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Research & Development Information

PCA R&D Serial No. 0882

Structural Thermal Break Systems for Buildings - Feasibility Study

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PCA R&D Serial No. 0882

ORNL/Sub/84-21006/1

STRUCTURAL THERMAL BREAK SYSTEMS

FOR BUILDINGS -

FEASIBILITY STUDY

Final Report

by

S. C. Larson and M. G. Van Geem

Report Prepared by

CONSTRUCTION TECHNOLOGY LABORATORIES, INC.
5420 Old Orchard Road
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under Subcontract No. DE-AC05-84CE-84CE21006

Prepared for
Building Thermal Envelope Systems and Materials Program
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
Operated by
MARTIN MARIETTA ENERGY SYSTEMS INC.
for the
U.S. DEPARTMENT OF ENERGY
Under Contract No.
DE-AC05-84OR21400

March 1987

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes--Printed Copy: A06 Microfiche A01

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

STRUCTURAL THERMAL BREAK SYSTEMS FOR BUILDINGS -

FEASIBILITY STUDY

by

S. C. Larson and M. G. Van Geem*

ABSTRACT

This report presents results from the first phase of a program to investigate lightweight concrete systems for potential use as structural thermal breaks in buildings.

The primary objective of the project is to develop a portland cement concrete with sufficient thermal resistance and strength properties to serve as an effective structural thermal break in building envelopes. Desirable properties of the proposed concrete are a density of less than 50 pcf (800 kg/m^3), a compressive strength of 1000 to 1500 psi (6.9 to 10.3 MPa), and a thermal conductivity of less than 1.5 Btu•in./hr•ft^2•°F (0.22 W/m•K).

The first phase of work, presented in this report, is a feasibility study to identify uses for the lightweight portland cement concrete. The report is subdivided into three sections. Section 1 presents suggested assemblies where lightweight concrete can be used in place of steel, other metal, or normal weight concrete to prevent thermal bridges or thermal bypasses. Potential uses for the proposed lightweight concrete include exterior walls, interior walls, columns, chimneys, foundations, and floor slabs. Thermal conductivity of the proposed lightweight concrete is approximately 1/10th that of normal weight concrete and 1/100th that of steel.

Section 2 presents analyses using the Building Loads Analysis and System Thermodynamics (BLAST) computer program. Analyses were performed to determine annual energy use for a one-story commercial building and a three-story residential building with 8-in. thick walls constructed with the proposed lightweight concrete. Results were compared to previous investigations of conventional wall systems to determine potential energy savings of the lightweight concrete wall system. Results from the commercial building modeled with lightweight concrete walls indicated lower total annual load than a commercial building with metal wall systems of the same thermal resistance, for all cities considered in the BLAST analysis. Analysis of the residential building modeled with lightweight concrete walls indicated lower total annual load than a residential building with wood frame walls of the same thermal resistance. Results indicate the benefits of the thermal storage capacity of the lightweight concrete.

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Section 3 of the report presents a review of standards criteria to determine whether an 8-in. (200-mm) thick wall constructed of the lightweight concrete meets minimum energy requirements for exterior walls.

Based on the BLAST analyses and building standard requirements, the proposed lightweight concrete exterior wall system exceeds minimum thermal performance criteria for commercial and residential buildings in most regions of the continental United States.

EXECUTIVE SUMMARY

A significant amount of energy is lost from conditioned environments of buildings through thermal bridges. Reduction of energy loss can be achieved by providing thermal break materials in place of high conductivity materials that create thermal bridges.

The purpose of this project is to investigate lightweight concrete systems for potential use as structural thermal breaks in buildings.

The program was conducted at Construction Technology Laboratories, Inc. (CTL). The project is sponsored jointly by the U.S. Department of Energy (DOE) Office of Buildings and Community Systems, and the Portland Cement Association. It is part of the Building Thermal Envelope Systems and Materials Program (BTESM) at Oak Ridge National Laboratory (ORNL).

A thermal break is an element made of a material with a high thermal resistance used in place of a material with a lower thermal resistance to reduce energy losses through a building envelope. A thermal break may range in size from a small plastic nail used in place of a metal nail, to a large sheet of insulation used to prevent energy losses through a building foundation. The term "structural" used as an adjective to "thermal break" implies the material has load-bearing capabilities.

The primary objective of this project is to develop a portland cement concrete with sufficient thermal resistance and strength properties to serve as an effective thermal break in building envelopes. The project goal is to develop a concrete with a density of less than 50 pcf (800 kg/m^3), a compressive strength of 1000 to 1500 psi (6.9 to 10.3 MPa), and a thermal conductivity of less than 1.5 $Btu \cdot in./hr \cdot ft^2 \cdot °F$ (0.22 $W/m \cdot K$). The most commonly used concrete, normal weight concrete, has a density of approximately 145 pcf

(2320 kg/m^3), a compressive strength in the range of 2500 to 6000 psi (17 to 41 MPa), and a thermal conductivity of 12 to 16 Btu•in./hr•ft^2•°F (1.7 to 2.3 W/m•K). Lightweight concretes have not been previously developed with the combination of low density and moderate strength proposed for this project.

Although it is envisioned that the proposed lightweight concrete could be used for many building components, project emphasis is to evaluate the concrete for use in exterior walls for low-rise buildings. The portland cement concrete developed for this project will combine the structural, thermal insulation, and heat storage capacity functions of exterior walls in one element. For many climates the concrete developed can be used as a complete wall system in low-rise buildings without the need for additional insulation.

The project is divided into five major tasks. This report summarizes results of Task 1, which is a feasibility study to identify uses for the proposed lightweight portland cement concrete in buildings. Task 2 includes work to select materials and mix designs for the lightweight portland cement concrete and a lightweight polymer concrete. Physical and thermal properties of candidate concretes will be determined in Task 3. Casting and surface finishing techniques for the most desirable mixes will be developed in Task 4. Task 5 includes measuring thermal performance of full-size wall assemblies constructed of the developed portland cement concrete. Results from Tasks 2 through 5 will be presented in future reports.

This report, a feasibility study to identify uses for the lightweight portland cement concrete, is subdivided into three sections. Section 1 presents suggested assemblies where lightweight concrete can be used in place of steel, other metal, or normal weight concrete to prevent thermal bridges or thermal bypasses. Potential uses for the proposed lightweight concrete include exterior walls, interior walls, columns, chimneys, foundations, and floor slabs. Thermal conductivity of the proposed lightweight concrete is approximately 1/10th that of normal weight concrete and 1/100th that of steel.

Section 2 presents analyses using the Building Loads Analysis and System Thermodynamics (BLAST) computer program. Analyses were performed to determine annual energy use for a one-story commercial building and a three-story residential building with 8-in. thick walls constructed with the proposed lightweight concrete. Results were compared to previous investigations of conventional wall systems to determine potential energy savings of the lightweight concrete wall system.

Walls used for comparison of commercial building energy loads were metal, normal weight concrete with exterior insulation, and normal weight concrete with interior insulation. Results from the commercial building modeled with lightweight concrete walls indicated lower total annual load than a commercial building with metal wall systems of the same thermal resistance, for all cities considered in the BLAST analysis.

Residential building energy loads for the lightweight concrete wall system were compared to similar buildings with wood frame construction, all concrete masonry construction, and two intermediate configurations of wood-frame and concrete-masonry construction. Analysis of the residential building modeled with lightweight concrete walls indicated lower total annual load than a residential building with wood-frame walls of the same thermal resistance.

Results of the BLAST analysis indicate the benefits of thermal storage capacity of the lightweight concrete. The advantage of the lightweight concrete system compared to the alternative concrete and masonry systems is that an R-value of 6.18 $hr \cdot ft^2 \cdot °F/Btu$ (1.09 m^2 K/w) can be achieved without added insulation.

Section 3 of the report presents a review of the ANSI/ASHRAE/IES Standard 90A-1980 for residential and commercial buildings to determine whether an 8-in. (200-mm) thick wall constructed of the lightweight concrete meets minimum energy requirements for exterior walls. The standard's requirements were evaluated for fourteen cities representing all climatic regions of the continental United States. Building characteristics were assumed to be the same as those for buildings analyzed in the BLAST investigation. The lightweight concrete wall system meets the standard's requirements for the commercial building considered in all fourteen selected cities. For the residential building, the lightweight concrete wall system meets the standard's requirements for all selected cities except Minneapolis.

Based on the BLAST analyses and building standard requirements, the proposed lightweight concrete exterior wall system exceeds minimum thermal performance criteria for commercial and residential buildings in most regions of the continental United States.

STRUCTURAL THERMAL BREAK SYSTEMS FOR BUILDINGS - FEASIBILITY STUDY

by

S. C. Larson and M. G. Van Geem*

INTRODUCTION

The purpose of this project is to investigate lightweight concrete systems for potential use as structural thermal breaks in buildings. A thermal break is an exterior building element made of a material with a high thermal resistance used in place of a material with a lower thermal resistance to reduce energy losses through a building envelope. A thermal break may range in size from a small plastic nail used in place of a metal nail, to a large sheet of insulation used to prevent energy losses through a building foundation. The term "structural" used as an adjective to "thermal break" implies the material has load bearing capabilities.

The primary project objective is to develop portland cement concrete with sufficient thermal resistance and strength properties to serve as an effective thermal break in building envelopes. The project goal is to develop a concrete with a density of less than 50 pcf (800 kg/m^3), a compressive strength of 1000 to 1500 psi (6.9 to 10.3 MPa), and a thermal conductivity of less than 1.5 Btu•in./hr•ft^2•°F (0.22 W/m•K). Although it is envisioned that concrete with these properties could be used for many building components, project emphasis is to evaluate the concrete for use in exterior walls for low-rise buildings.

*Respectively, Structural Engineer, Analytical Design Section, and Senior Research Engineer, Fire/Thermal Technology Section, Construction Technology Laboratories, Inc., Skokie, Illinois 60077

The portland cement concrete developed for this project will combine the structural, thermal insulation, and heat storage capacity functions of exterior walls in one element. For many climates the concrete developed can be used as a complete wall system in low-rise buildings without the need of additional insulation.

A secondary project objective is to develop a polymer concrete with sufficient thermal resistance and strength to serve as a thermal break material. The polymer concrete would be used to provide a thermal insulating layer adjacent to conventional construction materials whereas the portland cement concrete would be used either as an insulating layer or as an entire component such as a wall.

The program was conducted at Construction Technology Laboratories, Inc. (CTL). The project is sponsored jointly by the U.S. Department of Energy (DOE) Office of Buildings and Community Systems, and the Portland Cement Association. It is part of the Building Thermal Envelope Systems and Materials Program (BTESM) at Oak Ridge National Laboratory (ORNL). Work was authorized by a contract signed September 25, 1984 by Walker K. Love. The DOE Project Manager is Dr. George E. Courville, (ORNL).

OBJECTIVES AND SCOPE

The project is divided into five major tasks. This report summarizes results of Task 1, which is a feasibility study to identify uses for the proposed lightweight portland cement concrete in buildings. Task 2 includes work to select materials and mix designs for the lightweight portland cement and lightweight polymer concretes. Physical and thermal properties of candidate concretes will be determined in Task 3. Casting and surface finishing techniques for the most desirable mixes will be developed in Task 4. Task 5 includes measuring thermal performance of full size wall assemblies constructed of the developed portland cement concrete. Results from Tasks 2 through 5 will be presented in future reports.

The objective of this report, which covers Task 1 activities, is threefold:

1. To describe potential uses for the lightweight portland cement concrete as a thermal break material in buildings elements, such as exterior walls, interior walls, columns, chimneys, foundations, and floor slabs.

2. To calculate annual heating and cooling loads for a residential building and a commercial building modeled with the lightweight concrete wall system. Analyses are performed using the Building Loads Analysis and System Thermodynamics (BLAST)[(1)*] computer program for six cities in the United States. Results are compared to BLAST program studies[(2,3)] of buildings with conventional wood and metal wall systems to determine potential energy savings from using the lightweight concrete wall system.

3. To determine whether the lightweight concrete wall system meets minimum energy requirements for exterior walls from ANSI/ASHRAE/IES Standard 90A 1980.[(4)] The criteria is evaluated for residential and commercial buildings for fourteen cities in the United States.

BACKGROUND

Thermal Bridges, Bypasses, and Breaks

A significant amount of energy is lost from conditioned environments of buildings through thermal bridges. Awareness of thermal bridges is increasing in the building community. Recently, a report entitled "A Survey of Building Envelope Thermal Anomalies and Assessment of Thermal Break Materials for

*Superscript numbers in parentheses refer to references listed at the end of this report.

Anomaly Correction"[5] was prepared by Dynatech R/D Company for the U.S. Department of Energy. This report defines thermal bridges, thermal bypasses, and thermal breaks as follows:

> Thermal bridges are BETAs [Building Envelope Thermal Anomalies] that are caused solely by heat conduction. Included in this category are the following broad classifications:
>
> - Structural Elements
> - Component Connections
> - Envelope Penetrations
> - Corner Effects
> - Faulty Workmanship
>
> Thermal bypasses are BETAs that are caused by convective or radiative effects. Included are the broad categories:
>
> - Interior Cavities
> - Exterior Wall Defects
> - Hollow Wall Convection
> - Conduit/Pipe Convection Paths
>
> Thermal breaks are any arrangements of building configuration or materials that will eliminate or reduce a heat loss path...

The lightweight concrete developed for this project could serve as thermal break material when used in place of normal weight concrete or steel. Table 1 presents the thermal conductivity values for selected building materials. The data show the thermal conductivity of the proposed lightweight concrete material is approximately 1/10th that of normal weight concrete and 1/100th that of steel.

The lightweight concrete will not have a thermal conductivity as low as some traditional insulating materials. However, the thermal resistance of lightweight concrete components will be about the same as the thermal resistance of many insulated components because the concrete components will be thicker than conventionally used insulation systems. Additionally, lightweight concrete has improved storage capacity compared to traditional insulating materials. Finally, the lightweight concrete will have structural capabilities that cannot be achieved with conventional insulation materials.

TABLE 1 - THERMAL CONDUCTIVITY OF SELECTED BUILDING MATERIALS

Material	Thermal Conductivity	
	$\frac{Btu \cdot in.}{hr \cdot ft^2 \cdot {}^\circ F}$	$\frac{W}{m \cdot K}$
Traditional Insulating Materials	0.20-0.50[6]	0.03-0.07
Proposed Lightweight Concrete	1.5	0.22
Normal Weight Concrete	12-16[6,7]	1.7-2.3
Steel	180-330[6,8]	26-48

Types of Concrete

Concrete is available in a wide range of weights and strengths. Normal weight concrete utilizes sand and gravel aggregate and is most commonly used for construction of structural concrete members. Normal weight concretes have a unit weight of approximately 145 pcf (2320 kg/m^3), and compressive strengths of approximately 2500 to 6000 psi (17 to 41 MPa) are common. High strength normal weight concretes have been developed with strengths exceeding 15,000 psi (100 MPa).

Concretes in the 90 to 130 pcf (1440 to 2080 kg/m^3) range are known as structural lightweight aggregate concretes. These concretes have compressive strengths in the range of 2500 to over 9000 psi (17.2 to over 62.1 MPa), depending on materials, mix design and other factors.

A second category of lightweight concretes is in the unit weight range of 50 to about 90 pcf (800 to about 1440 kg/m^3). These are usually called fill concretes. Concretes in this weight range have not been widely used.

Concretes weighing 50 pcf (800 kg/m^3) or less are called insulating concretes. Current technology limits the compressive strengths of these concretes to about 600 psi (4.1 MPa). The project objective is to develop concretes in the 45 to 55 pcf (720 to 800 kg/m^3) range that not only have sufficient insulative properties, but also have strength to meet the design requirements of exterior walls of low-rise buildings.

Thermal Properties of Concrete

Aggregates are available in a wide range of unit weights to make the concrete with a desired unit weight. The thermal conductivity of concrete is dependent on the constituent aggregate, and to a lesser extent, the cement paste. Generally, concrete conductivity increases exponentially with unit weight.

Concrete with a unit weight of 50 pcf (800 kg/m^3) has a thermal conductivity of approximately 1.5 Btu•in./hr•ft^2•°F (0.22 W/m•K) while concrete with a unit weight of 140 pcf (2240 kg/m^3) has a thermal conductivity of approximately 16 Btu•in./hr•ft^2•°F (2.3 W/m•K).[7]

Heat flow through a homogeneous wall subjected to steady-state temperature conditions is linearly related to the thermal conductivity of the wall material and the temperature differential across the wall. For dynamic temperature conditions, heat flow is dependent on the storage capacity of the wall material in addition to its thermal conductivity.

Exterior building walls are seldom in a steady-state condition. Outdoor air temperatures and solar effects cause cyclic changes in outdoor surface temperatures.

Conditioned buildings with massive walls will have less energy losses to the outdoor environment than the same building with low mass walls of equivalent thermal resistance. Energy savings are most significant for outdoor diurnal temperature cycles that cause reversals in heat flow through walls.

Optimally, the least heat will flow through a wall with high thermal resistance and high storage capacity. Heat transmission properties are more sensitive to changes in thermal resistance than to changes in storage capacity. The goal of this project is to develop a concrete with the highest resistance or lowest unit weight. The concrete unit weight is limited by the need for sufficient structural capacity, because strength decreases with decreasing unit weight.

Previous Work

Construction Technology Laboratories, Inc. developed a new energy-conserving concrete for Battelle Pacific Northwest Laboratory in 1984 as part of the Buildings Innovative Concepts Program sponsored by the U.S. Department of Energy.[9] Expanded clay and shale coarse aggregates were used with expanded polystyrene beads and expanded perlite fine aggregates to obtain concretes having air-dry unit weights in the range of 60 to 65 pcf (960 to 1040 kg/m^3) and compressive strengths of approximately 2000 psi (14 MPa). Specific heats and thermal conductivities of small scale specimens were also determined.

SECTION 1 - POTENTIAL LIGHTWEIGHT CONCRETE USES

It is proposed that lightweight concrete being developed for this project will serve as thermal break material when used in place of steel, other metal, or normal weight concrete.

Potential uses for the lightweight concrete are divided into the following six categories of building components.

1. Exterior walls
2. Interior walls
3. Columns
4. Chimneys
5. Foundations
6. Floor slabs

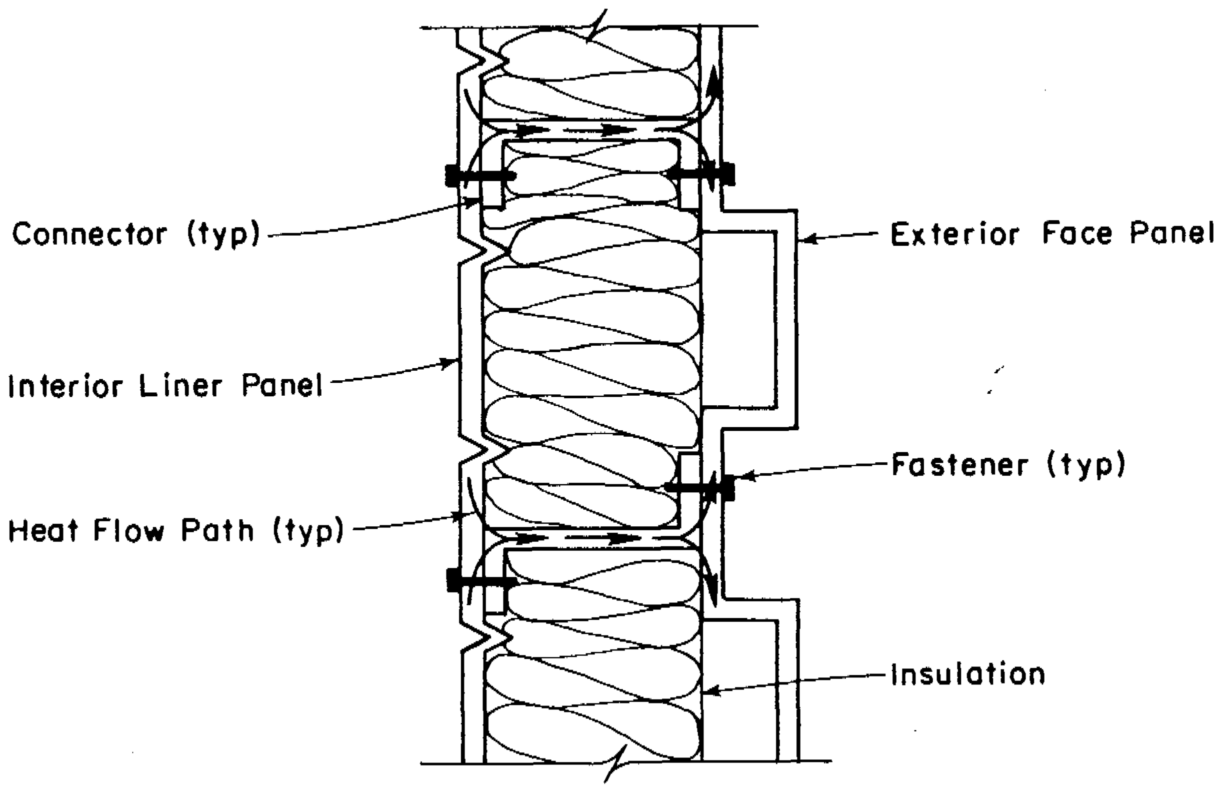
It should be noted that this report does not present the magnitude of heat loss for all thermal bridges and bypasses given as examples. Actual heat loss through a bridge, for instance, will primarily depend on the relative cross-sectional area of the bridge, the thermal conductivity of the bridge material, the thermal conductivity of the surrounding insulating material, and the given temperature conditions.

Detailed descriptions of thermal breaks and thermal bypasses, including many of those presented in this report, are given in Ref. 5.

Exterior Walls

Thermal Bridges

Metal connectors or other elements that penetrate an insulation layer act as thermal bridges when their conductivity is large compared to insulation. Figures 1 through 5 show examples of thermal bridges that can be eliminated by using a wall constructed with the proposed lightweight concrete.



PLAN VIEW

Fig. 1 Thermal Bridge Through Insulated Metal Wall (Adapted from Ref. 5)

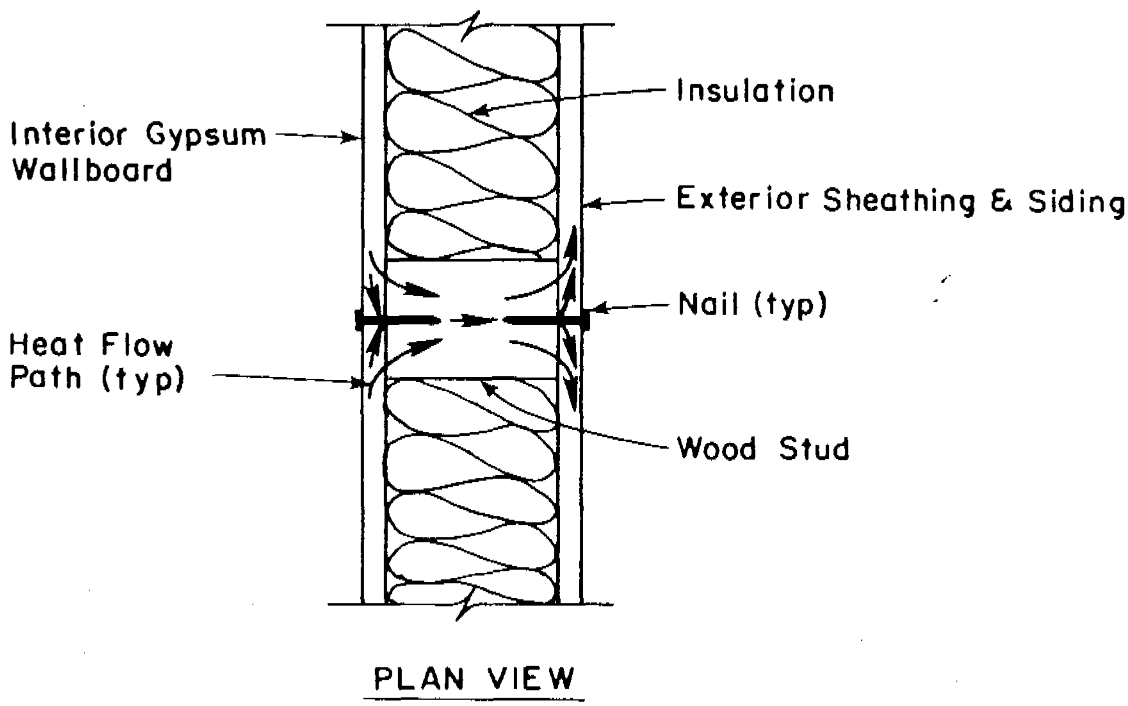


Fig. 2 Thermal Bridge Through Insulated Frame Wall (Adapted from Ref. 5)

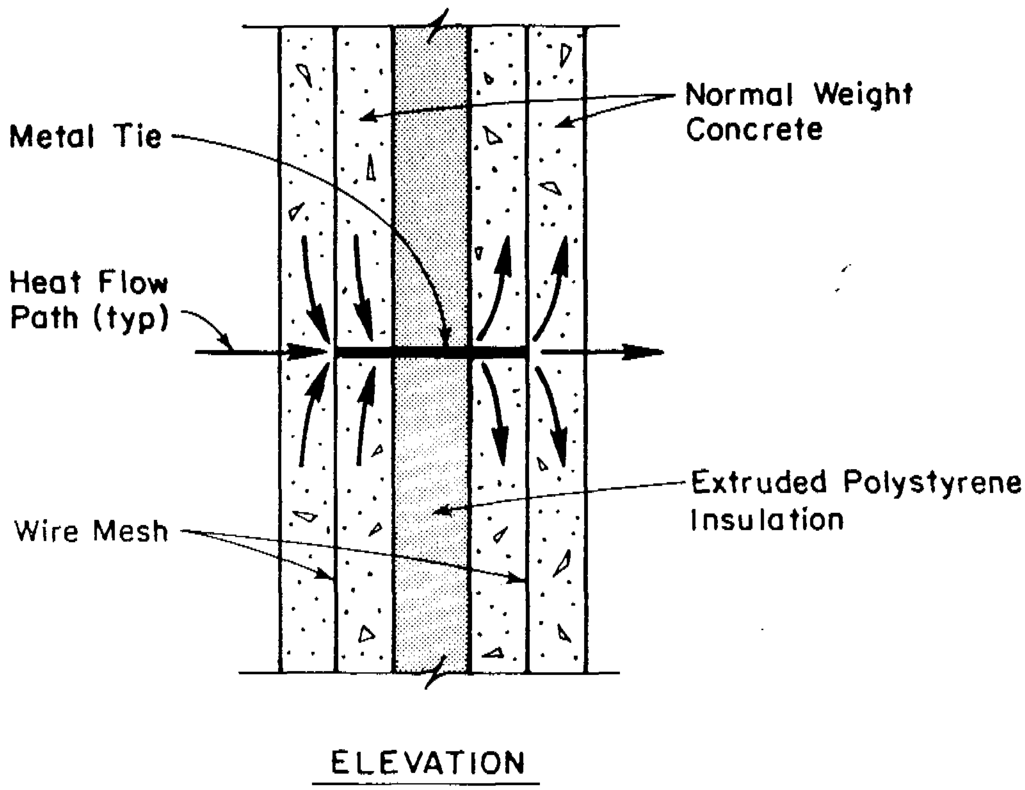


Fig. 3 Thermal Bridge Through Insulated Concrete Sandwich Panel Wall

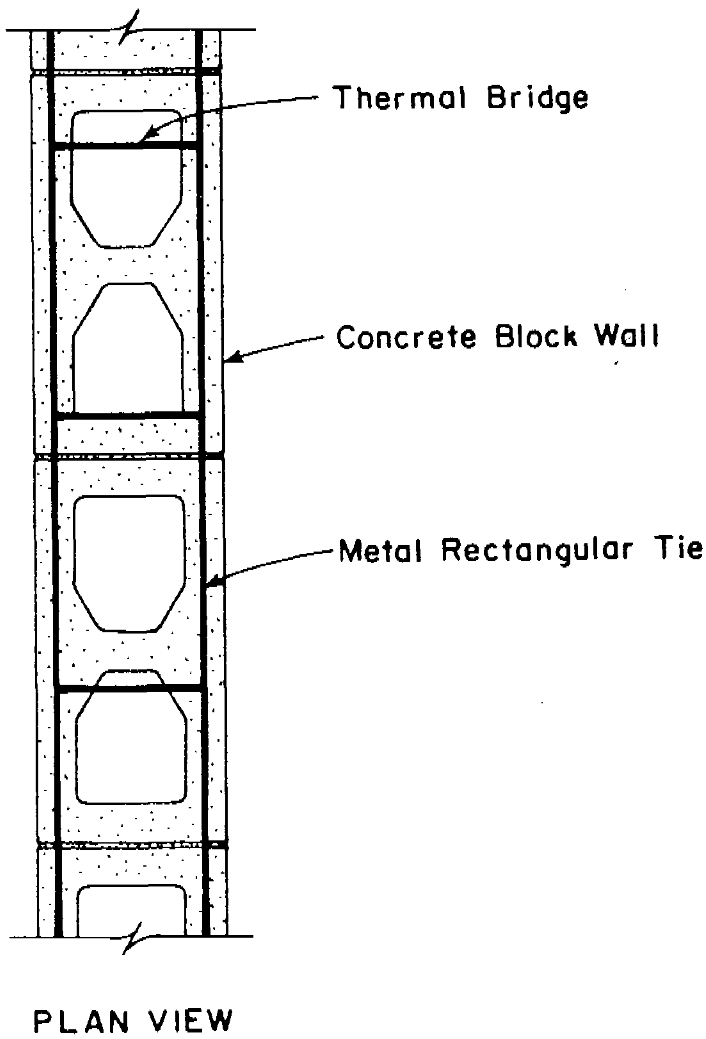
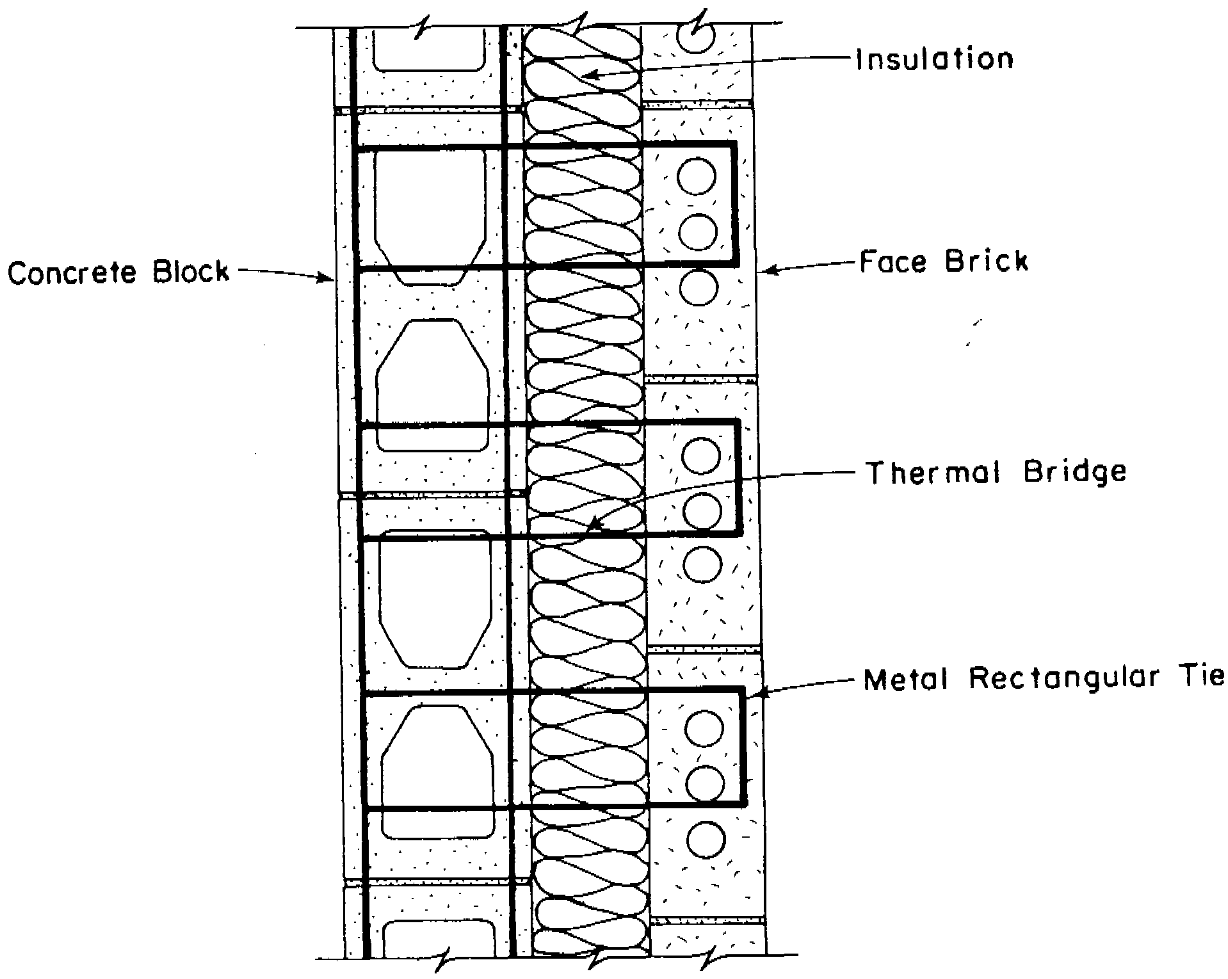


Fig. 4 Thermal Bridge Through Masonry Wall



PLAN VIEW

Fig. 5 Thermal Bridge Through Insulated Masonry Cavity Wall

Insulated metal walls generally consist of exterior and interior metal panels separated by insulation as shown in Fig. 1. Channels or clips that connect metal panels act as thermal bridges. Heat flows along a highly conductive metal panel through connectors and to the opposite panel. The lateral heat flow along the metal panel is called the fin effect.

Thermal bridges in wood frame walls are caused by wood studs and nails as shown in Fig. 2.

Insulated concrete sandwich panel walls consist of a layer of insulation sandwiched between two layers of concrete. Metal ties or fasteners, shown in Fig. 3, are often used to connect the three layers to provide stability and load transfer. Heat flows laterally along the concrete panels. Heat losses are concentrated at the metal ties, which act as thermal bridges.

Figures 4 and 5 show metal rectangular ties used to reinforce masonry walls and insulated concrete masonry walls, respectively. The ties that are parallel to heat flow act as thermal bridges.

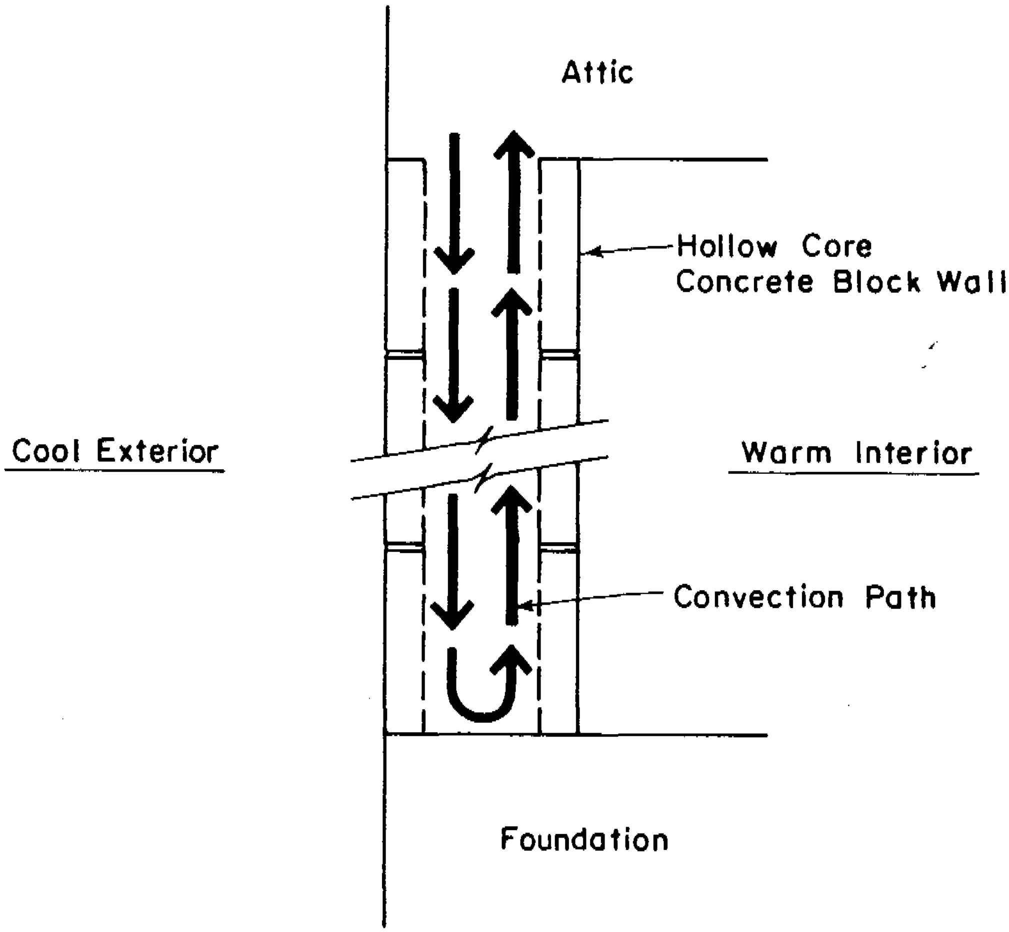
Thermal Bypasses

Thermal bypasses can occur in wall cavities that connect to unconditioned portions of a building. Figures 6 and 7 show examples of thermal bypasses within an uninsulated hollow core concrete block wall and a poorly insulated frame wall, respectively. Thermal bypasses may also occur within metal walls when insulation does not completely fill the volume between the liner and face panels.

Heat is transferred by conduction through the interior wall surface and then by convection up to an unconditioned attic or down to a foundation.

Lightweight Concrete Wall

An 8-in. (200-mm) thick wall constructed using the proposed lightweight concrete will eliminate thermal bridges and bypasses shown in Figs. 1 through 7. The homogeneous wall has no air cavities to cause thermal bypasses. The



ELEVATION

Fig. 6 Thermal Bypass Through Hollow Core Concrete Block Wall (Adapted from Ref. 5)

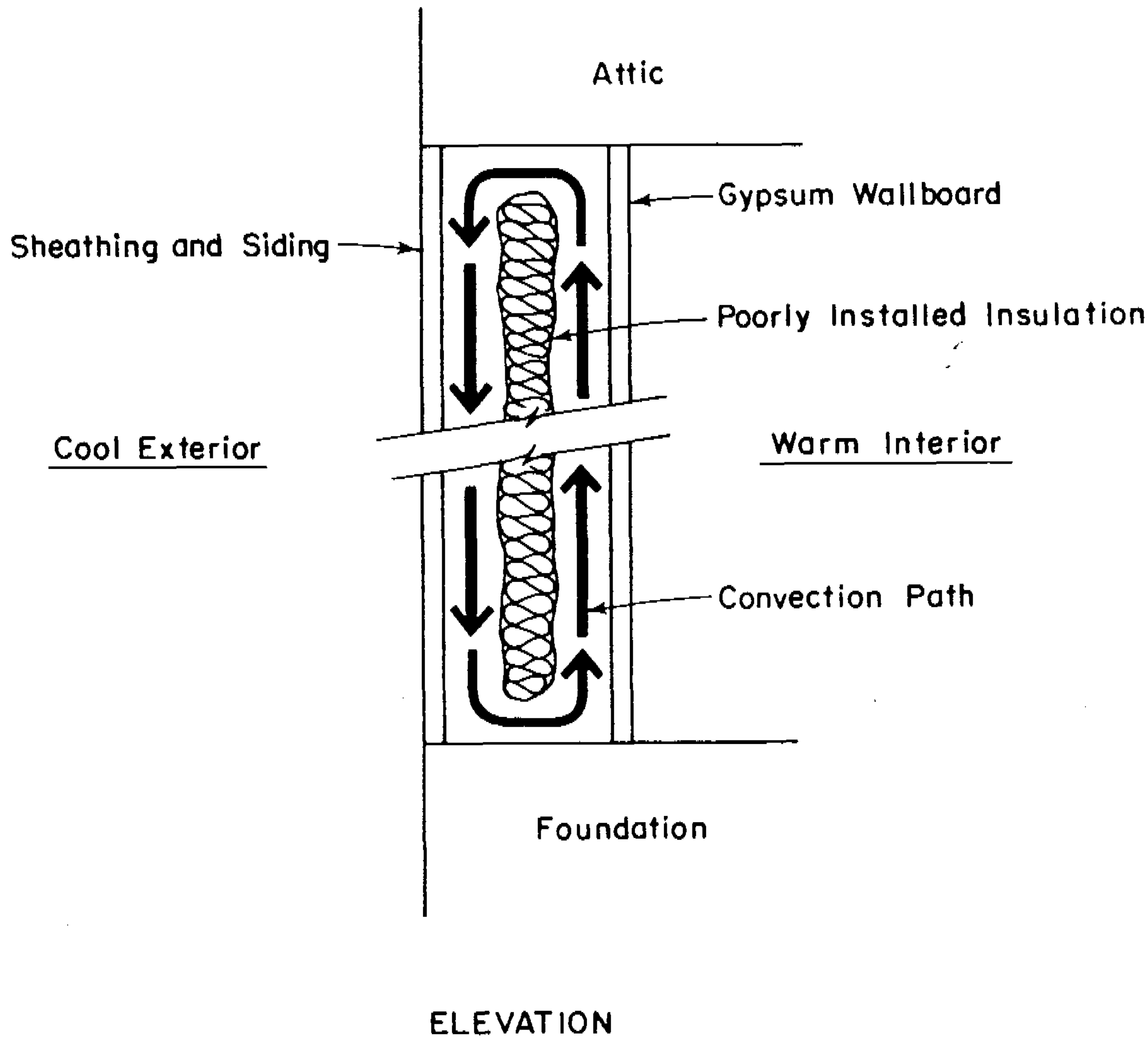


Fig. 7 Thermal Bypass Through Poorly Insulated Frame Wall (Adapted from Ref. 5)

wall construction does not require metal parallel to heat flow, which causes thermal bridges. Although the wall will require reinforcement as shown in Fig. 8, this reinforcement is perpendicular to heat flow and does not create thermal bridging.

Interior Walls

Uninsulated frame walls and hollow core block walls used as interior walls can create thermal bypasses similar to those shown in Figs. 6 and 7 for exterior walls. An example of a multi-story thermal bypass is a concrete block party wall that extends from a foundation up to an attic. Heat is conducted through the block face shells to the hollow cores. The heat is then transferred by convection to the unconditioned attic or foundation. Heat is lost by convection through the attic and by conduction through the foundation.

An 8-in. (200-mm) thick wall constructed using the proposed lightweight concrete will eliminate a thermal bypass due to an interior wall since the homogeneous wall has no air cavities.

Columns

Common building materials for structural columns include normal weight reinforced concrete and structural steel. Columns made from these materials result in thermal bridging when one face is in contact with a conditioned environment and one or more other faces are exposed to an unconditioned environment. Using the proposed lightweight structural concrete for exterior columns will reduce heat loss from the conditioned air spaces.

A simplified comparative analysis was performed to assess the effect of thermal bridges through columns. In this example, columns with a 12-in. sq (300-mm sq) cross sectional area were assumed spaced 20 ft (6.1 m) on centers as shown in Fig. 9(a). The parallel path calculation method[6] was used to

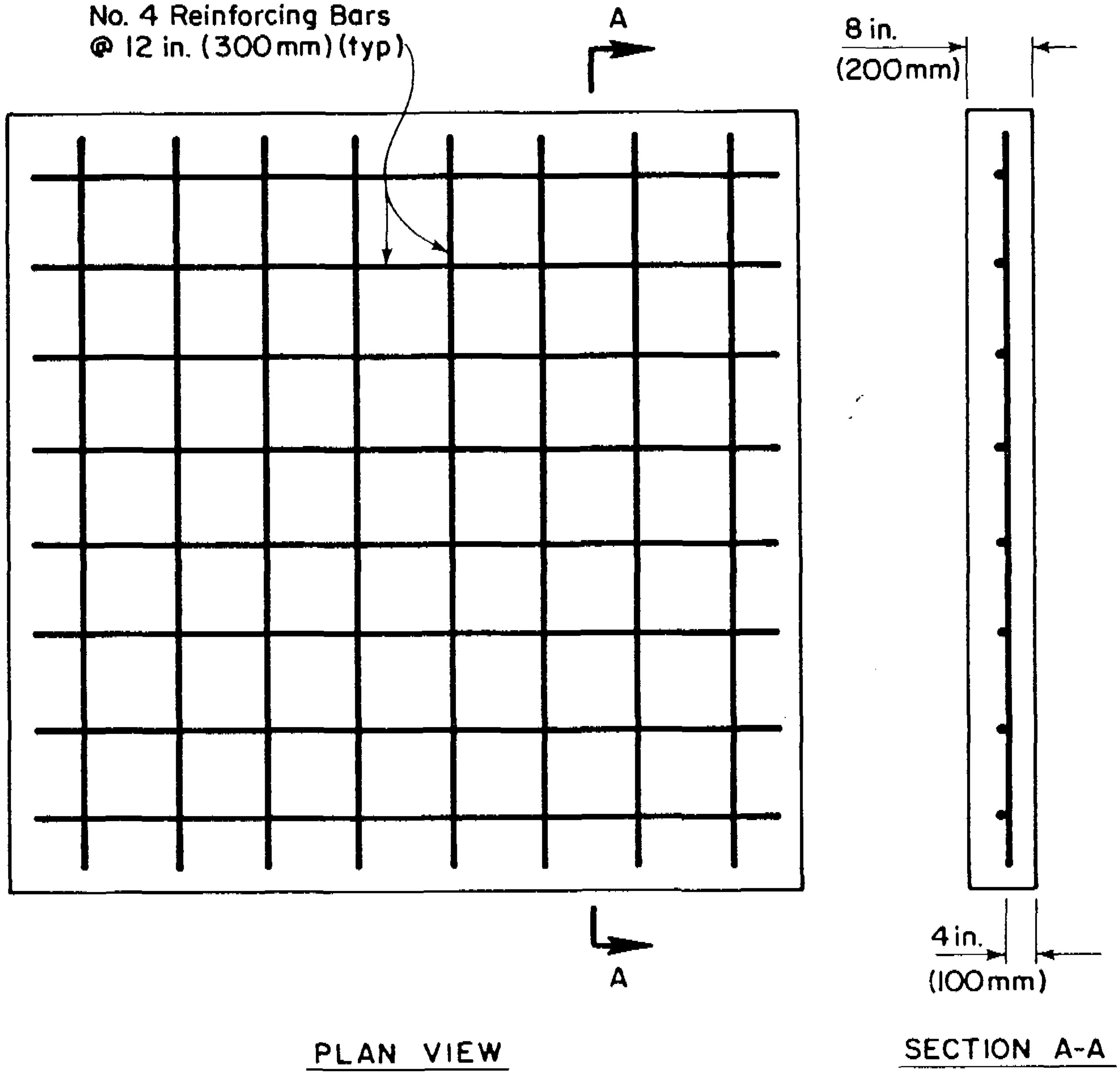
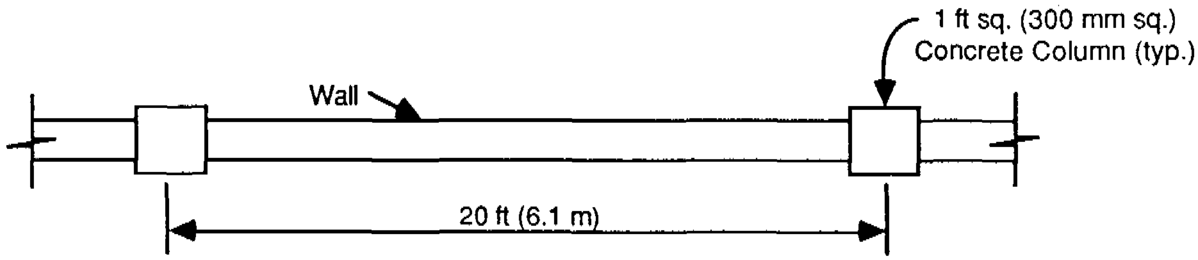
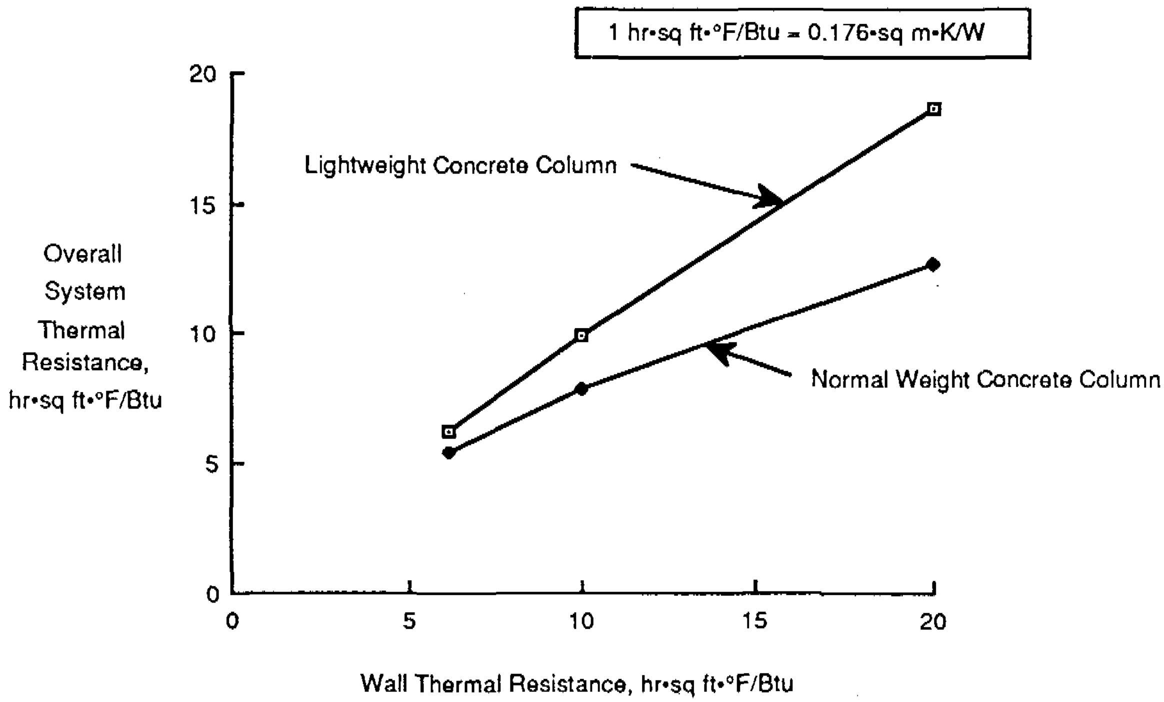


Fig. 8 Typical Reinforcement for 8-in. (200-mm) Lightweight Concrete Wall



(a) Plan View of Column / Wall System



(b) Comparing Thermal Resistances of Wall / Column Systems with Normal Weight and Lightweight Concrete Columns

Fig. 9 Thermal Bridge Through Column

compare the wall/column system performance assuming normal weight and lightweight columns, and various wall resistances. Thermal conductivities for the normal weight and lightweight concretes, respectively, were assumed to be 16 and 1.5 Btu•in./hr•ft^2•°F (2.3 and 0.22 W/m•K). Calculations neglect the effect of any steel reinforcement parallel to heat flow.

Actual column sizes are generally determined from structural loading conditions. Lightweight and normal weight concrete columns designed for the same loading conditions may not be the same size since the concretes have different physical properties. A lightweight concrete column may need to be larger in size than a normal weight concrete column for the same loading conditions. The example is conservative since a larger lightweight column would have a larger resistance than the 12-in. (300-mm) column assumed.

Figure 9(b) shows significantly reduced thermal resistance for the wall/column system when normal weight concrete columns are used. Use of the lightweight concrete in columns significantly increases the system thermal resistance, particularly for walls with high thermal resistance.

Use of the lightweight concrete will also reduce thermal bridges through columns that penetrate roof insulation. One example is a building with 12-in. sq (300-mm sq) normal weight concrete columns spaced 20 ft (6.1 m) on centers, extending above a roof to support window washing equipment. Overall roof thermal resistance is reduced by a factor of 2 over a 4 ft sq (1.22 m sq) area around a column due to the normal weight concrete thermal bridge.[10] The proposed lightweight concrete could be designed to support the window washing equipment loads. This would significantly reduce the thermal bridge present in the normal weight concrete column system even if the lightweight concrete column had a crossectional area 100% larger than the normal weight concrete column.

Chimneys

Masonry chimneys as shown in Fig. 10 represent a thermal bridge similar to the one previously discussed for columns penetrating roof insulation. The proposed lightweight concrete may be used in lieu of masonry to reduce thermal bridging through chimneys and other roof penetrations. Chimneys may be either precast or cast-in-place. Research would need to be performed to assess the proposed concrete's durability at high temperatures, for freeze-thaw conditions, and for exposure to chemical environments.

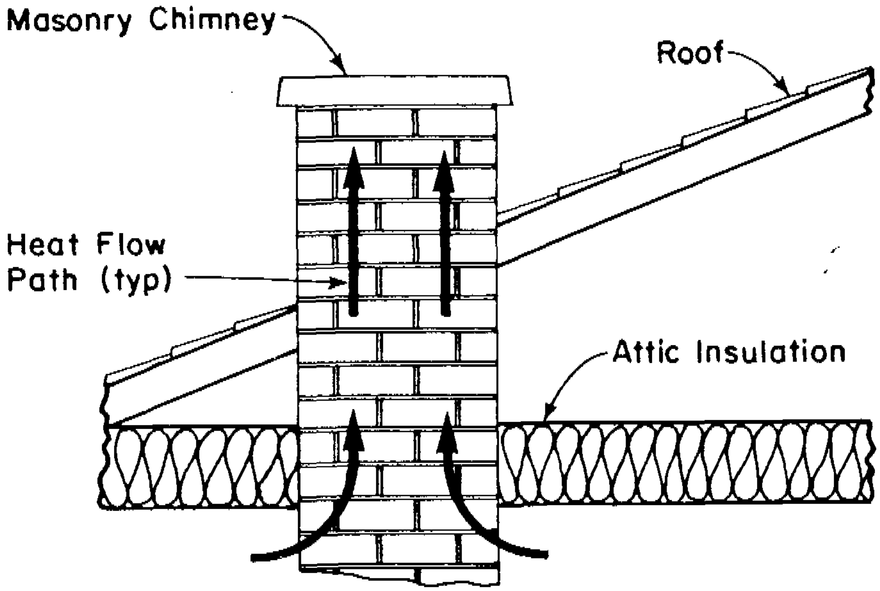
Foundations

Thermal bridging may also occur through structural members in thermal contact at concrete foundation walls. Heat loss through wood or metal framing, a floor joist, a sill, and a normal weight concrete foundation is shown in Fig. 11. Figure 12 shows the same type of heat loss through a normal weight concrete floor slab in thermal contact with a foundation. Use of the proposed lightweight concrete for foundations would reduce this type of thermal bridging. More research would need to be performed to assess the proposed concrete's durability for ground contact conditions.

Floor Slabs

A thermal bridge may also be formed when a beam or floor penetrates an exterior wall to form an exterior balcony as shown in Fig. 13. Using the lightweight concrete would reduce heat losses at the exterior wall. However, steel reinforcement parallel to heat flow is required for this application. The steel would contribute to thermal bridging.

The lightweight concrete could also be used in place of normal weight concrete for basement floors or slab-on-grade foundations to reduce heat losses to the ground. More research would need to be performed to assess the proposed concrete's abrasion resistance and durability for impact loading.



ELEVATION

Fig. 10 Thermal Bridge Through Masonry Chimney (Adapted from Ref. 5)

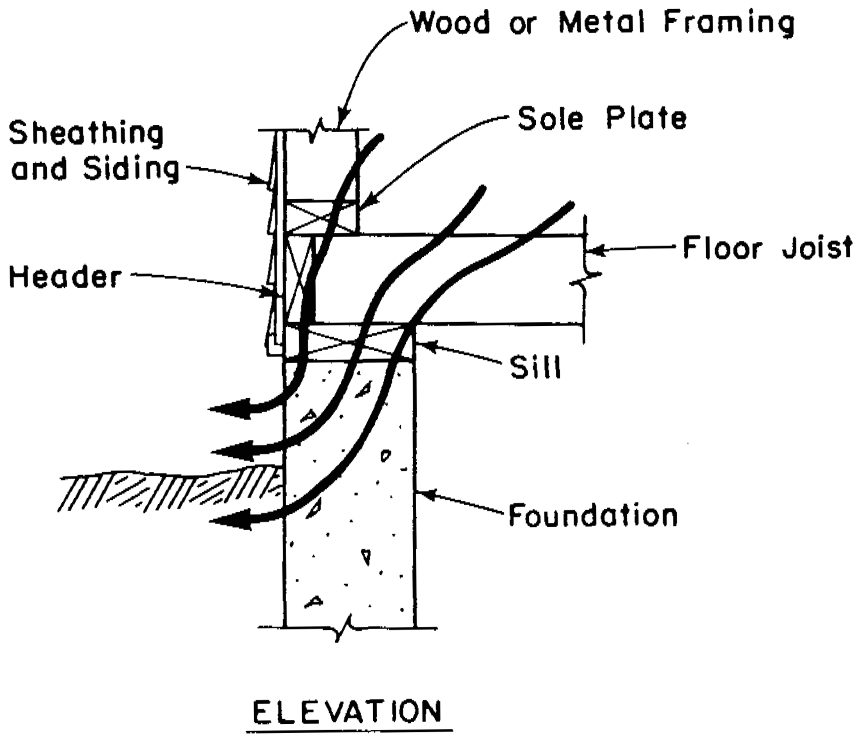


Fig. 11 Thermal Bridge Through Floor Joist, Sill, and Foundation

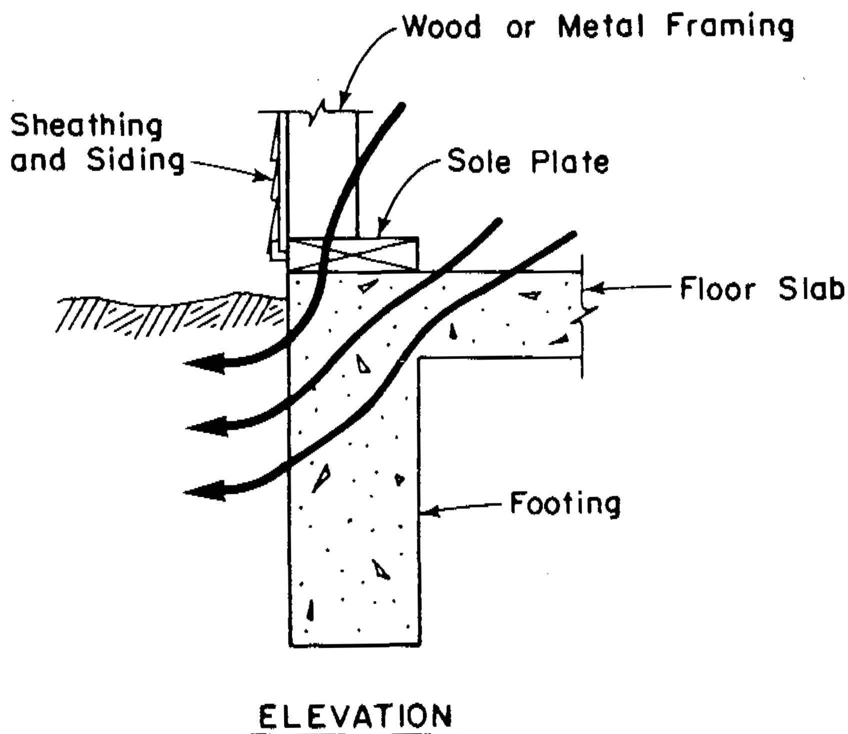
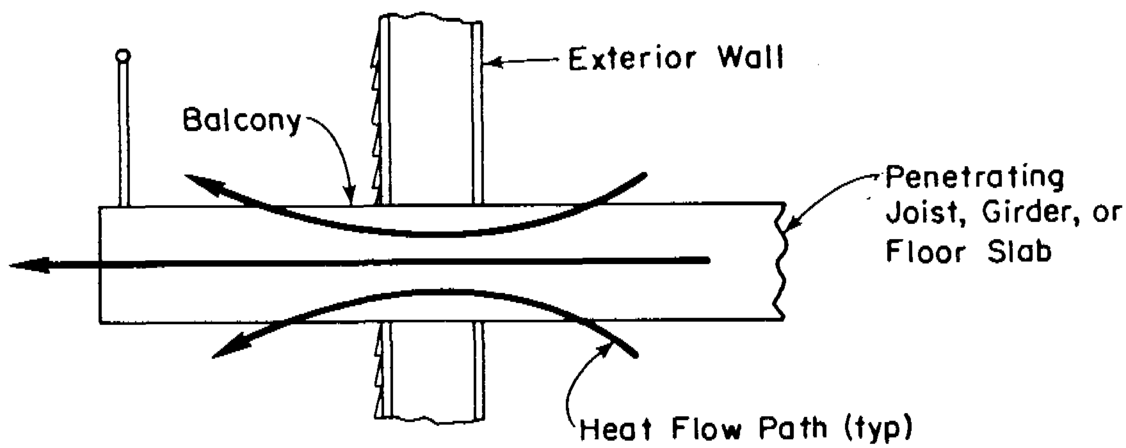


Fig. 12 Thermal Bridge Through Concrete Floor Slab and Foundation



ELEVATION

Fig. 13 Thermal Bridge Through Floor Slab
Extending to Balcony

Other Considerations

The proposed lightweight concrete material has enough strength to be load-bearing in certain applications, but has a thermal conductivity significantly lower than commonly used structural materials. The concrete would be used primarily in new buildings either as precast or cast-in-place components.

Later reports for this project will include physical and thermal properties tests related to using the concrete in exterior walls. Research is needed to determine suitability of the concrete for other proposed uses previously described. For example, additional durability tests are needed to determine adequacy for foundations, chimneys, and floors. Also, some building codes require structural and fire tests on full size building components before the material can be used.

SECTION 2 - BLAST COMPUTER ANALYSES

Analyses were conducted using the BLAST computer program to determine annual heating and cooling loads of residential and commercial buildings with walls composed of the proposed lightweight concrete. The two buildings selected were a one-story commercial building and a three-story apartment building. These buildings were each analyzed for six cities in the United States. Results were compared to previous BLAST program studies[2,3] of buildings with conventional wood and metal wall systems to determine potential energy savings from using the lightweight concrete wall system.

Annual heating and cooling loads determined from the BLAST analysis include the effects of heat storage capacity of building elements. Comparisons of the lightweight concrete wall system to alternative systems show the benefits of heat storage capacity in the exterior envelopes of buildings. Realistic assessments of building energy use must include the effects of thermal mass as well as thermal resistance of wall components.

The analysis was carried out using the Building Loads Analysis and System Thermodynamics (BLAST)[1] computer program. This program determines annual heating and cooling loads based on an hour-by-hour analysis for a full year. Climatic data were obtained from Test Reference Year[11] weather tapes. For this investigation, only the loads portion of the BLAST program was used.

Building Descriptions

Commercial Building

The commercial building analyzed in this investigation is shown in Figs. 14 and 15. The one-story building had slab-on-grade construction with 20,000 sq ft (1900 m^2) of floor area. The 4-in. (100-mm) thick slab-on-grade was assumed to be normal weight concrete.

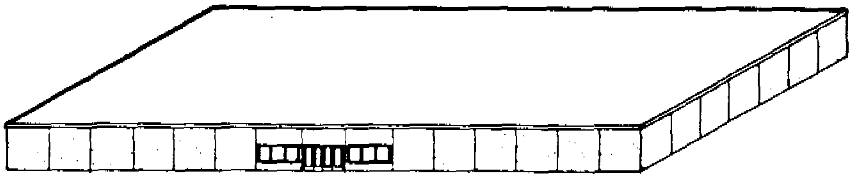


Fig. 14 Commercial Building Isometric(2)

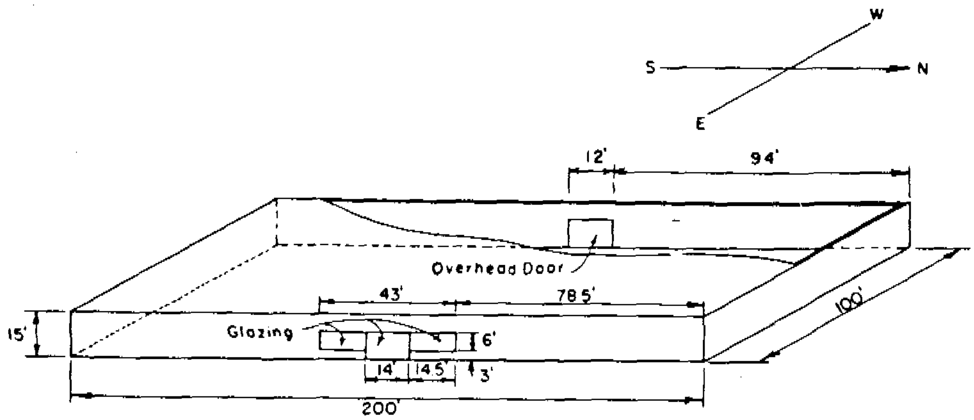


Fig. 15 Commerical Building Geometry(2)

Windows and door glazing comprised approximately 10% of the surface area of the east wall. No windows were placed on the north, south, and west walls.

The building had a flat roof consisting of open-web steel joists, metal deck, rigid board insulation, and built-up roofing. Roof construction is shown in Figure 16. Roof insulation was selected to satisfy the requirements of ASHRAE Standard 90A-1980.(4) A light colored roof with an absorptivity of 0.5 was used at locations having less than 4000 heating degree days. A dark colored roof with an absorptivity of 0.9 was used at locations having more than 4000 heating degree days. Acoustical tile, 3/4-in. (19-mm) thick, was used as an inside ceiling finish for all roof constructions.

For the feasibility study, performance of a building with lightweight concrete walls is compared to performance of a building with metal exterior wall systems analyzed in a previous study.(2)

The lightweight concrete wall was 8-in. (200-mm) thick and had no interior or exterior finishes. The concrete was assumed to have a unit weight of 50 pcf (800 kg/m^3) and thermal conductivity of 1.5 $Btu \cdot in./hr \cdot ft^2 \cdot °F$ (0.22 $W/m \cdot K$). The total R-value of the lightweight concrete wall was 6.18 $hr \cdot ft^2 \cdot °F/Btu$ (1.09 $m^2 \cdot K/W$). This includes surface resistance coefficients of 0.68 $hr \cdot ft^2 \cdot °F/Btu$ (0.12 $m^2 \cdot K/W$) on the indoor side and 0.17 $hr \cdot ft^2 \cdot °F/Btu$ (0.03 $m^2 \cdot K/W$) on the outdoor side. These values are commonly used in design and represent still air on the indoor wall surface and an air flow of 15 mph (24 km/hr) on the outdoor wall surface.

Wall systems evaluated in the previous study are shown in Figure 17. Concrete walls were 8-in. (200-mm) thick and constructed of normal weight concrete. Thermal and physical properties of the concrete were based on those measured in a laboratory investigation using a calibrated hot box. The interior finish of the wall was 1/2-in. (13-mm) gypsum board. Exterior finish was stucco. Rigid-board insulation was placed between the concrete and gypsum board for walls

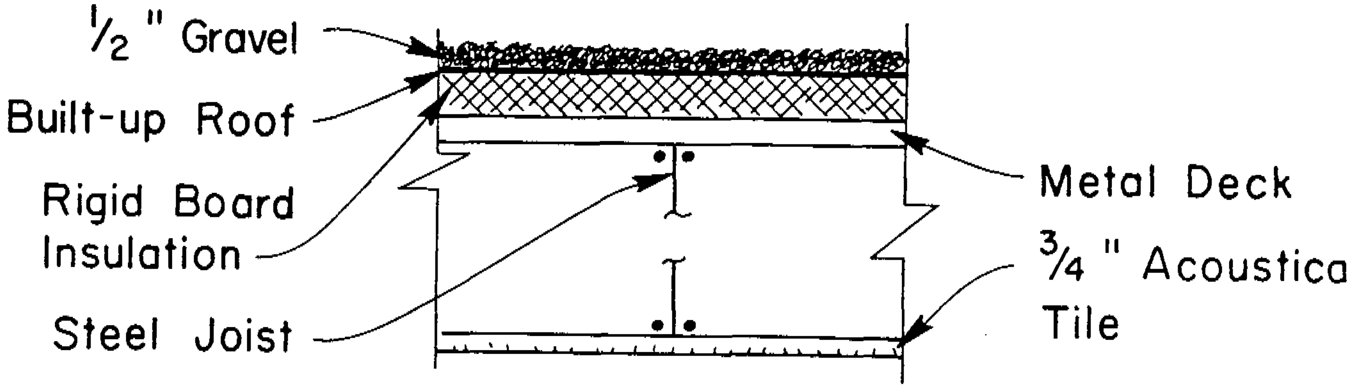
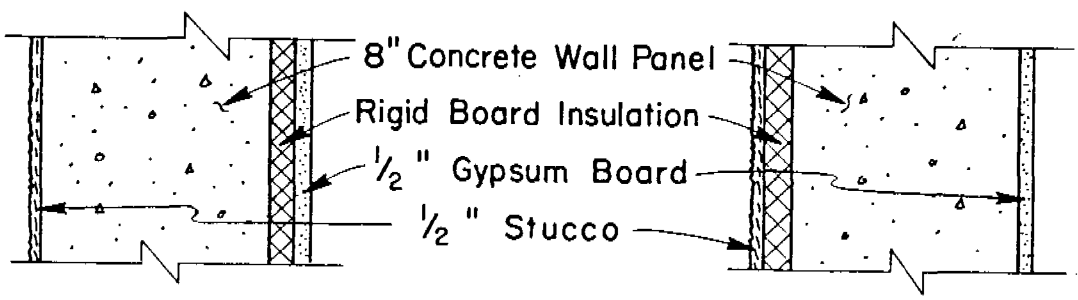
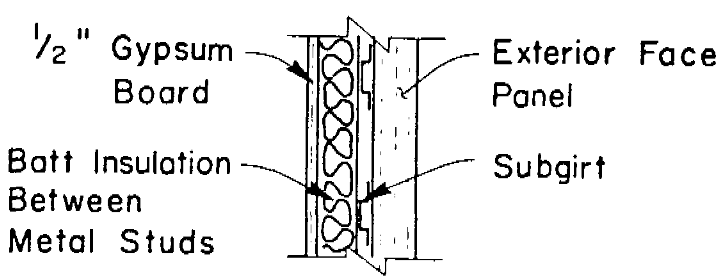


Fig. 16 Commercial Building Roof Construction(2)



(a) Concrete Wall with Interior Insulation

(b) Concrete Wall with Exterior Insulation



(c) Metal Wall

Fig. 17 Commercial Building Wall Constructions From Previous Study(2) insulated on the inside. Insulation was placed between concrete and stucco for walls insulated on the outside. The thickness of insulation was varied to obtain several wall R-values.

Metal wall systems consisted of exterior metal siding supported by steel girts. The inside was finished with 1/2-in. (13-mm) gypsum board supported by steel studs. Insulation was located between the studs. This construction is typical of that found in metal buildings. The thickness of insulation was varied to obtain several wall R-values.

Building occupancy and operational profiles were based on those specified for shopping centers in the Standard Building Operating Conditions of the Building Energy Performance Standards (BEPS)[12] issued by the Department of Energy. Assumed values for occupancy and lighting heat gains are shown in Table 2.

The inside temperature during occupied periods was allowed to fluctuate between 67°F (19°C) and 76°F (24°C) without mechanical heating or cooling. Mechanical heating was activated when the inside temperature dropped below 67°F (19°C) and mechanical cooling was activated when the inside temperature rose above 76°F (24°C). During unoccupied periods, the inside temperature was allowed to drop to 62°F (17°C). There was no upper temperature limit during unoccupied periods.

Heat losses through the slab-on-grade were calculated using ground temperatures and soil resistances as described in Appendix E of the BLAST Program Users Manual.[1]

Extra levels of mass for furnishings and merchandise were not included in the BLAST analysis so that results could be compared to a previous study of the same building with different exterior wall systems.[2]

TABLE 2 - COMMERCIAL BUILDING INTERNAL HEAT GAINS ASSUMED FOR ANALYSIS

Source	Peak Value, kBtu/hr (kW)	Hourly Average, kBtu/hr (kW)
Occupancy	384* (113)	104 (30.5)
Lighting	205** (60.0)	85 (25)

*600 people
**10.2 Btu/hr•ft^2 (32.3 W/m^2)

Residential Building

The low-rise multifamily residential building analyzed in this investigation is shown in Fig. 18. This three-story apartment building had 18,000 sq ft (1700 m^2) total floor area. A typical floor plan is shown in Fig. 19.

Windows on the north and south walls comprised about 10% of the area of these walls. Sliding glass doors and windows on the east and west walls totaled approximately 26% of the area of these walls. Shading was provided on the east and west sides by 6-ft (2-m) balconies for the lower floors and 6-ft (2-m) overhangs for the top floor. No shading was provided on the north and south walls. Double glazing was used in all windows and doors.

For the feasibility study, performance of the building with lightweight concrete walls is compared to performance of the building with wood frame exterior walls analyzed in a previous study.(3) Floor, roof, and interior partition construction vary depending on exterior wall construction.

The lightweight concrete wall was 8-in. (200-mm) thick and had no interior or exterior finishes. The concrete was assumed to have a unit weight of 50 pcf (800 kg/m^3) and thermal conductivity of 1.5 $Btu{\cdot}in./hr{\cdot}ft^2{\cdot}°F$ (0.22 $W/m{\cdot}K$). The total R-value of the lightweight concrete wall including surface resistances was 6.18 $hr{\cdot}ft^2{\cdot}°F/Btu$ (1.09 $m^2{\cdot}K/W$).

Roof construction of the building with lightweight concrete exterior walls consisted of built-up roofing on rigid-board insulation supported by 8-in. (200-mm) precast hollow-core slabs as shown in Fig. 20. Roof thermal resistance values, listed in Table 3, satisfied the minimum requirements of the HUD Minimum Property Standards for Multi-Family Housing (HUD-MPS)(13) for each location.

Floor construction consisted of 8-in. (200-mm) precast normal weight concrete hollow-core slabs with padded carpeting as the floor finish. Ground

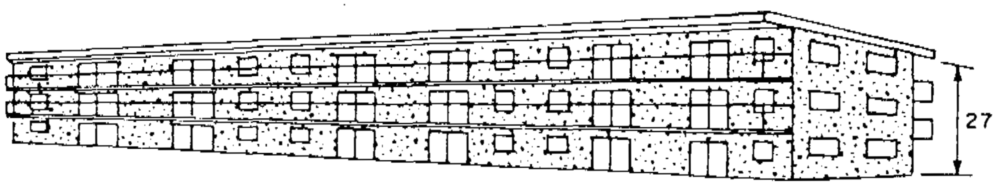


Fig. 18 Residential Building Isometric (3)

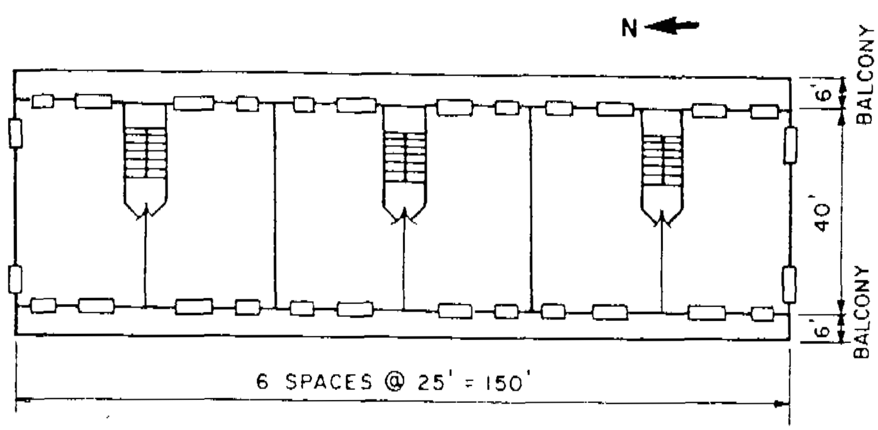


Fig. 19 Typical Floor Plan of Residential Building (3)

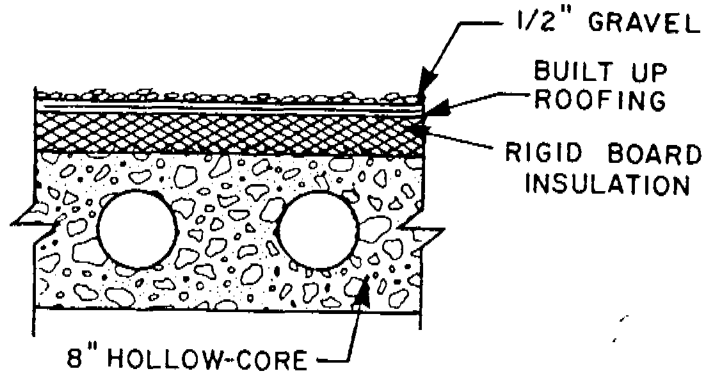


Fig. 20 Precast Concrete Hollow-Core Roof for Residential Building (3)

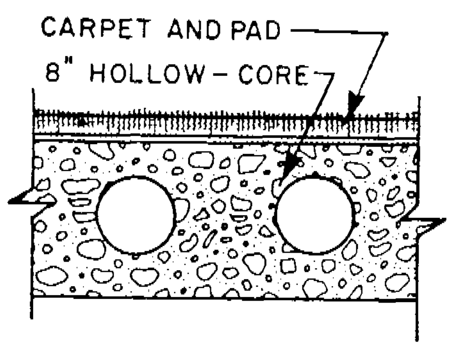


Fig. 21 Precast Concrete Hollow-Core Floor for Residential Building (3)

TABLE 3 - ROOF THERMAL RESISTANCE VALUES USED FOR RESIDENTIAL BUILDING

Location	Thermal Resistance R-Value, hr•ft^2•°F/Btu (m^2•K/W)
Atlanta	10.1 (1.78)
Chicago	10.1 (1.78)
Phoenix	11.1 (1.95)
Seattle	8.6 (1.51)
Tampa	11.2 (1.97)
Washington, D.C.	10.1 (1.78)

floor construction consisted of carpet with padding over a 5-1/2-in. (140-mm) normal weight concrete slab on grade. Concrete floor and slab-on-grade constructions are shown in Figs. 21 and 22, respectively. Thermal resistances of the carpeted floor and carpeted slab-on-grade, respectively, were 2.84 and 1.91 hr•ft^2•°F/Btu (0.50 and 0.34 m^2•K/W) not including air film resistances.

Heat losses through the slab-on-grade were calculated using ground temperatures and soil resistances as described in Appendix E of the BLAST Program Users Manual.[1]

Interior partition construction consisted of 4x8x16-in. (100x200x400-mm) concrete masonry between apartments and wood frame partitions within apartments. These partitions are shown in Fig. 23.

The three-story, 18-unit apartment building analyzed in this investigation was modeled as three zones, one for each floor. A zone is a conditioned space with a particular set of both control and functional parameters and envelope and partition construction. For this investigation, no heat transfer was permitted between adjacent zones. However, building components separating zones could store and release heat.

For a previous study,[3] a nine-zone building subjected to Altanta temperature conditions was modeled using high-mass and low-mass building components to determine the effect of zoning. Each floor in these buildings had three zones--two end zones representing the end apartments and a third zone representing the typical interior apartments. The comparison indicated that the building could be modeled as three zones without significant loss of accuracy in determining annual heating and cooling loads. Detailed results of the comparison are reported in Reference 3.

The total mass of the building with lightweight concrete exterior walls was 138 lbs per sq ft of floor area (676 kg/m^2). Total building mass includes

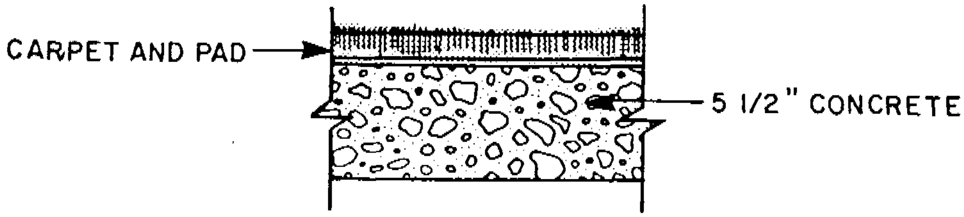
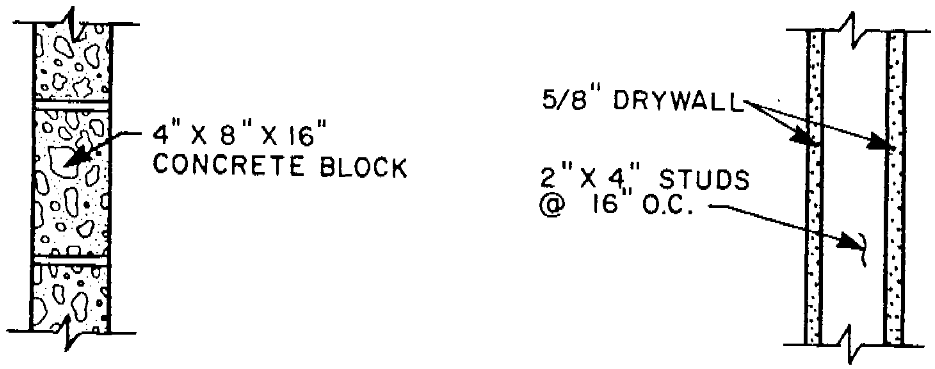


Fig. 22 Slab on Grade for Residential Building [3]



(a) Concrete Masonry [3]

(b) Wood-Frame [3]

Fig. 23 Partition Walls for Residential Building From Previous Study [3] total weight of walls, floors, partitions, and slab on grade. The building had internal mass of 116 lbs per sq ft of floor area (568 kg/m^2). Internal mass includes the mass of floors (excluding slab-on-grade), partitions, and that portion of exterior walls and roofs not insulated from the living space. Extra levels of mass for furnishings and possessions were not included in the BLAST analysis so that results could be compared to a previous study of the same building with different exterior wall systems.[3]

A previous study[3] investigated the performance of this three-story apartment building having different combinations of wood frame and concrete component constructions with varying amounts of thermal mass. Table 4 summarizes combinations of building components analyzed. Combinations A through D in Table 4 correspond to building thermal mass levels from the highest to the lowest of those considered. The level of internal mass associated with each combination is listed in Table 4.

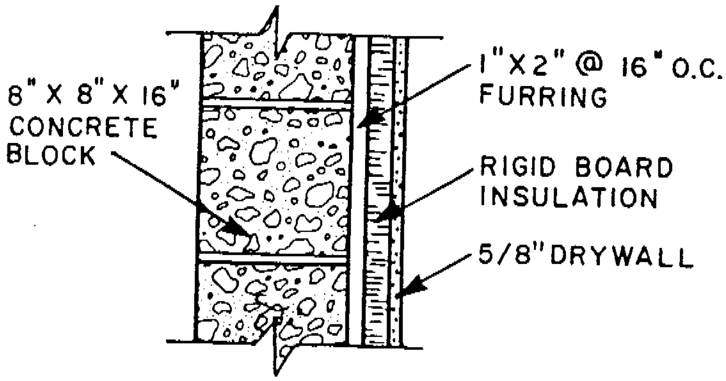
Masonry and wood frame exterior wall constructions are shown in Fig. 24. Wood-frame wall construction consisted of 2x4-in. (50x100-mm) studs at 16 in. (400-mm) on center covered with 5/8-in. (16-mm) drywall on the interior and sheathing and siding on the exterior. A wall R-value of 4.8 $hr \cdot ft^2 \cdot °F/Btu$ (0.85 $m^2 \cdot K/W$), the minimum considered in this investigation for wood-frame construction, was achieved by using 1/2-in. (13-mm) fiberboard sheathing and no batt insulation. An R-value of 12.2 $hr \cdot ft^2 \cdot °F/Btu$ (2.15 $m^2 \cdot K/W$) was achieved by replacing the fiberboard with 1/2-in. (13-mm) plywood sheathing and providing R-11 batt insulation between the studs. A wall R-value of 21.3 $hr \cdot ft^2 \cdot °F/Btu$ (3.75 $m^2 \cdot K/W$), the maximum considered in this investigation, was achieved by using 1-in. (25-mm) rigid-board insulation as sheathing and R-13 batt insulation between the studs.

TABLE 4 - COMBINATION OF COMPONENTS FOR RESIDENTIAL BUILDING[3]

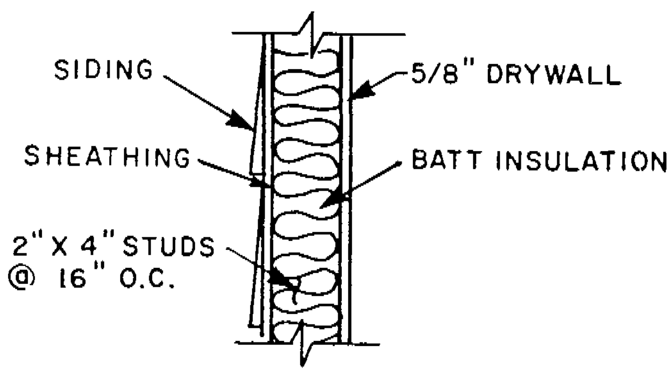
Combination	Total Bldg. Mass,* psf (kg/m^2)	Internal Mass,** psf (kg/m^2)	Building Components		
			Floors and roof	Exterior walls	Interior partitions
A	154.2 (752.9)	80.7 (394)	Hollow-core	Concrete masonry	Concrete masonry
B	106.2 (518.5)	31.7 (155)	Wood-frame	Concrete masonry	Concrete masonry
C	88.5 (432)	14.0 (68.4)	Wood-frame	Concrete masonry	Wood-frame
D	73.0 (356)	14.4 (70.3)	Wood-frame	Wood-frame	Wood-frame

*Total building mass includes total weight of walls, floors, partitions, roof, and slab on grade. Units are per square foot of floor area.

**Internal mass includes mass of floors (except slab-on-grade), partitions, and roofs (that portion of the roof in direct contact with the living space). It also includes exterior wall mass not insulated from the living space. Slab-on-grade mass was included in the BLAST analyses but not in this table because this value was constant for all combinations. Mass of building furnishings and household possessions were not included in the BLAST analyses. Units are per square foot of floor area.



(a) Concrete Masonry



(b) Wood-Frame

Fig. 24 Exterior Wall Constructions for Residential Building From Previous Study (3)

Concrete masonry exterior wall construction consisted of single-wythe 8x8x16-in. (200x200x400-mm) concrete masonry units. On the inside, 5/8-in. (16-mm) dry wall and reflective-foil-backed rigid-board insulation were nailed to 1x2-in. (25x50-mm) furring strips at 16 in. (400-mm) on center. Use of furring strips created a 3/4-in. (20-mm) reflective air space between the insulation and masonry surfaces. Wall R-values of 9.4 and 15.4 $hr \cdot ft^2 \cdot °F/Btu$ (1.7 and 2.7 $m^2 \cdot K/W$) were achieved by using 1/2-in. (13-mm) and 1-1/4-in. (32-mm) polyisocyanurate rigid-board insulation, respectively.[6] A wall R-value of 3.9 $hr \cdot ft^2 \cdot °F/Btu$ (0.69 $m^2 \cdot K/W$) was achieved by eliminating the rigid-board insulation. The wall R-value was increased to 5.3 $hr \cdot ft^2 \cdot °F/Btu$ (0.93 $m^2 \cdot K/W$) by replacing the drywall with a 5/8-in. (16-mm) reflective foil-backed drywall and providing no rigid-board insulation.

Hollow-core roofs, hollow-core floors, slab-on-grade, masonry interior partitions, and wood-frame interior partitions used in the previous study were the same as those used for the residential building with lightweight concrete exterior walls. These building components are illustrated in Figs. 20 through 23.

The wood-frame roof system construction, illustrated in Fig. 25, consisted of built-up roofing on 5/8-in. (16-mm) plywood supported by 2x8-in. (50x200-mm) joists at 16 in. (400 mm) on center. Batt insulation was provided between the joists and 5/8-in. (16-mm) drywall was used as the interior finish. This roof system was used only with floors of wood-joist construction.

Roof R-values for all buildings analyzed satisfied the minimum requirements of HUD Minimum Property Standards for Multifamily Housing (HUD-MPS)[13] for each location. Values used were the same as those listed in Table 3 for the building with lightweight concrete walls. A light roof color was used in locations with 4000 heating degree days or less and a dark color in locations having more than 4000 heating degree days.

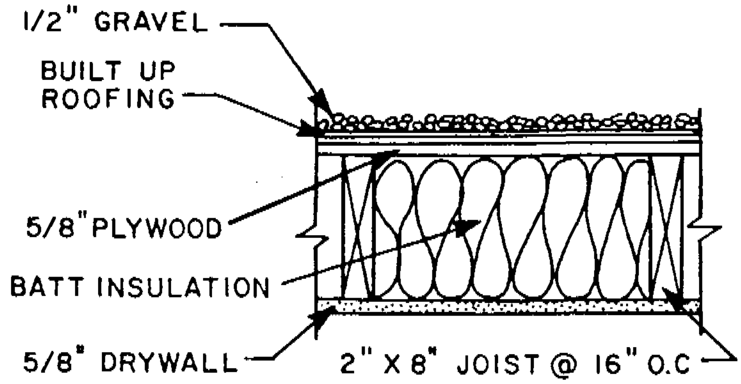


Fig. 25 Wood-Frame Roof for Residential Building(3)

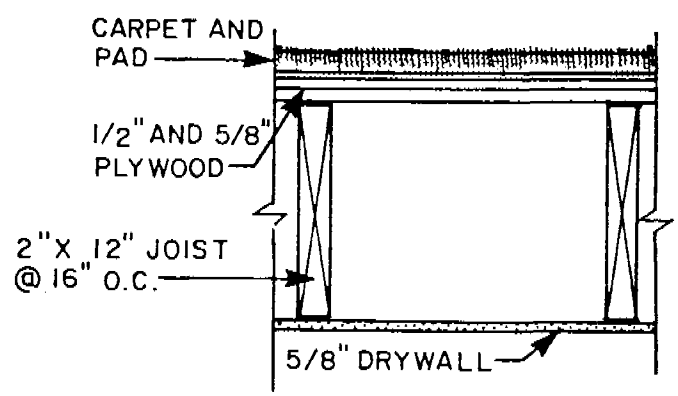


Fig. 26 Wood-Frame Floor for Residential Building (3)

The wood-frame floor system, illustrated in Fig. 26, consisted of 2x12-in. (50x300-mm) joists supporting a double layer of plywood. Plywood thicknesses were 1/2 in. (13 mm) and 5/8 in. (16 mm). This floor construction is representative of that commonly used in multifamily residential buildings.

The ceiling finish was 5/8-in. (16 mm) drywall. The floor finish was padded carpeting.

Building occupancy and operational profiles were representative of multifamily residential buildings. Values for occupancy, lighting, and electrical appliance internal gains are presented in Table 5.

Indoor temperatures during the day were allowed to fluctuate between 70°F (21°C) and 76°F (24°C) without mechanical heating or cooling. Mechanical heating was activated when the indoor temperature fell below 70°F (21°C) and mechanical cooling when the indoor temperature rose above 76°F (24°C). Indoor temperatures during the night were allowed to drop to 64°F (18°C) before mechanical heating was activated. The nighttime cooling limit was 76°F (24°C).

Peak winter infiltration was equivalent to 0.6 air changes per hour for all commercial and residential buildings analyzed.

Results of BLAST Analysis

The BLAST computer analysis was performed on a residential and a commercial building with the lightweight concrete wall system previously described.

The effect of thermal mass is influenced by certain operating and functional parameters such as solar gains; internal heat gains from occupancy, lighting, and appliances; level of internal mass; building geometry, orientation, and color; and temperature control strategy. The results reported here are for one set of such parameters. Other combinations of these

TABLE 5 - RESIDENTIAL BUILDING INTERNAL HEAT GAINS ASSUMED FOR ANALYSIS

Source	Peak Value, kBtu/hr (kW)	Hourly Average, kBtu/hr (kW)
Occupancy	30.7* (9.00)	24.6 (7.21)
Lighting	31.9** (9.35)	8.3 (2.4)
Electrical Appliances	63.4*** (18.6)	34.7 (10.2)

*60 people
**1.77 Btu/hr•ft^2 (5.6 W/m^2)
***3.51 Btu/hr•ft^2 (11.1 W/m^2)

parameters may result in thermal performance different from that reported here. However, a consideration of the effects of all these factors is beyond the scope of this investigation.

Commercial Building

Table 6 shows annual heating load, annual cooling load, and annual total load for the one story commercial building with lightweight concrete exterior walls for the six cities indicated. Heating degree day and cooling degree day values are based on 65°F (18°C) and were obtained from the ASHRAE Handbook - 1981 Fundamentals.[6]

In Fig. 27, annual heating load is plotted against heating degree days for the six cities. In Fig. 28, annual cooling load is plotted against cooling degree days. There is a linear relationship between annual load and degree days in both cases. Since the heating load for Tampa is small, it was not included in the heating load versus heating degree days line shown in Fig. 27.

For this particular building, with the operating conditions assumed for the BLAST analysis, heating and cooling loads for any location can be estimated using Figs. 27 and 28 and the heating and cooling degree days at that location. Locations with less than about 1800 heating degree days will have low heating loads for this building under the specified operating conditions.

Residential Building

Table 7 shows annual heating load, annual cooling load, and annual total load for each level of the three-story apartment building for the six cities indicated. Table 7(a) gives values in U.S units and Table 7(b) gives values in SI units. Heating degree days, cooling degree days, and total loads for all three levels are shown in Table 8. Cooling degree day values are based on 65°F (18°C) and were obtained from the ASHRAE Handbook - 1981 Fundamentals.[6]

TABLE 6 - ANNUAL LOADS FOR COMMERCIAL BUILDING WITH LIGHTWEIGHT CONCRETE EXTERIOR WALLS

Location	Heating Degree Days,(6) °F-days (°C-days)	Cooling Degree Days,(6) °F-days (°C-days)	Annual Heating Load, Btux10^6 (MW•hr)	Annual Cooling Load, Btux10^6 (MW•hr)	Annual Total Load Btux10^6 (MW•hr)
Chicago	6155 (3419)	713 (396)	336.0 (98.5)	199.1 (58.3)	535.1 (156.8)
Seattle	5145 (2858)	134 (74)	215.1 (63.0)	99.4 (29.1)	314.5 (92.1)
Wash., DC	4224 (2347)	1491 (828)	181.2 (53.1)	289.7 (84.9)	470.9 (138.0)
Atlanta	2961 (1645)	1469 (816)	65.8 (19.3)	406.5 (119.1)	472.3 (138.4)
Phoenix	1765 (981)	3334 (1852)	17.0 (5.0)	687.8 (201.6)	704.8 (206.6)
Tampa	683 (379)	3152 (1751)	2.1 (0.6)	731.5 (214.4)	733.6 (215.0)

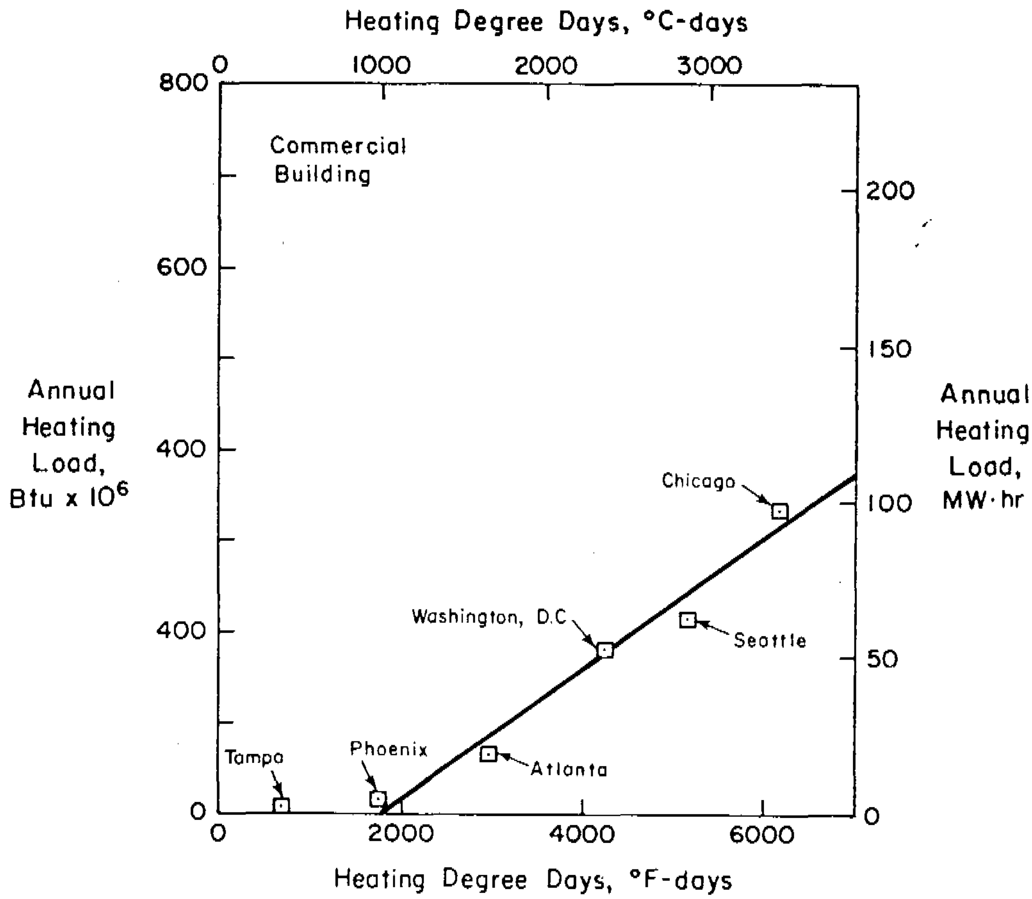


Fig. 27 Commercial Building - Heating Load from BLAST Analysis

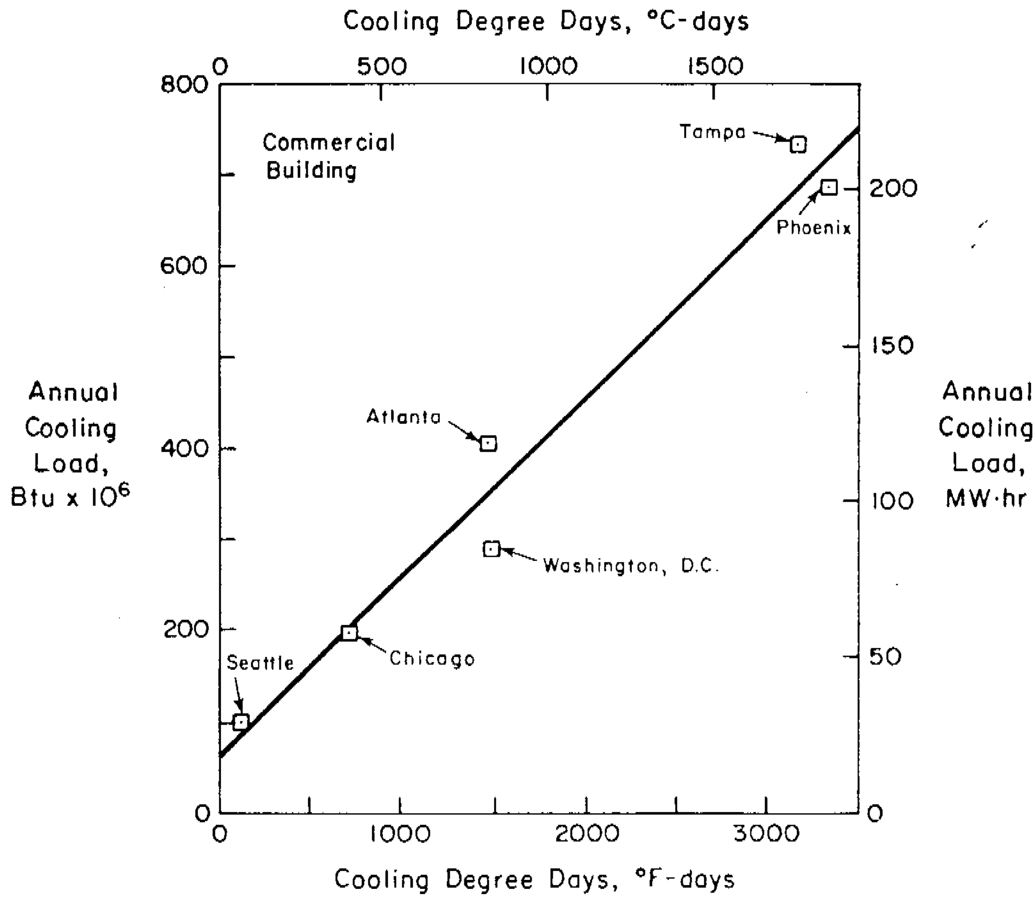


Fig. 28 Commercial Building - Cooling Load from BLAST Analysis

TABLE 7(a) - LOADS FOR EACH LEVEL OF RESIDENTIAL BUILDING WITH LIGHTWEIGHT CONCRETE EXTERIOR WALLS, U.S. UNITS

Location	Level	Annual Heating Load, Btux10^6	Annual Cooling Load, Btux10^6	Annual Total Load, Btux10^6
Chicago	Top	129.0	87.3	216.3
	Middle	60.9	91.6	152.5
	Bottom	123.4	27.5	150.9
Seattle	Top	93.5	42.5	136.0
	Middle	30.0	56.6	86.6
	Bottom	91.8	5.0	96.8
Wash., D.C.	Top	64.8	136.9	201.7
	Middle	23.7	129.3	153.0
	Bottom	65.0	51.1	116.1
Atlanta	Top	37.7	131.4	169.1
	Middle	9.8	139.9	149.7
	Bottom	25.1	78.9	104.0
Phoenix	Top	4.0	261.3	265.3
	Middle	0.1	243.2	243.3
	Bottom	2.2	167.1	169.3
Tampa	Top	0.3	235.9	236.2
	Middle	0.0	237.4	237.4
	Bottom	0.0	177.8	177.8

TABLE 7(b) - LOADS FOR EACH LEVEL OF RESIDENTIAL BUILDING WITH LIGHTWEIGHT CONCRETE EXTERIOR WALLS, SI UNITS

Location	Level	Annual Heating Load, MW•hr	Annual Cooling Load, MW•hr	Annual Total Load, MW•hr
Chicago	Top	37.8	25.6	63.4
	Middle	17.8	26.8	44.6
	Bottom	36.2	8.1	44.3
Seattle	Top	27.4	12.5	39.9
	Middle	8.8	16.6	25.4
	Bottom	26.9	1.5	28.4
Wash., D.C.	Top	19.0	40.1	59.1
	Middle	6.9	37.9	44.8
	Bottom	19.0	15.0	34.0
Atlanta	Top	11.0	38.5	49.5
	Middle	2.9	41.0	43.9
	Bottom	7.4	23.1	30.5
Phoenix	Top	1.2	76.6	77.8
	Middle	0.0	71.3	71.3
	Bottom	0.6	49.0	49.6
Tampa	Top	0.1	69.1	69.2
	Middle	0.0	69.6	69.6
	Bottom	0.0	52.1	52.1

TABLE 8 - ANNUAL LOADS FOR RESIDENTIAL BUILDING WITH LIGHTWEIGHT CONCRETE EXTERIOR WALLS

Location	Heating Degree Days,(14) °F-days (°C-days)	Cooling Degree Days,(6) °F-days (°C-days)	Annual Heating Load, Btux10^6 (MW•hr)	Annual Cooling Load, Btux10^6 (MW•hr)	Annual Total Load Btux10^6 (MW•hr)
Chicago	6640 (3689)	713 (396)	313.3 (91.8)	206.4 (60.5)	519.7 (152.3)
Seattle	5190 (2883)	134 (74)	215.2 (63.1)	104.2 (30.5)	319.4 (93.6)
Wash., DC	4240 (2356)	1491 (828)	153.5 (45.0)	317.3 (93.0)	470.8 (138.0)
Atlanta	2990 (1661)	1469 (816)	72.5 (21.3)	350.2 (102.6)	422.7 (123.9)
Phoenix	1680 (933)	3334 (1852)	6.3 (1.9)	671.6 (196.8)	677.9 (198.7)
Tampa	700 (389)	3152 (1751)	0.3 (0.1)	651.1 (190.8)	651.4 (190.9)

Heating degree day values are based on 65°F (18°C) and were obtained from Reference 14. Sources of heating and cooling degree day values were chosen to agree with previous investigations[2,3] to facilitate comparisons.

Figures 29 and 30 show annual heating load versus heating degree days and annual cooling load versus cooling degree days, respectively. In both cases, there is a linear relation between annual load and degree days. Since the heating load for Tampa is small, it was not included in the heating load versus heating degree days line shown in Fig. 29.

For this particular building, with the operating conditions assumed for the BLAST analysis, the heating and cooling loads for any location can be estimated using Figs. 29 and 30 and the heating and cooling degree days at that location. Locations with less than about 1700 heating degree days will have low heating loads for this building under the specified operating conditions.

Comparison with Previous Studies

Previous investigations[2,3] determined total annual loads for the one-story commercial building and the three-story apartment building under a variety of conditions.

The one-story commercial building was analyzed with three different wall configurations as described in the "Building Descriptions" section of this report. Total annual loads were determined over a range of wall R-values. Total annual loads are shown as a function of wall R-value in Figs. 31(a) through (e). Curves on the figures represent annual building loads for each of the three exterior wall systems. Each figure shows results for a particular geographic location.

The three-story residential building was analyzed using four levels of thermal mass. The wall R-value was varied to give results of total annual load versus wall R-value. Total annual heating and cooling loads are shown as

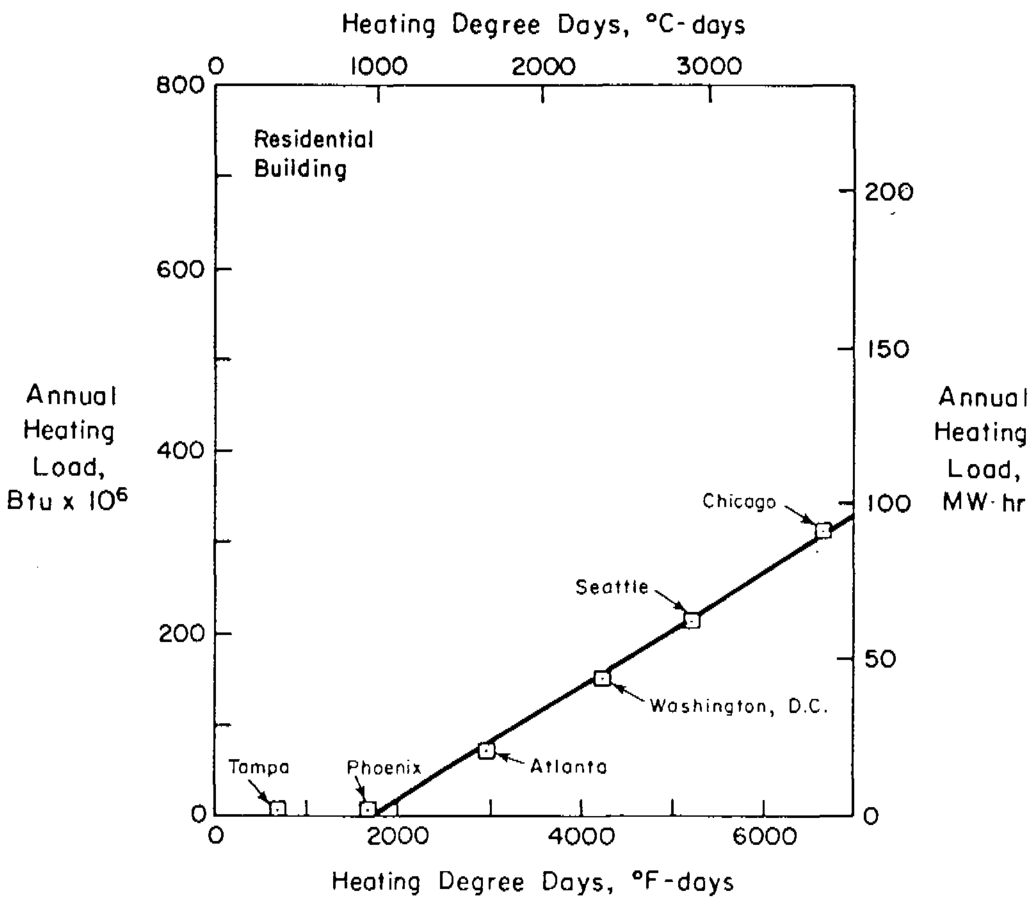


Fig. 29 Residential Building - Heating Load from BLAST Analysis

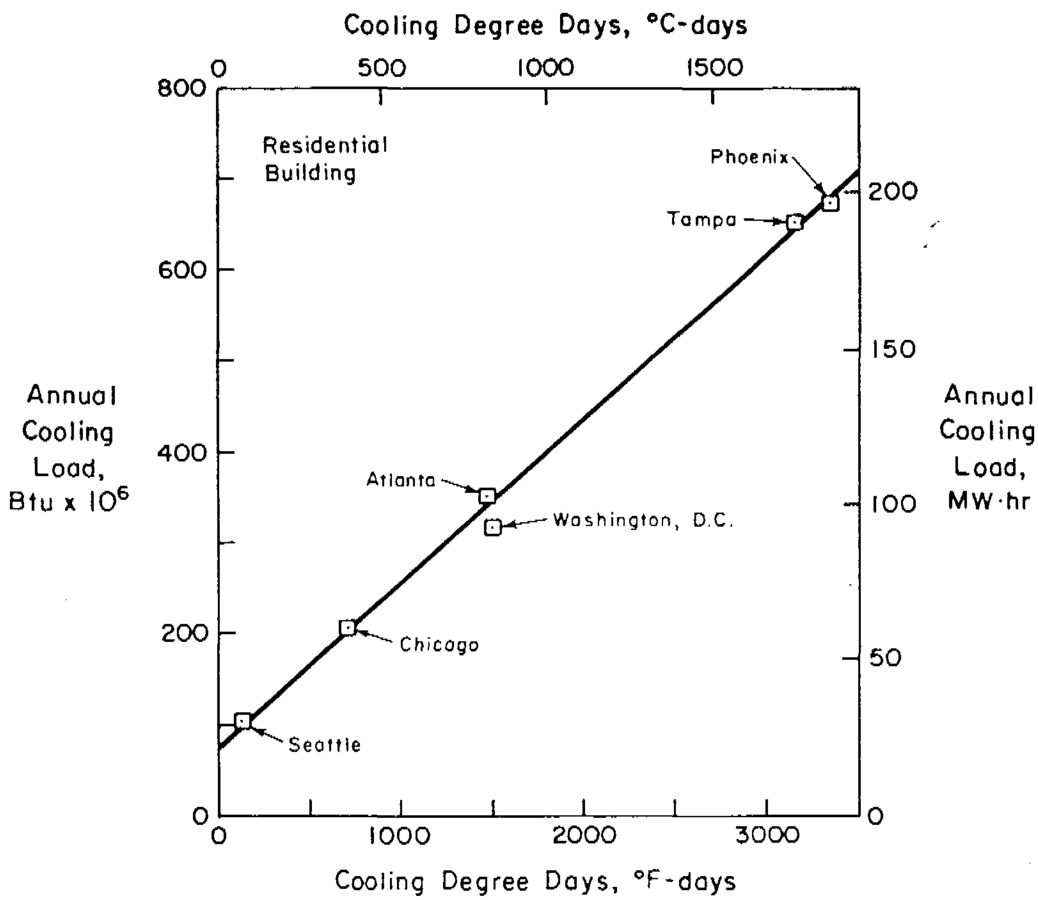


Fig. 30 Residential Building - Cooling Load from BLAST Analysis

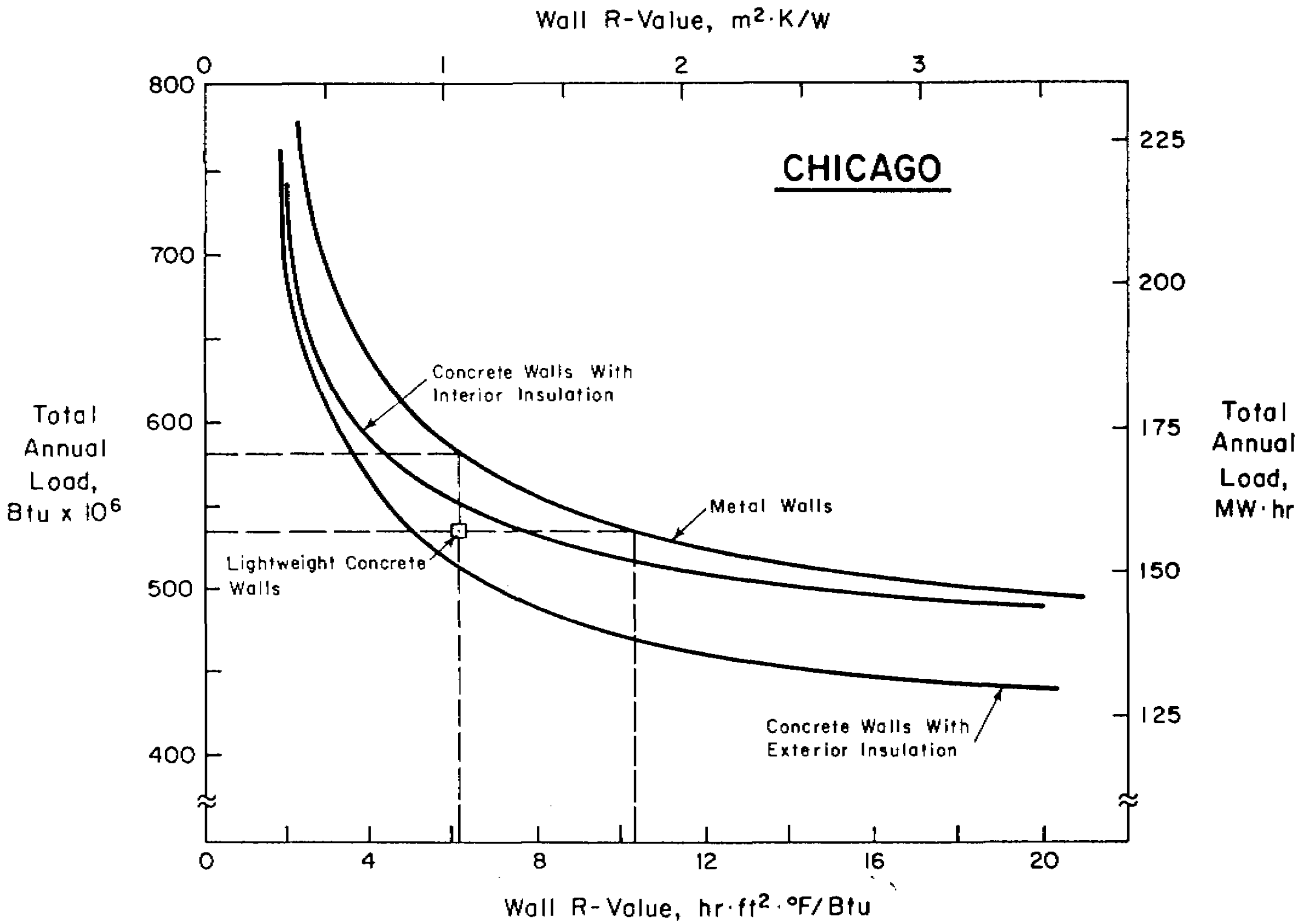


Fig. 31 (a) Total Annual Load from BLAST Analysis of Commercial Building - Chicago (Adapted from Ref. 2)

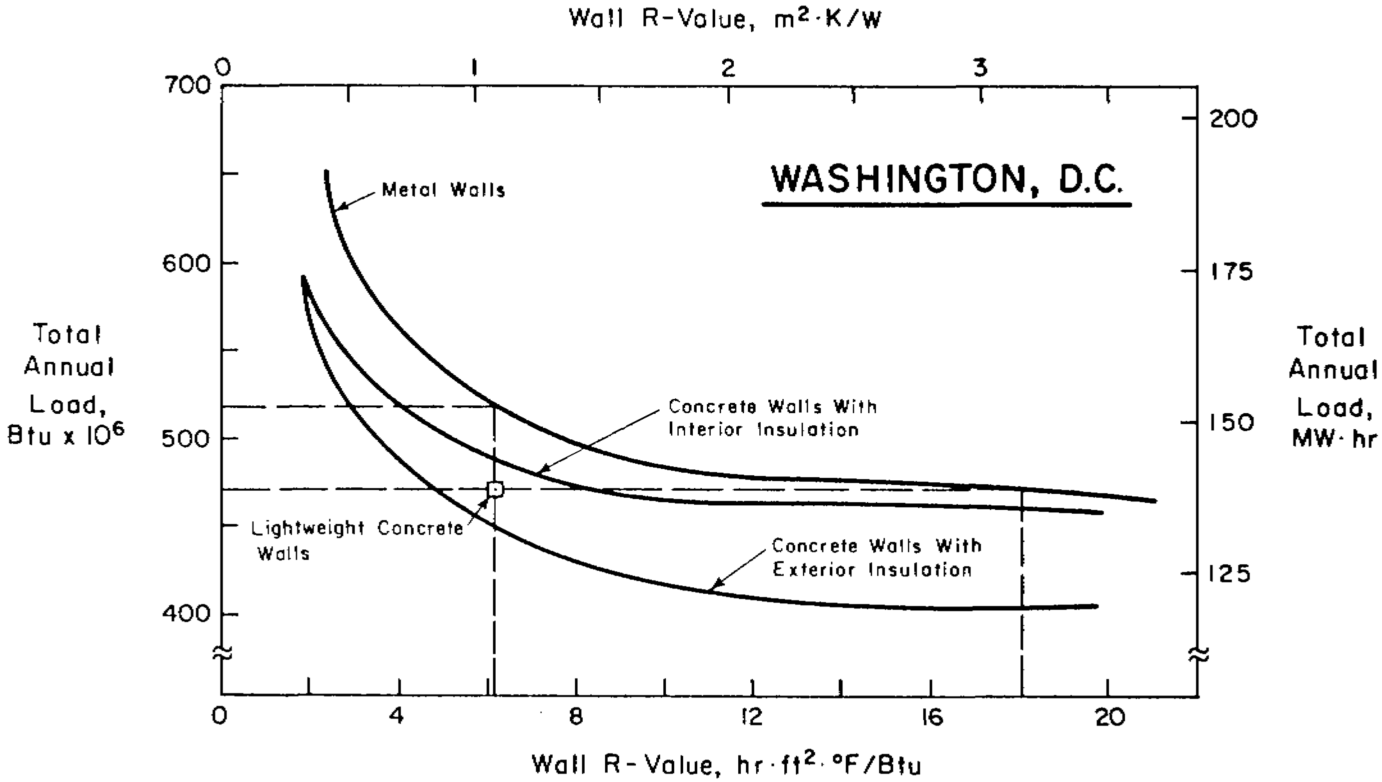


Fig. 31 (b) Total Annual Load from BLAST Analysis of Commercial Building - Washington, D.C. (Adapted from Ref. 2)

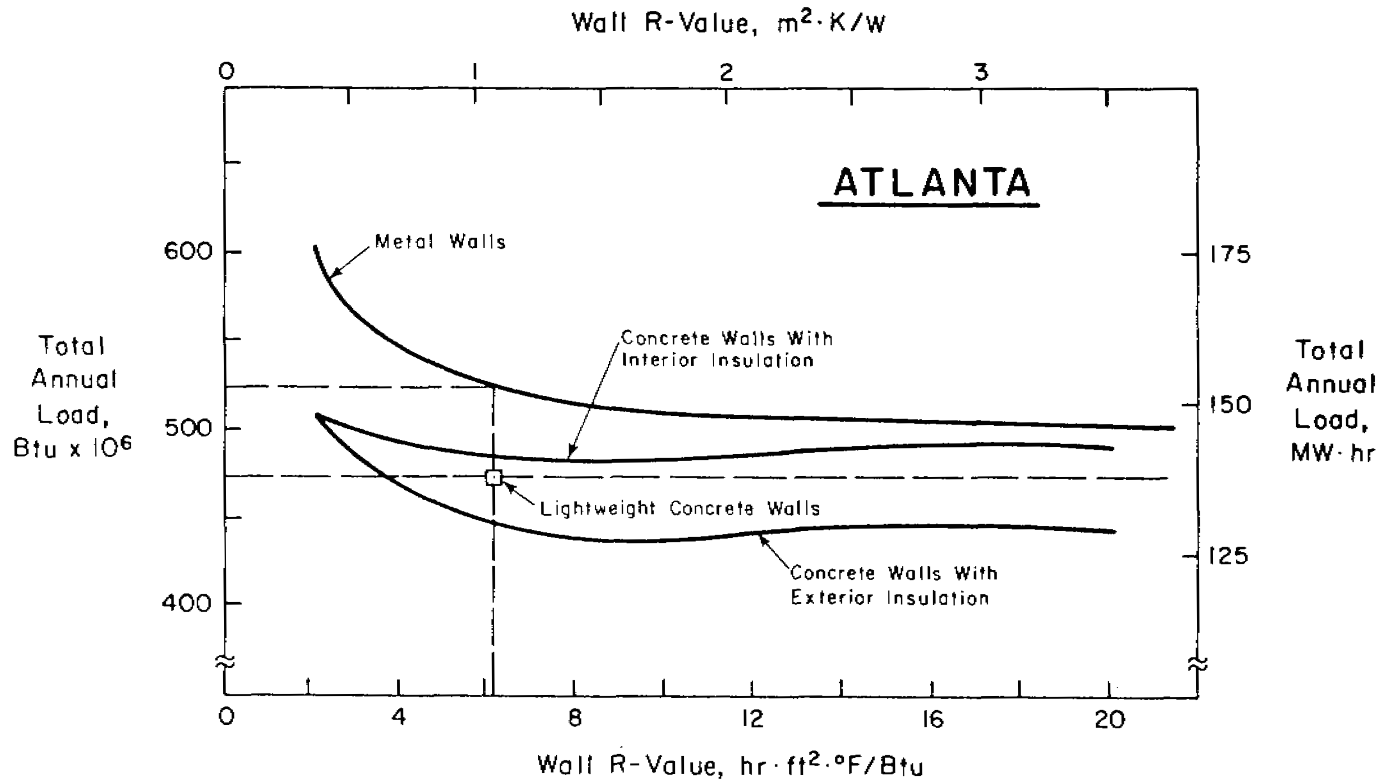


Fig. 31 (c) Total Annual Load from BLAST Analysis of Commercial Building - Atlanta (Adapted from Ref. 2)

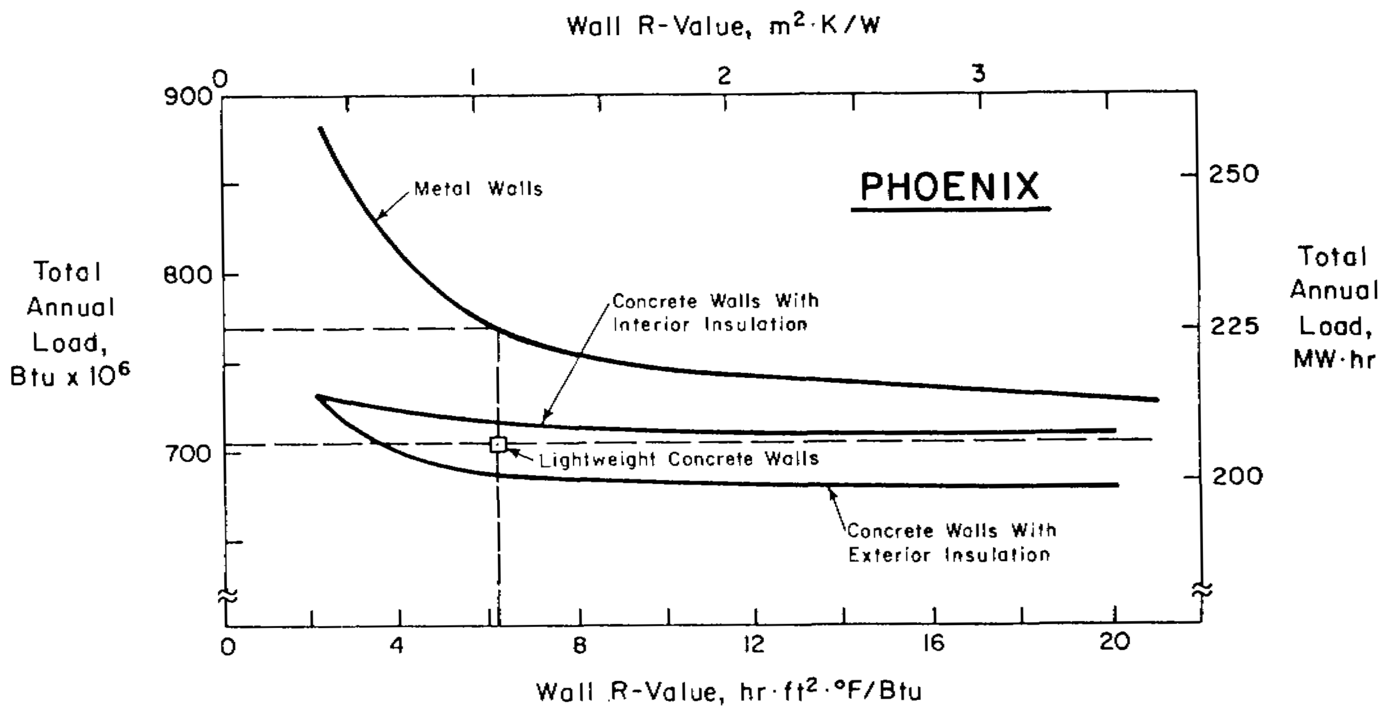


Fig. 31 (d) Total Annual Load from BLAST Analysis of Commercial Building - Phoenix (Adapted from Ref. 2)

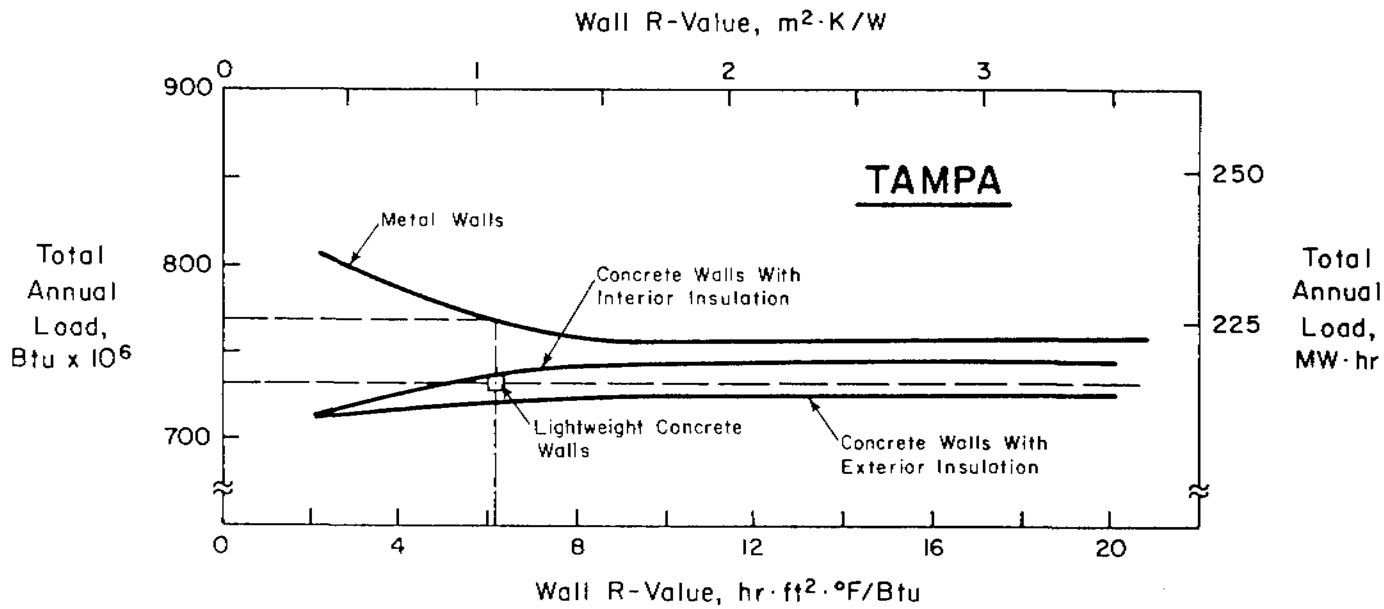


Fig. 31 (e) Total Annual Load from BLAST Analysis of Commercial Building - Tampa (Adapted from Ref. 2) a function of wall R-value in Figs. 32(a) through (e). Curves on the figures represent annual loads for each quantity of building mass. Each figure shows results for a particular geographic location.

With the exception of the commercial building in Tampa and Atlanta and the residential building in Tampa, total annual load decreases with increasing wall R-value for all wall R-values considered. For the noted exceptions, the addition of insulation increases the cooling load more than it decreases the heating load. Generally, massive concrete and masonry walls result in a lower total annual load than lightweight metal stud or wood-frame walls. Further discussion of results of these investigations are given in References 2 and 3.

Results of the BLAST analyses of the commercial building and the residential building with the proposed lightweight concrete wall system are also included in Figs. 31 and 32. For the one story commercial building, total annual load from Table 6 is shown as a point corresponding to a wall R-value of 6.18 $hr \cdot ft^2 \cdot °F/Btu$ (1.09 $m^2 \cdot K/W$) in Figs. 31(a) through (e). For the three-story residential building, total annual load from Table 8 is shown as a point corresponding to a wall R-value of 6.18 $hr \cdot ft^2 \cdot °F/Btu$ (1.09 $m^2 \cdot K/W$) in Figs. 32(a) through (e).

In the previous investigations, BLAST analyses were not performed for the commercial building in Seattle and the residential building in Phoenix. These cases are not included in the comparisons of building performance in this section.

Equivalent R-values and equivalent total loads are two criteria used to evaluate performance of the buildings with lightweight concrete walls. Performance of these buildings is compared to the performance of the metal wall commercial building and the wood frame residential building.

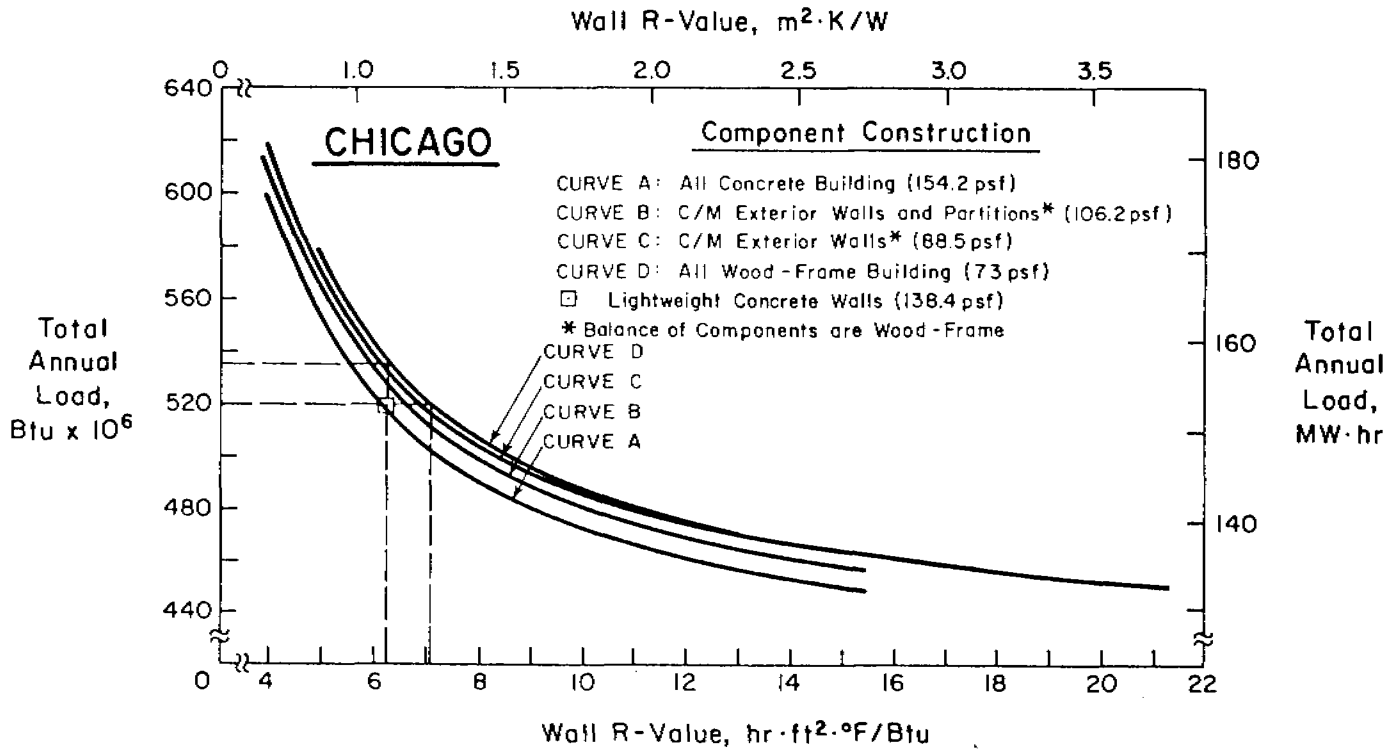


Fig. 32 (a) Total Annual Load from BLAST Analysis of Residential Building - Chicago (Adapted from Ref. 3)

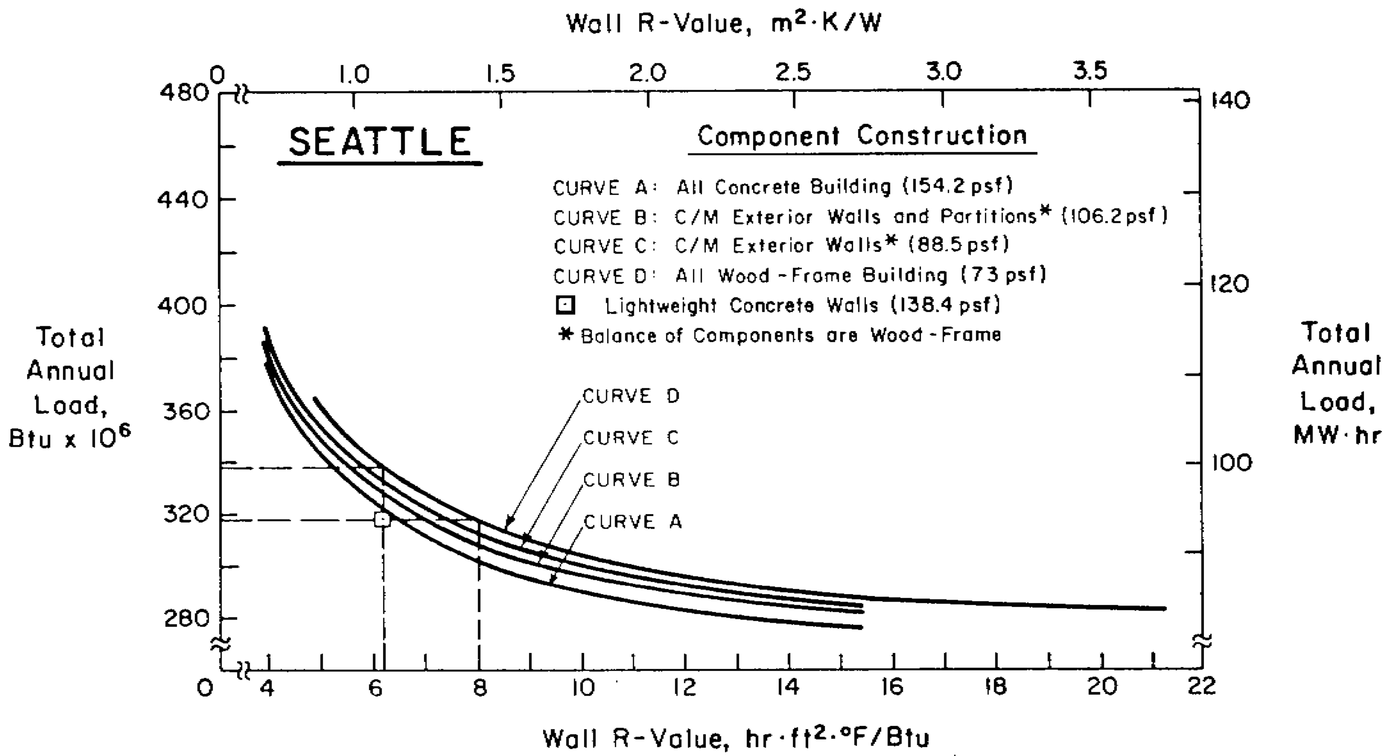


Fig. 32 (b) Total Annual Load from BLAST Analysis of Residential Building - Seattle (Adapted from Ref. 3)

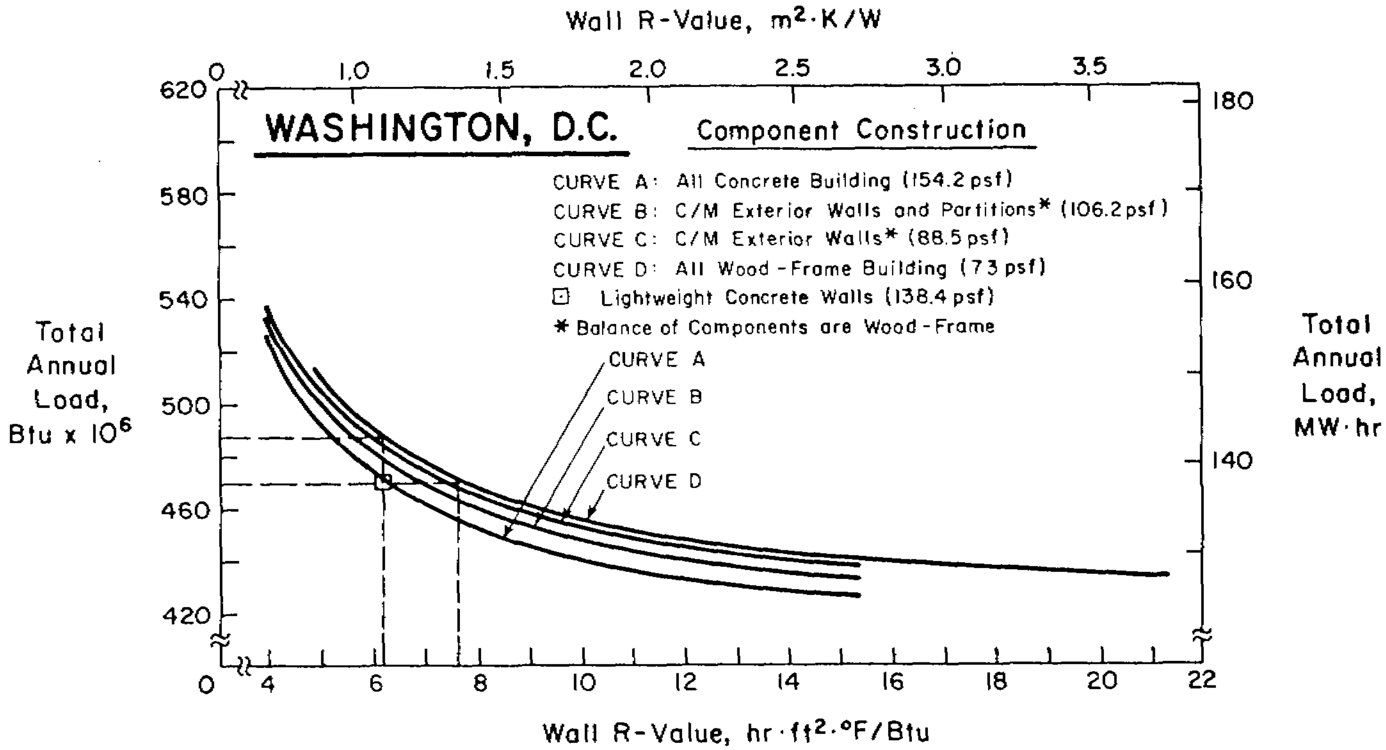


Fig. 32 (c) Total Annual Load from BLAST Analysis of Residential Building - Washington, D.C. (Adapted from Ref. 3)

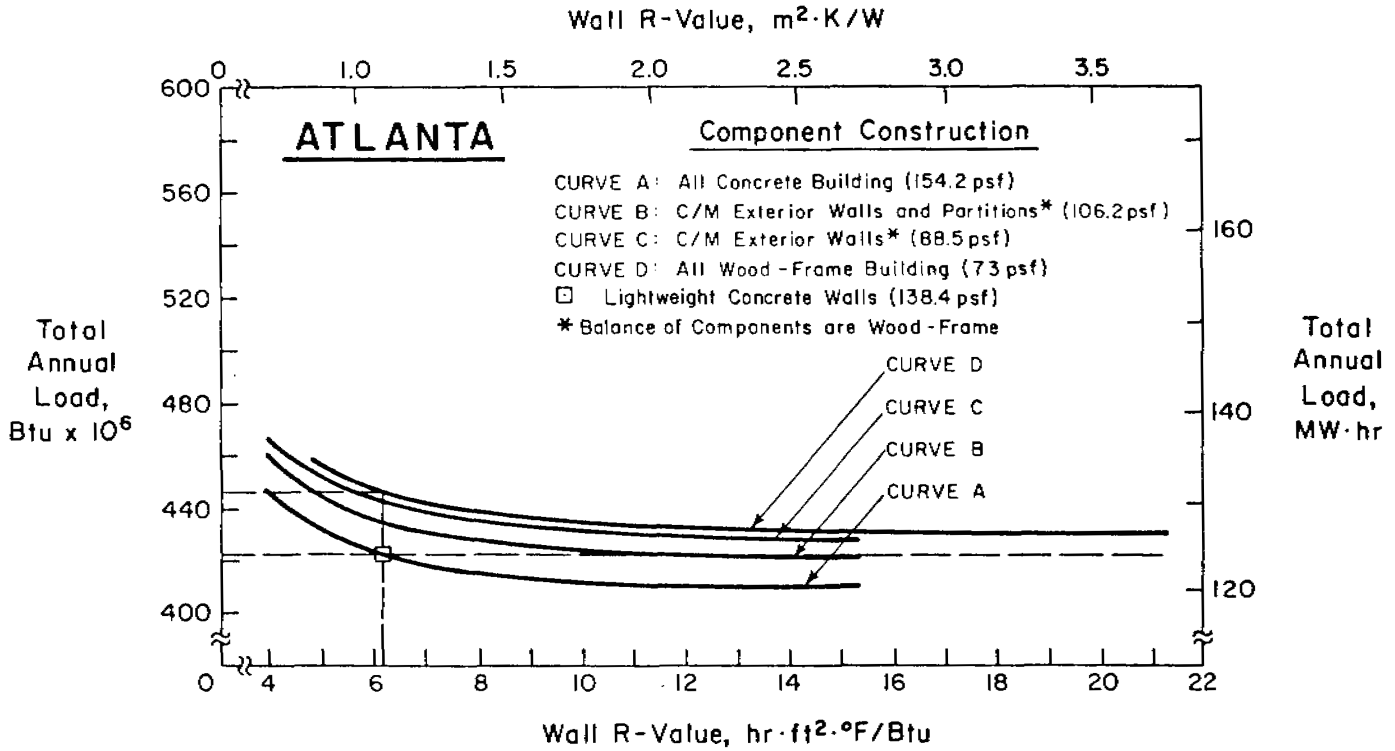


Fig. 32 (d) Total Annual Load from BLAST Analysis of Residential Building - Atlanta (Adapted from Ref. 3)

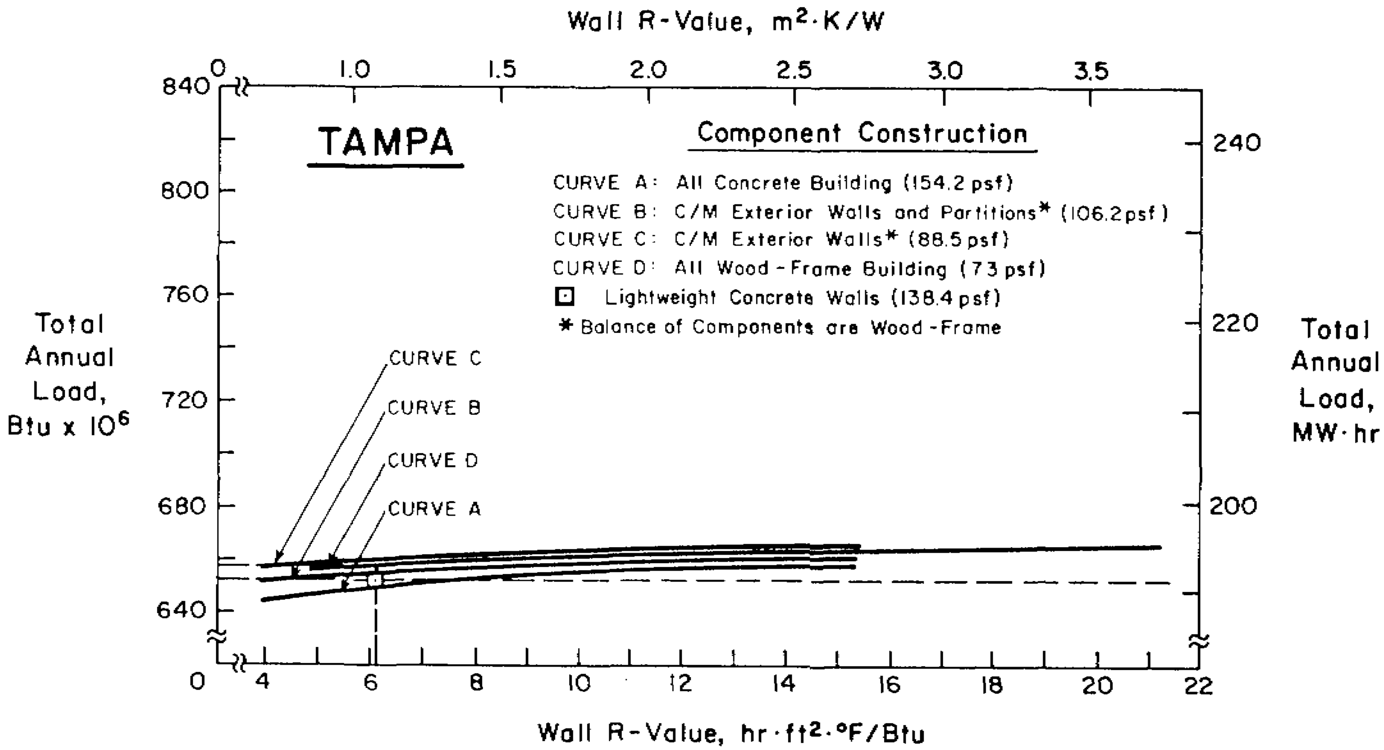


Fig. 32 (e) Total Annual Load from BLAST Analysis of Residential Building - Tampa (Adapted from Ref. 3)

Results of the following comparisons are specific to the building configurations, operating conditions, and locations given. However, it is assumed that these building configurations are representative of multifamily residential and commercial buildings so that the results may be applied to buildings with similar geometries and operating conditions.

Equivalent and Correspondent R-Values

For any wall R-value of a low-mass building, the equivalent R-value in a high-mass building is the R-value resulting in the same annual heating and cooling loads. This performance approach to energy conservation is allowed in several energy standards including the HUD Minimum Property Standards[13] and ASHRAE Standard 90A-1980, Energy Conservation in New Building Design.[4] Performance standards do not require adherence to prescribed U-values or R-values, provided that an acceptable level of annual energy consumption is maintained. This important concept allows the designer flexibility to choose the combination of conservation strategies that provides the desired performance at the lowest cost.

For this study, the equivalent R-value of the lightweight concrete walls in the commercial and residential buildings is 6.18 $hr \cdot ft^2 \cdot °F/Btu$ (1.09 $m^2 \cdot K/W$). Correspondent R-values for other wall systems that give the same total annual load as the lightweight concrete wall building can be found by using Figs. 31 and 32. A horizontal line is drawn at the total annual load of the lightweight concrete wall system. The intersection of this line with the curve for the building with a particular wall system gives the correspondent R-value for that system. This method of determining correspondent R-values is shown for metal walls in Fig. 31 and for the all wood-frame building in Fig. 32.

In eight cases, a correspondent R-value cannot be determined. The total annual load of the lightweight concrete wall system is less than that for the alternative wall system for all wall R-values shown in the respective Figures.

Table 9 contains correspondent wall R-values for the commercial building at cities for which data are available for comparison. The lightweight concrete wall system has an R-value lower than the correspondent R-value of the metal wall and concrete wall with interior insulation at all locations. Correspondent R-values which are greater than the R-value of the lightweight concrete wall indicate the effect on thermal performance of the thermal mass of the lightweight concrete wall system. The concrete wall with exterior insulation has lower correspondent R-values than the proposed lightweight concrete because of the combined effect of the insulation and mass, and the placement of insulation relative to the mass.

Correspondent wall R-values for the residential building are presented in Table 10. For all locations, the lightweight concrete wall system has an R-value lower than the correspondent R-value of the wood-frame wall and concrete masonry walls in buildings with intermediate amounts of mass. The lightweight concrete wall has an R-value similar to the correspondent R-value of the walls in the all concrete building for all locations considered.

<u>Correspondent Annual Load</u>

For any total annual load of a high-mass building with a given wall R-value, the correspondent annual load of a low-mass building is the annual load resulting from the same wall R-value.

The correspondent total annual load for the commercial and residential buildings at all locations can be determined by finding the total annual load for

TABLE 9 - COMMERICAL BUILDING CORRESPONDENT R-VALUES

Location	Total Annual Load Ltwt. Concrete Walls, Btux10^6 (MW•hr)	Correspondent R-Value, hr•ft^2•°F/Btu (m^2•K/W)		
		Metal Walls	Concrete Walls with Int. Insul.	Concrete Walls with Ext. Insul.
Chicago	535 (157)	10.3 (1.8)	7.7 (1.4)	5.1 (0.9)
Wash., D.C.	471 (138)	18.0 (3.2)	8.4 (1.5)	4.8 (0.8)
Atlanta	472 (138)	*	*	3.7 (0.7)
Phoenix	705 (207)	*	*	3.5 (0.6)
Tampa	734 (215)	*	**	**

*Correspondent R-value cannot be determined. Lightweight concrete wall system has lower total annual building load than all other computed wall R-values.

**Correspondent R-Value not determined since increases in wall R-values cause increases in total annual building loads.

Note: Equivalent wall R-value of lightweight concrete wall system is 6.18 hr•ft^2•°F/Btu (1.09 m^2•K/W).

TABLE 10 - RESIDENTIAL BUILDING CORRESPONDENT R-VALUES

Location	Total Annual Load Ltwt. Concrete Walls, Btux10^6 (MW•hr)	Correspondent R-Value, hr•ft^2•°F/Btu (m^2•K/W)			
		All Wood-Frame Building	C/M Ext. Walls	C/M Ext. Walls and Partitions	All Concrete Bldg.
Chicago	520 (152)	7.1 (1.3)	6.8 (1.2)	6.5 (1.1)	6.1 (1.1)
Seattle	319 (94)	8.0 (1.4)	7.4 (1.3)	7.0 (1.2)	6.5 (1.1)
Wash., D.C.	471 (138)	7.7 (1.4)	7.4 (1.3)	6.9 (1.2)	6.3 (1.1)
Atlanta	423 (124)	*	*	11.5 (2.0)	6.2 (1.1)
Tampa	651 (191)	*	**	**	**

*Correspondent R-value cannot be determined. Lightweight concrete wall system has lower total annual building load than all other computed wall R-values.

**Correspondent R-Value not determined since increases in wall R-values cause increases in total annual building loads.

Note: Equivalent wall R-value of lightweight concrete wall system is 6.18 hr•ft^2•°F/Btu (1.09 m^2•K/W).

the alternative wall system with a wall R-value of 6.18 hr•ft^2•°F/Btu (1.09 m^2•K/W). A vertical line is drawn at an R-value of 6.18 hr•ft^2•°F/Btu (1.09 m^2•K/W), the R-value of the lightweight concrete wall. The intersection of this line with the curve for the alternative walls in Figs. 31 and 32 gives the correspondent total annual load of the alternative wall system. This method of determining correspondent total annual load is shown in Fig. 31 for the building with metal walls and Fig. 32 for the wood-frame building.

Table 11 lists correspondent annual loads for the commercial building at the cities for which data are available for comparison. For all locations, the lightweight concrete wall system results in a lower total annual load than the metal wall system with a comparable R-value. In all locations, the concrete wall systems with interior insulation had slightly higher annual building loads than the lightweight concrete wall system. Concrete wall systems with exterior insulation had slightly lower building loads than the lightweight concrete wall system.

The percent change in load, also given in Table 11, represents the result of using the lightweight concrete wall system rather than an alternative wall system with the same R-value. Building load changes range from -10% for the building with metal walls in Atlanta to +6% for the building with exterior insulation on concrete walls in Atlanta.

Table 12 lists correspondent annual loads for the residential building at the cities for which data are available for comparison. The percent change in annual building loads is also listed. For all locations, the lightweight concrete wall system results in a lower total annual load than the wood-frame wall system with a comparable R-value. The percent change in annual load for the other three wall systems compared to lightweight concrete is less than for the wood-frame wall system.

TABLE 11 - COMMERCIAL BUILDING CORRESPONDENT ANNUAL LOADS

Location	Type of Exterior Wall						
	Ltwt. Concrete	Metal		Concrete with Int. Insul.		Concrete with Ext. Insul.	
	Total Annual Load, Btux10^6 (MW•hr)	Corres. Annual Load, Btux10^6 (MW•hr)	Change in Load, %	Corres. Annual Load, Btux10^6 (MW•hr)	Change in Load, %	Corres. Annual Load, Btux10^6 (MW•hr)	Change in Load, %
Chicago	535 (157)	581 (170)	- 8	552 (162)	- 3	512 (150)	+ 4
Wash., D.C.	471 (138)	518 (152)	- 9	489 (143)	- 4	450 (132)	+ 5
Atlanta	472 (138)	524 (154)	-10	485 (142)	- 3	446 (131)	+ 6
Phoenix	705 (207)	770 (226)	- 8	718 (210)	- 2	686 (201)	+ 3
Tampa	734 (215)	770 (226)	- 5	737 (216)	0	719 (211)	+ 2

TABLE 12 - RESIDENTIAL BUILDING CORRESPONDENT ANNUAL LOADS

Location	Type of Building								
	Ltwt. Concrete	Metal		C/M Ext. Walls		C/M Ext. Walls and Partitions		All Concrete	
	Total Annual Load, Btux10^6 (MW•hr)	Corres. Annual Load, Btux10^6 (MW•hr)	Change in Load, %	Corres. Annual Load, Btux10^6 (MW•hr)	Change in Load, %	Corres. Annual Load, Btux10^6 (MW•hr)	Change in Load, %	Corres. Annual Load, Btux10^6 (MW•hr)	Change in Load, %
Chicago	520 (152)	536 (157)	- 3	535 (157)	- 3	528 (155)	- 2	517 (151)	+ 1
Seattle	319 (94)	338 (99)	- 6	332 (97)	- 4	328 (96)	- 3	322 (94)	- 1
Wash., D.C.	471 (138)	487 (143)	- 3	484 (142)	- 3	479 (140)	- 2	473 (139)	0
Atlanta	423 (124)	446 (131)	- 5	443 (130)	- 5	435 (127)	- 3	423 (124)	0
Tampa	651 (191)	657 (193)	- 1	660 (193)	- 1	655 (192)	- 1	650 (190)	0

The advantage of the lightweight concrete system compared to the alternative concrete and masonry systems is that an R-value of 6.18 $hr \cdot ft^2 \cdot °F/Btu$ (1.09 $m^2 \cdot K/W$) can be achieved without added insulation.

SECTION 3 - STANDARD REQUIREMENTS

Current building standards specify minimum thermal requirements which should be met in new building construction in order to conserve energy. The proposed lightweight concrete wall system has been reviewed for compliance with one of these standards to determine if the system may be used in various regions of the United States. The standard requirements were evaluated for fourteen cities representing all climatic regions of the continental United States.

Eleven of the cities were used in Reference 15 to represent eleven climate regions within the U.S. Each city was chosen to represent a region "based on its ability to most closely match regional population-weighted averages of selected climatic parameters representing heating and cooling severity, humidity, and solar gains."[15] The eleven regions and cities are shown in Fig. 33. Standards are also evaluated for Chicago, Tampa, and Washington, D.C., also shown in Fig. 33. These cities were included in the "BLAST Computer Analysis" portion of this report.

The ANSI/ASHRAE/IES Standard 90A-1980[4] was used for the residential building and the commercial building. Building characteristics are assumed to be the same as those for the buildings analyzed in the BLAST investigation. Although the ASHRAE standards' requirements are specific to the building configuration involved, the results are considered to be representative of multifamily residential and commercial buildings.

Commercial Building

The one story commercial building was analyzed using ASHRAE Standard 90A-1980 to determine the adequacy of the proposed lightweight concrete wall system in commercial buildings in 14 cities in the U.S. Commercial buildings which are mechanically heated and cooled must meet the requirements of Section

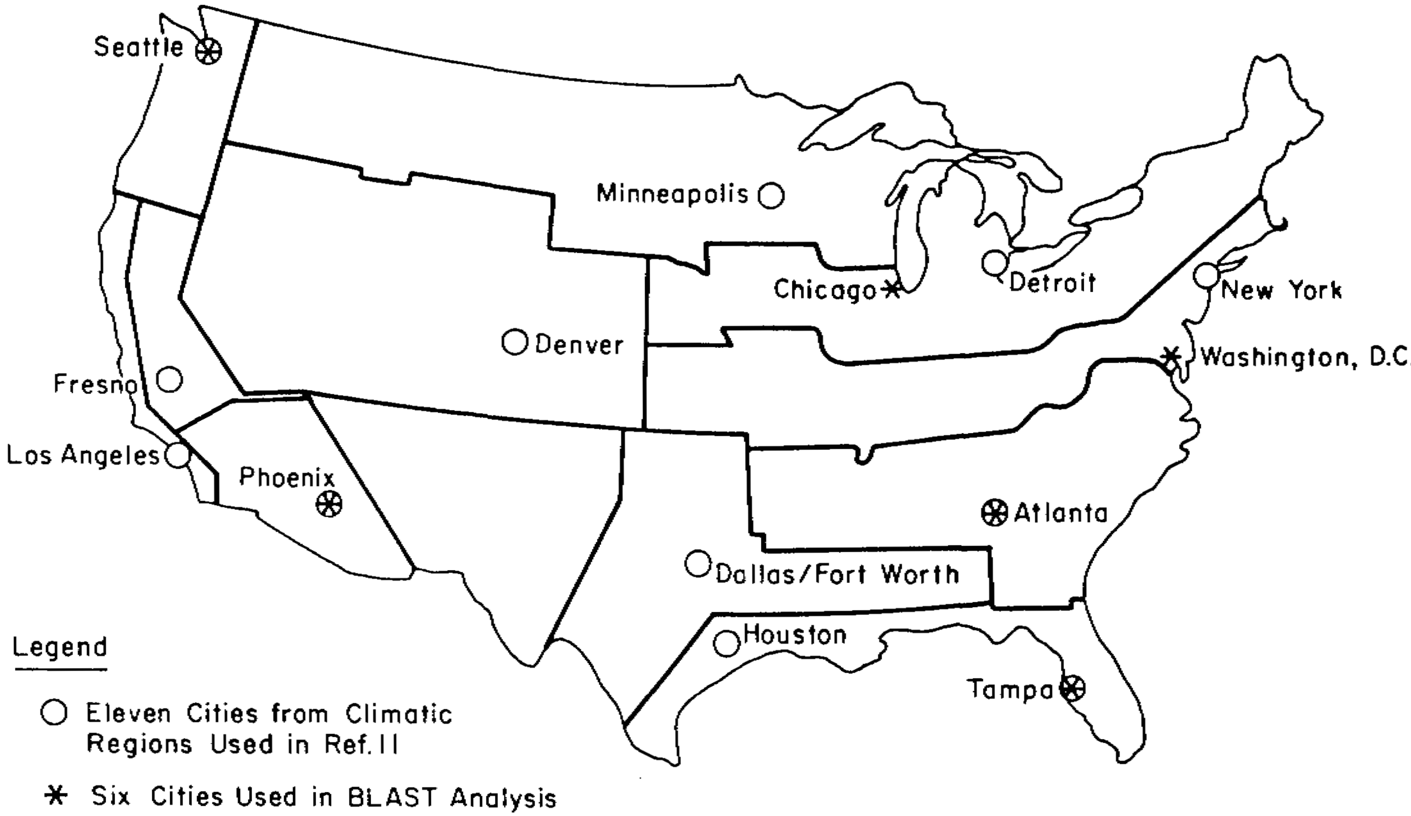


Fig. 33 Cities Used for Standard Requirements

4.4.2 of the standard for heating and Section 4.4.3 for cooling. In all locations, the heating requirement governed for this building. Details of the cooling requirement calculations will not be presented here.

The following procedure was used to determine the required R-value of the opaque portions of the walls. The characteristics of the building are determined or assumed. In this case, the building characteristics are the same as those used in the BLAST computer analysis for the lightweight concrete wall system. Areas and thermal transmittances of the building components of the one story commercial building are summarized in Table 13. The maximum permissible thermal transmittance of the opaque portion of the exterior wall (U_w) is determined using the ASHRAE Standard.

The maximum allowable U_w is determined using Fig. 4 and Equation 1 of Section 4.0, "Exterior Envelope Requirements", of ASHRAE Standard 90A-1980. For a particular location and its annual heating degree days, Fig. 4 (ASHRAE) gives a maximum permissible combined thermal transmittance (U_0) for the gross wall area. This U_0 value is a weighted average by area of the thermal transmittance values of the wall components.

After U_0 is determined from Fig. 4 (ASHRAE), U_w is the only unknown in Equation 1 of the Standard. Therefore, U_w can be determined using the U_0 value from Fig. 4 (ASHRAE) and the values for area and thermal transmittance in Table 10 of this report. The resulting U_w is then inverted to determine a minimum permissible R-value for the opaque portion of the wall. If this required R-value is less than 6.18 hr•ft^2•°F/Btu (1.09 m^2•K/W), the proposed lightweight concrete wall system is adequate for the location in question.

The value 6.18 hr•ft^2•°F/Btu (1.09 m^2•K/W) for the lightweight concrete wall includes an outdoor surface film resistance of 0.17 hr•ft^2•°F/Btu (0.03 m^2•K/W) and an indoor surface film resistance of 0.68 hr•ft^2•°F/Btu (0.12 m^2•K/W).

TABLE 13 - WALL COMPONENTS FOR COMMERCIAL BUILDING

Component	Area A, ft^2 (m^2)	Thermal Transmittance U, $Btu/hr \cdot ft^2 \cdot °F$ ($W/m^2 \cdot K$)
Windows	174 (16.2)	1.10 (6.25)
Overhead Doors	120 (11.1)	0.16 (0.91)
Glass Doors	126 (11.7)	0.53 (3.01)
Opaque Wall	8580 (797)	U_w*
Overall Wall	9000 (836)	U_o**

*Maximum permissible value to be determined using ASHRAE Standard 90A-1980.(4)

**From Fig. 4, ASHRAE Standard 90A-1980.(4)

Table 14 lists the fourteen cities checked, annual heating degree days, the overall thermal transmittance (U_o), the maximum allowable thermal transmittance (U_w) of the opaque wall, and the required minimum R-value of the opaque portion of the exterior walls. The lightweight concrete wall system exceeds the required thermal resistance in all 14 cities.

Residential Building

The three story residential building was analyzed using ASHRAE Standard 90A-1980[4] to determine the adequacy of the proposed lightweight concrete wall system in multifamily residential buildings in 14 cities in the U.S. This standard forms the basis for the CABO Model Energy Code[16] and HUD-Minimum Property Standards for Multifamily Housing.[13]

Residential buildings which are mechanically heated and/or cooled must meet the heating and cooling criteria of Section 4.3.2 of ANSI/ASHRAE/IES Standard 90A-1980. This requirement is similar to the heating requirement for commercial buildings as briefly described above with the exception that Fig. 1 in the ASHRAE Standard is used to obtain the overall thermal transmittance value (U_o).

The characteristics of this residential building are the same as those of the residential building analyzed in the BLAST investigation. The exterior envelope consists of two components. Glass windows and glass sliding doors make up 22.7% of the gross wall area. All glass is double glazed and has a thermal transmittance of 0.55 $Btu/hr \cdot ft^2 \cdot °F$ (3.12 $W/m^2 \cdot K$). The remaining 77.3% of the exterior envelope is opaque wall.

The maximum allowable wall thermal transmittance, U_w, is determined from Equation 1 (ASHRAE) using the U_o value from Fig. 1 (ASHRAE) and known area and transmittance values. The resulting U_w value is inverted to obtain a minimum R-value for the opaque portion of the wall. If this required R-value

TABLE 14 - ANSI/ASHRAE/IES STANDARD 90A-1980 FOR COMMERCIAL BUILDING

Location	Heating Degree Days,* °F-days (°C-days)	Maximum Overall Thermal Transmittance U_o, Btu/hr•ft^2•°F (W/m^2•K)	Maximum Overall Thermal Transmittance U_w, Btu/hr•ft^2•°F (W/m^2•K)	Minimum Required Wall R-Value, hr•ft^2•°F/Btu (m^2•K/W)
Minneapolis	8158 (4532)	0.231 (1.31)	0.210 (1.19)	4.76 (0.84)
Chicago	6640** (3689)	0.260 (1.48)	0.240 (1.36)	4.16 (0.73)
Detroit	6228 (3460)	0.272 (1.54)	0.253 (1.44)	3.95 (0.70)
Denver	6016 (3342)	0.272 (1.54)	0.253 (1.44)	3.95 (0.70)
Seattle	5184 (2880)	0.289 (1.64)	0.271 (1.54)	3.69 (0.65)
New York	5033 (2796)	0.291 (1.65)	0.273 (1.55)	3.66 (0.64)
Washington, D.C.	4240** (2356)	0.307 (1.74)	0.290 (1.65)	3.45 (0.61)
Atlanta	3094 (1719)	0.329 (1.87)	0.313 (1.78)	3.20 (0.56)
Fresno	2650 (1472)	0.338 (1.92)	0.322 (1.83)	3.10 (0.55)
Dallas/Fort Worth	2335 (1297)	0.343 (1.95)	0.327 (1.86)	3.05 (0.54)
Los Angeles	1818 (1010)	0.351 (1.99)	0.336 (1.91)	2.98 (0.52)
Phoenix	1552 (862)	0.358 (2.03)	0.343 (1.95)	2.91 (0.51)
Houston	1433 (796)	0.361 (2.05)	0.346 (1.96)	2.89 (0.51)
Tampa	700** (398)	0.374 (2.12)	0.360 (2.04)	2.78 (0.49)

*65°F (18°C) Base, from Reference 15 unless otherwise noted.
**65°F (18°C) Base, from Reference 14

is less than 6.18 $hr \cdot ft^2 \cdot °F/Btu$ (1.09 $m^2 \cdot K/W$), the proposed lightweight concrete wall system is adequate for the location in question.

Table 15 lists results of this check for 14 cities in the U.S. The lightweight concrete wall system exceeds the required thermal resistance in all cities except Minneapolis, where the required R-value is 7.21 $hr \cdot ft^2 \cdot °F/Btu$ (1.27 $m^2 \cdot K/W$).

Compliance with the standard requirement for Minneapolis could be achieved by addition of insulation with an R-value of 1.03 $hr \cdot ft^2 \cdot °F/Btu$ (0.18 $m^2 \cdot K/W$). The required R-value could also be obtained with a 10-in. (250 mm) thick lightweight concrete wall with no insulation.

Although the 8-in. (200-mm) thick lightweight concrete wall system is not adequate for Minneapolis according to the ASHRAE Standard 90A-1980 minimum thermal resistance requirements for residential buildings, the standard does not distinguish between massive and non-massive walls in determining required thermal resistance. For massive wall systems, the standard allows exceptions if it can be demonstrated that the wall system performs efficiently. This enables a builder to take advantage of the benefits of heat storage capacity in exterior walls.

A BLAST analysis of the lightweight concrete wall system in a residential building in Minneapolis should be done. This would indicate whether the lightweight concrete wall system outperforms a low mass wall with the ASHRAE minimum thermal resistance of 7.21 $hr \cdot ft^2 \cdot °F/Btu$ (1.27 $m^2 \cdot K/W$).

It should be noted that many states, including California, Florida, and Minnesota, have state energy codes that govern R-value requirements for exterior walls. Therefore, the "Minimum Required Wall R-Value" listed in the

TABLE 15 - ANSI/ASHRAE/IES STANDARD 90A-1980 FOR RESIDENTIAL BUILDING

Location	Heating Degree Days,* °F-days (°C-days)	Maximum Overall Thermal Transmittance U_o, Btu/hr•ft^2•°F (W/m^2•K)	Maximum Overall Thermal Transmittance U_w, Btu/hr•ft^2•°F (W/m^2•K)	Minimum Required Wall R-Value, hr•ft^2•°F/Btu (m^2•K/W)
Minneapolis	8158 (4532)	0.232 (1.32)	0.139 (0.79)	7.21 (1.27)
Chicago	6640** (3689)	0.261 (1.48)	0.176 (1.00)	5.68 (1.00)
Detroit	6228 (3460)	0.269 (1.53)	0.186 (1.06)	5.36 (0.94)
Denver	6016 (3342)	0.272 (1.54)	0.190 (1.08)	5.25 (0.92)
Seattle	5184 (2880)	0.289 (1.64)	0.212 (1.20)	4.71 (0.83)
New York	5033 (2796)	0.292 (1.66)	0.216 (1.23)	4.62 (0.81)
Washington, D.C.	4240** (2356)	0.307 (1.74)	0.236 (1.34)	4.24 (0.74)
Atlanta	3094 (1719)	0.328 (1.86)	0.263 (1.49)	3.81 (0.67)
Fresno	2650 (1472)	0.337 (1.91)	0.274 (1.56)	3.64 (0.64)
Dallas/Fort Worth	2335 (1297)	0.342 (1.94)	0.281 (1.60)	3.56 (0.63)
Los Angeles	1818 (1010)	0.351 (1.99)	0.293 (1.66)	3.42 (0.60)
Phoenix	1552 (862)	0.358 (2.03)	0.302 (1.71)	3.32 (0.58)
Houston	1433 (796)	0.360 (2.04)	0.304 (1.73)	2.29 (0.58)
Tampa	700** (398)	0.374 (2.12)	0.322 (1.83)	3.10 (0.55)

*65°F (18°C) Base, from Reference 15 unless otherwise noted.
**65°F (18°C) Base, from Reference 14

last column of Tables 11 and 12 may not represent the actual R-value required for all locations listed. Cities selected for the Standard Requirements Comparison were chosen to determine the feasibility of the lightweight concrete wall system, according to the ANSI/ASHRAE/IES Standard 90A-1980, for a variety of U.S. climates.

SUMMARY AND CONCLUSIONS

The purpose of this project is to investigate lightweight concrete systems for potential use as thermal breaks in buildings. The project objective is to develop a portland cement concrete with a density less than 50 pcf (800 kg/m^3), compressive strength of 1000 to 1500 psi (6.9 to 10.3 MPa), and thermal conductivity of less than 1.5 $Btu \cdot in./hr \cdot ft^2 \cdot °F$ (0.22 $W/m \cdot K$).

The project is divided into five major tasks. This report summarizes Task 1, a feasibility study which identifies uses for the lightweight portland cement concrete in buildings.

The report is subdivided into three sections. The first section shows where the lightweight concrete can be used in place of steel, other metal, or normal weight concrete to prevent thermal bridges or thermal bypasses. The second section presents BLAST analyses to determine annual energy use for a one-story commercial building and a three-story residential building with 8-in. thick walls constructed using the proposed lightweight concrete. Results were compared to previous investigations of conventional wall systems to determine potential energy savings of the lightweight concrete wall system. In the third section, standards criteria are checked to determine whether an 8-in. (200-mm) thick wall constructed of the lightweight concrete meets minimum energy requirements for exterior walls.

The following conclusions are based on results obtained in this program.

Lightweight Concrete Uses

1. Thermal conductivity of the proposed lightweight concrete material is approximately 1/10th that of normal weight concrete and 1/100th that of steel.

2. The lightweight concrete has potential to serve as thermal break material when used to prevent thermal bridges and thermal bypasses in the following building components: exterior walls, interior walls, columns, chimneys, foundations, and floor slabs.

BLAST Computer Analyses

1. Based on the BLAST analysis, total annual loads for the one-story commercial building and three-story residential building may be predicted using the relationships between heating and cooling loads and heating and cooling degree days, respectively.
2. The commercial building with lightweight concrete walls had lower total annual load than the metal wall system commercial building for all cities considered in the BLAST analysis. The comparison was for walls with the same thermal resistance. Results indicate the benefits of the thermal storage capacity of the lightweight concrete.
3. The residential building with lightweight concrete walls had lower total annual load than the wood frame wall residential building. The comparison was for walls with the same thermal resistance. Results indicate the benefits of the thermal storage capacity of the concrete.
4. The advantage of the lightweight concrete system compared to the alternative concrete and masonry systems described is that an R-value of 6.18 $hr \cdot ft^2 \cdot °F/Btu$ (1.09 $m^2 \cdot K/W$) can be achieved without added insulation.

The effect of thermal mass is influenced by many operating and functional parameters such as solar heat gains, internal heat gains, and temperature control strategy, building geometry, and level of internal mass. The results reported here are for specific sets of such parameters. Other combinations of these parameters may result in thermal performance different from that reported here. However, results reported here are representative of commercial and residential buildings having operational profiles and building geometry similar to those assumed for this investigation.

Standard Requirements

1. The lightweight concrete wall system meets ASHRAE Standard 90A-1980 requirements for the commercial building considered in this study for 14 cities representing a range of climates in the continental U.S.
2. The lightweight concrete wall system meets ASHRAE Standard 90A-1980 requirements for the residential building considered in this study for 13 of 14 cities representing a range of climates in the continental U.S.
3. Based on the BLAST analyses and ASHRAE Standard requirements, the proposed 8-in. (200-mm) structural lightweight concrete wall system exceeds minimum thermal performance criteria for commercial and residential buildings in most regions of the continental United States.

ACKNOWLEDGMENTS

Mr. J. S. Balik, Building Design Engineer, Building Design and Construction Department, Portland Cement Association, performed the BLAST analyses and assisted with the Building Standard requirement check.

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