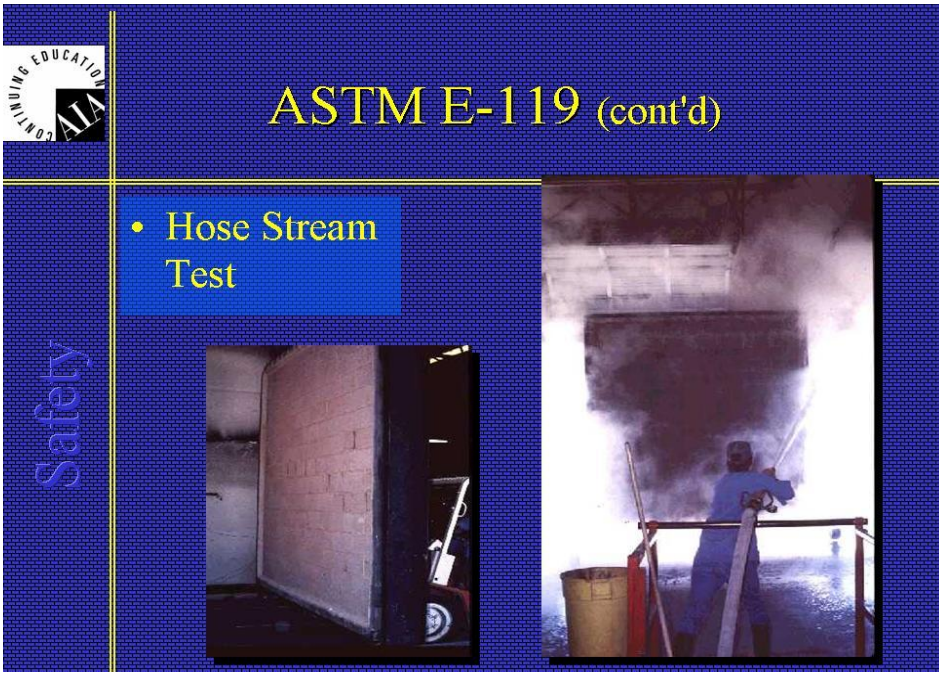
Table 11.2.7 ACI 216.1 Fire Resistance Rating of Concrete Masonry Assembly Compared to Underwriters UL 618 and the Results of Tests on CMU Walls Sponsored by NCMA at Omega Point Laboratories

Eq. Th. Fire Endurance Requirements

	2 Hours				4 Hours		
RATINGS (Reference)	**ACI 216.1**	**NCMA Omega**	**UL 618**		**ACI 216.1**	**NCMA Omega**	**UL 618**
TIME	**1997**	**1990**	**1998**		**1997**	**1990**	**1998**
AGGREGATE TYPE							
Expanded Slag	**3.2**	**3.83**	**4.10**		**4.7**	**5.67**	**5.3**
Expanded Slag blended with Sand		**4.07**				**6.07**	
Expanded Slag blended Limestone		**4.12**				**5.82**	
Pumice	**3.2**	**3.62**			**4.7**	**4.83**	**4.4**
Pumice blended with sand		**3.87**				**5.42**	
ESCSI	**3.6**		**3.6**		**5.1**		**5.1**
Limestone, cinders, unexpanded slag	**4.0**	**4.34**			**5.9**	**6.39**	
Calcareous	**4.2**				**6.2**		
(Limestone/S&G)		**4.34**				**6.54**	
Siliceous	**4.2**	**4.2**			**6.2**	**6.45**	
Natural or By-Product W or W/O sand (700 psi)			**4.2**				
Natural or By-Product W or W/O sand (1800 psi)							**6.5**

Field Performance of Lightweight Concrete Masonry Units

Lightweight concrete masonry walls have an outstanding record of exceeding all the requirements of the fire testing standard, ASTM E 119 tests (Fig 11.2.12).



ASTM E-119 (cont'd)

- Hose Stream Test

Safety

Figure 11.2.12. ***12" LWCMU Wall Passing Hose Stream Pressure After 4 hour Fire Test.***

The LWC masonry unit wall successfully endured the full 4 hour fire test with almost no visible cracking, without any spalls and with insignificant lateral bowing. Immediately after reaching the fire test time limit the wall was extracted from the furnace and exposed to the standard ASTM E 119 hose stream test. Despite the force of the high pressure hose stream and the intense thermal shock developed by the cold water impacting on the fiery hot exposed face that had experienced 4 hours of gas flames at temperatures approaching 2000ºF, there was no damage to the wall.

On the following day, the wall was deliberately demolished by a fork lift for disposal. To demonstrate the remarkable inherent structural integrity, three fire exposed LW concrete masonry units were salvaged from the rubble of the collapsed wall and taken to an independent testing laboratory for standard compression tests. All three units failed in compression on the fire tested side with average net strengths approaching 1400 psi. Developing such high residual compression strengths in a standard test, despite non-uniform loading developed due to the non-homogeneous concrete block properties (exposed versus unexposed sides) is outstanding performance. After enduring 4 hours of high temperature fire exposure, despite the thermal shock of the hose stream test, and after being demolished by a fork lift, these LWCM units still had sufficient capacity to maintain wall integrity to protect fire fighters. This remarkable performance confirms the fact that a commercially available LWCMU wall can function both as a structural and thermally insulating fire wall barrier to contain fire spread (See Fig. 11.2.13).

Figure 11.2.13. ***LWCMU Fire Wall Meets Expectations! Proven Performance in Actual Fires.***

Safety - Safety! That's what it's about. Just how long can a fire be contained to save lives? How long can a fire be contained to give firemen a chance to save the building? The answer to these questions is related to the fire resistance and structural stability of walls, columns, floors, and other building members exposed to the fire.

When tested side by side in actual fires in real world structures, concrete masonry unit walls have outperformed other fire resistant, non-masonry wall systems. The photographs in Fig. 11.2.13 and 11.2.14 shows the aftermath of a catastrophic fire to an essentially completed, but fortunately unoccupied, retirement complex in Kentucky. The fire destroyed 120 units and caused 6 million dollars in damage. The flames spread unchecked from end to end of the structure without any fuel load other than the construction materials used. A nearby hospital had to be evacuated due to intense radiant heat temperatures sufficient to buckle glass. The only assembly remaining intact in the path of the fire was the elevator shaft, constructed just prior to the fire with lightweight aggregate concrete masonry units (Fig. 12).

When the complex was rebuilt, the decision to use lightweight aggregate concrete masonry units to replace alternate containment materials in other parts of the project was based on a solid performance record under conditions significantly more severe than laboratory test.

Figure 11.2.14. ***The only remaining assembly is the Elevator shaft constructed with lightweight Aggregate concrete masonry units.***

11.3 Acoustical Resistance of Walls of Lightweight Concrete and Lightweight Concrete Masonry

Resistance to Transmission of Airborne Sound

Introduction - The control of sound in rooms of buildings may be classified with respect to the origin of the sound-namely, sounds originating within the room and sounds originating outside the room. Efficient and economical control of sound is dependent not only upon its origin, but also upon the design of the enclosure and type of occupancy.

For reduction of sound originating within a room, the sound absorption qualities of the walls, ceiling and flooring, as well as furnishings, are important. The type and use of the room affords the architect latitude in the selection of sound absorption materials for elements of the room. Enclosures with high ceilings and large expanse of wall areas, as in gymnasiums and churches, might utilize sound absorbing textured masonry walls as an economical solution. On the other hand, for enclosures with relatively low ceilings, and rather small exposed wall areas, as in offices and classrooms, the use of acoustical ceilings, floor coverings, and interior furnishings might be the more effective solution.

This section is concerned primarily with utilizing concrete and concrete masonry to reduce the sources of sound transmitted through building partitions from sources outside of rooms. These sounds are transmitted as solid-borne, as well as air-borne, noise. For example, a bare concrete floor transmits the sound of footsteps between rooms, the sound traveling through the rigid concrete slab. Solid-borne impact sound should be suppressed at the source. A concrete floor for example, should be covered with a resilient material, to minimize the amount of solid-borne sound transmission.

Air-borne sound may be effectively reduced by barriers such as concrete masonry partitions. Obviously, attention should be given to doors and their closures, as well as connections of the walls to the ceilings and floors. Too often the effectiveness of a concrete masonry partition, which should provide satisfactory acoustical isolation, is unnecessarily lost, by failure to take into account the other important factors that are involved, such as continuing the partition to the structural ceiling. Also, cutting of continuous holes through the wall for ducts, and electrical outlets should be avoided.

The Energy of Sound - Sound energy is measured in decibels. The decibel is a convenient unit because it is approximately the smallest change in energy that the ear can detect. The following table 11.3.1. Of sound intensities will aid in an understanding of decibel values.

Table 11.3.1. Representative Sound Levels

Loudness	Decibels	Sound
Deafening	**110-150**	**Jet plane takeoff Siren at 100 ft (30 m) Thunder-sonic boom Hard rock band**
Very Loud	**90-100**	**Power lawn mower Pneumatic jackhammer**
Loud	**70-80**	**Noisy office Average radio**
Moderate	**50-60**	**Normal conversation Average home**
Faint	**30-40**	**Private office Quite home**
Very Faint	**3-20**	**Whisper at 4 ft (1.2 m) Normal breathing**

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Sound Transmission Resistance of Concrete Masonry - Sound is transmitted through most walls and floors by setting the entire structure into vibration. This vibration generates new sound waves of reduced intensity on the other side. The passage of sound into one room of a building from a source located in another room or outside the building is termed “sound transmission”.

Transmission loss is a measure of the effectiveness of a wall, floor, door or other barrier in restricting the passage of sound. The transmission loss varies with frequency of the sound and the loss is usually greater with higher frequencies. Sound transmission loss measurements are conducted in accordance with American Society for Testing and Materials ASTM E 90 “*Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions”*. A concrete or concrete masonry wall eleven (11) feet (3.35 m) wide and nine (9) feet (2.74 m) high mounted on a movable base is rolled between two isolated reverberation rooms (Fig. 11.3.1 & 11.2.2). Measurements are made at 16 frequencies in 1/3-octave bands, from 125 to 4000 cycles per second, (cps) (generally called Hertz (Hz). The unit of measure of sound transmission loss is the decibel (dB). The higher the transmission loss of a wall the better it functions as a barrier to the passage of unwanted noise.

Lightweight concrete masonry units produced under strict laboratory supervision and inspection were made and shipped to Kowaris Acoustical Laboratories where the blocks were made into movable wall panels of various thicknesses with a wall area of 99 sq. ft. These panels rolled between two isolated reverberations rooms, where measurements of sound transmission loss were made.

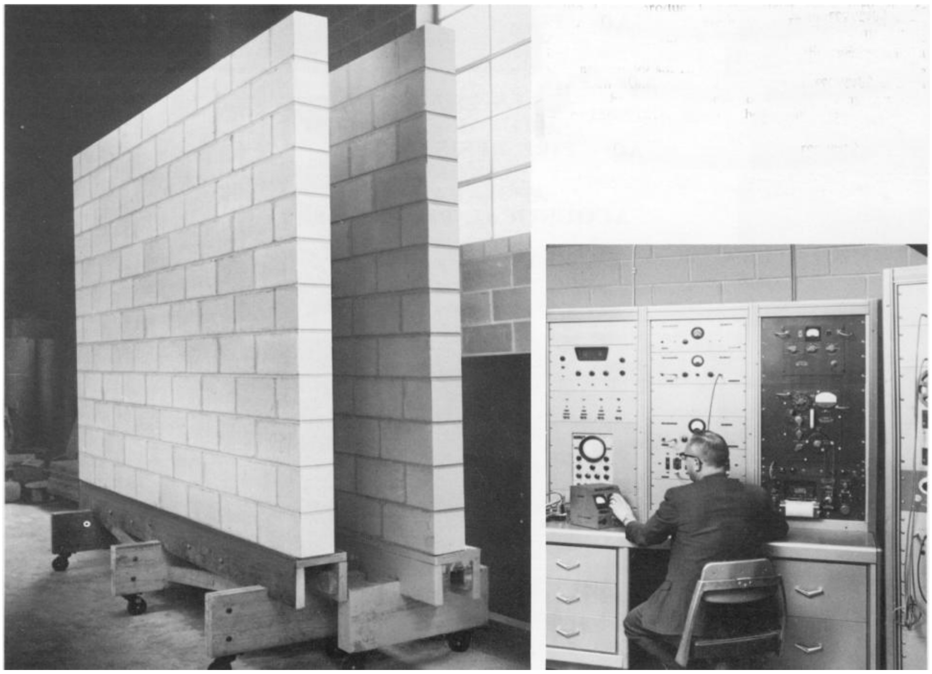


Figure 11.3.1. ***Testing for sound transmission resistance of lightweight concrete masonry units by procedures of ASTM E 90.***

Sound transmission loss tests were conducted in accordance with the American Society for Testing and Materials designation E 90 on a lightweight concrete masonry unit wall 11 feet wide and 9 feet high mounted on a movable base. The lightweight concrete masonry unit wall was rolled between two isolated reverberation rooms. Measurements were made at 16 frequencies in 1/3-octave hands, from 125 to 4000 cps.

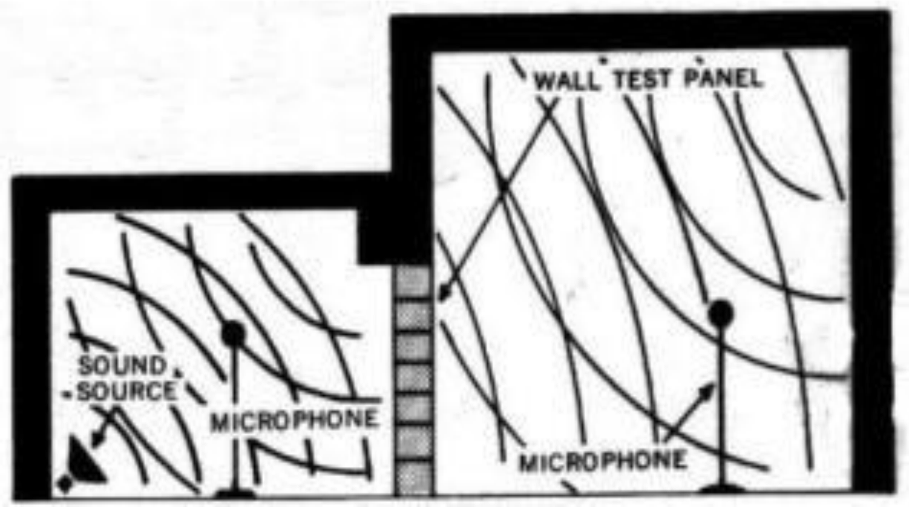


Figure 11.3.2. ***Laboratory set-up for measurements of sound transmission loss.***

Determination of Sound Transmission Class (STC) - Sound transmission class (STC) provides an estimate of the performance of a wall in certain common sound insulation applications.

The STC of a wall is determined by comparing plotted transmission loss values to a standard contour. Sound transmission loss (STL) is the decrease or attenuation in sound energy, in dB, of airborne sound as it passes through a wall. Although STC is a convenient index of transmission loss, it may be necessary in some cases to study the sound transmission loss data across a range of frequencies. This may be desirable in a case where the main source of noise is of one known frequency. In this case, the STL curve is checked to ensure there is not a “hole”, or low STL value, at the particular frequency of interest.

To determine STC, the standard curve is superimposed over a plot of the STL curve obtained by test (Figure 11.3.3) and shifted upward or downward relative to the test curve until some of the measured transmission loss values fall below those of the standard STC contour and the following conditions are fulfilled:

1. The sum of the deficiencies (deviations below the standard contour are not greater than 32 dB, and
2. The maximum deficiency at a single test point is not greater than 8 dB.

When the contour is adjusted to the highest value that meets the above criteria, the sound transmission class is taken to be the transmission loss value read from the standard contour at the 500 Hz frequency line. For example, the STC for the data plotted in Figure 11.3.3 is 45.

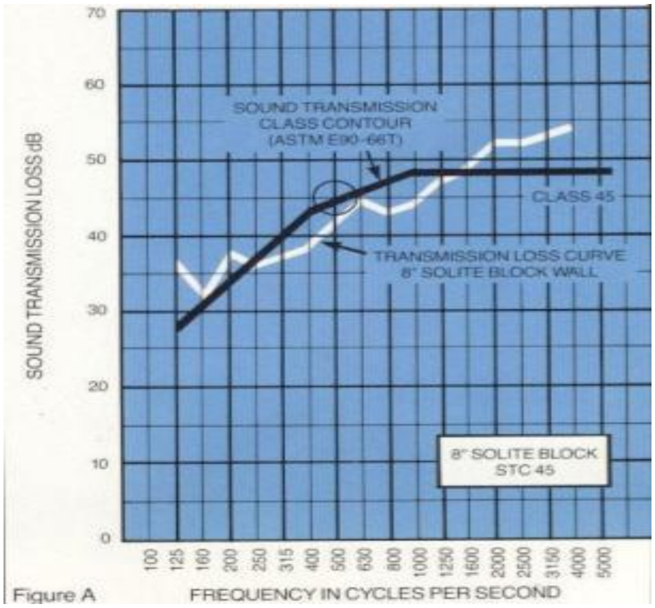


Figure 11.3.3. ***Frequency in cycles per second.***

Results of laboratory tests on walls of lightweight concrete masonry units. Many walls constructed with lightweight concrete masonry units produced with expanded shale, clay or slate by the rotary kiln method has been tested. Tests of these various walls are listed in Table 11.3.2.

Table 11.3.2. Test results sound transmission class (STC) for lightweight concrete masonry walls

MASONRY WALL THICKNESS	4 inch	6 inch	8 inch	12 inch
Plain	40	44	45	
Painted	41	45	46	50
Wall Board attached one side	47	49	56	
Plastered	50	50	51	
Cores filled with insulation	-	-	51	
COMPOSITE*-Cavity*-Grouted*				
8”				
4” Block plus 4” Concrete Brick		plain	51	
		plastered on block surface	53	
		½” gyp. Board on block face	56	
10”CAVITY				
4” Block-2” Cavity-4” Concrete Brick		plain	54	
		½” plastered on block	57	
		½” gyp on block	59	
		All cells grouted	48	
		½” plaster both sides	56	
		½” gyp. both sides	60	

***The National Concrete Masonry Association was sponsor of the composite, cavity & grouted walls.**

Calculated STC Values – Analysis of the results of sound transmission loss tests on a wide range of concrete masonry walls yield the following equation:

$$\text{STC} = 0.18W + 40$$

Where W = wall weight in psf

The equation is applicable to uncoated fine- or medium-textured concrete masonry. Coarse-textured units, however, may allow airborne sound to enter the wall, and therefore require a surface treatment to seal at least one side of the wall. Coatings of acrylic, alkyd latex, or cement-based paint, or of plaster are specifically called for in The Masonry Society Standard 0302, although other coatings that effectively seal the surface are also acceptable. The equation above also assumes the following:

1. Walls have thickness of 3 in. (76mm) or greater.
2. Hollow units are laid with face shell mortar bedding, with mortar joints the full thickness of the face shell.
3. Solid units are fully mortar bedded.
4. All holes, cracks, and voids in the masonry that are intended to be filled with mortar are solidly filled with mortar.

If STC tests are performed, the Standard requires the testing to be in accordance with ASTM E 90, "*Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions*" for laboratory testing or ASTM E 413 "*Standard Classification for Rating Sound Insulation*" for field testing.

Table 11.3.3. Calculated STC Ratings for CMU's, Excerpted from Table 8.3.2 from TMS Standard TMS 0302.00.

Nominal Unit Size	**Density (pcf)**	**STC**				**Nominal Unit Size**	**Density (pcf)**	**STC**			
		Hollow Unit	**Grout Unit**	**Sand Filled**	**Solid Units**			**Hollow Unit**	**Grout Unit**	**Sand Filled**	**Solid Units**
4	**80**	**43**	**45**	**45**	**45**	**4**	**85**	**43**	**46**	**45**	**45**
6	**80**	**44**	**49**	**47**	**47**	**6**	**85**	**44**	**49**	**47**	**47**
8	**80**	**45**	**53**	**60**	**50**	**8**	**85**	**45**	**53**	**50**	**50**
10	**80**	**46**	**56**	**52**	**52**	**10**	**85**	**46**	**56**	**53**	**53**
12	**80**	**47**	**60**	**55**	**55**	**12**	**85**	**47**	**60**	**55**	**55**
Nominal Unit Size	**Density (pcf)**	**STC**				**Nominal Unit Size**	**Density (pcf)**	**STC**			
		Hollow Unit	**Grout Unit**	**Sand Filled**	**Solid Units**			**Hollow Unit**	**Grout Unit**	**Sand Filled**	**Solid Units**
4	**90**	**44**	**46**	**45**	**45**	**4**	**95**	**44**	**46**	**45**	**45**
6	**90**	**44**	**50**	**48**	**48**	**6**	**95**	**44**	**50**	**48**	**48**
8	**90**	**45**	**53**	**50**	**51**	**8**	**95**	**46**	**53**	**51**	**51**
10	**90**	**47**	**57**	**53**	**53**	**10**	**95**	**47**	**57**	**53**	**54**
12	**90**	**48**	**60**	**56**	**56**	**12**	**95**	**48**	**61**	**56**	**57**
Nominal Unit Size	**Density (pcf)**	**STC**				**Nominal Unit Size**	**Density**	**STC**			
		Hollow Unit	**Grout Unit**	**Sand Filled**	**Solid Units**			**Hollow Unit**	**Grout Unit**	**Sand Filled**	**Solid Units**
4	**100**	**44**	**46**	**45**	**46**	**4**	**105**	**44**	**46**	**46**	**46**
6	**100**	**45**	**50**	**45**	**49**	**6**	**105**	**45**	**50**	**48**	**49**
8	**100**	**46**	**54**	**51**	**52**	**8**	**105**	**46**	**54**	**51**	**52**
10	**100**	**47**	**57**	**54**	**55**	**10**	**105**	**48**	**58**	**54**	**55**
12	**100**	**48**	**51**	**57**	**58**	**12**	**105**	**49**	**62**	**57**	**59**

Sound Transmission Resistance of Structural Lightweight Concrete - According to various studies, the weight per unit of wall area is a most important factor influencing sound transmission loss. Knudsen and Harris (2) have presented a chart representing the average relationship between transmission loss and weight of the barrier. This chart was published in the November, 1956 issue of the ACI Journal on logarithmic coordinates. Figure 11.3.4 represents this relationship plotted on linear coordinates.

Figure 11.3.4 presents rather clearly the decreasing value of wall weight in effecting sound transmission loss. It will be noticed that whereas the first 15 lbs. per square foot of wall area furnish a loss of 40 decibels, the next 15 lbs. per square foot increase the loss only 5 decibels.

Results of tests conducted on cast-in-place structural lightweight concrete are superimposed on the Knudsen and Harris curve shown in Fig. 11.3.4. Test walls were constructed with a nominal 3000 psi concrete with air 4.5% and a fresh density of 116 pcf. The tests confirm the weight vs. sound transmission loss curve (Table 11.3.4).

Table 11.3.4. Comparison of STC vs. Weight

Wall (in.)	Weight (psf)	Test Results	MH Curve	TMS 302-00
4	37	46	45	47
8	74	52	50	53

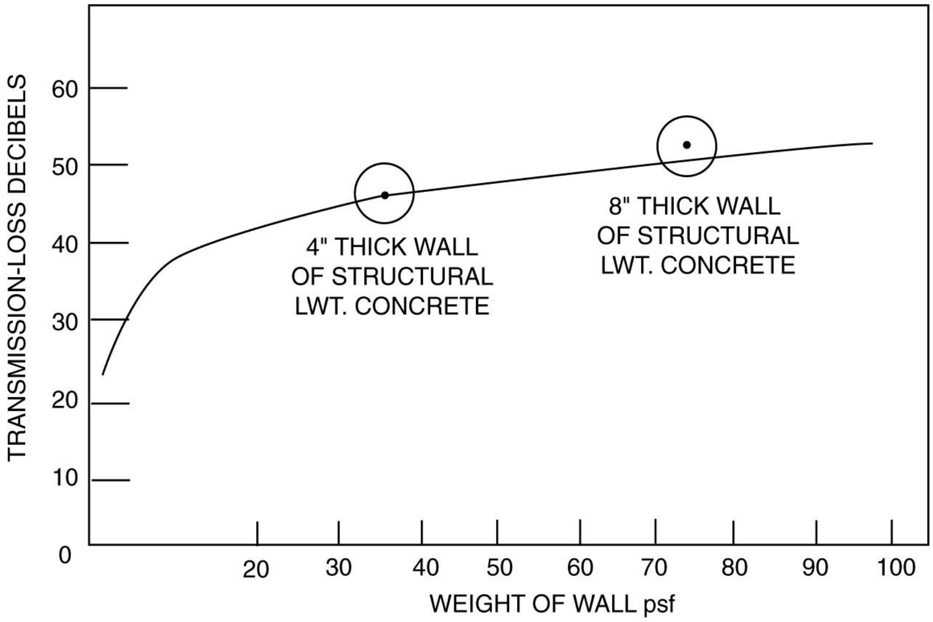


Figure 11.3.4. ***Sound Transmission Loss as a Function of Wall Weight***

Sound Absorption of Concrete Masonry Walls

Introduction - Sound absorption control deals with the reduction and control of sound emanating from a source *within* the room. Control is dependent on the shape, as well as the efficiency, of the many surfaces in the room in absorbing (i.e., not reflecting) sound waves.

The study of sound conditioning and acoustical control is highly specialized field, and for a thorough and accurate solution, particularly of special problems, authorities on the subject and more detailed manuals should be consulted. This section will serve as an introduction to some of the principles involved.

Principal of Control - Sound waves created by voices, equipment, and other sources, radiate in all directions in a room until they strike a surface, such as a wall, ceiling, floor, or furnishings. There the energy of the sound wave is partly absorbed and partly reflected, the extent of each depending on the nature of the surface it strikes. Reduction of the amount of sound reflected, therefore, is essentially a matter of selection of materials for walls, floor, ceiling, and furnishings which will absorb the desired degree of sound. In the control of sound where a speaker or music is to be heard, such as in a church or auditorium, reverberation time in the room should also be considered.

Absorption Control - The following three terms are introduced to define and evaluate sound absorption: Sound Absorption Coefficient, Sabin, and Noise Reduction Coefficient.

The Sound Absorption Coefficient is a measure of the proportion of the sound striking a surface which is absorbed by that surface, and is usually given for a particular frequency. Thus, a surface which would absorb 100% of the incident sound would have a Sound Absorption Coefficient of 1.00, while a surface which absorbs 45% of the sound, and reflects 55% of it, would have a Sound Absorption Coefficient of 0.45. The Sound Absorption Coefficient usually varies with each frequency tested.

A Sabin is defined as the amount of sound absorbed by one square foot of surface having a Sound Absorption Coefficient of 1.00. The number of Sabins (Absorption Units) of a given area is then the product of the area and the Sound Absorption Coefficient. A 100 sq. ft. area of a surface with a Sound Absorption Coefficient of 0.25 furnishes 25 Sabins (Absorption Units).

Most materials are tested at frequencies from 125 to 4000 cycles per second (cps) in octave steps. The Noise Reduction Coefficient is the average of the Sound Absorption Coefficient at 250, 500, 1000 and 2000 cps in octave steps. Table 1 lists approximate values of the Noise Reduction Coefficients of numerous materials.

Texture - The Noise Reduction Coefficient of a surface is, to a large degree, dependent on the porosity of the material and the texture of the surface. For example, a sheet of painted fiberboard with its relatively smooth paint covering would be expected to reflect a major portion of sound striking it, thereby furnishing low sound absorption. On the other hand, if the surface were punctured with a number of holes, sound could then penetrate the porous core and be dissipated, thus appreciable increasing its sound absorption.

Concrete masonry produced with ESCS offers an extremely strong material with countless minute pores and void spaces due to the modern processes of aggregate and block manufacture. These pores and void spaces naturally appear on the surface of the unit, thereby permitting sound waves to enter the unit and be dissipated within the material, this characteristic results in good sound absorbing properties, when compared to ordinary concrete surfaces.

Painting the concrete masonry will tend to seal the surface, reducing the sound absorption. Tests indicate the extent of sealing depends upon the type of paint and method of applications (See Table 11.3.5).

Table 11.3.5 Noise Reduction Coefficients

MATERIAL	APPROX. N.R.C.	
Expanded Shale Block, Medium Texture, unpainted	**0.45**	**Increase 10% for Coarse Texture Decrease 10% for Fine Texture**
Heavy Aggregate Block Medium Texture, unpainted	**0.27**	**Increase 5% for Coarse Texture Decrease 5% for Fine Texture**

REDUCTIONS OF ABOVE FOR PAINTED BLOCK

PAINT TYPE	APPLICATION	ONE COAT	TWO COATS	THREE COATS
Any	**Spray**	**10%**	**20%**	**70%**
Oil Base	**Brushed**	**20**	**55**	**75**
Latex or Resin Base	**Brushed**	**30**	**55**	**90**
Cement Base	**Brushed**	**60**	**90**	**—**

MATERIAL	N.R.C.	MATERIAL	N.R.C.
Brick wall-unpainted	**.05**	**Fabrics**	
Brick wall-painted	**.02**	**Light, 10 oz. Per sq. yd.**	
Floors		**hung straight**	**.20**
Concrete or terrazzo	**.02**	**Medium, 14 oz. Per sq. yd.**	
Wood	**.03**	**draped to half area**	**.57**
Linoleum, asphalt, rubber or cork	**.03-.08**	**Heavy, 18 oz. Per sq. yd.**	
Tile on concrete		**draped to half area**	**.63**
Glass	**.02**		
Marble or glaze tile	**.01**		
Plaster, gypsum or lime, smooth			
Finish on tile or brick	**.04**		
Same on lath	**.04**		
Plaster, gypsum or lime, rough			
Finish on lath	**.05**		
Plaster, acoustical	**.21**		
Wood Paneling	**.06**		
Acoustical Ceiling Tile	**.55-.85**		
Carpet, heavy, on concrete	**.45**		
Carpet, heavy, hairfelt underlay	**.70**		

Note: Adapted from ESCSI Information Sheet 3430.2 “Sound Absorption of Concrete Masonry Walls”

Reverberation - Reverberation is the persistence of sound within an enclosed space after the source of sound has been cut off. Its effect on hearing is to prolong syllables in speech or tones in music which, if not in the right range, make hearing difficult and irritating.

Reverberation time is defined as the time in seconds for the intensity level to fall 60 decibels. The factors which affect reverberation time are (1) the volume of the room and (2), the sound absorbing properties of the room's surfaces.

In small rooms, such as offices, reverberation generally is not the major factor. In assembly areas where speech or music is to be heard, as in churches and auditoriums, an investigation of reverberation time is necessary.

Reverberation time may be computed by the .05V formula developed by Prof. W.C. Sabine:

$$\mathrm{T} = \frac{0.05}{\mathrm{a}} \text{ where}$$

T=reverberation time
V=volume of the room in cubic feet
a=absorption of the surfaces in Sabins

The desirable reverberation times for hearing may be taken from the chart in Fig. 11.3.5. The shaded area on this chart represents acceptable reverberation times for various room sizes. When treating rooms for speech or with public address systems, the times should fall nearer the lower limit of tolerance. In churches or rooms designed for music or without public address systems, the time selected should fall nearer the upper limits.

Sound Absorption Calculations - Tabulated or tested values of the Sound Absorption Coefficient, plus the concept of the Sabin (Absorption Unit) provide a means of estimating the total sound absorbed in a room, and permit a choice of materials to accomplish the desired value.

Experience of acoustical engineers has indicated that for noise reduction comfort, the total number of Absorption Units in a room (exclusive of the absorption provided by the occupants), should be between 20% and 50% of the total surface area in square feet. The lower range is generally satisfactory for enclosures such as offices and classrooms, whereas the upper range is desirable for such areas as libraries. Where a speaker or music is to be heard by an audience, reverberation time becomes the controlling factor in comfort design.

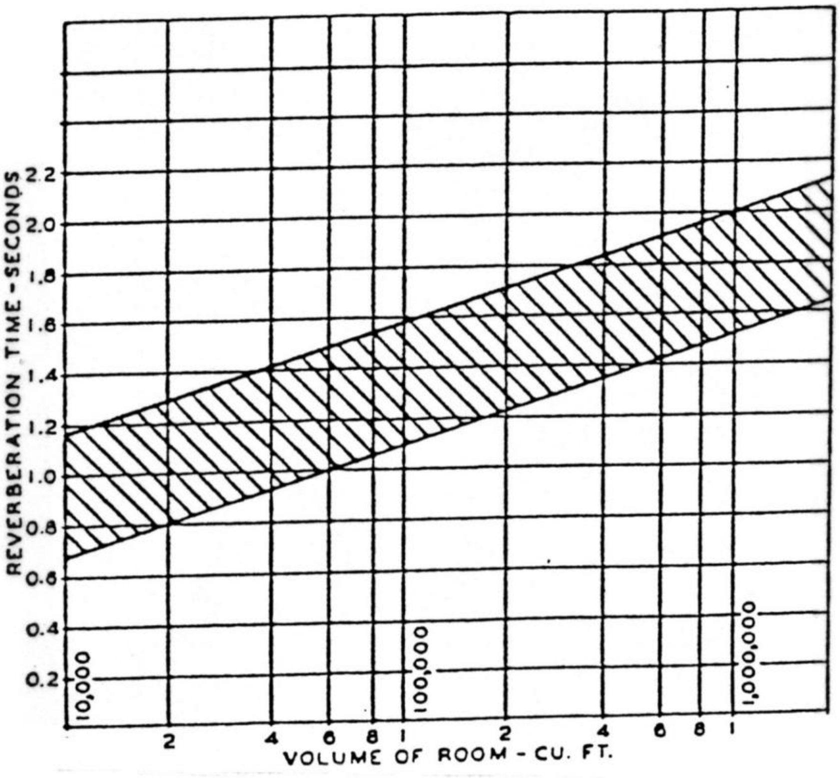


Figure 11.3.5 ***Reverberations time-seconds.***

The following example will serve to illustrate Sound Absorption calculations.

An office 15 x 25 ft. with 9-foot ceilings: medium textured concrete masonry walls sprayed with two coats of latex base paint, asphalt tile floors, and acoustical tile ceiling. Interior Surface Area-(15x25x2)+(30+50)x9=1,470 sq. ft. 1,470x20%=294, minimum number of Absorption Units desired for comfort. 1470 x 50% = 735, desirable number of Absorption units.

Absorption Units Calculations (See Table 1 for Noise Reduction Coefficients).

Floor	12x25	375 sq.ft.x0.05	=	19.0
Ceiling	15x25	375 sq.ft.x0.70	=	262.0
Window	6x4	25 sq.ft.x0.02	=	0.5
Door	6.5x4	26 sq.ft.x0.06	=	1.5
Walls	(30+50)x9	720 sq.ft.		
Masonry	720-(24+26)	670 sq.ft.x0.36*	=	241.0
				524.0

*LW cmu med. texture 0.45-(.2x.45)=0.36

Since the total Absorption Units are greater than the minimum required, 294, and less than the maximum, 735, the office should be satisfactory.

References

1. *"Less Noise-Better Hearing*", 6th Edition, Hale J. Sabine, The Celotex Corporation.
2. *"Theory and use of Architectural Acoustical Materials",* 2nd Edition, Paul E. Sabine, Acoustical Material Association.
3. "*Sound Reduction Properties of Concrete Masonry Walls",* 1955, National Concrete Masonry Association.
4. *"Sound Absorbing Value of Portland Cement Concrete",* by F.R. Watson and Keron C. Morrical, ACI Journal, May-June 1936.
5. *"Insulating Concrete",* by R.C. Valore, Jr., ACI Journal November, 1956.

Resistance to Impact Sound

Introduction - The increased noisiness of our environment has led to concern for the isolation of impact noise. Footsteps, dropped toys and some appliances cause impact noise. Isolation against impact noise provided by a given floor construction is measured in accordance with ISO recommendation R 140-60. This procedure utilizes a standard tapping machine that is placed in operation on a test floor specimen, which forms a horizontal separation between two rooms, one directly above the other. The transmitted impact sound is measured in 1/3-octave bands over a frequency range of 100 to 3150 Hz in the receiving room below. From the data collected a single figure rating, called Impact Insulation Class (IIC), is derived in a prescribed manner from the values of the impact sound pressure levels measured in the receiving room. The rating provides an estimate of the impact sound insulating performance of a floor-ceiling assembly. Details of the procedures are outlined in ASTM E-492.

Laboratory Testing Program - The Expanded Shale, Clay & Slate Institute sponsored a test program at Riverbank Laboratories, Geneva, Illinois, to determine the effect of the concrete density and Modulus of Elasticity on impact sound transmission. Slab thicknesses of 5 inches and 10 inches were selected for study. Three concretes designed to weigh approximately 95, 115, and 150 pounds per cubic foot were used so the weight per square foot of floor would cover a broad range. The slabs were designed for a compressive strength of 3000-psi (21 Mpa) and included reinforcement in keeping with flat plate design.
The impact Noise Reduction (INR) factors determined from the Riverbank Laboratory tests have been converted to the current designation, Impact Insulation Class (IIC), and are shown in Table 11.3.6.

Table 11.3.6. Impact Noise Ratings as a Function of Slab Thickness, Concrete Density and Slab Surface.

TEST NO.	SLAB THICKNESS (INCHES)	CONCRETE DENSITY (PCF)	CONCRETE SURFACE	IMPACT NOISE RATING
1	10	85	Bare	-23
2	10	115	Bare	-21
3	10	145	Bare	-20
4 (#2)	10	115	Standard carpet	+23
5 (#2)	10	115	1/8” Vinyl tile	-18
6	5	85	Bare	-28
7	5	115	Bare	-27
8	5	145	Bare	-27
9	5	115	Standard carpet	+17

Conclusion - Analysis of Table 11.3.6 suggest that for bare concrete floors, that despite variation in slab thickness and concrete density will not provide acceptable resistance to impact sound. When a standard carpet is provided the resistance to impact sound is significantly improved.

11.4 Resistance to the Environment of Lightweight Concrete and Lightweight Concrete Masonry

Dimension Stability

General - Masonry is undeniably the most enduring of all construction materials, and yet paradoxically, it is never quiescent. As with all construction materials, the assemblage of units and mortar as we know as masonry is an eternal state of movement caused by the inevitable changes in temperature, moisture and chemistry. Additionally, as masonry is usually connected to other structural members, the differential movements between the various building elements must also be accommodated. An attitude of accommodation to movement is essential as the forces of nature cannot be resisted without causing distress.

This section will briefly account for the factors causing volumetric changes in units and elements and then suggest practical methods of accommodating these movements. Frequently in masonry construction there are conflicting desires to provide isolation of individual building elements and yet maintain continuity of the structure as a whole. These considerations are mutually exclusive and a design professional must apply judgment in trade-offs between these considerations and promote the optimized structure. Comprehensive information and recommendations on masonry movements and crack control is available from The National Concrete Masonry Association (NCMA) including TEK 10-1A, 2B, 3 and 4.

Of the numerous considerations involved in the analysis of movements in joints there are a few global views of masonry that are especially useful. First, any attempt to resist the forces of nature is unlikely to succeed. In general, free unimpeded movement of units and elements will not cause stress. It is the restrained segment that will develop opposing forces that may produce cracking and buckling in the masonry or distress in the adjoining elements. The magnitude of the movements developed in laboratory testing programs must be adjusted to the temperature regimes the structure endure as built. Timing of construction can be significant in evaluating the residual movements that are restrained by adjoining elements.

Buildings constructed today are taller, thinner, with longer spans and higher strength to weight ratios than in earlier days. While the structural frames can accommodate all the horizontal and vertical movements that are attendant with taller, thinner buildings, the interaction between the various non-structural elements of walls and piping, however, should be closely examined due to the interaction of these elements with the structural frame. In addition, the compelling economic drive toward more efficient, higher strength to weight materials will inevitably result in less forgiving structures and walls. Older buildings composed of stiffer frames and thick walls were less responsive to external temperature changes, lower strength units and softer mortars have behaved well with resistance to cracking.

In the analysis of movements and joints one must not be excessively jaundiced by the limited amount of cracking programs in masonry. The test of time has demonstrated masonry as one of the most forgiving, enduring of all construction materials.

The rate at which various phenomenon occur is of crucial importance. For example, it can be demonstrated by a simplistic example below that the amount of strain developed in the exterior wall of a masonry building exposed to solar radiation and large diurnal temperature variations is of the order of magnitude as that concerned with drying shrinkage that develops over a period of perhaps several months. The diurnal temperature strain occurs at a rate of perhaps 200 to 300 times that of drying shrinkage and does not allow for accommodation of these strains due to relaxing due to creep.

Table 11.4.1 Hypothetical comparison of the relative influence of thermal/drying shrinkage of typical lightweight and normalweight concrete masonry units.

	Lightweight	**Normalweight**
In wall restrained drying shrinkage over several months (x 10^{-6} in/in)	**400**	**300**
Thermal shrinkage west wall hot day, cool shower ($\Delta T = 60^{\circ}F$)	**3.9 x 60 = 234**	**5.5 x 60 = 330**
Cumulative Strain	**634**	**630**

Another factor generally not given due consideration is the extensibility of the masonry materials. Extensibility may be defined as the capacity to accommodate strain. High strength, low modulus materials such as lightweight concrete masonry are materials of choice to accommodate strains from various sources.

Thermal movements in concrete and masonry - All construction materials change volume when exposed to a temperature change. The amount of volume change that results from a change in material temperature depends on the coefficient of linear thermal expansion and on the magnitude of the temperature change. The values for concrete and concrete masonry are listed in Table 11.4.2. The values for the coefficient of linear thermal expansion of a concrete masonry unit are strongly dependent on the coefficient of the aggregate and the matrix fractions and the various percentages of both. The dispersion of published data on coefficient of linear thermal expansion is well known from studies in cast-in-place concrete and serves to explain the apparent differences between the results published by different investigators, which in fact, is directly related to the mixture composition. In addition, the generic words commonly used in concrete, for example, “gravel”, in fact represents a wide dispersion of mineralogical materials with widely differing coefficient of linear thermal expansion. Specific results in individual geographical areas may be obtained from local manufacturers.

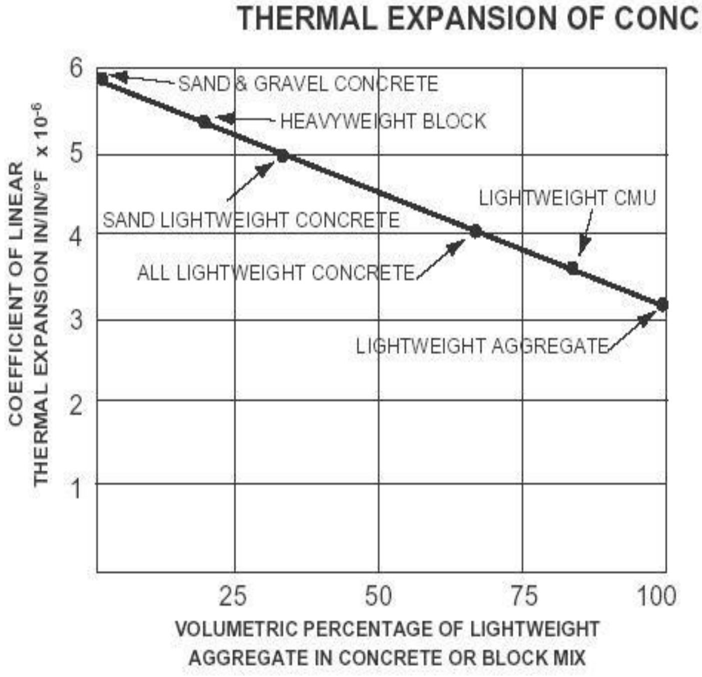
Table 11.4.2. Laboratory Determination of Coefficient of Linear Thermal Expansion

Mix Data Materials (SSD*)	Regular Concrete	LWCA and Natural Sand	LWCA and LWFA
Cement Bags	**6.0**	**6.0**	**6.0**
Darex, oz	**3.0**	**3.6**	**4.2**
Sand, lb	**1068**	**1320**	**….**
Gravel, lb	**1940**	**….**	**….**
LWFA, lb	**….**	**….**	**1180**
LWCA, lb	**….**	**930**	**750**
Water, gal	**34.5**	**38.0**	**39.0**
Slump, in.	**5**	**4**	**4**
Air content percent	**4.0**	**6.0**	**6.0**
35-day results:			
Thermal expansion from 40 to 140 deg F, Average of 3	**0.058**	**0.050**	**0.040**
Expansion, in. per in. per deg.	**0.0000058**	**0.0000050**	**0.0000040**
***Saturated Surface Dry**			

Reduce thermal movements:

Laboratory tests have shown that using Lightweight aggregates result in significantly lower coefficients of thermal expansion in concrete produced lightweight concrete masonry units, 3.67 x 10^{-6} in/in °F, heavyweight concrete masonry units 5.32 x 10^{-6} in/in °F.

As Fig. 11.4.1 indicates natural aggregates with high coefficients of thermal expansion added to the mixture will generally increase the coefficient of linear thermal expansion and result in greater thermal movements.



REDUCE THERMAL MOVEMENTS

Laboratory tests have shown that using lightweight aggregates results in a significantly lower coefficient of thermal expansion in concrete products.

Lightweight CMU

3.67×10^{-6} in/in°F

Heavyweight CMU

5.32×10^{-6} in/in°F

As the adjacent plot indicates natural ingredients with high coefficients of thermal expansion added to the mix will generally increase the coefficient of linear thermal expansion and result in greater thermal movements.

Figure 11.4.1 ***Thermal Expansion of Concrete Products.***

Impact Resistance of Lightweight Concrete Masonry Walls

Numerous prison type security structures have been successfully constructed with walls utilizing structural grade lightweight concrete masonry aggregate. Reported below is a summary of the results of research into the impact resisting performance of lightweight concrete masonry walls. The full report is included as Appendix 11.4A.

To provide adequate security barrier walls, tests were conducted on several grouted reinforced concrete walls where the strength of grout, strength and density of the CMU were varied. All walls exceeded the security grade requirements of ASTM F 2322, "*Standard Test Methods for Physical Assault on Vertical Fixed Barriers for Detention and Correctional Facilities",* shown in Table 11.4.3.

Table 11.4.3 Security Grade and Impact Load Requirements

Grade No.	Number of Impacts	Representative Barrier Duration Time, Min.
1	600	60
2	400	40
3	200	20
4	100	10

The testing program simulates a series of impacts from a pendulum ram fixed with two heads: a blunt impactor to simulate a sledgehammer and a sharp impactor simulating a fireman's axe. The testing protocol calls for blows from both the blunt and sharp impactors applied in sequences of 50 blows each. For testing setup and wall panels see Appendix A. See Fig. 11.4.2 for typical wall condition after 600 blows (Front and rear sides). CMU's used in the preparation of test specimen #4 met the SmartWall® requirements of:

Compressive strength 2610 psi > 2500 psi minimum

Concrete density 90.5 pcf < 93 pcf maximum

The grout used in test #4 had a compressive strength of 2880 psi

Failure of the test wall was reached at 924 blows which is in excess of Security Grade requirements of 600 blows.

Figure 11.4.2. ***Typical Wall Condition after 600 blows-Front side and Typical Wall Condition after 600 blows-Rear side.***

Air Barrier Resistance - Air barrier resistance requirements are increasing from both a commercial acceptance and future governmental regulation perspectives. The negative effects of air leakage include:

- Increased energy costs
- Metal stud corrosion
- Tie and reinforcement corrosion
- Increased possibility of efflorescence
- Mold and mildew
- Degradation of insulation

At the present time (August 2006) information on the performance of concrete masonry is limited. Research commitments have been supported and testing is currently underway.

Code Requirements - Air barrier system code requirements require air leakage control compliance:

- Material compliance – The air barrier material in an assembly must have an air permeance not to exceed a flow of 0.004 cfm/sf at 1.57 psf (0.02 l/s • m^2 @ 75 Pa) when tested in accordance with ASTM E 2178.
- Assembly compliance – An air barrier assembly must have an air permeance not to exceed 0.03 cfm/sf at 1.57 psf (0.15 l/s•m^2 at 75 Pa) when tested according to ASTM E 1677.

These requirements have been developed because of reports that up to 40% of the energy used by buildings for heating and cooling is lost due to infiltration. Several governmental agencies have recently developed code requirements mandating an air barrier system in the building envelope. A continuous air barrier system is the combination of interconnected materials, flexible sealed joints and the components of the building envelope that provide air-tightness.

Air Impermeability - Materials that have been identified as too air-permeable include fiberboards and uncoated single wythe concrete block. Canada and Massachusetts consider a flow of 0.004 cfm/sf as the maximum air leakage for a material that can be used as part of the air barrier system. Flow of 0.004 happens to be the air permeance of a sheet of 1/2" unpainted gypsum wall board.

According to one report the following materials do not qualify as an air barrier material without additional coatings:

- Uncoated concrete block
- Plain and asphalt impregnated fiberboard
- Expanded polystyrene
- Batt and semi-fibrous insulator
- Perforated house wraps
- Asphalt impregnated felt (15 or 30 lb.)
- Tongue and groove plank
- Vermiculated insulation
- Cellulose spray-on insulation

Walls that are constructed using materials that are very permeable to air, such as concrete block, must be air-tightened using a coating either as a specially formulated paint or air barrier sheet product, or a liquid spray-on or trowel-on material (ANIS 2004).

Table11.4.4 Status of Testing in Accordance with ASTM E 2178

Sponsor	Test Facility	CMU	Density	Un-coated	Coated	Note
NECMA 10/03 Program	Bodycote	12 NW		.046	.00102	Coated with
“	“	8 NW		.12	.00087	“ “
“	“	8 LW		-----	-----	(to be tested)
“	“	8 NW			.0005	Coated with (1)
NCMA (no date)	NCMA	HW		-----	.02	One coat of paint
NCMA (no date)	NCMA	HW		-----	.002	Two coats of paint
ESCSI 12/04	NCMA	LW	3820 92.6	-----	.0609	1 coat of prep rite primer and 1 coat of latex interior
ESCSI 12/04	NCMA	LW	3820 92.6	-----	.003	1 coat of prep rite primer and 2 coats of latex interior
ESCSI 8/05	NCMA	LW	3450 96	.33		Wait for cure Test @ 28
NCMA 8/05	NCMA	NW		0.6 to 1.0		Wait for cure Test @ 28

(1) Coated with Sherman Williams Conflex XL Elastomeric Coating (50-60 ft^2/gal) on top of Luxor block surfacer (50-75 ft^2/gal)

11.1A

ESCSI Information Sheet No. 4

“Thermal Insulation””

APPENDIX A

Lightweight Concrete
INFORMATION SHEET

NO. 4
Reprinted 6-83

EXPANDED SHALE CLAY AND SLATE INSTITUTE — BETHESDA, MARYLAND 20814

THERMAL INSULATION
OF
VARIOUS WALLS

With the many improvements being made in heating and air conditioning equipment for residences, commercial and office buildings, hotels, industrial buildings and the like, it is becoming increasingly important for architects and engineers to have ready access to information on the thermal insulation properties of building materials. This bulletin furnishes convenient information on insulating values of various walls and their components.

Since the mechanical engineer designs the heating and cooling plant on the basis of the total hourly heat transmission through the exterior parts of the building, optimum efficiency in economical structural design requires analysis of the relative heat losses through the elements of the structure. This data sheet has been prepared to present values on a number of commonly used building materials, and to aid in designing more economical structures.

The values shown in this bulletin are based on the American Society of Heating, Regrigerating, and Air Conditioning Engineers Guide and may be used directly for steady state heat transmission calculations. Table 2 contains a few values determined from recent tests at Pennsylvania State University and other sources. Reference should be made to the Guide when more detailed information is desired.

Nomenclature as used in the Guide for heat loss calculations is as follows:

U = overall coefficient of heat transmission or thermal transmittance (air to air); the time rate of heat flow expressed in Btu per (hour) (square foot) (Fahrenheit degree temperature difference between air on the inside and air on the outside of a wall, floor, roof or ceiling). The term is applied to the usual combinations of materials, and also to single materials, such as window glass, and includes the surface conductance on both sides. This term is frequently called the U value.

k = thermal conductivity; the time rate of heat flow through a homogeneous material under steady conditions (through unit area per unit temperature gradient in the direction of the gradient). Its value is expressed in Btu per (hour) (square foot) (Fahrenheit degrees per inch of thickness). Materials are considered homogeneous when the value of k is not affected by variation in thickness or size of sample within the range normally used in construction.

C = thermal conductance; the time rate of heat flow through a unit area of a material from one of its surfaces to the other per unit temperature difference between the two surfaces. Its value is expressed in Btu per (hour) (square foot) (Fahrenheit degree). The term is applied to specific materials as used, either homogeneous or heterogeneous.

f = film or surface conductance; the time rate of heat exchange by radiation, conduction, and convection of a unit area of a surface with the surroundings and the surrounding air or other fluid. Its value is expressed in Btu per (hour) (square foot of surface) (Fahrenheit degree temperature difference). Subscripts i and o are usually used to denote inside and outside surface conductances, respectively.

a = thermal conductance of an air space; the time rate of heat flow through a unit area of an air space per unit temperature difference between the boundary surfaces. Its value is expressed in Btu per (hour) (square foot of area) (Fahrenheit degree). The conductance of an air space is dependent on the temperature difference, the height, the depth, the position and the character and temperature of the boundary surfaces. Since the relationships are not linear, accurate values must be obtained by test and not by computation.

R = thermal resistance; the reciprocal of a heat transfer coefficient, as expressed by U, C, f, or a. Its unit is Fahrenheit degrees per Btu/(hour) (square foot). For example, a wall with a U value of 0.25 would have a resistance value of R = 1/U = 1/0.25 = 4.0 ru. The term "ru" is being used as an abbreviation for "resistance unit."

In Table 1 of this Information Sheet subscripts are used for clarification and convenience, as follows:

R_s = resistance of the exterior wall, but does not include the surface resistance.

R_i = resistance of interior wall treatment, and includes the surface resistance of both the inside and outside wall.

R_U = total resistance of the "complete" or "total" wall.

USE OF TABLES

Table 2 lists the conductivity (k) and conductance (C) of a number of materials. Table 1 provides the calculated values of the overall coefficient of heat transmission, frequently called the "U value," of 43 different exterior walls with 12 different interior treatments. The column designated R_s contains the resistance of the structural portion of the wall. The resistance of both the exterior and interior wall surfaces are included in the resistance R_i of each interior wall treatment.

(R_U is the sum of R_s and R_i. U is the reciprocal of R_U.)

In the event the desired combination of exterior wall and interior treatment is not shown in Table 1 the following example illustrates the calculations.

Example: Assume it is desired to use a precast curtain wall consisting of exposed granite-chip concrete backed up with lightweight concrete. The panel is composed of 1" granite concrete facing on 4" of 105 pcf structural lightweight concrete. To the inside of this panel is attached 1" polystyrene with ½" dry-wall for the interior facing.

From Table 2 the resistance, 1/k, of 105 pcf concrete is 0.25 and 140 pcf concrete, 0.11 (assume the granite-chip concrete to be about the same as sand and gravel concrete).

0.25 x 4 (thickness in inches)	=	1.00
0.11 x 1	=	0.11
R_s	=	1.11

The interior treatment is the same as Column 4 of Table 1, in which $R_i = 5.47$.

Then, 1.11 (R_s) + 5.47 (R_i) = 6.58 (R_U).
1/6.58 = 0.15 = U value.
Such an insulation value is considered excellent.

As mentioned above, Table 1 provides the calculated values of the overall coefficient of heat transmission U and total resistance R_U for a number of different composite walls. The use of this table by the architect and engineer generally will permit the selection of wall design that will economically and readily meet insulation requirements without the necessity of calculations from the data listed in Table 2.

Recent Department of Housing and Urban Development Minimum Property Standards for One and Two Family Dwellings require that the maximum Btu per hour heat loss through walls, including windows and doors but exclusive of infiltration, be 20 times the floor area of the space to be heated to 70 F. To conform with this requirement the designer will need Tables 3 and 4 for window and door coefficients and also must know the outside design temperature. The winter design temperatures vary for example from plus 20 to 30 degrees F in some parts of the country to -30 or less in other parts. Design temperatures are available from FHA Field Offices and from the ASHRAE Handbook of Fundamentals.

The following simplified example is offered to illustrate these calculations.

Consider a 28 x 40 foot one story dwelling with an 8 ft. ceiling height. Assume that doors and wood sash windows account for about 20 percent of the exterior wall area. The walls are 8-inch expanded shale concrete masonry, furred with dry wall interior treatment. The windows are single pane without storm windows. The winter design temperature is +16 F.

Total exterior wall area	1,088 sq. ft.
Window area	175 sq. ft.
Door area	40 sq. ft.
Net wall area	873 sq. ft.

From Table 1, Wall number 14-7 has a U value of 0.22 Btu. From Table 3A single glass has a U of 1.13. From Table 3C the correction factor for wood sash with 80 percent glass is 0.90, consequently the U value for the windows is 1.13 x .90 = 1.02 Btu. From Table 4 the U value for 1½-in. doors is 0.49 Btu. (without storm doors).

Concrete masonry wall area	873 x .22 = 192.1
Window area	175 x 1.02 = 178.5
Door area	40 x .49 = 19.6
Total Btu per hour per degree heat loss	390.2

The outside design temperature is +16 degrees therefore the degree range is 70 − 16 = 54 degrees. The total Btu per hour loss is 390.2 x 54 = 21,070 Btuh. The HUD requirement is 20 x 1,120 = 22,400 Btu, consequently the requirement is satisfied for this area and any area where the outside design temperature is +13 F or higher.

Suppose the outside design temperature is +5 instead of +16? In this case the loss is 390.2 x 65 = 25,360 Btuh and exceeds the requirements. This means more insulation is required. There are numerous alternatives which become apparent from the Interior Treatment columns as well as Structural Wall column of Table 1. The alternative selected is filling the cores of the unit with expanded shale which offers the wall a U value of 0.16 (#15-7). The concrete masonry walls become 873 x .16 = 139.7 reducing the total loss of the wall area to 337.8 Btuh per degree. For the design temperature of +5 the loss is 337.8 x 65 = 21,960 Btu per hour, which meets the required 22,400 Btu for the floor area in this locality.

To further reduce the heat loss for colder areas consideration may be given to storm windows and doors. Although the initial cost is high and installation and removal each year, a consideration, under some conditions storm windows and doors are economically justified. The reductions in heat loss in the example follows:

From Table 3A and 3C the U value for storm windows, wood sash is 0.56 x .90 = .504 Btuh/degree. From Table 4, the U value for storm doors is 0.27 Btuh/degree. The example becomes -

Concrete masonry with cores filled	873 x .16 = 139.7
Storm windows	175 x .504 = 88.2
Storm doors	40 x .27 = 10.8
Total Btu per hour per degree loss	238.7

The dwelling can meet the FHA requirements of maximum loss of 22,400 Btu per hour at a winter design temperature of -23 degrees F.

(238.7 x 93 = 22,200 Btu per hour.)

From these simplified examples it can be seen that the designer has numerous alternatives in satisfying insulation requirements. From Table 1 it can be seen that insulation board, reflective insulation or filling the cores with vermiculite or perlite would satisfy, for example, a +5 F design temperature. The designer will weigh the cost factors and furnish the most economical design that satisfies the insulation requirements.

TABLE 1

WALL CONSTRUCTION

NOTE: Surface Resistance included in "R_i" for Interior Wall Treatments.

Wall No.		Interior Wall Treatment Resist. →	1		2		3		4	
			Plain Wall No Plaster		Plaster Direct On Wall				1″ Polystrene	
					Gyp-Sand Plaster		Gyp-Lt.Wt. Plaster		½″Gyp. Dry-Wall	
			R_i=0.85		R_i=0.94		R_i=1.17		R_i=5.47	
		R_S	R_U	U	R_U	U	R_U	U	R_U	U
	CAST-IN-PLACE OR PRECAST CONCRETE									
1	8″ Expanded Shale Clay or Slate Aggregate 85 pcf.	2.88	3.73	.27	3.82	.26	4.05	.25	8.35	.12
2	8″ Expanded Shale Clay or Slate Aggregate 90 pcf.	2.56	3.41	.29	3.50	.29	3.73	.27	8.03	.12
3	8″ Expanded Shale Clay or Slate Aggregate 95 pcf.	2.40	3.25	.31	3.34	.30	3.57	.28	7.87	.13
4	8″ Expanded Shale Clay or Slate Aggregate 100 pcf.	2.24	3.09	.32	3.18	.31	3.41	.29	7.71	.13
5	8″ Expanded Shale Clay or Slate Aggregate 105 pcf.	2.00	2.85	.35	2.94	.34	3.17	.32	7.47	.13
6	8″ Expanded Shale Clay or Slate Aggregate 110 pcf.	1.84	2.69	.37	2.78	.36	3.01	.33	7.31	.14
7	8″ Expanded Shale Clay or Slate Aggregate 115 pcf.	1.68	2.53	.40	2.62	.38	2.85	.35	7.15	.14
8	8″ Sand & Gravel Aggregate 140 pcf.	0.88	1.73	.58	1.82	.55	2.05	.49	6.35	.16
	CONCRETE MASONRY									
9	12″ Expanded Shale Clay or Slate Aggregate	2.63	3.48	.29	3.57	.28	3.80	.26	8.10	.12
	Cores filled with:—									
10	Expanded Shale Clay or Slate	5.55	6.40	.16	6.49	.15	6.72	.15	11.02	.09
11	Vermiculite	7.14	7.99	.13	8.08	.12	8.31	.12	12.61	.08
12	Perlite	9.09	9.94	.10	10.03	.10	10.26	.10	14.56	.07
13	12″ Sand and Gravel Aggregate	1.28	2.13	.47	2.22	.45	2.45	.41	6.75	.15
14	8″ Expanded Shale Clay or Slate Aggregate	2.27	3.12	.32	3.21	.31	3.44	.29	7.74	.13
	Cores filled with:—									
15	Expanded Shale Clay or Slate	4.00	4.85	.21	4.94	.20	5.17	.19	9.47	.11
16	Vermiculite	5.00	5.85	.17	5.94	.17	6.17	.16	10.47	.10
17	Perlite	5.55	6.40	.16	6.49	.15	6.72	.15	11.02	.09
18	8″ Sand and Gravel Aggregate	1.11	1.96	.51	2.05	.49	2.28	.44	6.58	.15
	4 INCH FACE BRICK, PLUS:									
	4″ Concrete Masonry									
19	Expanded Shale Clay or Slate Aggregate	2.08	2.93	.34	3.02	.33	3.25	.31	7.55	.13
20	Sand and Gravel Aggregate	1.15	2.00	.50	2.09	.48	2.32	.43	6.62	.15
21	4″ Common Brick	1.24	2.09	.48	2.18	.46	2.41	.41	6.71	.15
22	4″ Clay Tile	1.55	2.40	.42	2.49	.40	2.72	.37	7.02	.14
	8″ Concrete Masonry									
23	Expanded Shale Clay or Slate Aggregate	2.71	3.56	.28	3.65	.27	3.88	.26	8.18	.12
	Cores filled with:—									
24	Expanded Shale Clay or Slate	4.44	5.29	.19	5.38	.19	5.61	.18	9.91	.10
25	Vermiculite	5.44	6.29	.16	6.38	.16	6.61	.15	10.91	.09
26	Perlite	5.99	6.84	.15	6.93	.14	7.16	.14	11.46	.09
27	Sand and Gravel Aggregate	1.55	2.40	.42	2.49	.40	2.72	.37	7.02	.14
	12″ Concrete Masonry									
28	Expanded Shale Clay or Slate Aggregate	3.07	3.92	.26	4.01	.25	4.24	.24	8.54	.12
	Cores filles with:—									
29	Expanded Shale Clay or Slate	5.99	6.84	.15	6.93	.14	7.16	.14	11.46	.09
30	Vermiculite	7.58	8.43	.12	8.52	.12	8.75	.11	13.05	.08
31	Perlite	9.53	10.38	.10	10.47	.10	10.70	.09	15.00	.07
32	Sand and Gravel Aggregate	1.72	2.57	.39	2.66	.38	2.89	.35	7.19	.14
33	1″Wood Sheathing, 2″ x 4″ studs	(1.48)	—	—						
	WOOD CONSTRUCTION									
	Bevel Siding, ½″ x 8″ Lapped, Building Paper									
34	Wood Sheathing, 2″ x 4″ studs	(1.85)	—	—						
	CAVITY WALLS									
	(Built with two units, separated with 1″ or larger air space.)									
	10-Inch Wall									
	4″ Face Brick & 4″ Concrete Masonry									
35	Expanded Shale Clay or Slate Aggregate	2.99	3.84	.26	3.93	.25	4.16	.24	8.46	.12
36	Sand and Gravel Aggregate	2.06	2.91	.34	3.00	.33	3.23	.31	7.53	.13
	4″ Concrete Masonry & 4″ Concrete Masonry									
37	Expanded Shale Clay or Slate Aggregate	4.19	5.04	.20	5.13	.20	5.36	.19	9.66	.10
38	Sand and Gravel Aggregate	2.33	3.18	.31	3.27	.31	3.50	.29	7.80	.13
	12-Inch Wall									
	4″ Face Brick & 6″ Concrete Masonry									
39	Expanded Shale Clay or Slate Aggregate	3.24	4.09	.24	4.18	.24	4.41	.23	8.71	.11
	Cores filled with:—									
40	Expanded Shale Clay or Slate	3.91	4.76	.21	4.85	.21	5.08	.20	9.38	.11
41	Vermiculite	4.47	5.32	.19	5.41	.18	5.65	.18	9.95	.10
42	Perlite	5.52	6.37	.16	6.46	.15	6.69	.15	10.99	.09
43	Sand and Gravel Aggregate	2.26	3.11	.32	3.20	.31	3.43	.29	7.73	.13

Note: The average of Winter and Summer values for air space conductanc

ABLE 1

4		5		6		7		8		9		10		11		12	
		¾ INCH FURRING										One Side Air Space Reflective Insulation					
1" Polystrene		3/8" Gypsum Lath				½"Gyp. Dry Wall		½" Fiber Insulation Board				3/8" Gypsum Lath				½"Gyp. Dry-Wall	
½"Gyp. -Wall		Gyp-Sand Plaster		Gyp-Lt.Wt. Plaster				Gyp-Sand Plaster		Gyp-Lt.Wt. Plaster		Gyp-Sand Plaster		Gyp-Lt.Wt. Plaster			
.47		R_i=2.17		R_i=2.40		R_i=2.21		R_i=3.28		R_i=3.51		R_i=4.26		R_i=4.49		R_i=4.30	
R_U	U	R_U	U	R_U	U	R_U	U	R_U	U	R_U	U	R_U	U	R_U	U	R_U	U
8.35	.12	5.05	.20	5.28	.19	5.09	.20	6.16	.16	6.39	.16	7.14	.14	7.37	.14	7.18	.14
8.03	.12	4.73	.21	4.96	.20	4.77	.21	5.84	.17	6.07	.16	6.82	.15	7.05	.14	6.86	.15
7.87	.13	4.57	.22	4.80	.21	4.61	.22	5.68	.18	5.91	.17	6.66	.15	6.89	.15	6.70	.15
7.71	.13	4.41	.23	4.64	.22	4.45	.22	5.52	.18	5.75	.17	6.50	.15	6.73	.15	6.54	.15
7.47	.13	4.17	.24	4.40	.23	4.21	.24	5.28	.19	5.51	.18	6.26	.16	6.49	.15	6.30	.16
7.31	.14	4.01	.25	4.24	.24	4.05	.25	5.12	.19	5.35	.19	6.10	.16	6.33	.16	6.14	.16
7.15	.14	3.85	.26	4.08	.25	3.89	.26	4.96	.20	5.19	.19	5.94	.17	6.17	.16	5.98	.17
6.35	.16	3.05	.33	3.28	.30	3.09	.32	4.16	.24	4.39	.23	5.14	.19	5.37	.19	5.18	.19
8.10	.12	4.80	.21	5.03	.20	4.84	.21	5.91	.17	6.14	.16	6.89	.15	7.12	.14	6.93	.14
11.02	.09	7.72	.13	7.95	.13	7.76	.13	8.83	.11	9.06	.11	9.81	.10	10.04	.10	9.85	.10
12.61	.08	9.31	.11	9.54	.10	9.35	.11	10.42	.10	10.65	.09	11.40	.09	11.63	.09	11.44	.09
14.56	.07	11.26	.09	11.49	.09	11.30	.09	12.37	.08	12.60	.08	13.35	.07	13.58	.07	13.39	.07
6.75	.15	3.45	.29	3.68	.27	3.49	.29	4.56	.22	4.79	.21	5.54	.18	5.77	.17	5.58	.18
7.74	.13	4.44	.23	4.67	.21	4.48	.22	5.55	.18	5.78	.17	6.53	.15	6.76	.15	6.57	.15
9.47	.11	6.17	.16	6.40	.16	6.21	.16	7.28	.14	7.51	.13	8.26	.12	8.49	.12	8.30	.12
10.47	.10	7.17	.14	7.40	.14	7.21	.14	8.28	.12	8.51	.12	9.26	.11	9.49	.11	9.30	.11
11.02	.09	7.72	.13	7.95	.13	7.76	.13	8.83	.11	9.06	.11	9.81	.10	10.04	.10	9.85	.10
6.58	.15	3.28	.30	3.51	.28	3.32	.30	4.39	.23	4.62	.22	5.37	.19	5.60	.18	5.41	.18
7.55	.13	4.25	.24	4.48	.22	4.29	.23	5.36	.19	5.59	.18	6.34	.16	6.57	.15	6.38	.16
6.62	.15	.3.32	.30	3.55	.28	3.36	.30	4.43	.23	4.66	.21	5.41	.18	5.64	.18	5.45	.18
6.71	.15	3.41	.29	3.64	.27	3.45	.29	4.52	.22	4.75	.21	5.50	.18	5.73	.17	5.54	.18
7.02	.14	3.72	.27	3.95	.25	3.76	.27	4.83	.21	5.06	.20	5.81	.17	6.04	.17	5.85	.17
	.12	4.88	.20	5.11	.20	4.92	.20	5.99	.17	6.22	.16	6.97	.14	7.20	.14	7.01	.14
9.91	.10	6.61	.15	6.84	.15	6.65	.15	7.72	.13	7.95	.13	8.70	.11	8.93	.11	8.74	.11
10.91	.09	7.61	.13	7.84	.13	7.65	.13	8.72	.11	8.95	.11	9.70	.10	9.93	.10	9.74	.10
11.46	.09	8.16	.12	8.39	.12	8.20	.12	9.27	.11	9.50	.11	10.25	.10	10.48	.10	10.29	.10
7.02	.14	3.72	.27	3.95	.25	3.76	.27	4.83	.21	5.06	.20	5.81	.17	6.04	.17	5.85	.17
8.54	.12	5.24	.19	5.47	.18	5.28	.19	6.35	.16	6.58	.15	7.33	.14	7.56	.13	7.37	.14
11.46	.09	8.16	.12	8.39	.12	8.20	.12	9.27	.11	9.50	.11	10.25	.10	10.48	.10	10.29	.10
13.05	.08	9.75	.10	9.98	.10	9.79	.10	10.86	.09	11.09	.09	11.84	.08	12.07	.08	11.88	.08
15.00	.07	11.70	.09	11.93	.08	11.74	.09	12.81	.08	13.04	.08	13.79	.07	14.02	.07	13.83	.07
7.19	.14	3.89	.26	4.12	.24	3.93	.25	5.00	.20	5.23	.19	5.98	.17	6.21	.16	6.02	.17
		3.65	.27	3.88	.26	3.69	.27	4.76	.21	4.99	.20	5.74	.17	5.97	.17	5.78	.17
		4.02	.25	4.25	.24	4.06	.24	5.13	.19	5.36	.18	6.11	.16	6.34	.16	6.15	.16
8.46	.12	5.16	.19	5.39	.19	5.20	.19	6.27	.16	6.50	.15	7.25	.14	7.48	.13	7.29	.14
7.53	.13	4.23	.24	4.46	.22	4.27	.23	5.34	.19	5.57	.18	6.32	.16	6.55	.15	6.36	.16
9.66	.10	6.36	.16	6.59	.15	6.40	.16	7.47	.13	7.70	.13	8.45	.12	8.68	.12	8.49	.12
7.80	.13	4.50	.22	4.73	.21	4.54	.22	5.61	.18	5.84	.17	6.59	.15	6.82	.15	6.63	.15
8.71	.11	5.41	.18	5.64	.18	5.45	.18	6.52	.15	6.75	.15	7.50	.13	7.73	.13	7.54	.13
	.11	6.08	.16	6.31	.16	6.12	.16	7.19	.14	7.42	.13	8.17	.12	8.40	.12	8.21	.12
9.95	.10	6.64	.15	6.87	.15	6.68	.15	7.75	.13	7.98	.13	8.73	.11	8.96	.11	8.77	.11
10.99	.09	7.69	.13	7.92	.13	7.73	.13	8.80	.11	9.03	.11	9.78	.10	10.01	.10	9.82	.10
7.73	.13	4.43	.23	4.66	.21	4.47	.22	5.54	.18	5.77	.17	6.52	.15	6.75	.15	6.56	.15

space conductance is used in these calculations, i.e. $\frac{.97 + .86}{2} = .91$

TABLE 2

No.	MATERIAL	THICKNESS (Inches)	DENSITY p.c.f. (oven dry)	CONDUCTIVITY OR CONDUCTANCE		RESISTANCE	
				k	C	1/k	1/C
	CONCRETE						
1	Expanded shale clay or slate aggregate		70	2.10		0.48	
2	Expanded shale clay or slate aggregate		75	2.30		0.43	
3	Expanded shale clay or slate aggregate		80	2.50		0.40	
4	Expanded shale clay or slate aggregate		85	2.80		0.36	
5	Expanded shale clay or slate aggregate		90	3.10		0.32	
6	Expanded shale clay or slate aggregate		95	3.30		0.30	
7	Expanded shale clay or slate aggregate		100	3.60		0.28	
8	Expanded shale clay or slate aggregate		105	4.00		0.25	
9	Expanded shale clay or slate aggregate		110	4.30		0.23	
10	Expanded shale clay or slate aggregate		115	4.80		0.21	
11	Sand and gravel aggregate		140	9.00		0.11	
	CLAY MASONRY						
12	Hollow clay tile	4			0.90		1.11
13	Face brick	4	130	9.00		0.11	
14	Common brick	4	120	5.00		0.20	
	CONCRETE MASONRY						
	12–8–16						
15	Expanded shale, clay or slate aggregate	12			0.38		2.63
	Cores filled with:						
16	Expanded shale, clay or slate	12			0.18		5.55
17	Vermiculite	12			0.14		7.14
18	Perlite	12			0.11		9.09
19	Sand and gravel aggregate	12			0.78		1.28
	8–8–16						
20	Expanded shale, clay or slate aggregate	8			0.44		2.27
	Cores filled with:						
21	Expanded shale, clay or slate	8			0.25		4.00
22	Vermiculite	8			0.20		5.00
23	Perlite	8			0.18		5.55
24	Sand and gravel aggregate	8			0.90		1.11
	6–8–16						
25	Expanded shale, clay or slate aggregate	6			0.53		1.89
	Cores filled with:						
26	Expanded shale clay or slate	6			0.39		2.56
27	Vermiculite	6			0.32		3.12
28	Perlite	6			0.24		4.17
29	Sand and gravel aggregate (est.)	6			1.10		0.91
	4–8–16						
30	Expanded shale, clay or slate aggregate	4			0.61		1.64
31	Sand and gravel aggregate	4			1.40		0.71
	FRAME CONSTRUCTION						
32	Wood siding, bevel, ½" x 8", lapped				1.23		0.81
	Sheathing or building board:						
33	Wood, fir or pine	25/32	32		1.02		0.98
34	Plywood	3/8	34		2.12		0.47
35	Wood or cane fiber, impregnated	25/32	20		0.49		2.04
	INSULATION						
	Blanket and Batt						
36	Mineral wool, fibrous form processed from rock, slag, or glass		0.5	0.32		3.12	
	Board and Slab						
37	Cellular glass		9	0.40		2.50	
38	Corkboard		6.5–8.0	0.28		3.57	
39	Glass fiber		9.5–11.0	0.25		4.00	
40	*Expanded polystyrene		1.6	0.24		4.17	
	Loose Fill						
41	Mineral wool (glass, slag, or rock)		2.0–5.0	0.30		3.33	
42	Perlite (expanded)		5.0–8.0	0.38		2.63	
43	Vermiculite (expanded)		7.0–8.2	0.48		2.08	
	PLASTER						
44	Cement plaster, sand aggregate	1/2	116		10.00		0.10
45	Plaster board (Dry-wall)	1/2	50		2.25		0.45
	Gypsum plaster						
46	Sand aggregate	1/2	105		11.10		0.09
47	Perlite aggregate		45	1.5		0.67	
48	Vermiculite aggregate		45	1.7		0.59	
	SURFACE CONDUCTANCE						
49	*fo* — Outside wall, 15 mph wind (winter)				6.00		0.17
50	*fo* — Outside wall, 7½ mph wind (summer)				4.00		0.25
51	*fi* — Inside wall				1.46		0.68
	AIR SPACE CONDUCTANCE						
	Vertical air space (¾" or larger)						
52	Winter				1.03		0.97
53	Summer				1.16		0.86
54	Reflective lining one side				0.33		3.00

*k = 0.24 is a compromise figure which reflects recent unpublished tests.

Table 3 . . . . Coefficients of Transmission (*U*) of Windows, Skylights, and Light Transmitting Partitions

(These values are for heat transfer from air to air. To calculate total heat gain including solar transmission, see Chapter 22.)
Btu per (hr) (sq ft) (F Deg)

PART A—VERTICAL PANELS (EXTERIOR WINDOWS, SLIDING PATIO DOORS, AND PARTITIONS)—FLAT GLASS, GLASS BLOCK, AND PLASTIC SHEET

Description	Exterior[a]		Interior
	Winter	Summer	
Flat Glass			
single glass	1.13	1.06	0.73
insulating glass—double[b]			
$\frac{3}{16}$ in. air space	0.69	0.64	0.51
$\frac{1}{4}$ in. air space	0.65	0.61	0.49
$\frac{1}{2}$ in. air space	0.58	0.56	0.46
$\frac{1}{2}$ in. air space, low emissivity coating[c]			
emissivity = 0.20	0.38	0.36	0.32
emissivity = 0.40	0.45	0.44	0.38
emissivity = 0.60	0.52	0.50	0.42
insulating glass—triple[b]			
$\frac{1}{4}$ in. air spaces	0.47	0.45	0.38
$\frac{1}{2}$ in. air spaces	0.36	0.35	0.30
storm windows			
1 in.–4 in. air space	0.56	0.54	0.44
Glass Block[d]			
6 × 6 × 4 in. thick	0.60	0.57	0.46
8 × 8 × 4 in. thick	0.56	0.54	0.44
—with cavity divider	0.48	0.46	0.38
12 × 12 × 4 in. thick	0.52	0.50	0.41
—with cavity divider	0.44	0.42	0.36
12 × 12 × 2 in. thick	0.60	0.57	0.46
Single Plastic Sheet	1.09	1.00	0.70

[a] See Part C for adjustment for various window and sliding patio door types.
[b] Double and triple refer to the number of lights of glass.
[c] Coating on either glass surface facing air space; all other glass surfaces uncoated.
[d] Dimensions are nominal.
[e] For heat flow up.
[f] For heat flow down.
[g] Based on area of opening, not total surface area.
[h] Refers to windows with negligible opaque area.
[i] Value becomes 1.00 when storm sash is spearated from prime window by a thermal break.

PART B—HORIZONTAL PANELS (SKYLIGHTS)—FLAT GLASS, GLASS BLOCK, AND PLASTIC BUBBLES

Description	Exterior[a]		Interior[e]
	Winter[e]	Summer[f]	
Flat Glass			
single glass	1.22	0.83	0.96
insulating glass—double[b]—			
$\frac{3}{16}$ in. air space	0.75	0.49	0.62
$\frac{1}{4}$ in. air space	0.70	0.46	0.59
$\frac{1}{2}$ in. air space	0.66	0.44	0.56
$\frac{1}{2}$ in. air space, low emissivity coating[c]			
emissivity = 0.20	0.46	0.31	0.39
emissivity = 0.40	0.53	0.36	0.45
emissivity = 0.60	0.60	0.40	0.50
Glass Block[d]			
11 × 11 × 3 in. thick with cavity divider	0.53	0.35	0.44
12 × 12 × 4 in. thick with cavity divider	0.51	0.34	0.42
Plastic Bubbles[g]			
single walled	1.15	0.80	—
double walled	0.70	0.46	—

PART C—ADJUSTMENT FACTORS FOR VARIOUS WINDOW AND SLIDING PATIO DOOR TYPES (MULTIPLY U VALUES IN PARTS A AND B BY THESE FACTORS)

Description	Single Glass	Double or Triple Glass	Storm Windows
Windows			
All Glass[h]	1.00	1.00	1.00
Wood Sash—80% Glass	0.90	0.95	0.90
Wood Sash—60% Glass	0.80	0.85	0.80
Metal Sash—80% Glass	1.00	1.20	1.20[i]
Sliding Patio Doors			
Wood Frame	0.95	1.00	—
Metal Frame	1.00	1.10	—

Table 4 . . . . Coefficients of Transmission (*U*) for Slab Doors

Btu per (hr) (sq ft) (F Deg)

Thickness[a]	*Winter*			*Summer, No Storm Door*
	Solid Wood, No Storm Door	Storm Door[b]		
		Wood	Metal	
1 in.	0.64	0.30	0.39	0.61
$1\frac{1}{4}$ in.	0.55	0.28	0.34	0.53
$1\frac{1}{2}$ in.	0.49	0.27	0.33	0.47
2 in.	0.43	0.24	0.29	0.42
	Steel Door[18]			
$1\frac{3}{4}$ in.				
A[c]	0.59	—	—	0.58
B[d]	0.40	—	—	0.39
C[e]	0.47	—	—	0.46

[a] Nominal thickness.
[b] Values for wood storm doors are for approximately 50 percent glass; for metal storm doors values apply for any percent of glass.
[c] A = Mineral fiber core (2 lb/cu ft).
[d] B = Solid urethane foam core.
[e] C = solid polystyrene core.

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No.	
	CONC
1	Ex
2	Ex
3	Ex
4	Ex
5	Ex
6	Ex
7	Ex
8	Ex
9	Ex
10	Ex
11	Sar
	CLAY
12	Ho
13	Fa
14	Co
	CONC
	12-
15	Ex
	C
16	
17	
18	
19	Sar
	8—
20	Ex
	(
21	
22	
23	
24	Sar
	6—
25	Ex
	C
26	
27	
28	
29	Sar
	4—
30	Ex
31	Sar
	FRAM
32	Wo
	Sh
33	W
34	Pl
35	W
	INSU
	Bla
36	M
	r
	Bo
37	C
38	C
39	C
40	*E
	Lo
41	M
42	F
43	V
	PLAS
44	Ce
45	F
	Gy
46	S
47	F
48	V
	SURF
49	*fo*
50	*fo*
51	*fi*
	AIR S
	Ve
52	
53	
54	
	*k

11.1B

“Thermal Inertia of Concrete and Concrete Masonry”

THERMAL INERTIA OF CONCRETE AND CONCRETE MASONRY

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Biography
(75 Words Maximum for each author)

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Keywords: Calibrated hot box; concrete; concrete masonry; density; diffusivity; specific heat; thermal conductivity; thermal damping; thermal inertia; thermal lag.

ABSTRACT

The thermal performance of wall systems is determined by two parameters. The steady-state thermal resistance is well established in building codes. Thermal inertia, the reluctance of the wall to change temperature when exposed to a dynamic temperature regime is considerably more complicated, less well understood and has been approximated in codes and standards by crude assumptions.

This paper reports the influence of density, conductivity and specific heat on the dynamic testing of wall and unit specimens and the impact of these criteria on thermal lag, reduction in amplitude and energy transfer. Also included is a theoretical determination of the optimum concrete density to maximize the thermal inertia of a single wythe, homogenous wall.

INTRODUCTION

The thermal performance of wall systems is described by two parameters:

- Thermal resistance: the walls resistance to a steady-state heat flow. This is well established and commonly referred to in building codes and marketing literature as the “R” value of the wall or as “R” values of individual wall components. The reciprocal of thermal resistance is thermal conductance, and for a homogenous material, thermal conductivity.
- Thermal inertia: Relates to the reluctance of the wall to change temperature when exposed to a variable temperature regime. Thermal inertia depends on thermal conductivity, specific heat, thermal diffusivity, and density.

Until recently, standard practice considered only the thermal resistance parameter because of the simplicity and relative accuracy of the calculation of a steady-state heat flow for “light frame” construction. Steady-state heat flow can be used to predict the thermal performance of wood and steel frame construction fairly accurately, but significantly under estimates the thermal performance of masonry and concrete walls. While the performance of substantial wall systems (masonry, concrete, etc.) have been intuitively understood and widely recognized for many centuries, the procedure for defining the beneficial behavior of thermal inertia remains complex to calculate and codify.

This paper presents data on the thermal characteristics of concrete mixtures used in the production of concrete and concrete masonry units (CMU). This data will allow an improved understanding of the influence on density of the block concrete on the thermal inertia of a masonry wall. The effects of a wall's thermal inertia on overall energy requirements of a building are complex and difficult to reduce to one factor. This is because of the significant influence of variables which include: seasonal and building orientation, diurnal weather conditions (particularly the solar affects and the daily fluctuation of outdoor temperature relative to a constant indoor setting), the location of insulation and many other factors beyond the scope of this paper.

RESEARCH SIGNIFICANCE

The International Energy Conservation Code (IECC) provides simple approximations that reflect the influence of the thermal/physical properties of concrete that are used in the determination of energy loss through building walls. This paper provides an analytical method for determining optimum properties of cast-in-place concrete as well as the concrete used in the manufacture of masonry units. Also reported on are modifications to specimen preparation that allow the determination of the thermal diffusivity for zero slump (high void) of fresh concrete obtained at the manufacturing facility. Thermal values obtained from these testing procedures support the changes made in recent modifications to the IECC (2004) in the approximations used to qualify walls for benefits obtained from thermal inertia.

THERMAL CONDUCTIVITY

Thermal conductivity is the rate at which heat flows through a material for a unit temperature difference and is used to determine a materials steady-state heat flow. Thermal conductivities of all types of concrete and masonry materials are documented in the "*Guide to Thermal Properties of Concrete and Masonry Systems"* (ACI 122R-02) [1], which provides data showing that lower thermal conductivity (higher thermal resistance) is generally achieved with lower density materials. Thermal conductivity of concretes of differing densities as measured by various methodologies was also reported in the paper "*Calibrated Hot Box Tests of Thermal Performance of Concrete Walls"* [2].

In a series of comprehensive papers, VanGeem et. al. reported the thermal conductivities measured on small specimens (guarded hot plate ASTM C 177 and hot wire) as well as results developed in a Calibrated Hot Box (ASTM C 976) under steady-state conditions on full sized walls (2.62 x 2.62 m, 8′ - 7" x 8′ - 7") [3, 4, 5]. Theses results are shown in **Table 1.**

SPECIFIC HEAT

Specific heat is the ratio of the amount of heat required to raise the mass of a material one degree to the amount of heat required to raise the same weight of water one degree. Harmathy and Allen report that for all practical purposes the specific heat of lightweight aggregate concrete is similar to that of normalweight concrete [6]. The ACI 122 guide [1] recommends specific heat values of 0.21 and 0.22 over a concrete density range of 80 to 140 lb/ft³.

THERMAL DIFFUSIVITY

Thermal diffusivity is a measure of how quickly a material changes temperature. It is calculated by:

$\alpha = k/Dc$, *where:*

α = *thermal diffusivity* (ft^2/h)

D = *density* (lb/ft^3)

k = *thermal conductivity* (Btu/h • ft^2 • ºF/ft)

c = *specific heat* (Btu • ºF)

High thermal diffusivity indicates that temperature change through a material will be fast. Wall materials such as concrete and masonry have low thermal diffusivity and respond slowly to an imposed temperature.

Test for thermal diffusivity:

The United States Army Corps of Engineers (USACE) provide a "*Method of Test for Thermal Diffusivity of Concrete"* CRD – C 36 [7]. The USACE have a traditional concern for the exothermic heat flow caused by the hydration of cement, which can impose significant thermal strains within mass concrete used in the construction of dams and other large navigational structures. Typically, thermal diffusivity is determined by measuring the temperature differentials between the interior and surface of a heated 6 x 12-in. concrete cylinder as it cools in a constant temperature bath of running water. **Fig. 1** taken directly from CRD – C 36 shows the measurements on a normalweight concrete cylinder.

Table 2 lists the results of diffusivity tests conducted in commercial testing laboratories in accordance with USACE CRD-C 36 on cast-in-place concretes and zero slump block concrete of different constituents and densities. Mixtures of block concrete were obtained from block plant mixers during production of commercial CMU's. The mixtures were rodded in three layers in a standard 6 x 12-in. cylinder mold with 25 blows/layer using a tamping rod in accordance with ASTM C 192 “*Standard Practice for Making and Curing Test Specimens in the Laboratory*”. Care was taken to locate the thermo-couple in the center of the cylinder.

Using the formula proposed by Valore [8] as an approximation for the thermal conductivity of moist concrete:

$$k = 0.6e^{0.02D}$$

where k and D are as defined before, then the calculated conductivity of block concrete specimen S5 would yield $k_{S5} = 0.6e^{0.02(90)} = 3.6$, *resulting in a calculated diffusivity of:*

$$\alpha_{s5} = \frac{3.6/12}{0.21 \text{ x } 90} = 0.016 \text{ (test results 0.016)}$$

It’s important to note that Valore’s formula is applicable only to lightweight concretes with densities less than 100 lb/ft³. Thermal conductivity of concretes containing normalweight aggregates with densities above 100 lb/ft³ can not be accurately estimated as a function of density because of the wide range of mineralogy that directly effect the thermal conductivity of natural aggregates giving them a large distribution range.

THERMAL LAG

Thermal lag is a measure of the response of the inside surface temperature to fluctuations in outdoor temperature. Lag is sensitive to both thermal resistance and thermal inertia properties of the wall. Using the calibrated hot box tests, references 3, 4 and 5 provide comprehensive data on the results of steady-state and dynamic tests on full scale single layer cast concrete walls of differing densities. These tests determined:

- Thermal lag: a measure of the response of inside and outside surface temperatures and heat flow to fluctuations in outdoor temperature.
- Reduction in amplitude: The damping effect on peak heat flow.

- Reduction in measured energy: The energy necessary to maintain a constant indoor temperature while outdoor temperature is varied compared to steady-state predictions.

It can be seen from **Table 3** that as the wall's concrete density was reduced from 143 to 98 to 56 lb/ft³:

- Average thermal lag increased from 4 to 5.5 to 8.5 hours;
- Amplitude reduction increased from 45 to 54 to 63%;
- The ratio of total energy decreased from 66 to 60 to 53%.

It should be noted that these results are only comparative and were developed on the basis of the wide temperature swing used in the NBS-10 test cycle (a simulated sol-air cycle used by the National Bureau of Standards, now the National Institute of Standards and Technology) in which mean outdoor temperature of the cycle was approximately equal to the mean indoor temperature. For further details of the test instrumentation, analysis and commentary on application to total energy demands, refer to reference 2.

Fig. 2 taken from Ref 11 depicts the thermal lag and reduction in amplitude (damping) on a normalweight concrete wall in a moderate climate.

Thermal lag increases with an increase in

$$\sqrt{\frac{L^2/\alpha}{P}}$$ where:

L = wall thickness (ft)

P = length of dynamic cycle (hr)

α = thermal diffusivity (ft²/hr)

Comparing walls of equal thickness L, subjected to the same dynamic cycle P, then thermal lag is proportional to

$$\sqrt{\frac{1}{\alpha}}$$

and a direct comparison of the thermal lag of the three walls would be:

Wall C2 compared to wall C1

$$\sqrt{\frac{1}{\alpha_{LW}}} \div \sqrt{\frac{1}{\alpha_{NW}}} = \sqrt{\frac{\alpha_{NW}}{\alpha_{LW}}}$$

For the walls tested this ratio would be

$$\sqrt{\frac{.037}{.0155}} = 1.5 \text{ or the thermal lag of C2 would be 1.5 times that of wall C1 and}$$

$$\sqrt{\frac{.037}{.00849}} = 2.1 \text{ or the thermal lag of C3 would be 2.1 times that of wall C1.}$$

In the dynamic tests conducted at CTLGroup the measured thermal lags for walls C2 and C3 were 1.4 and 2.1 times the thermal lag for wall C1, and therefore consistent with theoretical calculations. In a similar fashion an estimate of the theoretical increase in thermal lag obtained by reducing the density of the block concrete masonry walls from 114 lb/ft³ (Test No. S1) to 94 lb/ft³ (Test No. S2) would be approximately

$$\sqrt{\frac{0.022}{0.016}} = 1.17 \text{ (17\% increase)}$$

THERMAL MASS

The moderating effects on interior temperatures of internal walls are increased with higher concrete densities for a given wall thickness, which result in high heat storage capacity. This is commonly referred to as the effect of thermal mass. However, with regard to exterior single layer un-insulated concrete product walls, the beneficial effects of thermal inertia, as characterized by the reluctance to change temperature (as a result of lower diffusivity), are increased when density is reduced. These lower density concretes have enough density to provide thermal mass effects while having a lower thermal conductivity than normalweight concrete. These combine to provide a lower thermal diffusivity.

OPTIMUM CONCRETE DENSITY FOR MAXIMUM THERMAL INERTIA

Change in diffusivity with respect to concrete density is not linear, because thermal conductivity increases exponentially when compared to increases in density. The velocity of temperature penetration is further increased when the crystalinity of the minerals of ordinary sand and gravel aggregates increases. Therefore, the results of thermal inertia of concrete walls (thermal lag, amplitude reduction, lowering total energy) are significantly lower when density is reduced (structural lightweight, insulating lightweight and aerated lightweight concretes). Indeed, if the Valore formula for thermal conductivity is inserted into the diffusivity equation, then the relationship between thermal lag and concrete density would be:

$$\sqrt{\frac{1}{\alpha}} = \sqrt{\frac{Dc}{k}} = \sqrt{\frac{Dc}{0.6e^{0.02D}}}$$

differentiating thermal lag with respect to density $d\sqrt{{}^{1/\alpha}\!/_{dD}} = \left({}^{1}\!/_{2}D^{-1/2} - .01D^{1/2}\right)$

Setting, the results to zero, results in a density of 50 pcf that will provide maximum thermal lag. [9]. **See appendix.**

INTERNATIONAL ENERGY CONSERVATION CODE (IECC)

The IECC (2004 Supplement) provides decreased R-value requirements for above-grade mass walls compared to frame walls in commercial buildings. Article 802.2.1 in Chapter 8 *"Building Design for Commercial Buildings*" states that "mass walls" shall include walls weighing at least (1) 35 pounds per square foot (170 kg/m²) of wall surface area or (2) 25 pounds per square foot (120 kg/m²) of wall surface area if the material weight is not more than 120 pounds per cubic foot (1900 kg/m³)" (10, 11). For a typical 8" thick single width un-insulated concrete masonry wall a minimum block concrete density of approximately 80 lb/ft³ qualifies as a mass wall. As shown earlier decreasing concrete density results in the increase of **BOTH** steady-state thermal resistance and thermal inertia as expressed in thermal lag.

CONCLUSIONS

1. For the test results reported the steady-state resistance ("R" value) to heat flow through single layer un-insulated walls made from cast concrete and zero slump block concrete increases with decreasing density.
2. For the test results reported the resistance to variable heat flow through single layer un-insulated concrete walls increases with decreasing density.
3. Thermal inertia as represented by thermal lag, amplitude reduction and reduced energy requirements, increases with decreasing thermal diffusivity.
4. The increase in thermal inertia with respect to concrete density is not linear, because of the exponential increase in thermal resistance when compared to the decrease in density.
5. Net energy consumption as shown in Table 3 is reduced when the steady-state and dynamic resistance are improved by lower concrete densities, thereby helping the sustainability of critical energy sources.
6. USACE test procedures (CRD-C 36) for determination of diffusivity may be used on zero slump block concrete samples made with materials taken from the mixers of commercial block plants.

7. The requirement of IECC 2004 Supplement Article 802.2.1 requiring a lower wall weight (25 vs. 35 lb/ft³) for mass walls constructed with concrete densities less than 120 lb/ft³ is a simple and effective approximation of the influence of the reduction in diffusivity, and hence increased time lag of lower density concrete and concrete masonry.

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APPENDIX

OPTIMUM CONCRETE DENSITY FOR MAXIMUM THERMAL INERTIA

The thermal inertia of a single width homogenous wall is proprotional to :

$$\lambda = \sqrt{L^2 / P\alpha} = \sqrt{\frac{L^2}{P} \cdot \frac{Dc}{k}}$$

Where:

L = Wall thickness
P = Sinusoidal temperature cycle
α = Thermal diffusivity = *k/DC* where:
k = Thermal conductivity
D = Concrete Density
c = Specific heat

Comparing the behavior of a single width homogenous wall with the same specific heat (***c***) and exposed to the same temperature cycle (P), then:

$\lambda = \sqrt{\frac{D}{k}}$ *For concretes with a density of 40 - 100 pcf ACI 122 "Guide to the Thermal Properties of Concrete and Masonry Assemblages" recommends* $k = 0.5e^{0.02D}$

$\lambda = \sqrt{\frac{D}{0.5e^{0.02D}}}$ *If thermal lag(* α *) is differentiated with respect to density (D) then :*

$$\lambda = \sqrt{\cdot \frac{D}{e0.02\,D}} = D^{0.5} e^{-.01D}$$

$$\frac{\partial\lambda}{\partial D} = 1/_2 D^{0.5} e^{-.02D} - .01D^{0.5} e^{-0.02D}$$

$$\frac{\partial\lambda}{\partial D} = e^{-0.02D}\left(1/2D^{0.5} - 0.01D^{0.5}\right)$$

Setting $\frac{\partial\lambda}{\partial D} = 0$ Results in two possibilities $D \longrightarrow \infty, e^{-0.02D} = 0$

$$or \left(0.5D^{-0.5} - 0.01D^{0.5}\right) = 0 \text{ or } 0.5 - 0.01D = 0, D = \frac{0.5}{0.01} = 50$$

The solution is shown graphically in Figure A1.

TABLES AND FIGURES

List of Tables:

Table 1 - Thermal Conductivity for Concretes of Differing Densities as Measured From Small Sized Specimens and Full Sized Walls (Excerpted from Ref [2]).

Table 2 - - Results of Diffusivity Tests measured on Structural Concretes and zero slump block concrete of Different Densities

Table 3 - Excerpt from Table 5 "Summary of Dynamic Test Results for NBS-10 Test Cycle" (Ref 2)

List of Figures:

Fig.1 - Calculation of thermal diffusivity of a concrete cylinder

Fig. A1 - Optimum concrete density for maximum thermal lag (Graphical solution from equations in Appendix A)

Fig. 2 - Time Lag and Temperature Damping

Table 1 – Thermal Conductivity for Concretes of Differing Densities as Measured From Small Sized Specimens and Full Sized Walls (Excerpted from Ref [2]).

Concrete Wall	C1 Normalweight	C2 Structural Lightweight*	C3 Insulating Non-Structural
Density Fresh	147	103	56
Density Air Dry	144	99	48
Density Oven Dry	140	94	46
Thermal Conductivity measured by (Btu•in /h • ft² • °F)			
Hot Plate (ASTM C 177)	16.1	4.49	1.44
Hot Wire Conductivity at moisture content shown	21.3@3.1%	6.9@9.5%	3.1@28.9%
Hot Wire Conductivity Oven Dry	14.0	5.1	1.3
Calibrated Hot Box @ Temp 52 ± 3°F (steady-state) ASTM C 976	11.64	4.69	1.38

- **Structural lightweight concrete use both coarse and fine rotary kiln produced expanded shale.**

Table 2 – Results of Diffusivity Tests measured on Structural Concretes and zero slump block concrete of Different Densities

Test No.	Tested by	Date	Concrete Type	Density (lb/ft^3)	Diffusivity (ft^2/hr)
S1	Solite Corp	1974	Structural LTWT 4.5 ksi, Air Dry	114	.022
S2	Solite Corp	1974	Structural LTWT 4.1 ksi, Air Dry	94	.016
S3*	Solite Corp	1975	(Test No. S1 oven dried and coated)	107	.023
S4*	Solite Corp	1975	(Test No.S2 oven dried and coated)	90	.017
S5	Solite Corp	1977	ASTM C 90 Block Concrete	90	.016
S6	Solite Corp	1978	ASTM C 90 Block Concrete	129	.036
C1	CTL (ref 3)	1983	Structural NW Concrete	143	.037
C2	CTL (ref 4)	1983	Structural LTWT Concrete	99	.0155
C3	CTL (ref 5)	1983	Insulating Concrete	56	.00849

*The test numbers S3 and S4 were conducted on specimen numbers S1 and S2 after oven drying and then coating the specimens with a waterproof epoxy.

The tests C1, C2 and C3 were conducted at CTLGroup, Skokie, IL. [3]

Table 3 – Excerpt from Table 5 "Summary of Dynamic Test Results for NBS-10 Test Cycle" (Ref 2)

Wall No./ Density	Thermal Lag Hours			Reduction in Amplitude Avg %	Ratio of Total Energy %	Net Energy
	Temp	Max Heat Flow	Average			
C1/143	4.5/3	4.5/3	4	45	66	4342
C2/98	6/5	6/5	5.5	54	60	2510
C3/56	8.5/7	9/9	8.5	63	53	909

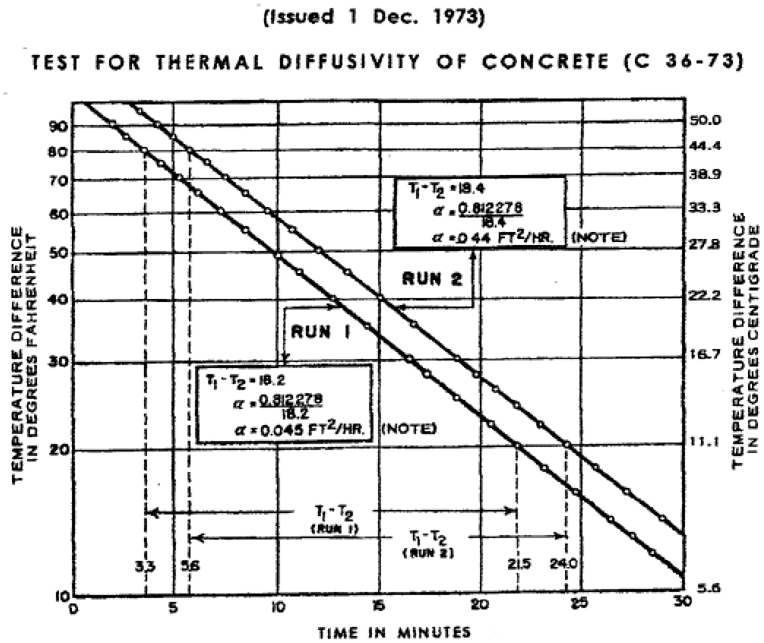

Figure 1 – ***Calculation of thermal diffusivity of a concrete cylinder***

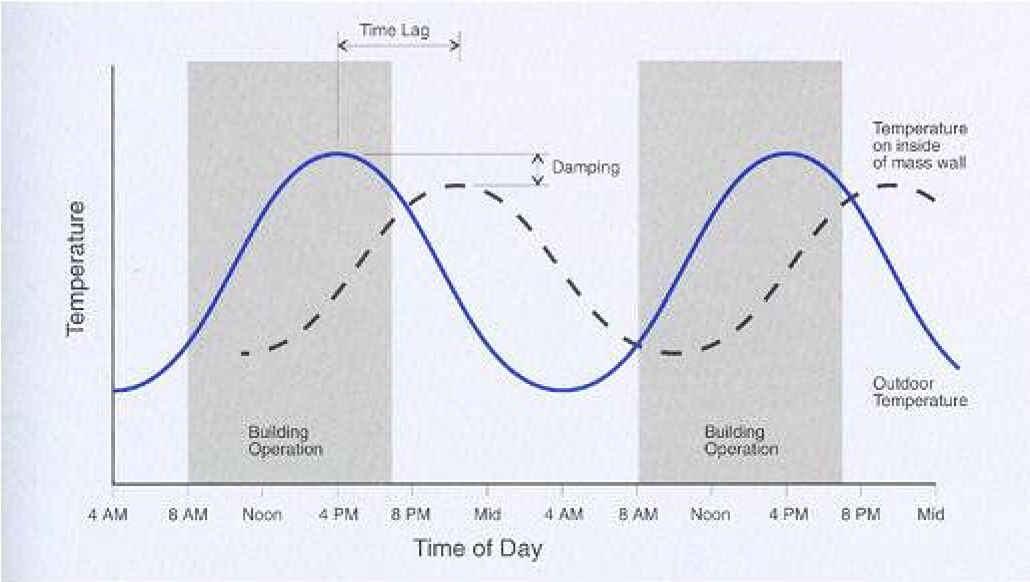

Figure 2 ***Time Lag and Temperature Damping***

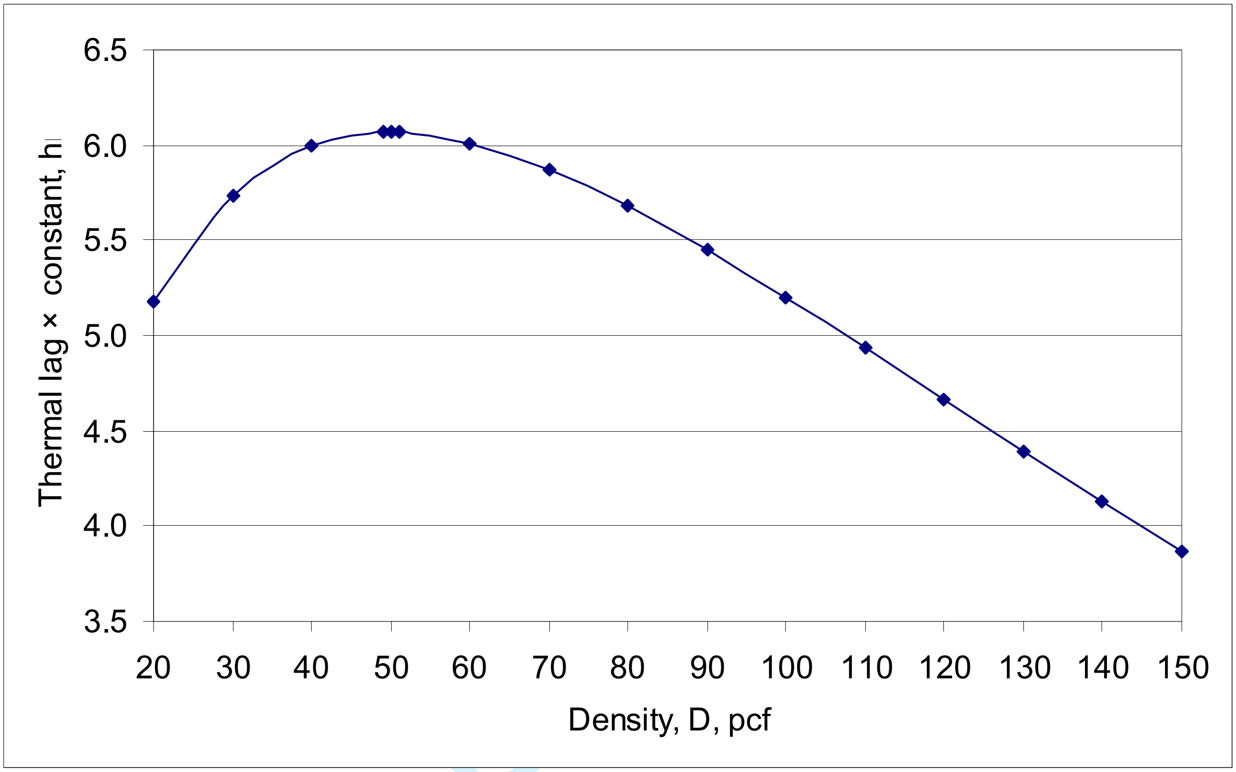

Figure A1 Optimum concrete density for maximum thermal lag (Graphical solution from equations in Appendix A)

11.1C

ESCSI Information Sheet 3201
"Energy Efficient Buildings With SmartWall Systems®"

Information Sheet 3201

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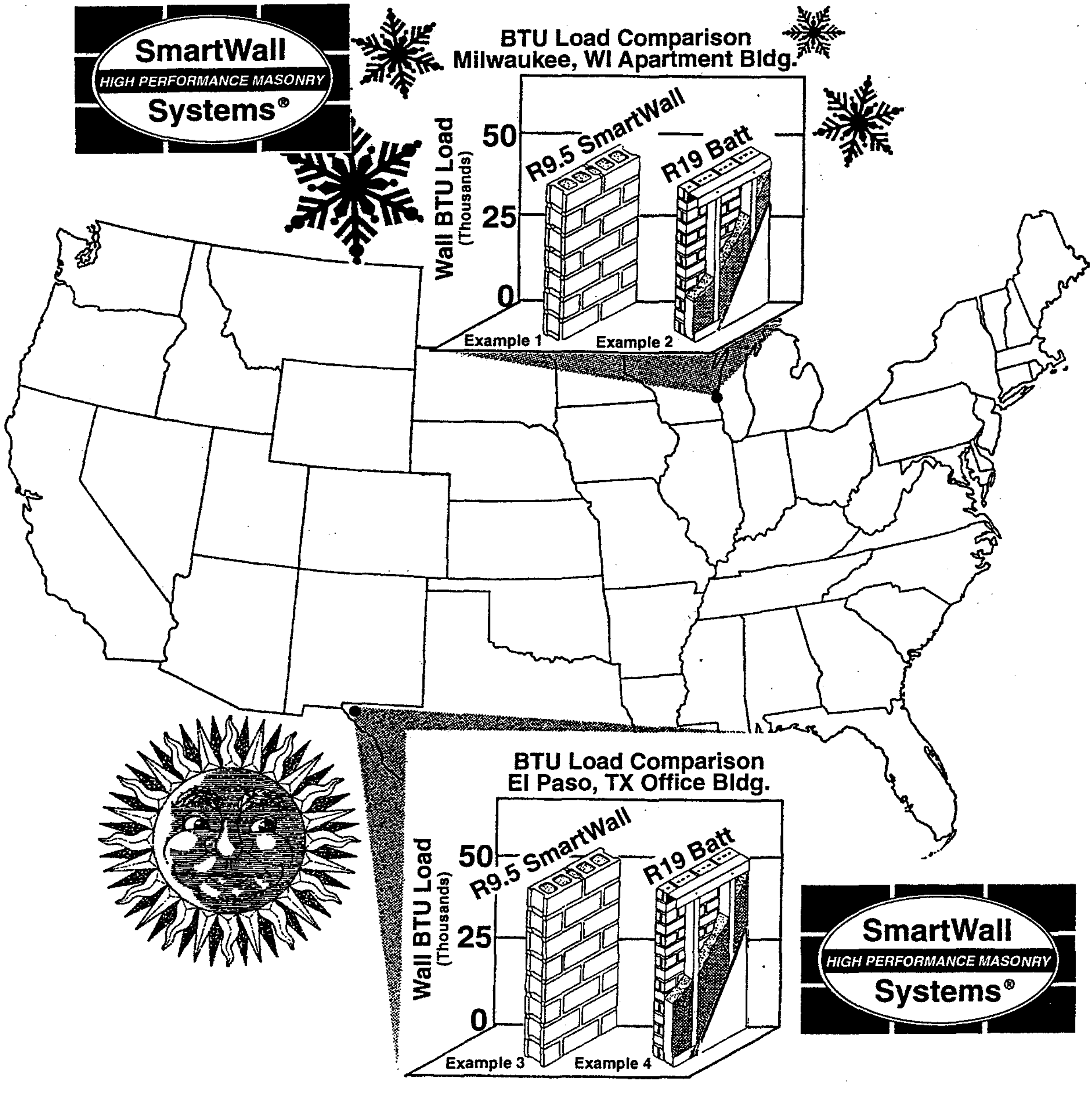


Engineering guide for using ASHRAE/IES 90.1 ENVelope StandarD (ENVSTD) computer program.

SmartWall Systems® is a registered trade mark of the Expanded Shale, Clay & Slate Institute

When it comes to energy performance SmartWall high performance concrete masonry systems outperform metal stud walls with batt insulation and provide lower heating and cooling cost. SmartWall Systems® is helping to decrease the overall global demand for energy

SmartWall Systems®

SmartWall is a high performance lightweight concrete masonry wall system that outperforms other masonry and non-masonry wall systems, especially in terms of energy efficiency, maintenance, appearance, fire resistance, durability and strength to weight ratio. SmartWall is a mason friendly, cost effective wall system that enhances speedy construction and has a very high degree of customer satisfaction.

The SmartWall System is Energy Efficient

SmartWall provides superior energy conservation by optimizing the combination of R-values, thermal mass and low thermal bridging. Wall heating and cooling costs may be reduced by more than 50%! The concrete in SmartWall has more than 2.5 times the thermal resistance of the concrete in a typical heavy block. This significantly reduces thermal bridging, maximizes the effectiveness of core insulation, and results in the high R-value of SmartWall. As shown in Table 1, an un-insulated SmartWall performs as well as core-insulated heavy units! Also, SmartWall with perlite fill offers maximum thermal performance.

In addition to thermal resistance, SmartWall also benefits from thermal mass— the *flywheel* effect that minimizes peaks and valleys in heat load as a wall responds to daily changes in ambient temperature. Walls with optimized thermal mass reduce overall energy use, compared to non-masonry walls. SmartWall has an ideal balance of thermal mass and thermal resistance for optimum performance.

Calculating the overall effect of thermal mass and thermal resistance in a wall's dynamic response to the environment is a complicated task. To perform this task, the ASHRAE 90.1 energy code uses a computer program called ENVSTD, and the results can be dramatic. For example, using ENVSTD to compare the energy performance of a 12" SmartWall with perlite core insulation to an R-19 batt insulated metal stud wall shows that SmartWall outperforms the metal stud system! ENVSTD factors many variables besides opaque wall properties, including glass area, shading, overhangs, and building orientation. Using ENVSTD and SmartWall, energy efficient buildings can be designed that comply with energy codes without the need for added-on insulation. In many cases a single-wythe SmartWall does the job.

TABLE 1 R-VALUES FOR CONCRETE MASONRY WALLS (1) (Exposed Both Sides)

Nominal Thickness	Concrete Unit Weight lbs/ft^3	Cores Empty	With Core Inserts	Cores Filled With Perlite
8"	SmartWall (2)	2.5	4.2	6.6
	Heavy CMU's (3)	1.9	2.6	3.2
12"	SmartWall (2)	2.7	4.4	9.5
	Heavy CMU's (2)	2.0	2.7	4.4

(1) R-Values are mid-range per NCMA TEK 6.1A & 6.2A.
R in (h•ft^2 •°F)BTU and includes 0.85 air film coefficient.
(2) SmartWall at 90 lbs/ft^3
(3) Heavy CMU's at 135 lbs/ft^3

ASHRAE Energy Conservation Standard

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) building energy conservation standard clearly demonstrates that SmartWall Systems incorporating high performance lightweight concrete masonry units are indeed energy efficient.

The Standard, ASHRAE/IES 90.1-1989 provides state of the art guidance regarding the design of energy efficient buildings. Standard 90.1 recognizes the performance characteristics of the materials used to construct the building rather than concentrating on the R-values alone as earlier versions did. These characteristics include the effects of wall thermal mass, thermal bridging and insulation position.

Thermal Mass - Heat Capacity

The effects of wall thermal mass are well known. High thermal inertia walls, such as stone, concrete masonry, SmartWall masonry, poured concrete or clay brick, have the ability (due to their high heat capacity) to delay and reduce the impact of outdoor temperature changes on conditioned indoor environments. This means less heat gain or loss, depending on the season, that must be supplied by energy consuming HVAC equipment. ASHRAE 90.1 quantifies thermal mass effects based on a wall's heat capacity. Heat capacity is defined as wall weight per square foot times specific heat. Table 2 lists heat capacity for concrete masonry units, and Table 3 lists heat capacity for other common building materials.

Thermal Bridging

In buildings, when insulating material is interrupted by a highly conductive material, thermal bridging takes place. Examples of thermal bridges include steel studs that interrupt the continuity of batt insulation and metal fasteners that go through heavily insulated exterior walls. Simply put, thermal bridges occur where differences in material thermal conductivities result in significant lateral heat flow; e.g., heat flowing along the surface of a wall and then flowing through the wall via a steel stud. ASHRAE 90.1 considers many thermal bridges. Table 4 (table 8C-2 in ASHRAE 90.1) lists the effect of thermal bridging in metal stud walls.

Example: The effects of thermal bridging in a typical metal stud wall with 2x4 studs 16" on center.

Uncorrected Insulation R-value = R 11
Correction Factor = .5
Effective Insulation R-value = R 5.5

Table 2 lists concrete masonry R-values calculated according to ASHRAE's series parallel method recommended by the National Concrete Masonry Association. This method accounts for thermal bridging within the CMU. **Because of its low thermal bridging characteristic, SmartWall Units with open cores (no insulation) have the same R-values as heavy CMU with core insulation as shown in Table 1.**

Thermal Performance

ASHRAE 90.1 provides two methods for determining how the thermal properties of walls impact building envelope energy-efficiency criteria. The first method is prescriptive and provides 38 Alternate Component Package (ACP) tables. The ACP tables list maximum wall U_o values, $U_o = 1/R$. The second method is the systems performance method and it employs a computer based program, Envelope Standard (ENVSTD). This approach requires input of many building parameters including wall heat capacity and wall U_o. ENVSTD uses these building-wide inputs to determine if the design meets the Standard's energy efficiency criteria. Because of this building-wide approach, SmartWall CMU wall systems, with an optimized combination of heat capacity and R-values, are found to be as energy efficient as "highly" insulated steel stud wall systems. For ease of comparison, four energy compliance examples are included on the following pages. The ENVSTD computer program was used to verify the excellent energy performance of SmartWall high performance concrete masonry walls. Each example uses the appropriate changes in the Wall U_o, Heat Capacity values and INsulation POSition with all other building parameters unchanged. Examples 1 & 2 compare an apartment building in Milwaukee, Wisconsin. Examples 3 & 4 compare an office building in El Paso, Texas. **CONCLUSION.....For the examples considered, ENVSTD proves that a 12" SmartWall System with perlite insulation uses less energy for heating and cooling than a metal stud frame wall with R-19 batt insulation.**

The Bottom Line

There are many ways to incorporate energy conservation into a building. One of the most cost effective and environmentally friendly ways is to consider the overall comfort of the users, as well as the total energy consumption over the life of the structure. This not only helps the person paying the heating and cooling bills, but also decreases the overall global demand for energy— benefitting both the user and the environment.

Thermal mass benefits are not new. Throughout the ages, high mass building materials were the product of choice for building strong, secure and comfortable structures and dwellings. It's only in the past few decades we have become misdirected with marketing emphasis only on the "R" value. Many have forgotten that the truly comfortable buildings of the past had the energy conservation built into the structural components. Now the ASHRAE 90.1 Standard provides the needed link between energy theory and the real world.

By designing buildings with the high performing SmartWall Systems, owners will get energy conservation built into the structure without complicated and expensive add-ons to insulate the building envelope. SmartWall masonry units are made with expanded shale, clay or slate (ESCS) aggregate. They are mason friendly and up to 40% lighter than obsolete heavy masonry units. Additionally, SmartWall offers superior fire resistance, sound absorption, reduced seismic loading and low shrinkage.

As a building owner or designer you can choose a system with a practical "R" number that when combined with thermal inertia, obtains proven energy performance with quiet comfort. The SmartWall system maximizes all the benefits of traditional masonry: design flexibility, economy, thermal mass and durability. In addition, the lighter weight SmartWall system benefits the mason because of fewer injuries, safer scaffolds, longer working career and the opportunity for female workers. Since increased productivity is a natural consequence of lighter units, overall construction time is often reduced. SmartWall meets the needs of today's market, and gives specifiers all the best reasons to choose concrete masonry. SmartWall is the Answer!

For additional information please contact ESCSI via Phone: (801) 272-7070, Fax: (801) 272-3377, e-mail: info@escsi.org or visit ESCSI's web site at www.escsi.org.

SmartWall Systems® Guide Specification

Guide Specification (Short Form): Sec 04810 - Unit Masonry Assemblies:

SmartWall Systems walls shall be constructed using high performance concrete masonry units manufactured by a SmartWall Systems producer certified by the Expanded Shale Clay and Slate Institute, Salt Lake City, Utah. The concrete masonry units shall meet the requirements of ASTM C 90 *Standard Specification for Load Bearing Concrete Masonry Units* and the following additional requirements:

- The concrete masonry unit shall have a minimum net compressive strength of 2500 psi (17 MPa) and a density not exceeding 93 lb/cu ft (1500 kg/m^3), determined in accordance with ASTM C 140 *Sampling and Testing Concrete Masonry Units.*
- The lightweight aggregate used in the manufacture of the concrete masonry units shall be structural grade expanded shale, clay or slate manufactured by the rotary kiln process, and shall meet the requirements of ASTM C 331 *Standard Specification for Lightweight Aggregate for Concrete Masonry Units*".

TABLE 2 THERMAL PROPERTIES OF CONCRETE MASONRY WALLS

Concrete Masonry Unit and Insulation Type		**SmartWall Systems®** 90 lbs/ft^3			"Heavy" Masonry 135 lbs/ft^3		
		U	R	HC	U	R	HC
4"	Uninsulated	0.482	2.1	4.2	0.627	1.6	5.7
6"	Uninsulated	0.438	2.3	5.6	0.561	1.8	7.8
8"	Uninsulated	0.407	2.5	6.7	0.535	1.9	9.6
	Insert , core (fig A)	0.236	4.2	6.8	0.391	2.6	9.7
	ESCS @ 50 lbs/ft^3 Loose Fill	0.318	3.1	10.2	0.362	2.8	13.1
	2" Insert, continuous (fig B)	0.187	5.4	6.6	0.326	3.1	9.4
	Vermiculite	0.161	6.2	7.3	0.314	3.2	10.2
	Perlite	0.152	6.6	7.2	0.308	3.2	10.1
	Foamed Cores	0.143	7.0	6.8	0.302	3.3	9.7
	4" Insert, continuous (fig B)	0.124	8.1	7.2	0.243	4.1	10.0
10"	Uninsulated	0.385	2.6	7.8	0.512	2.0	11.4
	Insert , core (fig A)	0.235	4.2	7.9	0.384	2.6	11.4
	ESCS @ 50 lbs/ft^3 Loose Fill	0.183	5.5	12.4	0.313	3.2	16.0
	2" Insert, continuous (fig B)	0.189	5.3	7.6	0.326	3.1	11.0
	Vermiculite	0.134	7.5	8.5	0.274	3.7	12.1
	Perlite	0.127	7.9	8.4	0.268	3.7	11.9
	Foamed Cores	0.120	8.3	7.9	0.263	3.8	10.2
	4" Insert, continuous (fig B)	0.126	7.9	8.2	0.242	4.1	11.6
12"	Uninsulated	0.377	2.7	8.8	0.493	2.0	12.6
	Insert , core (fig A)	0.230	4.4	8.8	0.369	2.7	12.9
	ESCS @ 50 lbs/ft^3 Loose Fill	0.153	6.5	14.6	0.266	3.8	18.7
	2" Insert, continuous (fig B)	0.185	5.4	8.6	0.315	3.2	12.5
	Vermiculite	0.111	9.0	9.6	0.231	4.3	13.7
	Perlite	0.105	9.5	9.5	0.226	4.4	13.6
	Foamed Cores	0.099	10.1	8.9	0.222	4.5	12.9
	4" Insert, continuous (fig B)	0.123	8.1	9.2	0.233	4.3	13.1

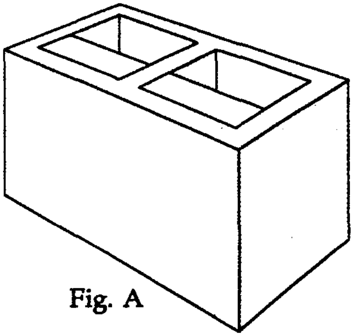


Fig. A

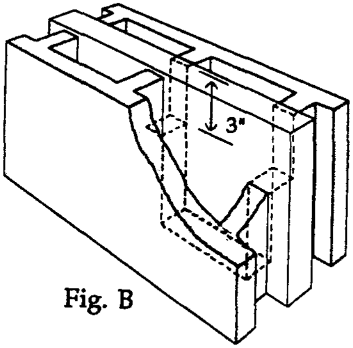


Fig. B

Notes:

1. All values are calculated using minimum dimensions for Load-Bearing Concrete Masonry per ASTM C-90.
2. The R-values are calculated using the NCMA R-value computer program (CMS 10911) using the series-parallel method.
3. Consult the manufacturer of cut web masonry units for structural compliance of their product.
4. ESCS - Expanded Shale, Clay and Slate aggregate.
5. The ESCS, vermiculite, and perlite thermal values are for loose fill poured into the erected block wall.
6. Film Coefficients of 0.85 are included in the R-values and the resultant U-value. R in (h • ft^2 • °F)/BTU U in BTU/(h • ft^2 • °F)
7. Wall HC (Heat Capacity) is based on ASTM minimum required block dimensions, 90 and 135 lbs/ft^3 concrete unit weight and mortar. HC in BTU/(ft^2 • °F)

TABLE 3 THERMAL PROPERTIES OF VARIOUS BUILDING MATERIALS
Thermal Resistance (R), and Heat Capacity (HC)

Building material R-values are from 1989 ASHRAE Handbook of Fundamentals, Chapter 22. HC-values are calculated from Density and Specific Heat from the same source, except as noted other wise.

		PER THICKNESS LISTED		
MATERIAL DESCRIPTION	THICKNESS (in.)	R VALUE (h•ft^2•°F / Btu)	HC VALUE (Btu / ft^2 • °F)	WEIGHT (pounds / ft^2)
BUILDING BOARD				
Gypsum Wallboard	0.5	0.45	0.54	2.1
Plywood (Douglas Fir)	0.5	0.62	0.41	1.4
Fiber board sheathing, regular density	0.5	1.32	0.23	0.8
Hardboard, medium density	0.5	0.69	0.65	2.1
Particleboard, medium density	0.5	0.53	0.65	2.1
INSULATING MATERIALS				
Mineral Fiber With Metal Stud Framing[1]				
R-11, 2x4 @ 16" (R-11 x .50 correction factor)		5.50	0.30	1.7
R-11, 2x4 @ 24" (R-11 x .60 correction factor)		6.60	0.27	1.4
R-19, 2x6 @ 16" (R-19 x .40 correction factor)		7.60	0.44	2.4
R-19, 2x6 @ 24" (R-19 x .45 correction factor)		8.55	0.39	1.9
Mineral Fiber With Wood Framing[2] (with lapped siding, 1/2" sheathing, and 1/2" gypsum board)				
R-11, 2x4 @ 16" on center		12.44	2.01	6.1
R-19, 2x6 @ 24" on center		19.11	2.13	6.5
Board, Slabs, and Loose Fill				
Cellular glass	1	2.86	0.13	0.7
Expanded polystyrene, extruded	1	5.00	0.08	0.3
Expanded polystyrene, molded beads[3]	1	4.00	0.03	0.1
Perlite[3]	1	3.13	0.11	0.4
Polyurethane	1	6.25	0.05	0.5
UF Foam[4]	1	4.35	0.02	0.1
Vermiculite[3]	1	2.44	0.13	0.4
Expanded Shale, Clay & Slate LWA[5]				
30# / CF Dry loose weight	1	1.21	0.53	2.5
40# / CF Dry loose weight	1	1.02	0.70	3.3
50# / CF Dry loose weight	1	0.88	0.88	4.2
Mortar[3], Plaster & Misc. Masonry				
Clay brick masonry	3.63	0.40	8.16	40.8
Stucco and cement plaster, sand aggregate	1	0.20	1.93	9.7
Gypsum plaster, perlite aggregate	1	0.67	1.20	3.8
Mortar	1	0.20	2.00	10.0
CONCRETE[3] (cast in place, precast)				
60 pcf	1	0.60	1.05	5.0
70 pcf	1	0.49	1.23	5.8
80 pcf	1	0.40	1.40	6.7
90 pcf	1	0.33	1.58	7.5
100 pcf	1	0.27	1.75	8.3
110 pcf	1	0.22	1.93	9.2
120 pcf	1	0.18	2.10	10.0
135 pcf	1	0.13	2.48	11.3
150 pcf	1	0.10	2.75	12.5
WOODS				
Southern Pine	1	1.00-0.89	1.16-1.34	3.0-3.4
California Redwood	1	1.35-1.22	0.80-0.91	2.0-2.3

1. R-Value corrected per ASHRAE / IES 90.1-1989 8C2; HC from vendors' data
2. Calculated per ASHRAE 1989 FUNDAMENTALS, Chapter 22
3. NCMA TEK 164 and NCMA "Concrete Masonry R-Value Program"
4. NBS Tech Note 946
5. R-Values from Thermophysical Properties of Masonry and its Constituents", Part I, by Rudolph Valore, Jr

TABLE 4 (ASHRAE 90.1 Table 8C-2)

Wall Sections with Metal Studs Parallel Path Correction Factors

Size of Members	Gauge of Stud	Spacing of Framing, in.	Cavity Insulation R - Value	Correction Factor	Effective Framing per Cavity R - Values
2 x 4	18 - 16	16 on Center	R - 11	0.50	R - 5.5
			R - 13	0.46	R - 6.0
			R - 15	0.43	R - 6.4
2 x 4	18 - 16	24 on Center	R - 11	0.60	R - 6.6
			R - 13	0.55	R - 7.2
			R - 15	0.52	R - 7.8
2 x 6	18 - 16	16 on Center	R - 19	0.37	R - 7.1
			R - 21	0.35	R - 7.4
2 x 6	18 - 16	24 on Center	R - 19	0.45	R - 8.6
			R - 21	0.43	R - 9.0
2 x 8	18 - 16	16 on Center	R - 25	0.31	R - 7.8
2 x 8	18 = 16	24 on Center	R - 25	0.38	R - 9.6

1. These factors can be applied to metal studs of this gauge or thinner.

EXAMPLE 1 - Apartment in Milwaukee, WI
12" SmartWall Systems® Wall

MATERIAL DESCRIPTION	HC	R
90 PCF LW CMU, with film coefficients All cells filled with Perlite loose fill	8.30	9.50 (Tbl 1) U=0.11

The insulationis"INTEGRAL" with the wall's thermalmass. Use insulation position #2.

```
                          ASHRAE/IES STANDARD 90.1-1989
     ENERGY EFFICIENT DESIGN OF NEW BUILDINGS EXCEPT LOW-RISE RESIDENTIAL BUILDINGS
CITY: 139 Milwaukee, WI.                        BUILDING:  Apartment
CODE <B,C,H>:Both Heated and Cooled             WALLS: 12" CMU 90 pcf w/Perlite Fill

                           WALL ORIENTATION                      WEIGHTED
            N      NE        E       SE       S      SW       W      NW  AVERAGE CRITERIA
WL AREA| 17158            59646            20896           58800        |  0.23 | 0.300
GL AREA|  3410            14130             4720           13800        |   WWR |   WWR
   SCx |  0.83             0.83             0.83            0.83        |  0.83 | 0.630
    PF |     0                0                0               0        |  0.00 |   0.0
   VLT |  0.79             0.79             0.79            0.79        |  0.79 |   N/A
   Uof | 0.520            0.520            0.520           0.520        |  0.52 | 0.480
WALL Uo|  .105             .105             .105            .105        |  0.11 | 0.077
    HC |   8.3              8.3              8.3             8.3        |  8.30 |     1
INS POS|     2                2                2               2        |  2    |   N/A
EQUIP  |   .38              .38              .38             .38        |  0.38 | 0.380
LIGHTS |   .67              .67              .67             .67        |  0.67 | 0.670
DLCF   |     0                0                0               0        |  0.00 |   0.0
                              L O A D S                                   TOTAL
HEATING| 3.139            8.451            2.256           8.579        | 22.424< 22.623
COOLING| 1.688            9.302            3.193           9.582        | 23.766< 24.779
TOTAL  | 4.827           17.753            5.449          18.161        | 46.190< 47.402
=========================================================================================
(Computer screen information, ENVSTD version 2.4)***********   PASSES    ***********
```

EXAMPLE 2 - Apartment in Milwaukee, WI
TYPICAL FACE BRICK STEEL STUD WALL

MATERIAL DESCRIPTION	HC	R
Face Brick, 4"	8.16	0.40
Fiber board sheathing 1/2" reg. density	0.23	1.32
Insulation R-19in 2/6 metal stud @ 16 o.c.	0.44	7.10
Gypsum Board, 1/2"	0.54	0.45
Film coefficients,(sum of inside & outside)	0.0	0.85
TOTALS	9.37	10.12

The insulation is "INTERIOR" to the wall's thermal mass. Use insulation position #3.

(U=.0988) Note: If uncorrected R22

```
                          ASHRAE/IES STANDARD 90.1-1989
     ENERGY EFFICIENT DESIGN OF NEW BUILDINGS EXCEPT LOW-RISE RESIDENTIAL BUILDINGS
CITY: 139 Milwaukee, WI.                        BUILDING:  Apartment
CODE <B,C,H>:Both Heated and Cooled             WALLS: Brick on R-19 Steel Stud @16oc

                           WALL ORIENTATION                      WEIGHTED
            N      NE        E       SE       S      SW       W      NW  AVERAGE CRITERIA
WL AREA| 17158            59646            20896           58800        |  0.23 | 0.300
GL AREA|  3410            14130             4720           13800        |   WWR |   WWR
   SCx |  0.83             0.83             0.83            0.83        |  0.83 | 0.630
    PF |     0                0                0               0        |  0.00 |   0.0
   VLT |  0.79             0.79             0.79            0.79        |  0.79 |   N/A
   Uof | 0.520            0.520            0.520           0.520        |  0.52 | 0.480
WALL Uo| .0988            .0988            .0988           .0988        |  0.10 | 0.077
    HC |  9.37             9.37             9.37            9.37        |  9.37 |     1
INS POS|     3                3                3               3        |  3    |   N/A
EQUIP  |   .38              .38              .38             .38        |  0.38 | 0.380
LIGHTS |   .67              .67              .67             .67        |  0.67 | 0.670
DLCF   |     0                0                0               0        |  0.00 |   0.0
                              L O A D S                                   TOTAL
HEATING| 3.121            8.393            2.283           8.537        | 22.333< 22.623
COOLING| 1.751            9.629            3.353           9.986        | 24.720< 24.779
TOTAL  | 4.872           18.022            5.636          18.523        | 47.053< 47.402
=========================================================================================
(Computer screen information, ENVSTD version 2.4)***********   PASSES    ***********
```

EXAMPLE 3 - Office Building in El Paso, TX

12" SmartWall Systems® Wall

MATERIAL DESCRIPTION	HC	R
0 PCF LW CMU, with film coefficients	8.30	9.50 (Tbl 1)
ll cells filled with Perlite loose fill		U=0.11

The insulation is "INTEGRAL" with the wall's thermal mass. Use insulation position #2.

```
                          ASHRAE/IES STANDARD 90.1-1989
     ENERGY EFFICIENT DESIGN OF NEW BUILDINGS EXCEPT LOW-RISE RESIDENTIAL BUILDINGS
CITY: 70 El Paso, TX.                          BUILDING: Medium Office Building
CODE <B,C,H>:Both Heated and Cooled            WALLS: 12" CMU 90 pcf w/Perlite Fill

                          WALL ORIENTATION                        WEIGHTED
           N      NE       E      SE       S      SW       W      NW  AVERAGE  CRITERIA
WL AREA|  4113            7137            4299            6023       | 0.284 | 0.281
GL AREA|  1096            1950            1170            1914       |   WWR |   WWR
   SCx | 0.482           0.482           0.482           0.482       | 0.482 | 0.500
   PF  |  0.20            0.18            0.18            0.20       | 0.190 | 0.000
   VLT |  0.36            0.36            0.36            0.36       | 0.360 |   N/A
   Uof | 1.042           1.042           1.042           1.042       | 1.042 | 1.150
WALL Uo|   .11             .11             .11             .11       | 0.110 | 0.158
   HC  |   8.3             8.3             8.3             8.3       | 8.300 |     1
INS POS|     2               2               2               2       |   N/A |   N/A
EQUIP  |  0.50            0.50            0.50            0.50       | 0.500 | 0.500
LIGHTS |  1.73            1.73            1.73            1.73       | 1.730 | 1.730
DLCF   |     0               0               0               0       | 0.000 | 0.000
------- -------------------- L O A D S -------------------- -TOTAL- -------
HEATING| 1.442           1.850           0.842           1.757       |  5.891<  6.992
COOLING| 7.404          16.562           9.281          15.112       | 48.360< 59.447
TOTAL  | 8.846          18.412          10.123          16.869       | 54.251< 66.439
==========================================================================
(Computer screen information, ENVSTD version 2.4)**********   PASSES    **********
```

EXAMPLE 4 - Office Building in El Paso, TX

TYPICAL FACE BRICK STEEL STUD WALL

MATERIAL DESCRIPTION	HC	R
Face Brick, 4"	8.16	0.40
Fiber board sheathing 1/2" reg. density	0.23	1.32
Insulation R-19 in 2/6 metal stud @ 16 o.c.	0.44	7.10
Gypsum Board, 1/2"	0.54	0.45
Film coefficients, (sum of inside & outside)	0.0	0.85
TOTALS	9.37	10.12

(U=.0988)Note:If uncorrected R=22

The insulation is "INTERIOR" to the wall's thermal mass. Use insulation position #3.

```
                          ASHRAE/IES STANDARD 90.1-1989
     ENERGY EFFICIENT DESIGN OF NEW BUILDINGS EXCEPT LOW-RISE RESIDENTIAL BUILDINGS
CITY: 70 El Paso, TX.                        BUILDING: Medium Office Building
CODE <B,C,H>:Both Heated and Cooled          WALLS: Brick on R-19 Steel Stud @16oc

                          WALL ORIENTATION                        WEIGHTED
------- ---N------NE------E-----SE------S-----SW------W-----NW- ------- --------
WL AREA|  4113            7137            4299            6023       | 0.284 | 0.281
GL AREA|  1096            1950            1170            1914       |   WWR |   WWR
   SCx | 0.482           0.482           0.482           0.482       | 0.482 | 0.500
   PF  |  0.20            0.18            0.18            0.20       | 0.190 | 0.000
   VLT |  0.36            0.36            0.36            0.36       | 0.360 |   N/A
   Uof | 1.042           1.042           1.042           1.042       | 1.042 | 1.150
WALL Uo| .0988           .0988           .0988           .0988       | 0.099 | 0.158
   HC  |  9.37            9.37            9.37            9.37       | 9.370 |     1
INS POS|     3               3               3               3       |   N/A |   N/A
EQUIP  |  0.50            0.50            0.50            0.50       | 0.500 | 0.500
LIGHTS |  1.73            1.73            1.73            1.73       | 1.730 | 1.730
DLCF   |     0               0               0               0       | 0.000 | 0.000
------- -------------------- L O A D S -------------------- -TOTAL- -------
HEATING| 1.449           1.861           0.917           1.792       |  6.021<  6.992
COOLING| 7.541          16.898           9.537          15.437       | 49.413< 59.447
TOTAL  | 8.990          18.759          10.455          17.230       | 55.434< 66.439
==========================================================================
(Computer screen information, ENVSTD version 2.4)**********    PASSES    **********
```

What Are SmartWall Unit Details?

General Information on SmartWall high performance concrete masonry units:
The information below is for general use only. For exact shapes and physical properties, contact your supplier:

Unit Size (inches)	Maximum Jobsite Weight lbs[1]	Minimum Weight Savings Percent[2]	Concrete Unit Weight Oven Dry lbs/ft³ (93 Max)	Wall R-Value[3]		Wall [4] HC Value
				No Insulation	UF Foam Insulation	
12x8x16	36	37	80-93	2.7	10.1	8.7
10x8x16	33	28	80-93	2.6	8.3	7.8
8x8x16	26	27	80-93	2.5	7.0	6.7
6x8x16	23	23	80-93	2.4	NA	5.6
4x8x16	18	31	80-93	2.1	NA	4.3
8x8x24	38	38	80-93	2.5	7.0	6.4

(1) Oven dry weights will be less than jobsite weights and will depend on unit shape and the concrete unit weight used. The maximum jobsite weights are given just for field control to help insure SmartWall units are being used. For maximum oven dry weights of SmartWall units, contact your supplier.

(2) When compared to heavy concrete masonry at 135 lbs/ft³

(3) R-Values are based on ASTM minimum required block dimensions and 90 lbs/ft³ concrete unit weight using series parallel method (air film included). R in (h • ft² • °F)/BTU.)

(4) Wall HC (Heat Capacity) is based on ASTM minimum required block dimensions, 90 lbs/ft³ concrete unit weight and mortar. HC in BTU/(ft² • °F)

11.1D

ESCSI Information Sheet 3530

“Life Cycle Cost Analysis”

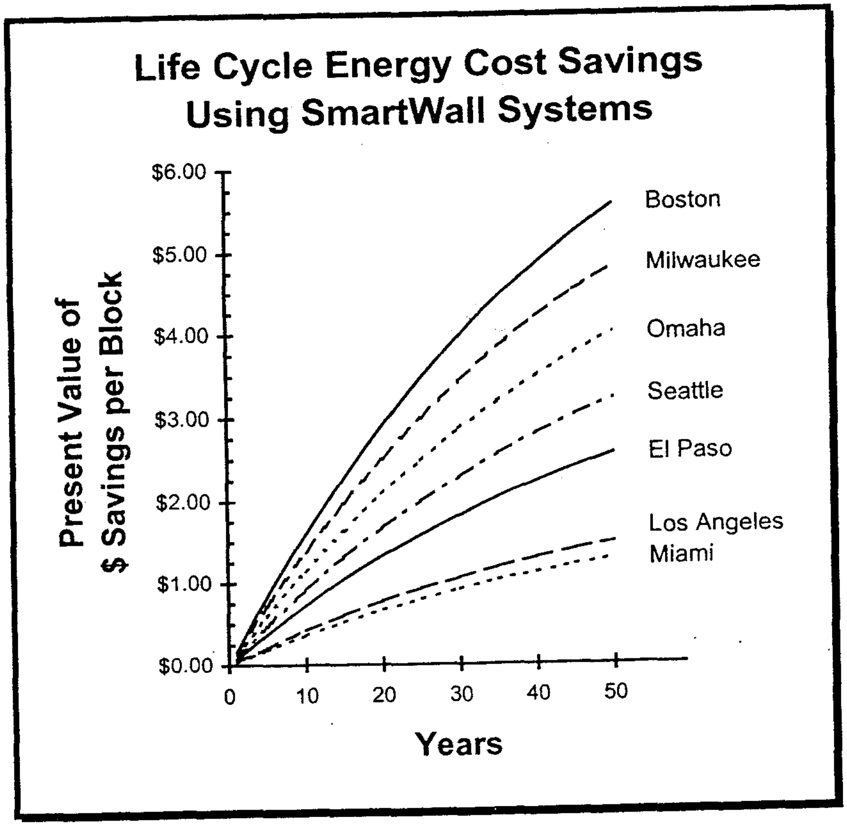
Information Sheet 3530
March, 2000

Life Cycle Energy Cost Analysis Shows That SmartWall Systems® Provides Significant Savings in All Climates

SmartWall Systems® is a concrete masonry wall system that outperforms other masonry and non-masonry wall systems. SmartWall Systems® offers superior performance, especially in terms of energy efficiency, maintenance, appearance, fire resistance, durability, and strength to weight ratio.

The built-in thermal resistance and low thermal bridging of SmartWall Systems® saves energy in both warm and cold climates.

The Life Cycle Cost analysis illustrated in the graph uses local climate data and energy costs for heating and cooling, and show the significant life cycle energy cost savings achieved by SmartWall Systems®. In many cases the present value of these savings will pay for the SmartWall System® itself. For example, the analysis shows that a SmartWall building in Omaha saves $1.15 per block over the first ten years of the building's life, and $2.86 over a thirty-year period.


Life Cycle Energy Cost Savings Using SmartWall Systems

The analysis compares SmartWall Systems® concrete masonry units at 90 lb/ft³ density to ordinary 135 lb/ft³ units. Units are standard 8" x 8" x 16" dimensions. The analysis uses steady-state heat flow calculations.

Detailed information on the thermal values, energy costs and the methodology of the Life Cycle Costing analysis illustrated above is shown on the following pages. For more information about SmartWall Systems®, contact the Expanded, Shale, Clay, and Slate Institute office or any ESCSI member.

SmartWall
HIGH PERFORMANCE MASONRY
Systems®

Life Cycle Energy Cost Savings by City For Ten and Thirty Year Periods

With Climate and Energy Costs

	Atlanta	Boston	Chicago	Cleveland	Dallas-Ft Worth	Denver	El Paso	Houston
Climate (WSO unless noted otherwise) (1)								
Heating degree Days HDD65	3025	5596	6459	6179	2420	6023	2672	1548
Cooling Degree Hours CDH74	16803	5358	6606	4772	36294	5908	22966	30474
Energy Costs Fall 1999(2)								
Natural Gas (for heating) $/mcf	$5.93	$7.23	$4.97	$6.23	$4.58	$4.06	$4.58	$4.58
Electricity (for cooling) $/kwh	$0.070	$0.100	$0.081	$0.095	$0.064	$0.055	$0.094	$0.068
Total LCC Savings @ 10 Years, $ / block	$0.82	$1.59	$1.28	$1.51	$0.71	$0.96	$0.73	$0.53
Total LCC Savings @ 30 Years, $ / block	$2.05	$3.96	$3.18	$3.76	$1.76	$2.40	$1.82	$1.31

	Indianapolis	Los Angeles	Memphis	Miami	Milwaukee	Minneapolis	New Orleans	New York JFK
Climate (WSO unless noted otherwise) (1)								
Heating degree Days HDD65	5653	1595	3214	198	7327	8010	1311	5171
Cooling Degree Hours CDH74	9082	4306	24504	39401	3313	6806	32758	7634
Energy Costs Fall 1999(2)								
Natural Gas (for heating) $/mcf	$5.44	$6.26	$6.11	$6.59	$4.89	$4.40	$5.65	$6.49
Electricity (for cooling) $/kwh	$0.065	$0.095	$0.062	$0.065	$0.064	$0.066	$0.070	$0.128
Total LCC Savings @ 10 Years, $ / block	$1.23	$0.43	$0.93	$0.93	$1.38	$1.38	$0.56	$1.39
Total LCC Savings @ 30 Years, $ / block	$3.07	$1.06	$2.32	$0.92	$3.43	$3.45	$1.41	$3.46

	Omaha	Phoenix	Raleigh	Sacramento	St. Louis	Salt Lake City	Seattle-Tacoma	Tulsa
Climate (WSO unless noted otherwise) (1)								
Heating degree Days HDD65	6201	1444	3538	2775	4948	5805	5122	3741
Cooling Degree Hours CDH74	13180	54404	11845	10464	17843	9898	1050	26468
Energy Costs Fall 1999(2)								
Natural Gas (for heating) $/mcf	$4.53	$5.95	$6.62	$6.26	$5.66	$4.35	$4.73	$5.23
Electricity (for cooling) $/kwh	$0.054	$0.080	$0.064	$0.083	$0.061	$0.056	$0.062	$0.046
Total LCC Savings @ 10 Years, $ / block	$1.15	$0.87	$0.98	$0.76	$1.19	$1.02	$0.92	$0.89
Total LCC Savings @ 30 Years, $ / block	$2.86	$2.17	$2.43	$1.90	$2.97	$2.54	$2.29	$2.22

LCC Savings Comparison between 90 pcf SmartWall units and ordinary 135 pcf masonry units. All units 8" x 8" x 16". This analysis uses steady-state heat flow calculations, and does not include the effects of thermal mass. An example of the calculation details is shown on the next page.

References for this page and the following page:

(1) Appendix A, Climatic Data for the US and Canada, ASHRAE 90.2, 1993.

(2) Natural Gas Costs: Natural Gas Monthly, US Department of Energy – Energy Information Administration, October, 1999. Table 22, page 57-59. Commercial gas costs by state were used for the most recent complete year available. Contact ESCSI for details.

Electricity Cost: *Electric Sales and Revenue 1998*, US Department of Energy – Energy Information Administration, October 1999, Table 15. Commercial Average Rates for the Utility serving the selected city.

(3) *R-values for Single Wythe Concrete Masonry Walls, TEK 6-2A*, National Concrete Masonry Association, 1996. The R-value is interpolated for 90 pcf. Values are for unreinforced walls. For walls with 32" o/c vertical grouting and reinforcing, the difference in U values between a 90 lb/ft^3 wall and 135 lb/ft^3 wall drops to 0.153, a 2.5% reduction. Life cycle savings will be reduced by a similar amount. Calculation procedures for grouted walls are shown in the referenced NCMA TEK.

(4) The 2% nominal discount rate was chosen as appropriate for this analysis because it represents the typical long-term two percent difference between short-term US T-bill rates and the CPI inflation rate. See Office of Management and Budget Circular A-94 *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs.*

This analysis was developed by Buildex Inc. for use with permission by members of the Expanded Shale, Clay, and Slate Institute, Salt Lake City, Utah and is This March 2000 edition replaces earlier versions of this publication, which used different furnace efficiencies and cooling SEER and a less comprehensive source of commercial electricity costs.

Life Cycle Energy Cost Analysis

Present Value of Annual Energy Cost Savings Using SmartWall Systems®
Over a Thirty Year Period

Wall construction:	Location:
Single wythe 8" w/foamed in place core insulation	Omaha, Nebraska

R Value Data	CMU Density		
	135 lb/ft³	105 lb/ft³	90 lb/ft³
R value (3)	3.40	5.60	7.30
Calc: U value	0.294	0.179	0.137
Calc: Difference in U values (vs 135 lb/ft³)	---	0.116	0.157

R-value in (hr – ft² - °F) / BTU. U value in BTU / (hr – ft² - °F)

The following analysis makes two comparisons. The left column compares lightweight units meeting ASTM C90 at 105 lb/ft³ to ordinary 135 lb/ft³ units. The second comparison (in the right hand column) is between a SmartWall Systems® unit at 90 lb/ft³ and the same 135 lb/ft³ unit. All units are conventional 8" x 8" x 16" size. *The analysis Shows that SmartWall Systems® units save substantial energy costs when compared to both ordinary 135 lb/ft³ units and regular ASTM C 90 lightweight units.*

	ASTM Lightweight 105 lb / ft³ CMU	SmartWall 90 lb / ft³ CMU
Heating Cost Calculations		
U value difference vs. 135 lb / ft³ cmu (from above)	0.116	0.157
Natural Gas Cost (2) per mcf	$4.53	$4.53
Furnace efficiency	0.80	0.80
Calc: $ Cost per Btu output	5.66E – 06	5.66E – 06
Heating Degree Days for This Location (1)	6201	6201
Calc: Energy Savings: $ / sq ft / yr	$0.0974	$0.1324
Calc: Energy Savings: $ / block / yr	$0.0866	$0.1177
Present Worth of Heating Savings		
n (years)	30	30
i (nominal rate – energy and money)(4)	2.00%	2.00%
Calc: Present Worth of Heating Energy Savings, $ / block	$1.94	$2.64

Cooling Cost Calculations		
Electricity Cost (2) per kwh	$0.0538	$0.0538
SEER	10	10
Cooling Degree Hours for This Location (1)	13180	13180
Calc: Energy Savings: $ / sq ft / yr	$0.0082	$0.0111
Calc: Energy Savings: $ / block / yr	$0.0073	$0.0099
Present Worth of Cooling Savings		
n (years)	30	30
i (nominal rate – energy and money) (4)	2.00%	2.00%
Calc: Present Worth of Cooling Energy Savings, $ / block	$0.16	$0.22

Calc: Present Worth of Total Energy Savings, $ / block	$2.10	$2.86

See previous page for Notes and References

Life Cycle Energy Cost Analysis

Present Value of Annual Energy Cost Savings Using SmartWall Systems™ Over a Thirty Year Period

Wall Construction:	Location:
Single wythe 8" w/ foamed in place core insulation	Omaha, Nebraska

R Value Data	CMU Density		
	135 lb / ft³	105 lb / ft³	90 lb / ft³
R value(3)	3.40	5.60	7.30
Calc: U value	0.294	0.179	0.137
Calc: Difference in U values (vs 135 lb / ft³)	—	0.116	0.157

R value in (hr · ft² · °F) / BTU.   U value in BTU / (hr · ft² · °F)

The following analysis makes two comparisons. The left column compares lightweight units meeting ASTM C90 at 105 lb / ft³ to ordinary 135 lb / ft³ units. The second comparison (in the right hand column) is between a SmartWall Systems unit at 90 lb / ft³ and the same 135 lb / ft³ unit. All units are conventional 8" x 8" x 16" size. *The analysis shows that SmartWall Systems units save substantial energy costs when compared to both ordinary 135 lb / ft³ units and regular ASTM C 90 lightweight units.*

	ASTM Lightweight 105 lb / ft³ CMU	SmartWall 90 lb / ft³ CMU
Heating Cost Calculations		
U value difference vs. 135 lb / ft³ cmu (from above)	0.116	0.157
Natural Gas Cost(2) per mcf	$4.53	$4.53
Furnace efficiency	0.80	0.80
Calc: $ Cost per Btu output	5.66E-06	5.66E-06
Heating Degree Days for This Location(1)	6201	6201
Calc: Energy Savings: $ / sq ft / yr	$0.0974	$0.1324
Calc: Energy Savings: $ / block / yr	$0.0866	$0.1177
Present Worth of Heating Savings		
n (years)	30	30
i (nominal rate - energy and money)(4)	2.00%	2.00%
Calc: Present Worth of Heating Energy Savings, $ / block	*$1.94*	*$2.64*

Cooling Cost Calculations		
Electricity Cost(2) per kwh	$0.0538	$0.0538
SEER	10	10
Cooling Degree Hours for This Location(1)	13180	13180
Calc: Energy Savings: $ / sq ft / yr	$0.0082	$0.0111
Calc: Energy Savings: $ / block / yr	$0.0073	$0.0099
Present Worth of Cooling Savings		
n (years)	30	30
i (nominal rate - energy and money)(4)	2.00%	2.00%
Calc: Present Worth of Cooling Energy Savings, $ / block	*$0.16*	*$0.22*

Calc: Present Worth of Total Energy Savings, $ / block	*$2.10*	*$2.86*

See previous page for Notes and References

11.2A

Underwriters Laboratory Report Of ESCSI ET's for 2, 3, and 4 hours

Table 4 ACI 216.1 “Fire Resistance Rating of Concrete Masonry Assembly Compared to Underwriters UL 618 and the Results of Tests on CMU Walls Sponsored by NCMA at Omega Point Laboratories”

Eq. Th. Fire Endurance Requirements

	2 Hours			4 Hours		
RATINGS (Reference)	ACI 216.1	NCMA Omega	UL 618	ACI 216.1	NCMA Omega	UL 618
TIME	1997	1990	1998	1997	1990	1998
AGGREGATE TYPE						
Expanded Slag	3.2	3.83	4.10	4.7	5.67	5.3
Expanded Slag blended with Sand		4.07			6.07	
Expanded Slag blended Limestone		4.12			5.82	
Pumice	3.2	3.62		4.7	4.83	4.4
Pumice blended with sand		3.87			5.42	
ESCSI	3.6		3.6	5.1		5.1
Limestone, cinders, unexpanded slag	4.0	4.34		5.9	6.39	
Calcareous	4.2			6.2		
(Limestone/S&G)		4.34			6.54	
Siliceous	4.2	4.2		6.2	6.45	
Natural or By-Product W or W/O sand (700 psi)			4.2			
Natural or By-Product W or W/O sand (1800 psi)						6.5

11.2B

Underwriters Laboratory UL 618

EXPANDED SHALE CLAY AND SLATE
Institute

HARRY C. ROBINSON, MANAGING DIRECTOR
6218 MONTROSE ROAD, ROCKVILLE, MARYLAND 20852
(301) 231-9497

MOTI LETTER #8-85
May 2, 1985

TO: ALL MEMBERS

FROM: Harry C. Robinson

RE: REVISED EDITION OF FIRE RESISTANCE RATINGS (Formerly GREEN BOOK)

A completely revised edition of FIRE RESISTANCE RATINGS has been produced by the Engineering and Safety Service of American Insurance Services Group, Inc., a subsidiary of the American Insurance Association. This is a revision of what ESCSI members called the GREEN BOOK.

The publication is widely used by building and fire inspectors and other public officials, architects, engineers, and others interested in fire safety in buildings. It provides clear, concise details for the construction of building assemblies that have fire resistance ratings of up to four hours.

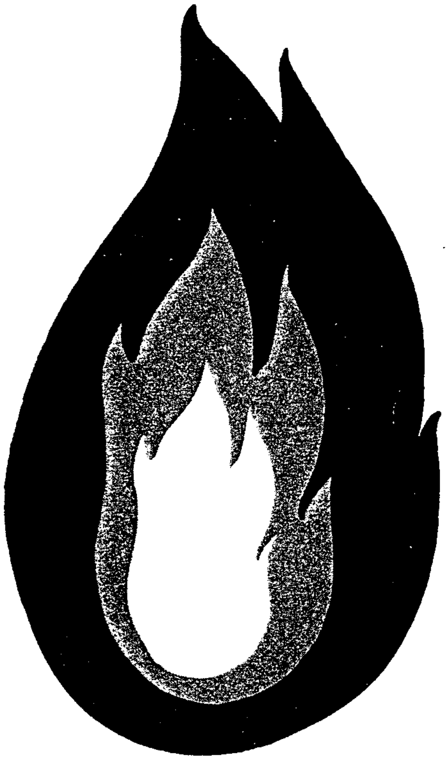
The new edition represents comprehensive revision of the Services's 1964 edition (Green Book) and it includes more complete details of construction, available new data, including all the Institute's latest equivalent thicknesses for concrete masonry. This guide is the only one of its kind in the country dealing with generic assemblies.

The 126 page reference is published in the standard 8½ x 11 inch format, punched for easy insertion into binders. The Institute will not stock this publication. Please order directly from the American Insurance Services Group for $15.00 per copy prepaid. Order from:

Publications Department
American Insurance Services Group, Inc.
85 John Street
New York, New York 10038

HCR:mvb

Fire Resistance Ratings



Engineering and Safety Service
American Insurance Services Group, Inc.
85 John Street, New York, N.Y. 10038

WALL AND PARTITION ASSEMBLIES

U

Concrete Masonry Units. (Continued)

The following ratings apply to wall or partition assemblies constructed using concrete masonry units not less than 7 5/8 in. thick, not more than 8 in. in height and 18 in. in length, and containing 2 or 3 rectangular or oval cores. The assemblies are erected using Type M, S or N mortar.

Aggregate Type	Minimum Equivalent Thickness[bb] (inches)	Minimum Face Shell Thickness (inches)	Minimum Web Thickness (inches)	Maximum Cement to Aggregate Ratio (by volume)	Unit Compressive Strength (psi) Min.	Unit Compressive Strength (psi) Avg.	Dry Rodded Weight (pcf)	RATING[†] (hours)
Natural, by-product and processed, except those given below* (Reference 92)	—	2 1/8	1 1/2	1:6	1600	1800	—	4
	—	1 1/2	1	1:7	600	700	—	3
	—	1 1/4	1	1:7	600	700	—	2
Expanded Clay, Shale or Slate, Rotary kiln (Reference 92)	5.10	1 3/4	—	1:10	800	1000		4
	—	1 3/8	1	1:7	600	700	42	3
	4.40[cc]	1 1/2	—	1:10	800	1000	to	3
	—	1 1/8	1	1:7	600	700	72	2
	3.60[cc]	1 1/4	—	1:10	800	1000		2
Expanded Clay, Shale or Slate, Sintering Process (Reference 92)	5.40	1 3/4	—	1:9	800	1000	42	4
	4.75	1 1/2	—	1:9	800	1000	to	3
	4.20	1 1/4	—	1:9	800	1000	72	2
Expanded Slag (References 92, 131)	—	1 5/8	1	1:7	600	700		4
	5.30	1 3/4	—	1:7	800	900	35	4
	—	1 3/8	1	1:7	600	700	to	3
	4.78[dd]	1 1/2	—	1:7	800	900	70	3
	—	1 1/8	1	1:7	600	700		2
	4.13[dd]	1 1/4	—	1:7	800	900		2
Fly Ash (Reference 92)	5.20	1 3/4	—	1:8.5	800	1000	50	4
	4.70	1 1/2	—	1:8.5	800	1000	to	3
	4.00	1	—	1:8.5	800	1000	70	2
Fly Ash and Sand** (Reference 92)	5.40	1 7/8	—	1:8.5	800	1000	50	4
	4.90	1 5/8	—	1:8.5	800	1000	to	3
	4.20	1 1/8	—	1:8.5	800	1000	78	2
Pumice (Reference 92)	4.40	1 1/2	—	1:7	600	700	35 to	4
	4.07	1 1/4	—	1:7	600	700	50	3

*Not more than 15% quartz, chert or flint or 65% siliceous material (by weight); cinders contain not more than 35% combustible material.

**Sand to not exceed 23% of total aggregate volume.

[†] Rated as load bearing with noncombustible members, or no members, framed into the wall.

WALL AND PARTITION ASSEMBLIES

Concrete Masonry Units. (Continued)
Estimated Ratings[j].

The following ratings apply to wall or partition assemblies constructed using concrete masonry units and Type M, S or N mortar. These estimated ratings are based substantially on Reference 42.

Aggregate Type	Minimum Equivalent Thickness[e]	Maximum Cement to Aggregate Ratio (by volume)	Unit Compressive Strength (psi), min.	Fineness Modulus	RATING[†] (hours)
Expanded Slag or Pumice	4.7	1:5	500	2.6	4
	4.0	1:5	500	2.6	3
	3.2	1:5	500	2.6	2
	2.1	1:5	500	2.6	1
Expanded Clay or Shale	5.7	1:7	630	3.5	4
	4.8	1:7	630	3.5	3
	3.8	1:7	630	3.5	2
	2.6	1:7	630	3.5	1
Limestone, Cinders[*] or Unexpanded Slag	5.9	1:7	750	3.5	4
	5.0	1:7	750	3.5	3
	4.0	1:7	750	3.5	2
	2.7	1:7	750	3.5	1
Calcareous Sand and Gravel	6.2	1:7	900	4.5	4
	5.3	1:7	900	4.5	3
	4.2	1:7	900	4.5	2
	2.8	1:7	900	4.5	1
Siliceous Sand and Gravel	6.7	1:8	500	4.25	4
	5.7	1:8	500	4.25	3
	4.5	1:8	500	4.25	2
	3.0	1:8	500	4.25	1

[†] Rating applies to load bearing assemblies with noncombustible members, or no members, framed into the wall.

[*] Cinders contain not more than 5%, by weight, of volatile matter.

5.3 ASTM E119 FULLSCALE FIRE TESTS

FIRE RESISTANCE RATINGS

WALL AND PARTITION ASSEMBLIES

Concrete Masonry Units. (Continued)

The following ratings apply to wall or partition assemblies constructed using concrete masonry units not less than 7⅝ in. thick, not more than 8 in. in height and 18 in. in length, and containing 2 or 3 rectangular or oval cores. The assemblies are erected using Type M, S or N mortar.

Aggregate Type	Minimum Equivalent Thickness (inches)	Minimum Face Shell Thickness (inches)	Minimum Web Thickness (inches)	Maximum Cement to Aggregate Ratio (by volume)	Unit Compressive Strength (psi) Min.	Unit Compressive Strength (psi) Avg.	Dry Rodded Weight (pcf)	RATING† (hours)
Natural, by-product and processed, except those given below* (Reference 92)	—	2⅛	1⅛	1:6	1600	1800	—	4
	—	1½	1	1:7	600	700	—	3
	—	1¼	1	1:7	800	700	—	2
Expanded Clay, Shale or Slate, Rotary kiln (Reference 92)	5.10	1¾	—	1:10	800	1000	42 to 72	4
	—	1⅜	1	1:7	600	700		3
	4.40^{ee}	1½	—	1:10	800	1000		3
	—	1⅛	1	1:7	600	700		2
	3.60^{ee}	1¼	—	1:10	800	1000		2
Expanded Clay, Shale or Slate, Sintering Process (Reference 92)	5.40	1¾	—	1:9	800	1000	42 to 72	4
	4.75	1½	—	1:9	800	1000		3
	4.20	1¼	—	1:9	800	1000		2
Expanded Slag (References 92, 131)	—	1¾	1	1:7	600	700	35 to 70	4
	5.30	1¾	—	1:7	800	900		4
	—	1⅜	1	1:7	600	700		3
	4.78^{dd}	1½	—	1:7	800	900		3
	—	1⅛	1	1:7	600	700		2
	4.13^{dd}	1¼	—	1:7	800	900		2
Fly Ash (Reference 92)	5.20	1¾	—	1:8.5	800	1000	50 to 70	4
	4.70	1½	—	1:8.5	800	1000		3
	4.00	1	—	1:8.5	800	1000		2
Fly Ash and Sand** (Reference 92)	5.40	1⅞	—	1:8.5	800	1000	50 to 78	4
	4.90	1⅝	—	1:8.5	800	1000		3
	4.20	1⅛	—	1:8.5	800	1000		2
Pumice (Reference 92)	4.40	1½	—	1:7	600	700	35 to 50	4
	4.07	1¼	—	1:7	600	700		3

*Not more than 15% quartz, chert or flint or 65% siliceous material (by weight); cinders contain not more than 35% combustible material.

**Sand to not exceed 23% of total aggregate volume.

†Rated as load bearing with noncombustible members, or no members, framed into the wall.

NOTE DIFFERENCE BETWEEN STRD ASTM E119 FULLSCALE TESTS AND NON-STRD, SMALL SCALE WALLS OF LOW STRENGTH, MOIST UNITS

NON-STRD FIRE TESTS (NOT FULL SCALE, TESTED MOIST, etc NOT ASTM C90 STRENGTHS

FIRE RESISTANCE RATINGS

WALL AND PARTITION ASSEMBLIES

Concrete Masonry Units. (Continued)
Estimated Ratings¹.

The following ratings apply to wall or partition assemblies constructed using concrete masonry units and Type M, S or N mortar. These estimated ratings are based substantially on Reference 42.

NOT C-90 STRENGTH

Aggregate Type	Minimum Equivalent Thickness*	Maximum Cement to Aggregate Ratio (by volume)	Unit Compressive Strength (psi), min.	Fineness Modulus	RATING† (hours)
Expanded Slag or Pumice	4.7	1:5	500	2.6	4
	4.0	1:5	500	2.6	3
	3.2	1:5	500	2.6	2
	2.1	1:5	500	2.6	1
Expanded Clay or Shale	5.7	1:7	630	3.5	4
	4.8	1:7	630	3.5	3
	3.8	1:7	630	3.5	2
	2.6	1:7	630	3.5	1
Limestone, Cinders* or Unexpanded Slag	5.9	1:7	750	3.5	4
	5.0	1:7	750	3.5	3
	4.0	1:7	750	3.5	2
	2.7	1:7	750	3.5	1
Calcareous Sand and Gravel	6.2	1:7	900	4.5	4
	5.3	1:7	900	4.5	3
	4.2	1:7	900	4.5	2
	2.8	1:7	900	4.5	1
Siliceous Sand and Gravel	6.7	1:8	500	4.25	4
	5.7	1:8	500	4.25	3
	4.5	1:8	500	4.25	2
	3.0	1:8	500	4.25	1

NOTE: C/AGG. RATIO ONLY ONE AGGREG TYPE IN MIXDESIGN

†Rating applies to load bearing assemblies with noncombustible members, or no members, framed into the wall

*Cinders contain not more than 5%, by weight, of volatile matter.

11.2C

Fire Resistance Ratings Including “Estimated Ratings”

APPENDIX A

UNDERWRITERS LABORATORIES INC.
333 PFINGSTEN ROAD · NORTHBROOK, ILLINOIS 60062
an independent, not-for-profit organization testing for public safety

June 28, 1982

R3746
79NK11623

Expanded Shale, Clay
and Slate Institute
4905 Del Ray Ave.
Suite 210
Bethesda, Maryland 20014

Attention: Mr. Harry C. Robinson
Managing Director

Subject: Investigation of Equivalent Thickness Requirements For Concrete Blocks Made From Expanded Shale, Clay or Slate Aggregates

Dear Mr. Robinson:

This Report describes the construction details, small-scale fire endurance tests, and equivalent thickness tests, which were conducted on flat concrete slabs of varying thicknesses.

The investigation was conducted to develop test data showing the relationship between concrete slab thicknesses, expressed in terms of equivalent thickness using the water displacement method, and fire resistance end point temperature time over the range of thicknesses required to obtain 2, 3 and 4 h fire resistance ratings for walls incorporating Class D-2, C-3 and B-4 masonry units, using the data from the small-scale fire tests described in this Report together with the full-scale wall fire test data described in Report R3746-7,-8, dated March 2, 1970. The resulting graphical representation of the full scale and small-scale tests would be used to determine the equivalent thickness requirements for Class D-2, C-3 and B-4 concrete units specified in Standard UL 618.

DESCRIPTION

MATERIALS:

The materials used in the construction of the flat concrete slabs are described below.

Aggregates - The aggregate selected for this investigation was representative of expanded clay, shale or slate, coated or uncoated aggregates, produced by the rotary kiln process, as described in UL 618. The aggregate consisted of particles less than 3/8 in. to dust in size. The dry rodded unit weight of the combined course and fine aggregates was 62.9 lb/ft^3, and the moisture content of the aggregate was 15.3 percent.

Both the dry-rodded unit weight and sieve analysis of the aggregate were found to be similar to those described in Report R3746-7,-8.

Cement - The cement used in the construction of the flat concrete slabs was identified as Portland Type III.

CONSTRUCTION OF SAMPLES:

The concrete slabs were constructed by the submittor under the observation of the technical staff of UL. The slabs were cast using forms supplied by the submittor so that the concrete density would be similar to that obtained from a typical block machine.

Based on the blended dry rodded unit weight and moisture content of the aggregate, the portland cement and the aggregate were mixed in the proportions of 1 ft^3 of cement to 10 ft^3 of aggregate, and 4.7 gal of water.

The aggregate and cement were placed in a mixer, and small amounts of water were added until the desired consistency was obtained. The average mixing time of the aggregate, cement and water was about 10 min.

The resulting mixture was then placed into the forms, leveled, and vibrated. A total of twelve slabs were cast; three each at measured thicknesses of 3.50, 4.25, 4.875 and 5.35 in.

SMALL SCALE FIRE TESTS

At the time of the fire tests, the samples had aged 131, 173 and 407 days, respectively. The relative humidity of each sample was measured using moisture sensitive elements inserted into short lengths of pipe placed into each sample and attached to a measuring instrument when readings were taken. The average relative humidity at the time of the fire tests was 70.3 percent.

During the fire tests, no attempt was made to restrain the expansion of the sample, no load was applied, and no deflection measurements were made. The furnace temperatures followed the time-temperature curve as defined in Standard UL 263 (ANSI A2.1, ASTM E119, NFPA 251).

METHOD

The temperatures of the furnace chamber were measured by three symmetrically located thermocouples, placed 12 in. below the exposed surface of each test sample.

The unexposed surface temperatures of each sample were measured by five thermocouples, each of which was covered by a 6 by 6 in. dry asbestos pad. See ILL. 1 for the thermocouple layout.

RESULTS

Character and Distribution of Fire - The furnace fire for each of the tests was luminous and well distributed, and the temperatures followed the Standard Time-Temperature Curve as outlined in the Standard for Fire Tests of Building Construction and Materials, UL 263.

Observations During Fire Exposure - Light intermittent steam issued from the unexposed surface of each test sample, and the exposed surfaces of each sample discolored slightly during the tests.

No other changes were observed, and each test was terminated after the limiting unexposed surface temperatures had been reached.

Temperatures of the Unexposed Surface - The time at which the average limiting unexposed surface temperature of each test sample occurred is shown in the following table:

Test No.	Measured Slab Thickness, In.	Occurrence Of Limiting Temperatures, min
1	3.50	131
2	4.25	177
3	4.875	247

Since the limiting temperature end point of the 4.875 in. thick slab was in excess of 240 min, the 5.35 in. thick slab was not subjected to a fire test.

EQUIVALENT THICKNESS TESTS

Equivalent thickness tests, using the water displacement method, were conducted on 12 by 12 in. sections of each slab thickness described previously. The results of these tests are shown below:

Measured Slab Thickness, in.	Equivalent Thickness, in.
3.50	3.23
4.25	4.03
4.875	4.73

EVALUATION OF TEST DATA

As discussed in the introduction of this Report, the object of this investigation was to evaluate the data contained in this Report together with the full scale fire test data contained in Report File R3746-7,-8, to revise the minimum equivalent thickness requirements specified in Standard UL 618. A summary of the test data is contained in the following Table:

Data Source	Equivalent Thickness Of Block or Slab, in.	Fire Resistance End Point, min
Wall No. 1, Report R3746-7,-8	3.97	143
Wall No. 2, Report R3746-7,-8	4.85	220
3.50 in. Thick Slab	3.23	131
4.25 in. Thick Slab	4.03	177
4.875 in. Thick Slab	4.73	247

To determine the minimum equivalent thickness requirements required to obtain Class D-2, C-3 and B-4 units, the data for the slabs was plotted with the aid of a computer analysis, as shown on ILL. 2. The computer analysis determined the "best fit" curve with respect to equivalent thicknesses versus unexposed surface temperature end point times for the flat slabs.

The resulting plot was compared with the data developed from the full scale fire tests described in Report R3746-7,-8.

In comparing the test data developed from full-scale block and slab tests, it was determined that the end point time for the slabs was greater than that obtained from block tests for the same equivalent thickness, particularly for the lesser hourly Classification periods.

In analyzing the fire test plots of full scale block walls and small-scale slabs, it was shown that the resulting graphs on log-log plots produced straight nonparallel intersecting lines. It was shown that the lines would intersect at the point that the block would have an equivalent thickness of about 7.63 in., or that the block was 100 percent solid. Review of other test data on nominal 4 and 6 in. blocks showed a similar trend. In general, as the ratio of the equivalent thickness of the blocks to the actual thickness of the block approached 1.0 (or as the block approached 100 percent solid), the closer the end point time would correspond to that of the flat slab. Therefore, it is anticipated that the end point times versus equivalent thicknesses for 4 and 6 in. units would more closely correspond to flat slabs than the 8 in. units.

In the case of block walls, the end point temperatures are determined by means of thermocouples located over the cored spaces of the units. These temperature readings appear to be higher than the readings taken over the solid section of flat slabs, particularly for thicker block walls having relatively thin face shell dimensions. It would appear that radiant and convective heat transfer from the exposed face to the unexposed face through the cored space is more critical than conductive heat transfer through the solid concrete.

In order to determine the relationship of equivalent thickness versus end point time for 8 in. hollow-masonry units, the end point time for a slab having an equivalent thickness of 7.63 in. was determined from the best fit curve developed from the small-scale fire tests. This is the point at which the slab and blocks should produce the same end point time. A line was drawn connecting this point with the point developed from the 4.85 in. equivalent thickness block test described in Report R3746-7-8. This point was selected because the moisture conditions of the test blocks were most representative of the fire test standard requirements and because it was closest to the 4 h classification period. From this graph, the equivalent thickness requirements were determined for Class D-2, C-3 and B-4 units at the 120, 180 and 240 min end point times. Safety factors were not used in determining the equivalent thickness requirements because the end point times from full scale wall tests were determined with the thermocouples located over the hottest areas of the wall and because the aggregate tested had a relatively high dry-rodded unit weight value, and was more critical with respect to heat transmission than lighter unit weight aggregates.

The results of the analysis are summarized below:

Wall Rating, h	Minimum Equivalent Thickness of Blocks, in.
2	3.60
3	4.40
4	5.10

SUMMARY

Based upon the test data and evaluation contained in this Report, Table 4.1 of Standard UL 618 can be proposed for revision to show the minimum equivalent thickness requirements as shown below:

Block	Minimum Equivalent Thickness, in.
D-2	3.60
C-3	4.40
B-4	5.10

It is understood that these equivalent thickness values are only recommendations and that it will be necessary to submit the proposal through the standards review process.

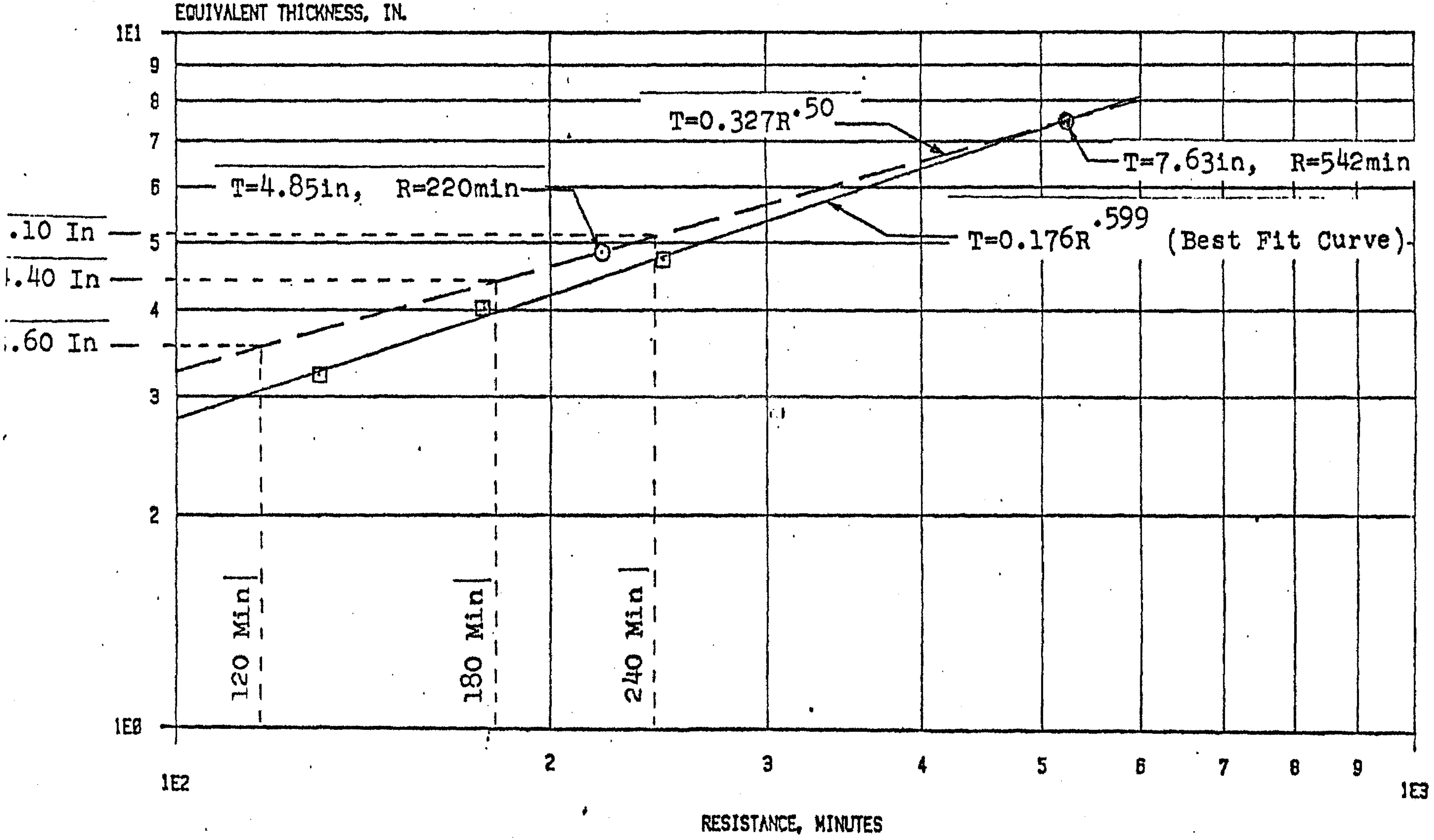
We understand that members of the Expanded Shale, Clay and Slate Institute wish to review this Report prior to proceeding with a proposed revision of UL 618. Your comments will be welcome. This report terminates our work in connection with R3746, Project 79NK11623, and you may expect to be invoiced for all final charges in connection with this Project.

Very truly yours,	Reviewed by:
Gerald D Palikij	K.W. Howell
GERALD D. PALIKIJ	K. W. HOWELL
Senior Engineering Assistant	Associate Managing Engineer
Fire Protection Department	Fire Protection Department

GDP/KWH:plh

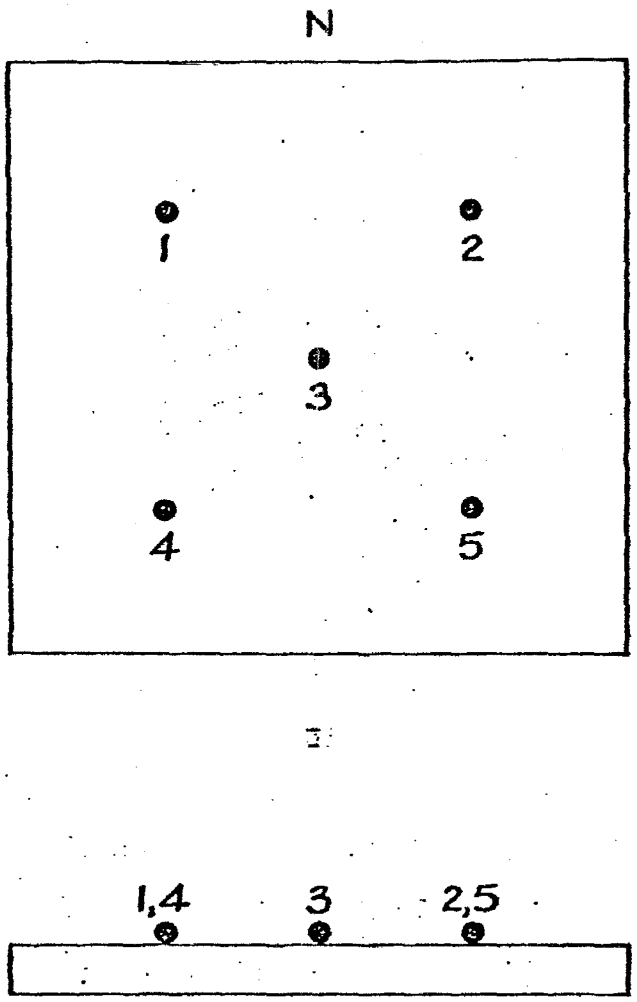
EQUIVALENT THICKNESS VS FIRE RESISTANCE

R3746/79NK11623



CALCULATED EQUIVALENT THICKNESS AND FULL SCALE TEST — — —

UNEXPOSED SURFACE THERMOCOUPLES



ILL. 1

11.2D

School Probably Will Open Despite Fire

MARK GORMUS/TIMES-DISPATCH

IN RUINS. The fire at Nuckols Farm Elementary School collapsed the tin roof, cracked the exterior walls and gutted the interior in one wing.

School probably will open despite fire

Blaze destroyed wing of classrooms being built

BY JANET CAGGIANO AND MARK BOWES

TIMES-DISPATCH STAFF WRITERS

A two-alarm fire destroyed a wing of an elementary school under construction in far western Henrico County, but the county's top school administrator is optimistic the building will open this fall as scheduled.

"We will have to do some serious work, but I still feel confident we will be ready to open the first day of school," Superintendent Mark A. Edwards said after surveying the destruction.

Damage was estimated at $1 million.

Authorities received a call at 5:03 a.m. yesterday that the roof of Nuckols Farm Elementary School in the 12100 block of West Broad Street was ablaze. It collapsed the tin roof, cracked the exterior walls and gutted the interior of the unfinished 10-classroom wing.

A fire official called for a second alarm as he was driving to the scene because the blaze could be seen from a half-mile away, said James Mellon, a spokesman for the Henrico Division of Fire.

The first firefighters on the scene reported heavy flames racing across the roof of the wing. The blaze was contained to that section of the school with the aid of a fire wall that had been installed a day earlier, Edwards said.

The wall separated the wing from the rest of the school. "That (wall) clearly was our saving grace," Edwards said.

"The fire wall did it's job . . . and for the most part saved that whole side of the building," Mellon said.

The cause of the fire remained under investigation. Henrico called on several members of the newly formed Metro Regional Fire Command, made up of investigators from six local, state and federal fire agencies, to help probe the blaze.

"It was a pretty significant fire and we're going to have to get some cranes to move some stuff around to help with the investigation," Mellon said. "So we did call out the metro investigation team to just help get everything under way and started."

Construction on the $8 million school located near North Gayton Road began last August and was about 65 percent complete before yesterday morning's blaze.

"They only had tar paper on certain parts of the [main building's roof] . . . and the majority of the framing work was done," Mellon said.

The destroyed section was at the front of the building and had about 11,000 square feet of space. The school will contain 30 classrooms and measure about 70,500 square feet when completed.

The wing was constructed of brick with wood trusses and a tin roof, Mellon said.

"That one wing was totally destroyed," said

PLEASE SEE **FIRE**, *PAGE* **B3** ▶

School likely to open on time despite blaze

▼ **FIRE** *FROM PAGE B1*

Henrico Fire Marshal Kenneth Shook. "The walls are cracked; they will have to come down."

Edwards said school officials will analyze structural damage and plan a schedule for rebuilding the wing. But because the project was ahead of schedule, he said, the school should open on time.

Shook agreed.

"I don't see that as a problem," he said. "This is a separate wing, it would have nothing to do with the rest of the school as far as operating."

Said Edwards: "Anytime you have a situation like this, it is very alarming. But it could have been so much worse."

Edwards, whose daughter will attend Nuckols Farm, received a call about the blaze at 5:20 a.m., 17 minutes after the first alarm sounded. He was at the site about 10 minutes later.

"When I drove up, I saw the flames," Edwards said. "It was one of the saddest things I've ever seen. But I was immediately relieved to see that it had been contained. I am very proud of the professional staff and teamwork we have in this county that prevented it from being much worse."

11.4A

“Impact Performance of Fully Grouted Concrete Masonry Walls”

Impact Performance of Fully Grouted Concrete Masonry Walls

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ABSTRACT

Concrete masonry walls designed as security barriers are fully grouted concrete masonry assemblies. Typically, vertical grouted cells have steel reinforcement in every cell, and reinforced horizontal bond beams may also be specified. This type of construction is found in prisons, secure facilities or other areas where the integrity of the building envelope or wall partition is vital to securing an area. This paper reports on two phases of research into the impact performance of these types of concrete masonry walls. The testing protocol used was based on ASTM F 2322, *Standard Test Methods for Physical Assault on Vertical Fixed Barriers for Detention and Correctional Facilities.* Each wall was subjected to a simulated attack from a sledgehammer and a firefighter's axe. The simulated attack was a series of impacts from a pendulum test apparatus. Failure was considered to be damage to the wall assembly such that forcible egress can be achieved. Forcible egress was defined as an opening created in the wall assembly which allows a 5 inch x 8 inch x 8 inch (127 x 203 x 203 mm) rigid rectangular box to be passed through the wall with no more that 10 lbf (44.5 N) of force.

KEYWORDS: concrete masonry, detention facility, impact test, physical security, security barrier

INTRODUCTION

Communities across the United States of America rely on concrete masonry for their prisons and detention centers. In addition to its strength and durability, the layout of concrete masonry walls and cells can be cost-effectively tailored to meet the facility's needs. Concrete masonry is a proven product for correctional facilities, providing secure construction with minimum long-term maintenance.

Concrete masonry walls designed as security barriers are most often fully grouted and reinforced. Typically, vertical grouted cells have steel reinforcement in every cell, and reinforced horizontal bond beams may also be specified. This type of construction is found in prisons, secure facilities or other areas where the integrity of the building envelope or wall partition is vital to securing an area.

Recent testing (refs. 2, 3) confirms the impact resistance of concrete masonry construction, and quantifies the performance of various concrete masonry wall systems.

IMPACT TESTING

Standard Test Methods for Physical Assault on Vertical Fixed Barriers for Detention and Correctional Facilities, ASTM F 2322 (ref. 1) was developed to help quantify levels of security for walls designed to incarcerate inmates in detention and correctional institutions. The standard is intended to help ensure that detention security walls perform at or above minimum acceptable levels to: control unauthorized passage to or from secure areas, to confine inmates, to delay and frustrate escape attempts and to resist vandalism. The test method is intended to closely simulate a sustained battering ram style attack, using devices such as benches, bunks or tables. It addresses only those threats which would be anticipated based on the limited weapons, tools and resources available to inmates within detention and correctional facilities.

ASTM F 2322 includes provisions to test monolithic wall panels as well as wall panels with a simulated window opening. The standard assigns various security grades for fixed barriers based on the wall's ability to withstand the simulated attack, as shown in Table1.

Table 1 - Security Grades and Impact Load Requirements (ref. 1)

Grade No.	Number of Impacts	Representative Barrier Duration Time, Min.
1	600	60
2	400	40
3	200	20
4	100	10

Attack is simulated via a series of impacts from a pendulum testing ram apparatus shown in Figure 1. The testing ram is fitted with two heads: a blunt impactor to simulate a sledgehammer, and a sharp impactor simulating a fireman's axe. The testing protocol calls for blows from both the blunt and sharp impactors, applied in sequences of 50 blows each.

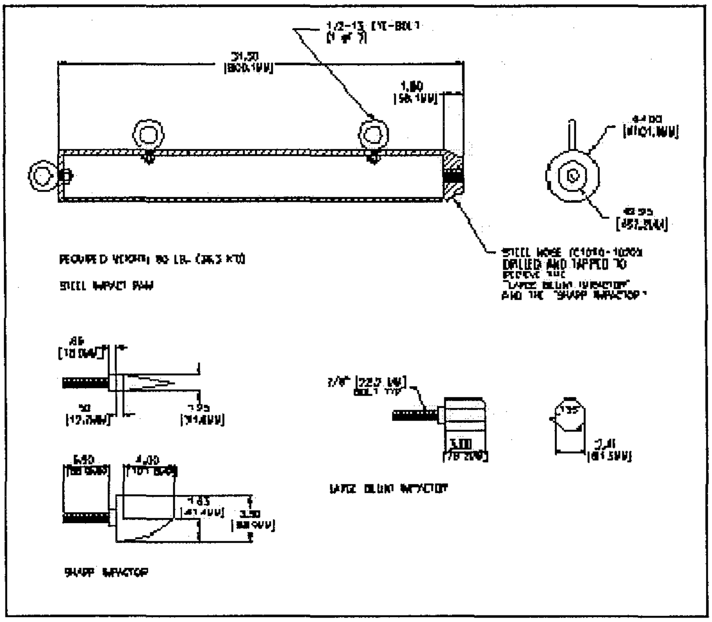


Figure 1 - Pendulum Testing Ram Apparatus

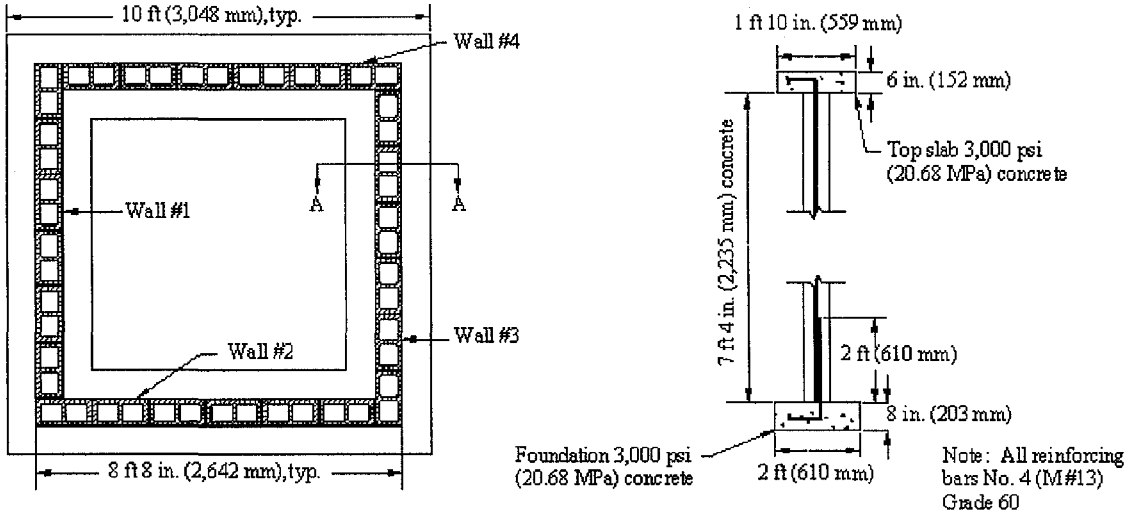
Failure of a wall assembly is defined as an opening through the wall which allows a 5 in. x 8 in. x 8 in. (127 x 203 x 203 mm) rigid rectangular box to be passed through the wall with no more than 10 lb (44.5 N) of force.

The ASTM F 2322 also assigns a representative barrier duration time, based on an historical testing observation that sustained manpower can deliver 400 blows of 200 ft-lb (271.2 J) each in 45 minutes. The element of time assigned to the various security grades is adjusted to achieve more manageable time periods than actual calculations provide. The amount of time is estimated and is offered solely as supplementary design information to assist the user in matching security grades with the attack resistance times and staff response times required for each barrier in the facility.

TEST SPECIMENS

Typical wall construction provided stiffness at both the top and bottom of the wall through interconnection with the foundation below and the floor slab above. Rather than constructing individual flat wall panels with both a foundation below and a slab above, as well as end returns (simulating stiffness provided by wall intersections), a four-sided closed cell was constructed. Each wall was reinforced vertically with a No. 4 (M #13) Grade 60 (400 MPa) reinforcing bar in each grouted cell of the CMU. Details of the foundation, top slab and individual walls are provided in Figure 2.

All panels were constructed using recommended construction techniques in accordance with ACI 530.1/ASCE 6/TMS 602, *Specification for Masonry Structures* (ref. 5).



(a) Plan view

(b) Section A-A

Figure 2 - Details of Prison Wall Test Panels

The foundation was constructed first with No. 4 (M #13) Grade 60 vertical dowels placed at an 8-inch (203-mm) spacing and two No. 4 (M #13) Grade 60 horizontal reinforcement around the entire perimeter of the foundation. Once the foundation concrete was placed and allowed to sufficiently cure, the four individual walls were constructed. Every CMU cell in all four walls was reinforced vertically with a No. 4 (M #13) Grade 60 reinforcing bar. Grout was placed and vibrated using a ¾ inch (19 mm) mechanical vibrator. The entire grouted assembly was cured in ambient conditions for 28 days prior to initiation of impact testing.

The five wall assemblies without openings differed in the types of concrete masonry units used and/or the grout strength used. These differences are fully described in Table 2. Three of the walls used normal weight concrete masonry units (with a concrete density of approximately 130 pcf (2,082 kg/m^3)), and the fourth used lightweight units (with a concrete density of 90.5 pcf (1,450 kg/m^3)). A fifth wall was tested with a typical window frame.

Table 2 - Concrete Masonry Wall Assemblies

Wall #	Description [a]	Average Compressive Strength, psi (MPa):		
		Units	Masonry	Grout
1	NW (130.3 pcf, 2,090 kg/m^3), low strength CMU, low strength grout	2,850 (19.65)	2,440 (16.82)	4,040 (27.85)
2	NW (131.6 pcf, 2,110 kg/m^3), high strength CMU, low strength grout	4,820 (33.23)	3,540 (24.40)	3,440 (23.71)
3	NW (131.6 pcf, 2,110 kg/m^3), high strength CMU, high strength grout	4,820 (33.23)	4,390 (30.27)	5,220 (35.99)
4	LW (90.5 pcf, 1,450 kg/m^3), CMU, low strength grout	2,610 (17.99)	2,610 (17.99)	2,880 (19.85)
5	MW (107.3 pcf, 1,720 kg/m^3), CMU, wall with window opening	N/A	N/A	N/A

[a] CMU = concrete masonry unit; NW = normal weight;LW = lightweight per ASTM C 90; mortar used conformed to ASTM C 270 Masonry Cement Type S

When testing the walls without openings, the impacts were applied to the intersection of a bed and head joint at the midpoint of the wall. This location was chosen to be the predicted weak point of the wall assembly. Therefore, using the testing ram, a series of strikes were set against the target area and each strike was within ± 2 in. (51 mm) horizontally and vertically from the designated target area.

For the panel with the typical prison window frame, the window frame was manufactured to meet *Guide Specifications for Detention Security Hollow Metal Doors and Frames*, ANSI/HMMA 863 (ref. 4) as required by ASTM 2322. The nominal dimensions of the frame were 14 in. wide, 38 in. high, with a jamb width of 8 ¾ in (356 x 965 x 222 mm). The window frame was constructed of ¼ in. (6.4 mm) thick steel. The frame came equipped with masonry anchors that accommodated the vertical reinforcing bars in the masonry and then attached to the window frame. Once installed, the hollow area at the jamb was grouted solid. The intent of this impact testing was to check the integrity of the frame-to-masonry connection by striking at a corner of the window frame. Figure 3 shows the prison impact test walls. Figure 4 shows a detail of the window frame.

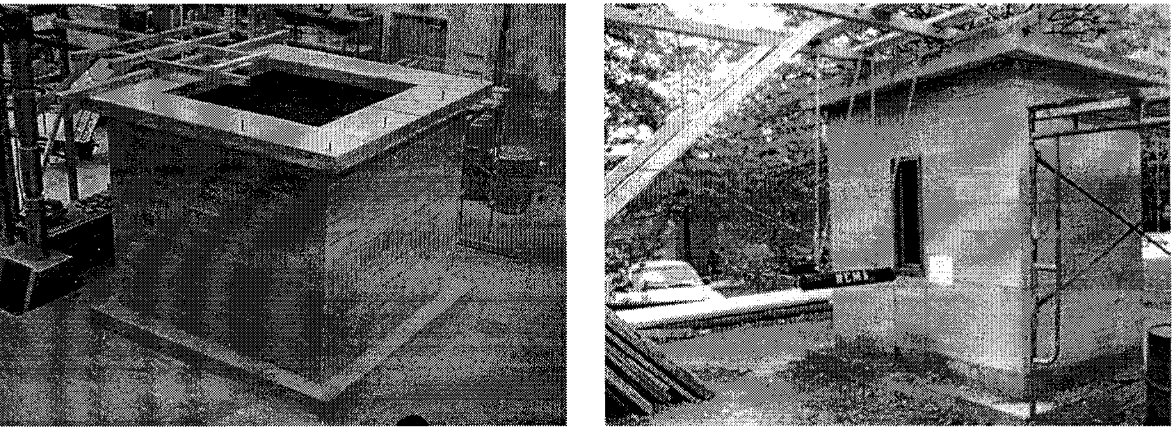


Figure 3 – Prison Impact Test Walls

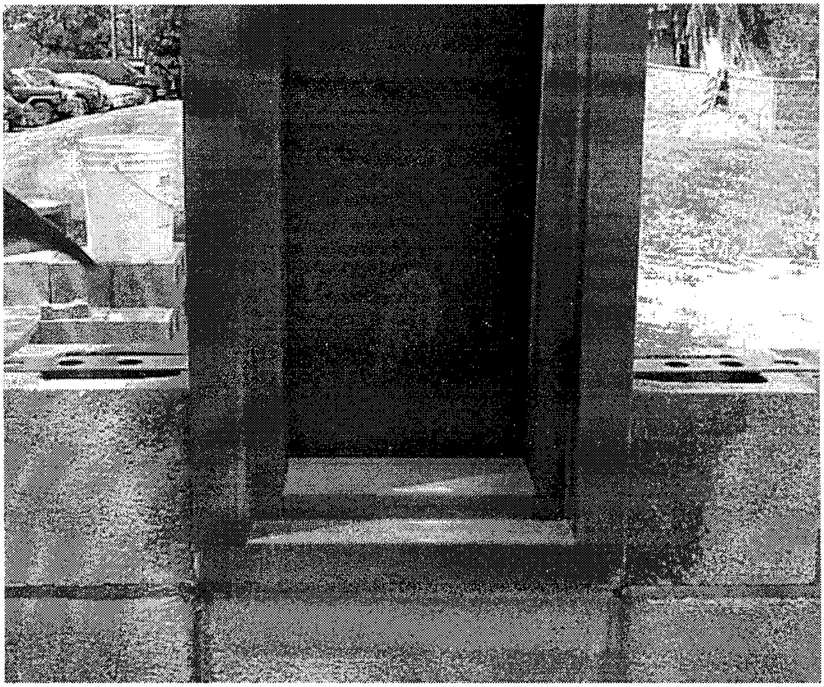


Figure 4 – Detail of Window Frame

RESULTS

For the walls without the window opening, a series of strikes using the testing ram were set against the target area and each strike was within +/- 2 inches (51 mm) horizontally and vertically from the designated target area. A target area was determined to be a head-bed joint intersection, representing a weak intersection of the wall assembly.

Starting with the blunt impactor, the target area was hit with a series of 50 blows. The sharp impactor was used for the next series of 50 blows and the blunt and sharp impactors were subsequently alternated in 50 blow increments until an opening large enough to achieve forcible egress was produced. Figure 5 shows the target area and the amount of damage after 50 blows. All wall assemblies showed similar damage after 50 blows.

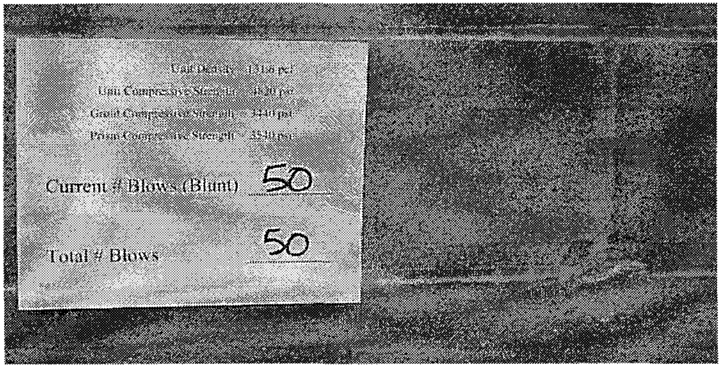
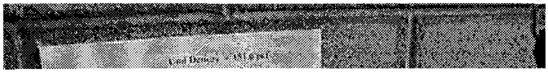
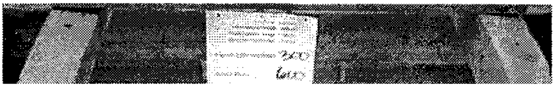


Figure 5 – Test Wall Assembly after 50 Blows

As noted previously, ASTM F 2322 contains security grades for fixed barriers. Grade #1, the most secure, calls for the wall assembly to withstand 600 blows from the blunt and sharp impactor applied in sequences of 50 blows each. This blow count is also equated to a representative barrier duration time of 60 minutes. Wall #1 through #4 were able to withstand the 600 blows and therefore would be designated as a Grade 1 wall in accordance with the ASTM F 2322. Additionally, the rear of each assembly was monitored after each sequence of 50 blows and no damage, included minor cracks, was observed during the 600 blows. Figure 6 shows typical damage after 600 blows of the wall assembly, and Figure 7 the undamaged backside of the wall.





The window frame connection withstood 935 blows from the impactor, exceeding the highest rating of 600 blows found in ASTM F 2322. The testing was stopped after 935 blows because the ram apparatus chain connection became disconnected. The frame damage at 935 blows is shown in the Figure 9.

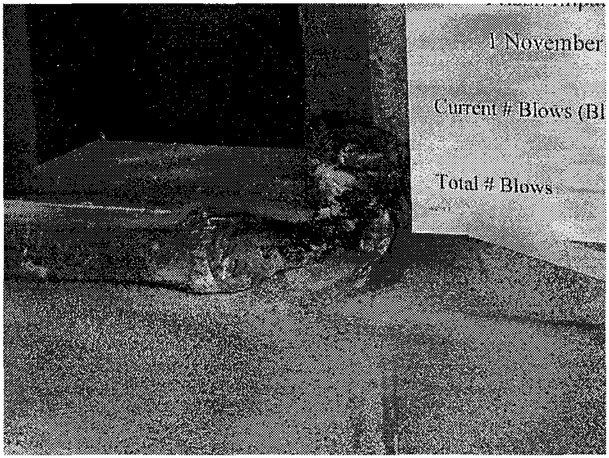


Figure 9- Close-up of Window Frame Damage at 935 Blows

CONCLUSION

Concrete masonry wall specimens were tested using a procedure that simulates attack by a sledgehammer and by a firefighter's axe. This testing is used to model a physical attack by inmates at a correctional facility where a security personnel response has not yet occurred. The test procedure and security requirements are contained in ASTM F2322. The concrete masonry wall specimens in this research were built using solid grouted construction with No. 4 (M #13) reinforcing bars in every cell.

Five concrete masonry wall assemblies were tested (refs. 1, 2), and are described in Table 3. All five concrete masonry walls were able to withstand 600 blows and therefore achieve the Grade 1 rating in accordance with ASTM F 2322. Additionally, the rear side of each wall assembly was monitored after each sequence of 50 blows and no penetration or damage, including minor cracks, was observed during the 600 blows.

Table 3 – 8 in. (203 mm) Concrete Masonry Wall Test Specimens[a]

Wall #	Description	Average Compressive Strength, psi (MPa):			Number of Blows:	Security Grade:	Representative Barrier Duration Time, Min:
		Units	Masonry	Grout			
1	NW (130.3 pcf, 2,090 kg/m^3), low strength CMU, low strength grout	2,850 (19.65)	2,440 (16.82)	4,040 (27.85)	1,134[b]	1	113[d]
2	NW (131.6 pcf, 2,110 kg/m^3), high strength CMU, low strength grout	4,820 (33.23)	3,540 (24.40)	3,440 (23.71)	600[c]	1	60
3	NW (131.6 pcf, 2,110 kg/m^3), high strength CMU, high strength grout	4,820 (33.23)	4,390 (30.27)	5,220 (35.99)	600[c]	1	60
4	LW (90.5 pcf, 1,450 kg/m^3), CMU, low strength grout	2,610 (17.99)	2,610 (17.99)	2,880 (19.85)	924[b]	1	92[d]
5	MW (107.3 pcf, 1,720 kg/m^3), CMU wall with window opening[a]	N/A	N/A	N/A	935[f]	1	93[d]

[a] CMU = concrete masonry unit; NW = normal weight; LW = lightweight per ASTM C 90 (ref. 3); mortar used conformed to ASTM C 270 Masonry Cement Type S (ref. 4)

[b] wall was taken to failure

[c] wall was not taken to failure, testing was terminated at 600 blows

[d] extrapolated from Table 1

[e] phase 2 testing, wall panel with window opening (ref. 2)

[f] window frame was not taken to failure, testing was terminated at 935 blows

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