Analytical Methods of Determining Fire Endurance of Concrete and Masonry Members—Model Code Approved Procedures

Fire endurance: *A measure of the elapsed time during which a material or assembly continues to exhibit fire resistance under specified conditions of test and performance. As applied to elements of buildings, fire endurance shall be measured by the methods and to the criteria defined by ASTM Methods E119, "Standard Methods of Fire Tests of Building Construction and Materials." (*Fire endurance *is a technical term.)*

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

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

PART I

INTRODUCTION AND STANDARD FIRE TEST

Fire-endurance periods for building components are normally determined by physical tests conducted according to ASTM E119, "Standard Methods of Fire Tests of Building Construction and Materials." Provisions of the ASTM E119 test require that specimens be subjected to a fire which follows the standard time-temperature curve shown in Fig. 1.

Under the E119 standard, the fire endurance of a member or assembly is determined by the time required to reach the first of any of the following three end points:

1. Ignition of cotton waste due to passage of flame through cracks or fissures.

2. A temperature rise of 325°F (single point) or 250°F (average) on the unexposed surface of the member or assembly. This is known as the heat transmission end point.

3. Inability to carry the applied design load, that is, structural collapse.

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

1. Concrete structural members: in some cases the average temperature of the tension steel at any section must not exceed 800°F for cold-drawn prestressing steel or 1100°F for reinforcing bars. Tests show that the respective steels retain approximately 50% of their original yield strength at these temperatures.

2. For wall sections: the ability to resist the impact, erosion, and cooling effects of a specific size hose stream.
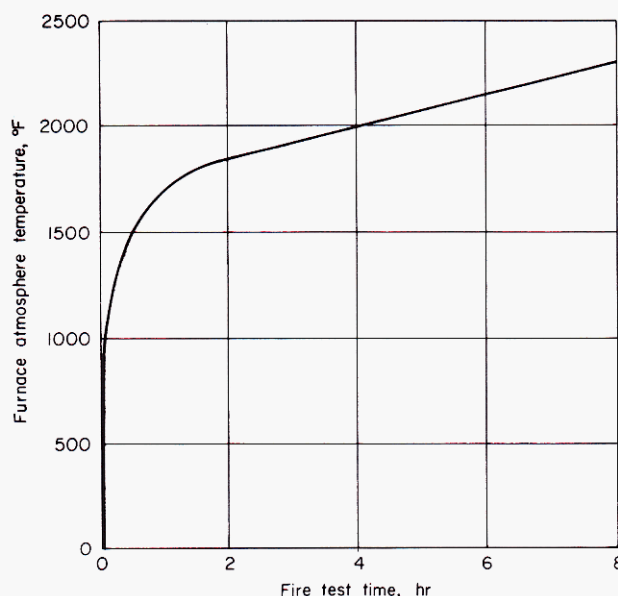

Fig. 1. ASTM Standard E119 time-temperature curve.

Table 1 presents a listing of ASTM E119 end-point criteria and test conditions and outlines applicable end points of various concrete and masonry members and assemblies.

ASTM E119 classifies beams, floors, and roofs as either restrained or unrestrained. A restrained member is one in which the thermal expansion is restricted. Reinforced concrete assemblies are generally classified as restrained if they have continuity at interior supports or are restricted from lateral movement at exterior supports. Table 2 should be referenced when determining the presence of thermal restraint.

The three model codes in the United States are the BOCA Basic National Building Code (B/NBC), ICBO Uniform Building Code (UBC), and SBCCI Standard Building Code (SBC). All require firetesting in accordance with ASTM E119 or analytical calculation based on ASTM E119 test data to satisfy all fire-resistance ratings required by the codes. These recently approved analytical methods present significant cost savings when compared to actual ASTM E119 firetesting.

ANALYTICAL METHODS

Over many years the results of ASTM E119 standard fire tests have been analyzed. Along with standard fire tests there has been research and development of data on strength of steel and concrete at elevated temperatures, temperature distribution within concrete, verification and modification of theory, and the effects of restraining thermal expansion during heating. This testing and research forms the basis for analytical, or calculation, methods of determining fire endurance.

Calculation of fire endurance can be classified into two categories: rational design and empirical design.

Rational Design

Rational design utilizes ASTM E119 fire-test results, data on steel and concrete strength at elevated temperatures, temperature distribution within heated concrete, and the effects of support conditions and restraint of thermal expansion to perform structural engineering calculations.

With the information listed, the engineer can then estimate by calculation the strength of members exposed to standard fire tests for various lengths of exposure time. Many fire tests have been performed to further develop and verify that rational design calculations correctly estimate strengths of members exposed to the standard fire test.

In a rational design calculation the fire endurance would be the length of time required for the load capacity of the member to be reduced to equal that of the applied loading.

Empirical Design

Empirical design utilizes tabulated results of ASTM E119 fire tests and design aids, such as data on strength of heated concrete and steel, and temperature distribu-

tions in concrete and masonry to calculate factors such as critical concrete thicknesses and cover. Application of empirical design is simpler than rational design in that no structural engineering calculations are required.

END-POINT CRITERIA AND ANALYTICAL METHODS

To analytically calculate the fire endurance of a given member it is useful to understand which end-point criteria will govern design of that member. As previously discussed, the first end point reached during the E119 fire test establishes the fire endurance period of the member. To further aid in understanding applicability of various end-point criteria, Table 1 should be referenced.

Walls

Concrete and masonry walls nearly always fail the heat transmission end point before allowing passage of flame or failing structurally. By examining heat transmission through various thicknesses of concrete, made with various types of aggregates, from E119 fire tests it is possible to determine a given thickness or equivalent thickness of concrete, masonry, or brick to limit the temperature rise to below 250°F (average) or to 325°F (single point) as specified in ASTM E119.

Beams

Prestressed and normally reinforced concrete beams cannot be so easily categorized. The ability of a beam to carry a design load is the primary end point and is dependent on several factors which are accounted for in rational design methods. The rational design of a beam would consider the applied load, amount of concrete cover, beam spacing, span length and beam dimension, concrete and steel strengths, aggregate type in the concrete, type of support, and restraint of thermal expansion. Considering the above factors, the structural designer would calculate the load-carrying capacity of the beam at a specific length of exposure time, that being the code-required-fire endurance period for the member being examined.

Empirical design of beams in accordance with, for example, Appendix P of the SBC replaces rational design and considers the above factors for specifying concrete cover requirements for beams of different aggregate type concrete of varying width in both restrained and unrestrained conditions as shown in Table 7. Tests show that with all other factors equal the primary factors in beam fire endurance are the amount of concrete cover over prestressing strands or reinforcing steel bars and the method of support.

Floors and Roofs

Calculation of fire endurance of reinforced and prestressed concrete roof and floor slabs is based on both analysis of heat transmission and of load-carrying capacity at elevated temperatures. The heat transmission end point can be analyzed similarly to walls. As with

Table 1. Applicable End-Point Criteria and Test Conditions for Concrete and Masonry Members and Assemblies (Based on ASTM E119 Standard Fire Tests)

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

[1]Non-load-bearing walls are restrained but not loaded during tests. Bearing walls are loaded but not restrained.
[2]Hose stream tests apply only to those walls required to have a one-hour rating or greater.
[3]Restrained floor and roof slabs utilizing concrete beams spaced greater than 4' center-to-center must not exceed steel temperature limits of 1100°F (reinforcing steel) and 800°F (prestressing steel) for one-half the rating period or 1 hour, whichever is greater.
[4]Reinforcing steel in concrete beams or joists spaced greater than 4' center-to-center and cast monolithically with floors and columns must be maintained below 800°F (prestressing) and 1100°F (reinforcing) for 1 hour or one-half the desired rating period, whichever is greater.

Table 2. Construction Classification, Restrained and Unrestrained

I. Wall bearing	
A. Single span and simply supported end spans of multiple bays[1]	
1. Open-web steel joists or steel beams supporting concrete slab, precast units, or metal decking	Unrestrained
2. Concrete slabs, precast units, or metal decking	Unrestrained
B. Interior spans of multiple bays	
1. Open-web steel joists, steel beams, or metal decking supporting continuous concrete slab	Restrained
2. Open-web steel joists or steel beams, supporting precast units or metal decking	Unrestrained
3. Cast-in-place concrete slab systems	Restrained
4. Precast concrete where the potential thermal expansion is resisted by adjacent construction[2]	Restrained
II. Steel framing	
A. Steel beams welded, riveted, or bolted to the framing members	Restrained
B. All types of cast-in-place floor and roof systems (such as beam-and-slabs, flat slabs, pan joists, and waffle slabs) where the floor or roof system is secured to the framing members	Restrained
C. All types of prefabricated floor or roof systems where the structural members are secured to the framing members and the potential thermal expansion of the floor or roof system is resisted by the framing system or the adjoining floor or roof construction[2]	Restrained
III. Concrete framing	
A. Beams securely fastened to the framing members	Restrained
B. All types of cast-in-place floor or roof systems (such as beam-and-slabs, flat slabs, pan joists, and waffle slabs) where the floor system is cast with the framing members	Restrained
C. Interior and exterior spans of precast systems with cast-in-place joints resulting in restraint equivalent to that which would exist in condition III A.	Restrained
D. All types of prefabricated floor or roof systems where the structural members are secured to such systems and the potential thermal expansion of the floor or roof systems is resisted by the framing system or the adjoining floor or roof construction[2]	Restrained
IV. Wood Construction	
All types	Unrestrained

[1]Floor and roof systems can be considered restrained when they are tied into walls with or without tie beams, the walls being designed and detailed to resist thermal thrust from the floor or roof system.
[2]For example, resistance to potential thermal expansion is considered to be achieved when:
    1. Continuous structural concrete topping is used.
    2. The space between the ends of precast units or between the ends of units and the vertical face of supports is filled with concrete or mortar, or
    3. The space between the ends of precast units and the vertical faces of supports or between the ends of solid or hollow-core slab units does not exceed 0.25 percent of the length for normal weight concrete members or 0.1 percent of the length for structural lightweight concrete members.

beams, the ability of roofs and floors to carry load is influenced by several factors in design. Tabulated values for concrete cover, similar to those for beams, exist for roof and floor slabs and are shown in Table 8.

Columns

The structural fire endurance of concrete columns is influenced primarily by the column size and the concrete aggregate type. The bases at present for column fire endurance design are tabulated minimum cover and column size requirements based on past ASTM E119 tests which were run to the structural failure end point.

Further research on columns is being conducted presently at the laboratories of the National Research Council of Canada and the Portland Cement Association. Preliminary results indicate that current code provisions are conservative and that cover thickness is relatively unimportant.

FACTORS INFLUENCING ENDURANCE OF CONCRETE AND MASONRY EXPOSED TO FIRE

Three principal factors influence the fire endurance of concrete and masonry. These factors, thickness and aggregate type, thermal restraint conditions, and temperature distribution through members are included in the code-approved methods for calculating fire resistance and need to be understood before attempting to carry out the calculations.

Effect of Thickness and Aggregate Type

The factors which determine the fire endurance of concrete and masonry members or assemblies subject to the heat transmission end point criteria (walls, floors, roofs) are the thickness and the aggregate type of concrete used.

This can be seen clearly in Table 3, which shows that for a given aggregate type the length of time to reach a 250°F temperature rise on the unexposed surface increases as the thickness of the concrete increases.

Table 3. Fire Endurances of Naturally Dried Specimens[1]

Slab Thickness, in.	Fire endurance, hr:min.		
	Siliceous aggregate	Carbonate aggregate	Sanded expanded shale aggregate[2]
1½	0:18	0:18	0:24
2½	0:35	0:41	0:54
4	1:18	1:27	2:18
5	2:01	2:17	3:00
6	2:50	3:16	4:55
7	3:57	4:31	—

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

Examination of Table 3 also shows that lightweight aggregate concrete transmits heat more slowly than normal-weight concrete, resulting in longer fire endurances. As unit weight, determined by aggregate type, is reduced, resistance to heat transmission increases.

Structural lightweight concretes use aggregate such as expanded shale, clay, and slate and have unit weights ranging from 100 lbs per cu ft to about 120 lbs per cu ft. Normal-weight concretes have unit weights ranging from 135 to 150 lbs per cu ft. Normal-weight concretes utilize siliceous aggregates obtained from natural sand and gravel or carbonate aggregates such as limestone. Lightweight insulating concretes with unit weights of as low as 30 lb per cu ft are also available.

Effect of Restraint of Members During Fire Loading

Most cast-in-place reinforced concrete members are considered restrained. Precast or prestressed concrete members are more difficult to classify, and conditions which affect thermal restraint should be carefully examined in every case involving a beam, floor, or roof assembly. The tabular methods contained within the model codes consider either fully restrained or fully unrestrained members subjected to ASTM E119 fire tests. In most cases the presence of restraint will enhance fire endurance.

Table 2, which is part of Appendix X3 of ASTM E119 and is contained within the UL Fire Resistance Directory, provides some criteria for identifying whether a given member or assembly is restrained or unrestrained.

Temperature Distribution Within Concrete and Masonry Members and Assemblies

In concrete and masonry, several factors influence temperature distribution through a member; primary are the shape or thickness of the member and the concrete aggregate type. Temperature distribution through or within the member during ASTM E119 firetesting is important in determining heat transmission rates in walls and floors and roofs and in determining steel and concrete temperatures in beams, floors and roofs, and columns.

PART II

CODE-APPROVED METHODS OF CALCULATION

The methods depicted in this portion of the report are empirical and tabular. As discussed, these procedures are accepted by the model codes to varying degrees. While the three model codes have adopted slightly different language regarding analytical methods, the technical bases for all code-approved analytical methods are set forth in references 1 and 2. It follows that most critical factors (wall thickness, concrete cover, and so forth) do not differ from code to code.

To limit redundancy in tables and figures, various minor differences between the codes will be pointed out by footnotes.
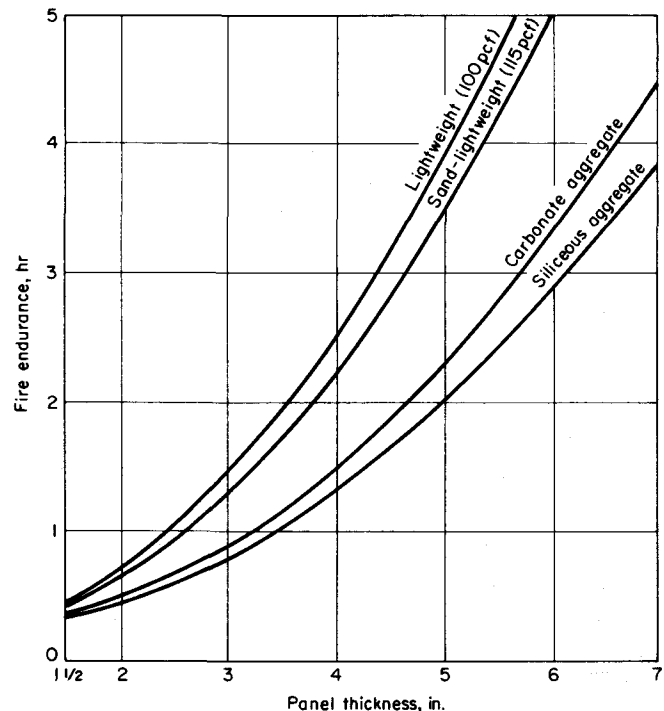
HEAT TRANSMISSION END POINT

Solid Concrete Walls, Floors, and Roofs of Constant Thickness

When considering flat, single-wythe concrete or masonry walls, floors, or roofs, heat transmission endurance periods are based on the actual or equivalent thickness of the assembly in accordance with Fig. 2 (concrete) or Table 4 (masonry).

When the building component in question is ribbed, tapered, undulating, or has hollow cores, an equivalent *solid thickness* must be determined. *Equivalent thickness* is the thickness obtained by considering *the gross cross-sectional area of a wall minus the area of voids or undulations in hollow or ribbed sections, all divided by the width of the member.* Calculation of equivalent thickness is outlined for several common concrete and masonry building components in Figs. 3, 4, and 5 and elsewhere within the text.

Tapered Flanges

Equivalent thickness for a concrete T-beam with tapered flanges is taken as the actual thickness of the flange measured at a distance of twice the minimum thickness or 6" from the end of the flange (whichever is less). This is shown in Fig. 3.

Note: SBC and UBC specify concrete wall thickness using tables similar to Table 4; BOCA specifies references 1 and 2 when referring to wall thickness. Values shown in Fig. 2 are valid for all model codes.

Fig. 2. Thickness of concrete required for fire endurances shown.

Fig. 3. Equivalent thickness of a tapered member.

Table 4. Minimum Equivalent Thickness in Inches of Load-Bearing Concrete Masonry Unit Walls for Fire-Resistance Ratings[1]

A. SBC[2]	4 hr	3 hr	2 hr	1 hr
Expanded slag or pumice aggregates	4.7	4.0	3.2	2.1
Expanded shale, clay, or slate aggregates	5.1	4.4	3.6	2.6
Limestone, cinders, or unexpanded slag aggregates	5.9	5.0	4.0	2.7
Calcareous gravel aggregates	6.2	5.3	4.2	2.8
Siliceous gravel aggregates	6.7	5.7	4.5	3.0
B. UBC[2]	4 hr	3 hr	2 hr	1 hr
Expanded slag or pumice	4.7	4.0	3.2	2.1
Expanded clay, shale, or slate*	5.1	4.4	3.6	2.6
Limestone, cinders, or air-cooled slag	5.9	5.0	4.0	2.7
Calcareous or siliceous gravel	6.2	5.3	4.2	2.8
*Recommended for approval				
C. BOCA[3]	4 hr	3 hr	2 hr	1 hr
Expanded slag or pumice	4.7	4.0	3.2	2.1
Expanded clay, shale, or slate	5.1	4.4	3.6	2.6
Limestone, cinders, or slag	5.9	5.0	4.0	2.7
Calcareous and siliceous gravel	6.2	5.3	4.2	2.8

[1]Fire ratings for thicknesses between tabulated values may be obtained by direct interpolation.
[2]SBC and UBC—Where all of the core spaces of hollow-core wall panels are filled with loose-fill material such as expanded shale, clay or slag, or vermiculite or perlite, the fire-resistance rating of the wall is the same as that of a solid wall of the same concrete type and of the same overall thickness.
[3]BOCA—Walls composed of hollow concrete masonry units having a nominal thickness of 8 inches or greater and having a fire-resistance rating of at least 2 hours shall be classified as 4 hours when the hollow spaces are completely filled with insulation, grout, or a dry granular material such as expanded slag, clay, shale, or sand.
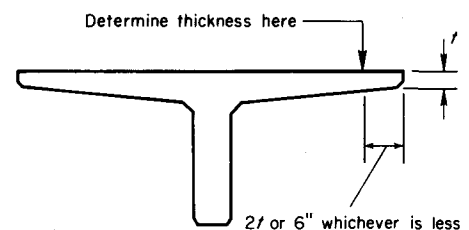
Ribbed Concrete Members

For ribbed or undulating surfaces, calculation of equivalent thickness is based on the spacing of the stem components and minimum thickness of the flange. Calculation of the equivalent thickness is determined based on the provisions shown in Fig. 4.

For $s \geq 4t$, the thickness to be used shall be t
For $s \leq 2t$, the thickness to be used shall be t_e

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

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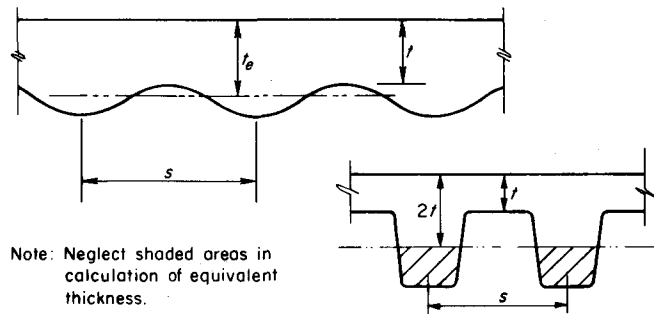

Note: Neglect shaded areas in calculation of equivalent thickness.

Fig. 4. Equivalent thickness of a ribbed or undulating section.

Hollow-Core Concrete Planks

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

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

where A_{net} is the gross cross section (thickness X width) minus the area of cores. This is shown in Fig. 5.

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

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

= 576 sq in. - 62.8 sq in. = 513.2 sq in.

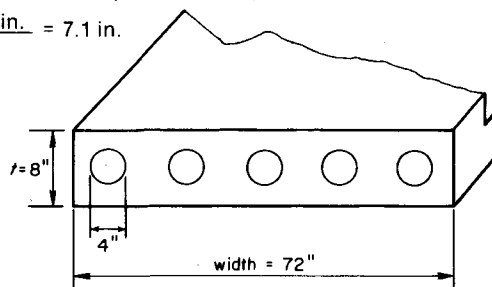$t_{eq} = \frac{513 \text{ sq in.}}{72 \text{ in.}} = 7.1 \text{ in.}$

Fig. 5. Typical hollow-core concrete plank.

Concrete Masonry Block

Hollow or solid concrete masonry units are available in nominal thicknesses of 2, 3, 4, 6, 8, 10, and 12 in. with varying percentages of solid area. The equivalent thickness for hollow block can be calculated using a procedure similar to that for hollow-core slabs. Equivalent thickness for concrete masonry can be determined from the following equation:

$$t_{eq} = \% \text{ solid X thickness}$$

The percent of solids in any given masonry unit can be obtained from the manufacturer. Once equivalent thickness is known, the fire-resistance rating of masonry walls can be determined from Table 4. See notes to Table 4 for each model code's provision regarding fire endurance of filled block. If 100% solid flat-sided concrete masonry units are used, the equivalent thickness is the actual thickness.

Brick

The model code fire ratings based on E119 tests of load-bearing, solid or hollow, shale or clay brick walls of various thicknesses and varying finishes (plastered, unplastered) are shown in Table 5 A-C. The fire endurance of brick walls is dependent on brick thickness, type of members that frame into the walls (combustible or noncombustible), and finishes such as plaster. As with concrete and masonry walls, brick walls generally reach the heat transmission end point before failing structurally.

Multi-Wythe Walls

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

$$R = \left(R_1^{0.59} + R_2^{0.59} \ldots + R_n^{0.59}\right)^{1.7} \qquad \text{Eq. 1}$$

where

R = total fire-endurance rating in minutes

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

For example, two wythes—each rated at 1 hour (see Fig. 2: 3.2 in. carbonate aggregate and 2.7 in. lightweight aggregate concretes)—will give

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

Graphical calculation is shown for this system in Fig. 6. The equation is not applicable in all cases and must be used keeping the following conditions in mind.

1. The fire endurances (determined in accordance with ASTM E119) of each wythe must be known.
2. The equation does not account for orientation of layering. It is known that if the more fire-resistant material is on the fire-exposed surface, a higher total rating would be obtained during actual testing than if the wythes were reversed.

Table 5. Fire-Resistance Periods for Clay or Shale, Solid or Hollow Brick Walls

A. SBC Fire-Resistance Ratings for Load-Bearing Walls and Partitions
(Minimum nominal thickness in inches for fire-resistance ratings indicated)

Wall or partition assembly	Members framed into wall or partition							
	Combustible				None or Noncombustible			
	4 hr	3hr	2 hr	1 hr	4 hr	3 hr	2 hr	1 hr
Solid-brick walls								
Solid (clay, shale, concrete, or sand-lime) —unplastered	12	12	8	8	8	8	8	OSU T-1971 T-1972
—clay or shale							6	4
Solid (as above) ½" (1:3) sanded gypsum plastered on one side	12 (1)	8 or 12 (1) (2)	8 (1)	8 (1)	8	8	8	
Solid (as above) ½" (1:3) sanded gypsum plastered on each side	12	8 or 12 (2)	8	8	8	8		
Brick (clay or shale)—4"-thick units at least 75 percent solid backed with a hat-shaped metal furring channel ¾" thick formed from 0.021" sheet metal attached to the brick wall on 24" centers with approved fasteners; and ½" Type X gypsum wallboard attached to the metal furring strips with 1"-long Type S screws spaced 8" on center							5	

(1) Rating is applicable only when plastered side of wall or partition is on exposed side.
(2) 8" for sand-lime or concrete brick, or 12" for clay or shale brick (3-hour rating).

B. UBC Rated Fire-Resistive Periods for Various Walls and Partitions
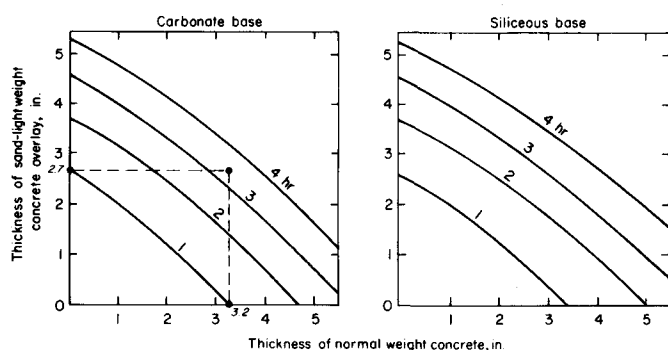
Material	Item number	Construction	Minimum finished thickness face-to-face[2] (in inches)			
			4 hr	3 hr	2 hr	1 hr
Brick of clay or shale	1	Solid units (at least 75 percent solid)	8		6	4
	2	Solid units plastered each side with ⅝" gypsum or portland cement plaster. Portland cement plaster mixed 1:2½ by weight, cement to sand			4¾	
	3	Hollow-brick units at least 71 percent solid[1]		8		
	4	Hollow-brick units at least 71 percent solid, plastered each side with ⅝" gypsum plaster[1]	8¾			
	5	Hollow (rowlock)[2]	12		8	
	6	Hollow (rowlock) plastered each side with ⅝" gypsum or portland cement plaster. Portland cement plaster mixed 1:2½ by weight, cement to sand[2]	9			
	7	Hollow-cavity wall consisting of two 4" clay brick units with air space between	10			
	8	Hollow-brick units at least 60 percent solid, cells filled with perlite loose-fill insulation	8			
	9	4"-thick units at least 75 percent solid backed with a hat-shaped metal furring channel ¾" thick formed from 0.021" sheet metal attached to the brick wall on 24" centers with approved fasteners; and ½" Type X gypsum wallboard attached to the metal furring strips with 1"-long Type S screws spaced 8 inches on center			5	

[1]Hollow-brick units 4-inch by 8-inch by 12-inch nominal with two interior cells having a 1½-inch web thickness between cells and a 1¾-inch-thick face shells.
[2]Rowlock design employs clay brick with all or part of bricks laid on edge with the bond broken vertically.

C. BOCA Fire-Resistance Periods for Load-Bearing Clay and Shale Brick Walls[1]

Nominal wall thick- ness, in.	Wall type	Ultimate fire-resistance period in hours				
		Noncombustible members framed into wall or no framed-in members			Combustible members framed into wall	
		No plaster	Plaster on one side[2]	Plaster on two sides[2]	No plaster	Plaster on exposed side[2]
4	Solid	1¼	1¾	2½	—	—
8	Solid	5	6	7	2	2½
12	Solid[3]	10	10	12	8	9
12	Solid[4]	12	13	15	—	—
9 to 10	Cavity	5	6	7	2	2½

[1]BOCA specifies BIA "Building Code Requiements for Engineered Brick Masonry." Table 5C is a reprint from that series.
[2]To achieve these ratings, each plastered wall face must have at least ½-in., 1:3 gypsum-sand plaster.
[3]Based on load failure.
[4]Based on temperature rise(for non-load-bearing walls).

Graphical Method

Calculation Method

3.20″ carbonate aggregate concrete from Fig. 2, R = 1.0 hr
2.70″ sand-lightweight concrete from Fig. 2, R = 1.0 hr

$$R_{Total} = \left((60)^{0.59} + (60)^{0.59} \right)^{1.7} = 197 \text{ minutes (3 hr, 17 minutes)}$$

Fig. 6. Fire endurance of multi-wythe walls—graphical versus calculation method (based on fire exposure on normal weight concrete side of assembly).

3. The exponent 1.7 and its reciprocal 0.59 are average values which vary from material to material.

The equation is generally accurate within ten percent. Graphical means of calculating multi-wythe fire resistance, as shown in Fig. 6, should be used when greater accuracy is required.

Table 6 shows values for $R^{0.59}$ to be used in the multi-wythe equation. Note that concrete masonry block and brick are not included. $R^{0.59}$ values may be obtained for any wall tested per ASTM E119 by simply raising the resistance, in minutes, to the 0.59 power. For example, from Fig. 2 it can be seen that 3.5 inches of siliceous aggregate concrete will provide one hour fire endurance, and $(60)^{0.59} = 11.3$. Referring to Table 6 we see that $R^{0.59}$ for 3.5 inches of siliceous aggregate concrete is 11.3.

To apply the multi-wythe equation to brick, masonry, and composite walls the resistance (R) values in minutes for brick (Table 5) and masonry (Table 4) should be used.

Sandwich Panel Wall Section

Precast concrete panels consisting of a layer of foamed insulation between two layers (wythes) of concrete have become a popular method of providing energy-efficient walls. Foam insulation can be considered to have a fire-resistance rating (R) of 5 minutes if one inch or thicker ($R^{0.59} = 2.5$ minutes). For thicknesses less than one inch, the effect of the foam insulation should not be considered in calculating the panel fire endurance.

Multicourse Concrete Floors and Roofs

Calculations of heat transmission fire endurance of multicourse floors and roofs are similar to analysis of multiwythe walls. Fig. 6 shows the required thickness of a siliceous or carbonate aggregate concrete base course and an overlay of sand-lightweight concrete required to achieve fire endurances from one to four hours. Ratings shown are based on the heat transmission end point. Graphs such as Fig. 6 have been approved for analytical calculation of multicourse floor, roof, and wall fire endurance by all model codes. Reference 1 is an excellent source of this graphical data.

STRUCTURAL END POINT
Reinforced and Prestressed Concrete Beams

Reinforced and prestressed concrete beam fire endurance is governed by the ability of the beam to carry structural loads. In addition, steel temperatures must in some cases be maintained below the ASTM E119 limits of 800°F for prestressing steel and 1100°F for reinforcing steel. Under the ASTM E119 standard, beams can be tested for either restrained or unrestrained conditions. A summary of ASTM E119 conditions of acceptance and steel temperature criteria for beams follows:

1. Beams—tested restrained and used restrained.

    For individual restrained beams spaced more than 4 feet on center, the steel temperatures must be limited to below 800°F (prestressing) or 1100°F (reinforcing) for one hour or one-half the desired rating period, whichever is greater.

Table 6. $R_n^{0.59}$ Values for Various Thicknesses of Concrete Floors, Roofs, and Walls; Various Aggregate Types[1]

Type of material	Values of $R_n^{0.59}$ for use in Eq. 1											
	1½ in.	2 in.	2½ in.	3 in.	3½ in.	4 in.	4½ in.	5 in.	5½ in.	6 in.	6½ in.	7 in.
Siliceous aggregate concrete	5.3	6.5	8.1	9.5	11.3	13.0	14.9	16.9	18.8	20.7	22.8	25.1
Carbonate aggregate concrete	5.5	7.1	8.9	10.4	12.0	14.0	16.2	18.1	20.3	21.9	24.7	27.2[4]
Sand-lightweight concrete	6.5	8.2	10.5	12.8	15.5	18.1	20.7	23.3	26.0[4]	[4]	[4]	[4]
Lightweight concrete	6.6	8.8	11.2	13.7	16.5	19.1	21.9	24.7	27.8[4]	[4]	[4]	[4]
Insulating concrete[2]	9.3	13.3	16.6	18.3	23.1	26.5[4]	[4]	[4]	[4]	[4]	[4]	[4]
Air Space[3]	—	—	—	—	—	—	—	—	—	—	—	—

[1] All model codes recognize the use of the listed $R_n^{0.59}$ values for concrete. To be used when calculating total resistance in minutes.
[2] Dry unit weight 35 pcf or less and consisting of cellular, perlite, or vermiculite concrete.
[3] The $R_n^{0.59}$ value for one ½- to 3½-inch air space is 3.3. The $R_n^{0.59}$ value for two ½- to 3½-inch air spaces is 6.7.
[4] The fire-resistance rating for this thickness exceeds 4 hours.

2. Beams—tested in an unrestrained condition and used unrestrained.

Steel temperature limits are waived, the beam is rated on its ability to carry the applied load.

3. Beams—tested in a restrained condition but used unrestrained.

Steel temperatures in concrete beams must be maintained below the limits of 800°F for prestressing and 1100°F for reinforcing for the entire endurance period.

The several different classifications for beams graphically illustrate the several conditions which influence beam fire endurance. Factors such as beam width and spacing, restraint conditions, and concrete cover are considered in Table 7. The tabulated cover requirements in Table 7 will maintain steel temperatures below the ASTM E119 limits for the listed exposure times for shown restraint conditions, beam widths, and concrete aggregate type (if prestressed).

Table 7. Minimum Cover in Inches for Reinforced and Prestressed Concrete Beams*

A. Minimum Cover to Main Reinforcing Bars for Reinforced Concrete Beams (Applicable to All Types of Structural Concrete)[1]

Restrained or unrestrained[2]	Beam width[3] (inches)	Cover thickness (inches) for fire-resistance rating				
		1 hr	1½ hr	2 hr	3 hr	4 hr
Restrained	5	¾	¾	¾	1[1]	1¼[1]
Restrained	7	¾	¾	¾	¾	¾
Restrained	≥ 10	¾	¾	¾	¾	¾
Unrestrained	5	¾	1	1¼	—	—
Unrestrained	7	¾	¾	¾	1¾	3
Unrestrained	≥ 10	¾	¾	¾	1	1¾

[1] The cover for an individual reinforcing bar is the minimum thickness of concrete between the surface of the bar and the fire-exposed surface of the beam. For beams in which several bars are used, the cover is assumed to be the average of the minimum cover of the individual bars, where the minimum cover for corner bars used in the calculation shall be reduced to ½ of the actual value. The cover for an individual bar must be not less than ½ of the value given in Table 7A nor less than ¾ inch.

[2] See Table 2 for guidance on restrained and unrestrained assemblies. Tabulated values for restrained assemblies apply to beams spaced more than 4 feet on centers; for restrained beams spaced 4 feet or less on centers, minimum cover of ¾ inch is adequate for ratings of 4 hours or less.

[3] For beam widths between the tabulated values, the minimum cover thickness can be determined by direct interpolation.

B. Minimum Cover for Prestressed Concrete Beams[1]

Restrained or unrestrained[2]	Concrete aggregate type	Beam width[3] (inches)	Cover thickness[4] (inches) for fire-resistance rating				
			1 hr	1½ hr	2 hr	3 hr	4 hr
Restrained	Carbonate or siliceous	8	1½	1½	1½	1¾[1]	2½[1]
Restrained	Carbonate or siliceous	≥ 12	1½	1½	1½	1½	1⅞[1]
Restrained	Sand-lightweight	8	1½	1½	1½	1½	2[1]
Restrained	Sand-lightweight	≥ 12	1½	1½	1½	1½	1⅝[1]
Unrestrained	Carbonate or siliceous	8	1½	1¾	2½	5[5]	—
Unrestrained	Carbonate or siliceous	≥ 12	1½	1½	1⅞	2½	3
Unrestrained	Sand-lightweight	8	1½	1½	2	3¼	—
Unrestrained	Sand-lightweight	≥ 12	1½	1½	1⅝	2	2½

[1] Minimum cover to nonprestressed reinforcing in prestressed concrete beams shall be determined by values shown in Table 7A.
For UBC jurisdictions, the cover requirements for reinforcing steel derived from calculation methods for determining fire endurance of structural members prescribed in Standard No. 43-9 of the Uniform Building Code shall not apply to precast prestressed single or double T units. Cover requirements for these members can be found in Table No. 43-A, items 30 and 31, of the UBC.

[2] See Table 2 for guidance on restrained and unrestrained assemblies. Tabulated values for restrained assemblies apply to beams more than 4 feet on center.

[3] For beam width between 8 and 12 inches, minimum cover thickness can be determined by direct interpolation.

[4] The cover for an individual tendon is the minimum thickness of concrete between the surface of the tendon and the fire-exposed surface of the beam, except that for ungrouted ducts the assumed cover thickness is the minimum thickness of concrete between the surface of the duct and the surface of the beam. For beams in which several tendons are used, the cover is assumed to be the average of the minimum cover of the individual tendons, where the minimum cover for corner tendons used in the calculation shall be reduced to one-half the actual value. The cover for any individual tendon must be not less than one-half of the value given in Table 7B nor less than 1 inch.

[5] Not practical for 8-inch-wide beam, but shown for purposes of interpolation.

*UBC (Standard Section 43-9) and SBC (Appendix P) both contain the tabulated values shown; B/NBC refers to references 1 and 2 of this report. Based on technical information in references 1 and 2, B/NBC jurisdictions may accept values shown in Table 7A and B.

Reinforced or Prestressed Concrete Floor and Roof Slabs

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

The values for slabs shown in Table 8 represent minimum required slab thickness and concrete cover requirements for reinforced or prestressed slabs for various aggregate type concretes in restrained or unrestrained conditions. The tabular fire endurances listed in Table 8 are based on examination of past ASTM E119 test results of slabs with similar cover, restraint conditions, and concrete aggregate type. The specified cover for unrestrained assemblies will maintain steel temperatures below the specified limits of 800°F for prestressing and 1100°F for reinforcing steel. Again, Table 2 should be referenced when determining whether a floor or roof is restrained or unrestrained.

Concrete Columns

Fire endurance of concrete columns is governed under ASTM E119 by their ability to carry the applied load under firetesting. The endurance is affected primarily by the size of the column and aggregate type. A summary of the tabular code-approved minimum column dimensions and concrete cover requirements is shown in Table 9.

Table 8. Minimum Slab and Concrete Cover Thickness in Inches for Listed Fire Resistance of Reinforced Concrete Floors and Roofs[1]

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

Concrete aggregate type	Minimum slab thickness (inches) for fire-resistrance rating				
	1 hr	1½ hr	2 hr	3 hr	4 hr
Siliceous	3.5	4.3	5.0	6.2	7.0
Carbonate	3.2	4.0	4.6	5.7	6.6
Sand-lightweight	2.7	3.3	3.8	4.6	5.4
Lightweight	2.5	3.1	3.6	4.4	5.1

B. Cover Thickness for Reinforced Concrete Floor or Roof Slabs[2]

Concrete aggregate type	Thickness of cover (inches) for fire-resistance rating							
	Restrained[3]				Unrestrained[3]			
	1 hr	1½ hr	2 hr	3 hr	1 hr	1½ hr	2 hr	3 hr
Siliceous	¾	¾	¾	¾	¾	¾	1	1¼
Carbonate	¾	¾	¾	¾	¾	¾	¾	1¼
Sand-lightweight	¾	¾	¾	¾	¾	¾	¾	1¼
Lightweight	¾	¾	¾	¾	¾	¾	¾	1¼

C. Cover Thickness for Prestressed Concrete Floor or Roof Slabs[2]

Concrete aggregate type	Thickness of cover (inches) for fire-resistance rating							
	Restrained[3]				Unrestrained[3]			
	1 hr	1½ hr	2 hr	3 hr	1 hr	1½ hr	2 hr	3 hr
Siliceous	¾	¾	¾	¾	1⅛	1½	1¾	2⅜
Carbonate	¾	¾	¾	¾	1	1⅜	1⅝	2⅛
Sand-lightweight	¾	¾	¾	¾	1	1⅜	1½	2
Lightweight	¾	¾	¾	¾	1	1⅜	1½	2

[1] Both the UBC (Standard Section 43-9) and SBC (Appendix P) contain the tabulated values shown in Table 8; B/NBC refers to references 1 and 2 of this report. Based on technical information in References 1 and 2, B/NBC jurisdictions may accept values shown in Table 8.
[2] The minimum thickness of concrete cover to the positive moment reinforcement is given in Table 8B for reinforced concrete and Table 8C for prestressed concrete. Table 8 is applicable for solid or hollow-core one-way or two-way slabs with flat undersurfaces. Slabs may be cast-in-place or precast. For precast prestressed concrete not covered elsewhere, the procedures contained in PCI *Design for Fire Resistance of Precast Prestressed Concrete* shall be acceptable.
[3] See Table 3 for guidance on restrained and unrestrained assemblies.

Table 9. Minimum Concrete Column Size and Concrete Cover*

Concrete aggregate type	Minimum column dimension (inches) for fire-resistrance rating				
	1 hr	1½ hr	2 hr	3 hr	4 hr
Siliceous	8	8	10	12	14
Carbonate	8	8	10	12	14
Sand-lightweight	8	8	9	10.5	12

Minimum Cover for Reinforced Concrete Columns. The minimum cover to the main reinforcement in columns for fire-resistance ratings of one hour, one and one-half hours, two hours, and three hours shall be 1½ inches; for four-hour rating, the minimum cover to the main reinforcement shall be 2 inches for siliceous aggregate concrete and 1½ inches for carbonate aggregate concrete or sand-lightweight concrete.

*UBC (Standard Section 43-9) and SBC (Appendix P) contain provisions as shown in Table 9. B/NBC refers to references 1 and 2 of this Report which contain similar provisions.

CONCLUSION

Calculation of fire endurance of concrete and masonry members has progressed from pure research to practical structural design applications. Further refinements of analytical methods are going on now, aided in great part by computer simulations of concrete and masonry performance under fire-test conditions.

The information contained in this report scratches the surface on the topic of analytical and empirical design. The practicing structural engineer will find references 1, 2, and 3 excellent sources of additional information on the rational methods for calculating fire resistance.

The engineer, architect, or building official will find this a handy and usable guide in assessing concrete and masonry requirements with regard to fire endurance.

Calculation procedures provide a viable timesaving and cost saving means of determining a member's fire endurance without running full scale ASTM E119 fire tests. Along with savings of time and money, the building official, architect, or engineer will have a much clearer concept of how certain variables affect fire endurance if analytical procedures are utilized.

REFERENCES

1. *Reinforced Concrete Fire Resistance,* Concrete Reinforcing Steel Institute, Schaumburg, Illinois, 1980.
2. Gustaferro, A. H. and Martin, L. D., *Design for Fire Resistance of Precast Prestressed Concrete,* Prestressed Concrete Institute, Chicago, Illinois, 1977.
3. *Guide for Determining the Fire Endurance of Concrete Elements,* 216R-81, American Concrete Institute, Detroit, Michigan, 1981.
4. *Fire Safety with Concrete Masonry,* NCMA-TEK 35-B, National Concrete Masonry Association, Herndon, Virginia, 1984.
5. *Fire Resistance,* BIA Technical Notes on Brick Construction No. 16, Brick Institute of America, October 1974.

Organizations represented on the CONCRETE AND MASONRY INDUSTRY FIRESAFETY COMMITTEE

BIA	Brick Institute of America
CRSI	Concrete Reinforcing Steel Institute
ESCSI	Expanded Shale Clay and Slate Institute
NCMA	National Concrete Masonry Association
NRMCA	National Ready Mixed Concrete Association
PCA	Portland Cement Association
PCI	Prestressed Concrete Institute

BEAM-SLAB EXAMPLE

The cast-in-place reinforced concrete beam and slab shown in Fig. 7 form a floor system in a multistory occupancy of Type I construction (SBC). Assume this assembly is required by code to have 3 hours of fire resistance. Can it attain this? If not, how can the fire resistance be increased to 3 hours?
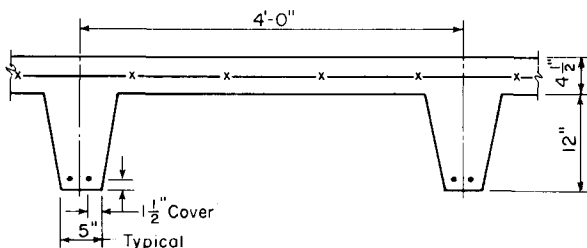

Fig. 7. Siliceous aggregate cast-in-place—restrained.

Solution

Beam-slab systems must satisfy *both* heat transmission and structural failure end points. The member shown in Fig. 7 is considered restrained due to its being cast-in-place with framing members.

HEAT TRANSMISSION END POINT
Referring to Fig. 4, the equivalent thickness is determined using the three equations comparing s (stem spacing) and t (slab thickness). Replacing 4'-0" for s, and 4½" for t, $s \geq 4t$. Therefore $t_{eq} = t = 4½"$.

The required slab thickness from Table 8A for a three-hour fire-resistance rating is 6.2 inches; the 4.5 inches will provide between one-and-a-half and two hours resistance to heat transmission to the unexposed surface, not three hours as required.

STRUCTURAL END POINT
Slab. For many cast-in-place concrete slabs, the structural cover exceeds cover required to achieve fire resistance. This is clearly the case with the example 2¼ inches cover versus ¾ inches required by Table 8B for three hours fire resistance.

Beam. Table 7A, for reinforced concrete beams, specifies 1 inch of concrete cover in 5-inch-wide restrained beams to attain three hours fire resistance. Note that the example beams are spaced 4 feet center to center. Footnote one states that for restrained beams spaced 4 feet or less on centers, the cover can be reduced to a minimum of ¾ inches for four-hour ratings or less. The 1½-inch cover provided clearly satisfies the code requirements for 3 hours fire resistance.

Conclusion

In order to attain three hours fire resistance, the slab must be made more resistant to heat transmission. The steel cover requirements for three hours structural fire resistance in both the slab and the beam stem are satisfied.
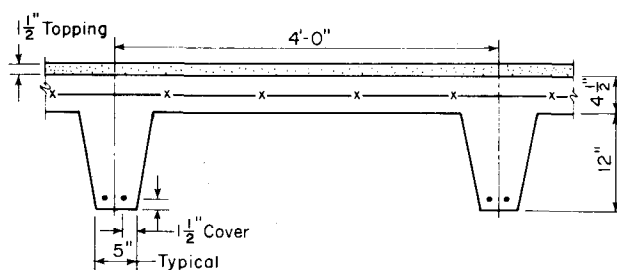

Fig. 8. Siliceous aggregate cast-in-place—restrained with 1½" lightweight concrete topping.

In discussing multi-wythe (multilayer) walls and floors earlier in the report, it was shown that significant resistance to heat transmission could be attained by considering the effect of layering of materials. This can be done using Eq. 1 or graphical methods.

In this example problem, referring to Fig. 9, a 4½-inch base slab of siliceous aggregate with approximately 1½ inches of sand-lightweight concrete topping will provide the additional required resistance to heat transmission to attain three hours fire resistance.

Checking Fig. 9 against Eq. 1, the 4½" of siliceous-aggregate concrete base slab has 1 hour, 36 minutes fire resistance (Fig. 2 or Table 8A). Fig. 2 shows that 1½ inches of sand-lightweight topping will provide approximately 24 minutes resistance to heat transmission. Using Eq. 1,

$$R = \left(R_1^{0.59} + R_2^{0.59} \right)^{1.7}$$

$$R = \left((96)^{0.59} + (24)^{0.59} \right)^{1.7} = 181 \text{ minutes}$$
$$\text{(3 hours, 1 minute)}$$

Therefore the slab system shown in Fig. 8 will provide three hours fire resistance if a 1½-inch topping of sand-lightweight concrete is applied.
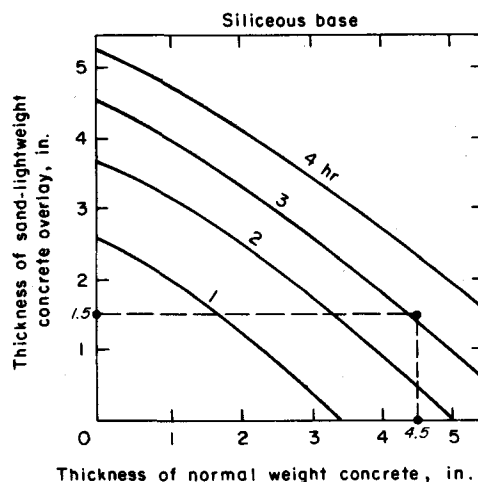

Fig. 9. Graphical solution of multi-wythe fire endurance.

Concrete and Masonry Industry Firesafety Committee