

Fire testing procedures in the United States and Europe are examined and compared. Notes that although the standards of different countries are similar in general considerations, differences exist in the details of application. Specimen restraint is discussed.

Fire Endurance TESTING PROCEDURES

By C. C. Carlson

STANDARD FIRE TESTS FOR ACCEPTANCE purposes, and often for research investigations, are conducted in the United States and Canada in accordance with methods and criteria in "Standard Methods of Fire Tests of Building Construction and Materials" (ASTM E 119). This same standard is also found under other designations such as Underwriters' Laboratories (UL) No. 263, National Fire Protection Association (NFPA) No. 251, and American Standards Association (ASA) No. A2-1.

ASTM E 119 is the product of effort and experience applied through the years (conceived in 1906 and published as a tentative standard in 1917) by many technically trained people who comprise a group which is now known as ASTM Committee E 5, Fire Tests of Materials and Construction. Currently, the membership of ASTM Committee E 5 is drawn from a number of areas of interest in the fire safety of building con-

struction: the building materials manufacturing industry, testing laboratories, insurance organizations, and governmental agencies.

ASTM E 119 describes and defines the fire testing procedures which are to be applied in the evaluation of the fire endurance of walls, columns, beams, and floor and roof assemblies. Certain criteria are also given for gaging and interpreting fire test results. Thus by close adherence to the procedures and performance criteria, fire test results may be appraised and compared from a common base.

Overseas countries also have their standards for fire tests, for example, British Standard 476, Dutch Standard NEN 1076, and West German Standard DIN 4102.

The standards of the different countries which engage in fire testing of building materials and structures are strikingly similar with respect to general considerations such as rate of heating the test furnace,

application of load, hose stream test, and determination of the end point in fire tests. This similarity had its beginning in certain agreements reached at the International Fire Prevention Congress held in London in 1903. However, differences will be found in some of the details for the conduct of standard fire tests. Some of these differences can lead to dif-

ferences in results. Hence, one should be cognizant of the factors which may affect the comparison of American fire test data with data from other countries.

The purpose of this paper is to examine some of the procedures for conducting standard fire tests in various countries and to point to some of the significant differences in the detailed application of the procedures.

TIME-TEMPERATURE CURVE

The furnaces which are used for standard fire tests of the different parts of buildings, that is, floors, walls, columns, beams, etc., assume a variety of shapes according to the needs of the tests and according to the ideas of the furnace designers. Furnace design has not been standardized. One element which is common to all testing furnaces, however, is the rate in which heat is applied. All are heated in accordance with a time-temperature relationship which is accepted and required under the standard of the particular country in question. A further requirement of all testing furnaces is that they be fired in a manner that insures uniform heating of all exposed surfaces of the specimen.

The time-temperature regime which is followed by all testing laboratories in the United States and Canada is shown graphically in Fig. 1. It will be noted from the graph that the furnace temperature must be raised very rapidly during the

first 30 min: to 1000 F in 5 min, to 1300 F in 10 min, and to 1550 F in 30 min. A slower rate is used for the balance of the exposure to 2300 F. Fire tests are seldom continued in America for periods beyond 8 hr. But when they are, the furnace temperature is maintained at a constant level of 2300 F.

European laboratories engaged in fire testing employ approximately the same time-temperature relationship as United States and Canadian laboratories. American and European time-temperature curves are compared in the composite plot shown in Fig. 2. The curves of countries not represented in Fig. 2 assume similar shapes.

With the possible exception of the German and Swedish standards, the variations of the standard time-temperature curves of other countries from the American standard curve are not in excess of allowable deviations from the standard of actually recorded furnace temperatures in American fire tests. ASTM E 119 stipulates, under Section 3(c), that in the conduct of standard fire tests "The accuracy of the furnace control shall be such that the area under the time-temperature curve, obtained by averaging the results from the pyrometer readings, is within 10 per-

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cent of the corresponding area under the standard time-temperature curve shown in Fig. 1† for fire tests of 1 hr or less duration, within 7.5 percent for those over 1 hr and not more than 2 hr, and within 5 percent for tests exceeding 2 hr in duration.”

When deviations occur, a correction of the indicated fire endurance time is required. Section 5(c), ASTM E 119, states the correction procedure as follows:

“When the indicated resistance period is $\frac{1}{2}$ hr or over, determined by the average or maximum temperature rise on the unexposed surface or within the test sample, or

†Fig. 1 in ASTM E 119 is essentially the same as Fig. 1 in this paper—Editor.

by failure under load, a correction shall be applied for variation of the furnace exposure from the prescribed, where it will affect the classification, by multiplying the indicated period by two thirds of the difference in area between the curve of average furnace temperature and the standard curve for the first three fourths of the period and dividing the product by the area between the standard curve and a base line of 68 F (20 C) for the same part of the indicated period, the latter area increased by 54 Fahr-hr or 30 Cent-hr (3240 Fahr-min or 1800 Cent-min), to compensate for the thermal lag of the furnace thermocouples during the first part of the test. For fire exposure in the test higher than standard, the indicated resistance period shall be increased by the amount of the correction and be similarly decreased for fire exposure below standard.

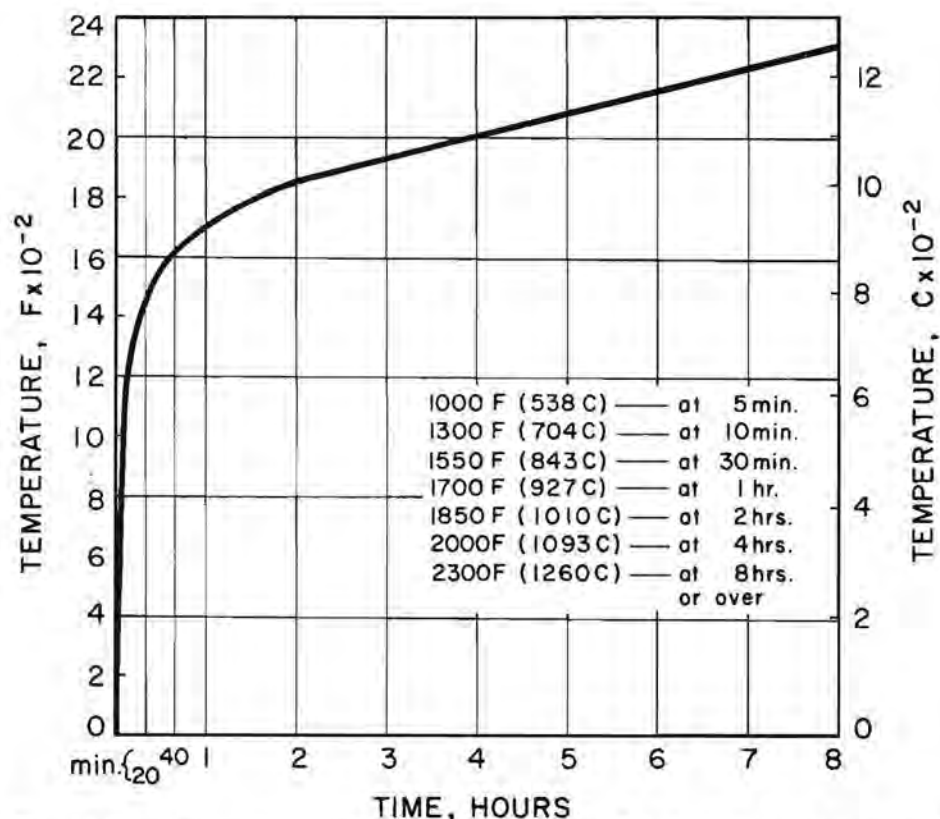


Fig. 1—Time-temperature relationship for heating fire testing furnaces in the United States and Canada (from ASTM E 119)

"The correction can be expressed by the following formula:

$$C = \frac{2I(A - A_s)}{3(A_s + L)}$$

where:

C = correction in the same units as I

I = indicated fire-resistance period

A = area under the curve of indicated

average furnace temperature for the first three fourths of the indicated period

A_s = area under the standard furnace curve for the same part of the indicated period

L = lag correction in the same units as A and A_s . [54 Fahr-hr or 30 Cent-hr (3240 Fahr-min or 1800 Cent-min)]"

TEMPERATURE MEASUREMENT

Viewing the similarity of standard time-temperature curves shown in Fig. 2, it might be concluded that American and European fire tests may be directly compared or corrections applied in the manner described above. However, furnace temperatures relative to the specimen are measured in American fire tests in a manner which differs in detail from the procedure employed in fire tests in other countries. In fire tests which are conducted according to ASTM E 119, the furnace thermocouples are encased in 1/2-in standard-weight wrought iron pipe tubes, sealed at the ends. As a permissible alternate, they may be encased in sealed ceramic tubes of comparable diameter and wall thickness. One purported reason for the use of thermocouple shields is to avoid the more rapid deterioration of chromel-alumel thermocouples which seems to occur in a reducing furnace atmosphere. Another reason is to avoid the rapid oscillations in recorded furnace temperature which are exhibited with bare thermocouples when flame may intermittently impinge upon the hot junctions.

Practices vary in Europe with regard to the protection of furnace thermocouples. The standard of Great Britain¹ stipulates the use of bare furnace thermocouples—the thermocouple assembly is sheathed in a

porcelain tube except for the tip or hot junction which is bare. The standard of Holland² is not clear on this issue but from the observations of visitors at the Holland laboratory it seems that bare furnace thermocouples are employed here too. From reports of visitors to the laboratories of West Germany, France, and Italy, shielded furnace thermocouples are used but it is not known whether the shielding is similar to that specified in ASTM E 119.

Thermocouple clearance

It was found that there are differences in American and European practices in the clearance between furnace thermocouples and the test specimen. For American fire tests of beams, columns, or floor and roof assemblies, the furnace thermocouples are placed 12 in. away at the beginning of a test. As the specimen deflects this clearance changes, since the thermocouples are fixed, but at no time are they to touch the specimen. For fire tests of walls and partitions, the clearance at the beginning of a test is 6 in. In Great Britain and Holland, the clearance between bare thermocouples and the specimen generally is 3 in.; maintained throughout the test by the furnace operator. In a published report of column tests performed in West Germany,³ it was noted that a clearance

of 4 in. between furnace thermocouple hot junctions and the specimen was employed.

Bare thermocouples will, of course,

respond more quickly to temperature changes than will thermocouples which are encased in protective tubes.

The correction formula of ASTM

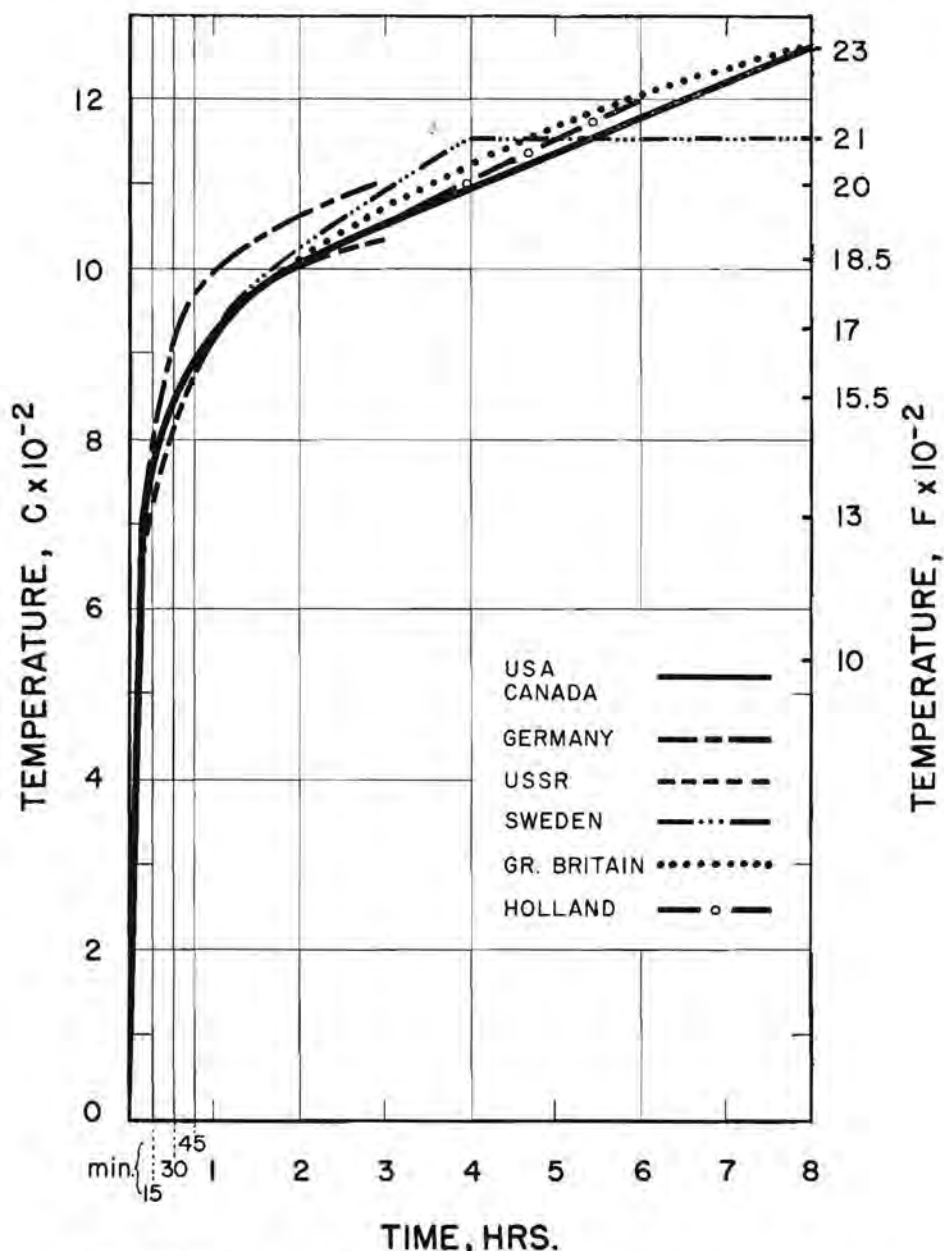


Fig. 2—Comparison of time-temperature curves of various countries

E 119, given on p. 4, recognizes the effect of shielding by the use of the thermal lag factor L . The temperature indicated by shielded thermocouples will lag that indicated by bare thermocouples to the greatest extent during the early portion of the fire test when the furnace temperature must be raised rapidly. As the test progresses, the temperature lag becomes less due to the slower rate of furnace temperature change.

From an unpublished study by the National Bureau of Standards in which the temperatures from shielded thermocouples were compared to temperatures from bare thermocouples, it was found that the shielded thermocouple temperatures lagged the temperatures registered by the bare thermocouples by 154 C at 5 min, 46 C at 1 hr, 34 C at 2 hr, and 26 C at 4 hr. These results were obtained in one test, of a series of fire tests of concrete beams, in which the furnace temperature was controlled by bare thermocouples positioned in the furnace, relative to the specimen, in accordance with the requirements of the British Standard.

Had the furnace been heated in the same manner as above but controlled by shielded thermocouples as required by ASTM, it would seem that the recorded time-temperature curve would have been located some-

what above the American time-temperature curve. In other words, the actual furnace temperature produced by the ASTM procedure at a given time will be somewhat higher than the temperature which may be registered by shielded thermocouples, assuming that the real furnace temperature is that measured by bare thermocouples.

Relative exposure severity

The relative severity of fire exposures may be more accurately determined by comparing the area under the resulting time-temperature curves of the tests. This comparison is made in Table 1 indicating that the American test is perhaps more severe than the British test.

It should be pointed out that these differences are within the limits of variation from the standard curve allowed by both British Standard 476 and ASTM E 119. The American standard requires that the recorded exposure be corrected to the standard exposure where the variation may effect the classification. The British standard does not require a correction so long as the recorded time-temperature curve is within the prescribed limits listed in BS 476 (Table 2).

As previously explained, the clearances between specimen and furnace control thermocouples vary under the American standard but are about the same for all specimen types tested under the standards of foreign countries. Just what effect the variation in clearance in American tests has on exposure severity is not known, but it is believed that the effect is small where the method of firing the testing furnace provides for good mixing and turbulence of furnace gases.

The differences shown in Table 1 were obtained from furnace thermo-

TABLE 1 — COMPARISON OF ACCUMULATIVE EXPOSURE

Test time, hr	Area under standard time-temperature curve, percent		Difference, percent
	Bare thermocouple	Protected thermocouple	
½	100.8	92.0	8.8
1	100.3	94.2	6.1
2	100.5	95.4	5.1
3	100.3	95.8	4.5
4	99.9	96.1	3.8
4½	99.7	96.3	3.4

couples placed at 3 in. (British) and 12 in. (American) away from the specimen. The furnace in which the tests were conducted was fired by gas burners which produced a brisk flame and considerable turbulence. Therefore, these indicated exposure differences stemmed largely from the effects of thermocouple shielding. Data from tests performed in Great

Britain on a wall specimen indicate that for clearances of 6 in. and 3 in. between the specimen surface and furnace thermocouples there was practically no difference in the temperature readings. But when the furnace thermocouples were placed on the fire exposed surface of the specimen, the resulting temperature readings were considerably lower.

METHODS OF HEATING TEST FURNACES

Another detail of standard fire testing procedure which has not been standardized is the mode for heating the test furnaces. ASTM E119 does not specify the fuel nor the manner of burning the fuel. Neither do the standards of other countries. Evidently the only requirement with respect to firing a test furnace is that the resulting heating follow the standard time-temperature curve and that the heating of the specimen, in turn, be uniform on all exposed surfaces. The fuel commonly used for firing test furnaces in America is gas and currently, with one or two exceptions, natural gas because of its wide availability and comparatively low cost. In Europe, manufactured gas, propane, gasoline, and fuel oil are among the fuels employed for testing furnaces.

One prominent laboratory in the United States fires its test furnaces with natural gas flames which are luminous and have been variously described as rolling, lazy, and somewhat smoky. The gas is burned in a manner that simulates the air-starved combustion which has been observed in actual building fires. Another American laboratory employs gas burners for its furnaces which produce active, short, and almost colorless flames while yet another fires

its furnaces with flames that are about a median between these extremes.

A furnace in Holland which is used for tests of long beams is fired by propane gas. The burners of this unit are directed downward upon a bed of crushed refractory material. The specimen is heated by a combination of radiation emitted by the glowing bed of refractory and the movement of hot products of combustion which are taken out of the furnace through ports near the top of the beam specimen. The furnaces employed at the Herts fire research station in England make use of multiple gas burners which produce short, bluish flames.

Apparently, in furnaces where the burner flame is short or where the burners are oriented in a manner

TABLE 2—MAXIMUM TOLERANCE FOR AREA UNDER TIME-TEMPERATURE CURVE (BS476)

Duration of test, hr	Elements subject to requirements of clause 11 a, b, c, [†] percent	Elements subject to requirements of clause 11 a, b, only, [†] percent
1/2	15	15
1/2-1	10	15
1-2	10	15
more than 2	5	—

[†]Refers to mode of failure: a = failure by collapse, b = failure by passage of flame, and c = failure by heat transmission.



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which avoids flame impingement, bare thermocouples can be successfully used. The bare furnace thermocouple is favored in Great Britain because of its more rapid response compared to shielded thermocouples. Nevertheless, shielded furnace thermocouples have been used in American fire tests for many years.

Influence of flame color

The question has been posed by persons engaged in fire research as to the influence of flame color on the heating of test specimens. Heat reaches a test specimen principally by radiation and by convection of furnace gases. Observations made in column tests at the Herts fire research laboratory showed that temperatures measured by thermocouples were, on the average, 150 C higher than temperatures measured by radiometers. It was therefore suggested⁴ that the main quantity of heat absorbed by the specimen was delivered by moving furnace gases.

Thermocouples do not readily register radiant heat effects unless mounted on the surface of the body receiving radiation. In instances where furnaces are fired by burners producing highly luminous flame or where radiant heat is purposely created as in the beam furnace in Holland, it is possible that the greater portion of heat absorbed by a specimen may come from radiation which would not be precisely detected by thermocouples located some distance away from the exposed surface. A person involved in the design of a test furnace might wonder about this detail and the differences in laboratory practices concerning it. It appears that these differences are not of important consequence 40 to 60 min after the start of a fire test since after this interval the refractory and other furnace parts become sufficiently heated as to serve in themselves as heat radiating bodies no matter what the fuel or how it is burned.

SIZE OF SPECIMENS FOR STANDARD FIRE TESTS

Minimum dimensions for fire test specimens are specified in the standards of a number of countries in which acceptance fire tests are carried on. Some advisory statements were encountered in the literature to the effect that test specimens ought to be full size whenever possible and shall truly represent the design, materials and workmanship for which classification is desired. When constructions exceed in size the practicable limits of furnace equipment, the testing agency is advised to employ a representative portion of the construction whose dimensions are to be no less than the specified minimum dimensions. Only when the actual construction is smaller may the

dimensions of the specimen be less than the given minimums. Table 3 gives the minimum dimensions or areas of specimens which are employed by several countries for fire tests of building components.

The dimensions given in Table 3 for countries other than Great Britain, Canada, and the United States are for furnace openings and were originally expressed in metric units. Only for British and American procedures was specific mention made of minimum areas or dimensions to be exposed to fire. It may be that all dimensions given in Table 3 for other countries refer to that proportion of the specimen which is to be exposed to fire, but this is not a cer-

tainty. If a specimen is mounted in a steel frame for purposes of applying restraint or for handling, the refractory protection of the frame in some designs could mask off or reduce the exposed area appreciably.

The size of the area exposed to the fire, relative to its thickness, is important in fire tests when the criteria relative to structural performance and passage of flame are applicable. If a specimen is restrained or is required to carry load during the exposure, the effects of restraint and load are more pronounced in large specimens than in small specimens, assuming that the thicknesses of the larger and smaller specimens are the same, which is usually the case in tests of walls and columns. Thus, in fire tests of larger specimens the effects of heat and load are shown by greater deflections; therefore, greater opportunity for cracking and buckling failures. It is for these reasons, for purposes of realism and authenticity, that the standards encourage the use of full scale specimens.

Size limitations

There are, of course, practical limitations as to the extent the "full

scale" philosophy can be carried in fire tests. For example, fire walls extending from the foundation to the roof, or beyond, may exceed 35 ft. Such walls are required, under some codes, to be self-sustaining and to withstand the effects of fire and the collapse of constructions on either side for at least 4 hr. Obviously, the fire resistance of such constructions can only be approximated. Current designs reflect experience from actual building fires.

It appears that data having to do with structural behavior of building components in fire exposures cannot be reliably extrapolated. In other words, data on structural performance obtained during fire tests of scaled models cannot be extended for application to the prototype, as is frequently possible with structural data obtained at normal temperatures. Some effort in the direction of extrapolation has been reported by Ashton and Bate⁵ in connection with a study of the fire resistance of prestressed concrete beams. In this work, fire test results from 1/2-scale beams were compared with the results from 4/5-scale and 6/5-scale members. The data showed that as the size of the member increased the mode of structural failure changed.

TABLE 3 — MINIMUM SPECIMEN DIMENSIONS FOR VARIOUS BUILDING COMPONENTS^{1,2,10,11}

Country	Floors and ceilings, ft	Walls and Partitions, ft	Columns, ft	Beams, ft
Great Britain†	10 x 10	10 x 10	10	10
U.S., Canada‡	180 sq ft	100 sq ft	9§	12
Holland	6.6 x 13.2	6.6 x 9.8	—	26.2
France	9.8 x 13.2	6.6 x 7.6	7.6	13.2
Italy	9.8 x 21.4	3.9 x 5.9	13.1	21.4
Sweden	6.6 x 14.8	6.6 x 9.8	9.8	14.8
West Germany	5.8 x 14.8	6.6 x 9.8	9.8	14.8

¹Dimensions refer only to that portion of the specimen which is exposed to the fire. The usual size of floor specimen is 10 x 12 ft although a new furnace is now available for specimens 12 x 24 ft.

²Areas and dimensions given refer only to that portion of the specimen which is exposed to the fire. The minimum dimension for floors and ceilings is 12 ft and the minimum dimension for walls and partitions is 9 ft.

[§]In tests of protected steel columns, the protected length exposed to fire shall be at least 8 ft.

LOAD REQUIREMENTS IN STANDARD FIRE TESTS

ASTM E 119 requires that during a standard fire test a load bearing element or assembly shall support a superimposed load calculated to develop stresses equal to those which would be produced in the prototype construction carrying the maximum load for which it is designed. This usually means that the test load in a standard fire test will consist of one dead load plus one live load. It appears that the same requirements regarding load are contained in the present day standards of foreign countries.

British requirements

Prior to 1953 the British standard provided for $1\frac{1}{2}$ live loads in the test load but in July 1953 the requirement was reduced to one live load. Two considerations were involved in the earlier requirement of $1\frac{1}{2}$ design loads: (1) to allow for possible overloading of parts of a building from falling debris or from water pumped into the building during the fire fighting period and (2) to compensate for possible superior quality of construction in the test specimen compared to that realized in practice.

The intensity of load induced stress in the critical parts of load bearing specimens during the fire exposure, particularly those taking bending stress, has an important influence on the fire endurance. Therefore, all load induced stresses should be considered when fire test results of similar constructions are compared. From some experience in tests of pre-stressed beams it is possible for a fire test specimen supporting one

dead load plus one and one-half live loads to exhibit a fire endurance of 25 percent less than would be the case if the test load were one dead load plus one live load.

Loading methods

Live loads are applied to column and wall specimens by means of hydraulic cylinders or jacks. Usually the thrust of the hydraulic cylinder is impressed upon a stiff steel plate or beam to distribute the load uniformly. In loading floor and roof systems and beams the use of weights is quite common although some of the newer laboratories that have come into being during recent years make use of hydraulic loading equipment of various designs. Those laboratories which use weights for loading have employed containers of water and sand, blocks of concrete, and blocks of cast iron. In most of these instances the weights rest on legs of various design to minimize the area of contact and permit the circulation of air beneath the weight assembly.

It has been observed in some reports of fire tests of floor specimens that the weights for live-load were placed in a manner which could draw appreciable amounts of heat away from the test specimen more rapidly than when the assembly is separated from the unexposed surface by an air space of 2 to 4 in. It would seem that to obtain a true measure of the unexposed surface temperature, weights placed on a specimen for live load should not in any way interfere with the natural process of heat transmission and the rate of rise of temperature on the unexposed surface of the specimen.

In hydraulic loading systems the problem is not so much one of interference with natural heat transmission but of distributing the thrust of hydraulic cylinders uniformly over the test area. Some laboratories make use of four hydraulic cylinders whose thrust is distributed through 32 or more load points on areas of, perhaps, 14 x 18 ft or 15 x 15 ft. The mechanical linkages which have been developed to accomplish this distribu-

tion are quite ingenious. Other laboratories have preferred the use of multicylinder arrangements containing as many as 30 hydraulic cylinders. These bear on the test specimen through square or rectangular steel load pads or load distributing tripods. Usually, the specimen surface-to-steel heat path is interrupted by layers of compressible asbestos board or blocks of concrete or clay brick.

MEASUREMENT OF UNEXPOSED SURFACE TEMPERATURES

The unexposed surface temperature criterion has application only in tests of walls, partitions, floors, and roofs. Since these constructions under normal conditions serve to enclose building space, one of their looked to functions in a fire is to contain and thus prevent the spread of fire. The unexposed surface temperature criterion considers the possibility of fire being spread by the ignition of combustibles in areas beyond the barrier constructions through the transmission of heat, should some of these combustibles be stored near or in contact with these constructions.

End point criteria

Under the provisions of ASTM E119, the end point by the above criterion is reached when the temperature of the surface away from the fire (1) rises 250 F above the starting temperature as determined by the average of temperature readings from at least nine thermocouples located in a specific manner, or (2) when the temperature at any one point of measurement rises 325 F; whichever is attained first.

The above limits are contained in the 1953 version of the British stand-

ard. Prior to 1953 these temperatures during British tests were fixed at 250 F (average) and 300 F (maximum). Somewhat lower temperatures are presently specified in the Dutch standard, namely, 130 C (234 F) for the average temperature rise and 170 C (306 F) for the maximum temperature rise at any one point of measurement. No information was obtained relative to the provisions of other standards regarding this aspect but it is believed that the limits do not vary greatly from those given above.

Methods of measurement

Differences were also found among the several standards in the manner in which the unexposed surface temperature is measured. The American standard requires that each of the surface thermocouples be covered by a flexible oven-dry felted asbestos pad 6 in. square and 0.4 in. thick (a tolerance of $\pm 1/8$ in. is allowed in the lateral dimensions and ± 0.05 in. in the thickness). The pad shall weigh 0.26 lb ± 10 percent. The insulating character of the American standard thermocouple pad is directed to a simulation of the temperature build-up which may occur on the unexposed surface of a separating

construction during a fire should combustible materials be stored in direct contact with this surface. This rather detailed specification for the construction of the pad is to insure a sameness in insulating effect wherever it may be used. Fig. 3 shows the standard pad and Fig. 4 shows its application to the surface of a floor test assembly.

The method for measuring the unexposed surface temperature which is specified by the British standard is shown in Fig. 5. Earlier, the British had experimented with an asbestos thermocouple pad similar to that specified by ASTM E 119 but practical difficulties were encountered in achieving consistent results. That shown in Fig. 5 was adopted as the preferred method. The Dutch standard states simply that the unexposed surface temperature shall be measured by thermocouples and in a manner such that "a correct measurement is guaranteed." Presumably, this means that the hot junctions are affixed in intimate contact with the surface by some suitable fastening

device. A further requirement of the Dutch specification is that the thermocouples (and surface) be protected from strong air currents. It is believed that some covering of surface thermocouples is used but no description of the cover was found.

Convection currents

This latter consideration (of air currents) points up the real difference between the various systems for measuring the exposed surface temperature. The need for protecting the unexposed surface against strong air currents or drafts is stated or implied in most standards. To those in fire research work, this need is obvious. The cooling action of wind could produce results which would be inconsistent with the performance of the construction in a building. With wind present during a test, the end points as determined by the unexposed surface criteria would be falsely postponed. However, no standard attempts to regulate or standardize the effects of convection currents.

Convection currents will increase in velocity as the temperature of the

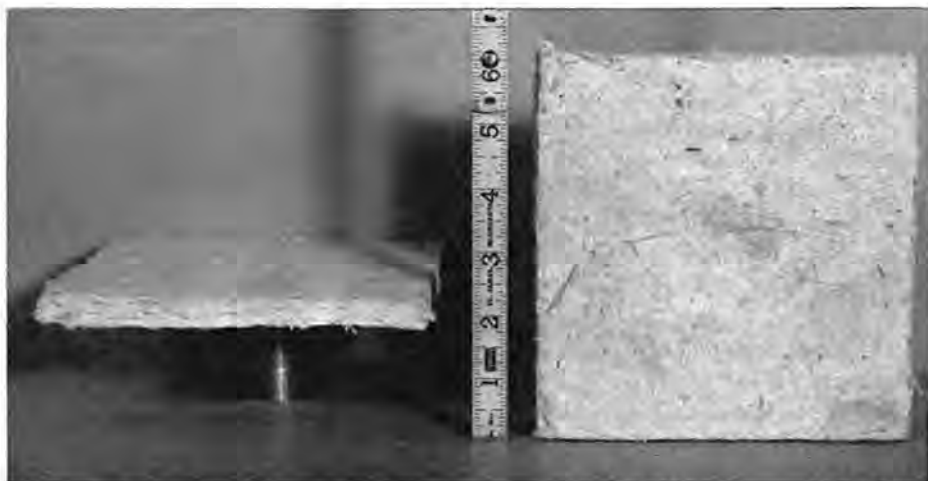


Fig. 3—Standard asbestos thermocouple pad used in the United States

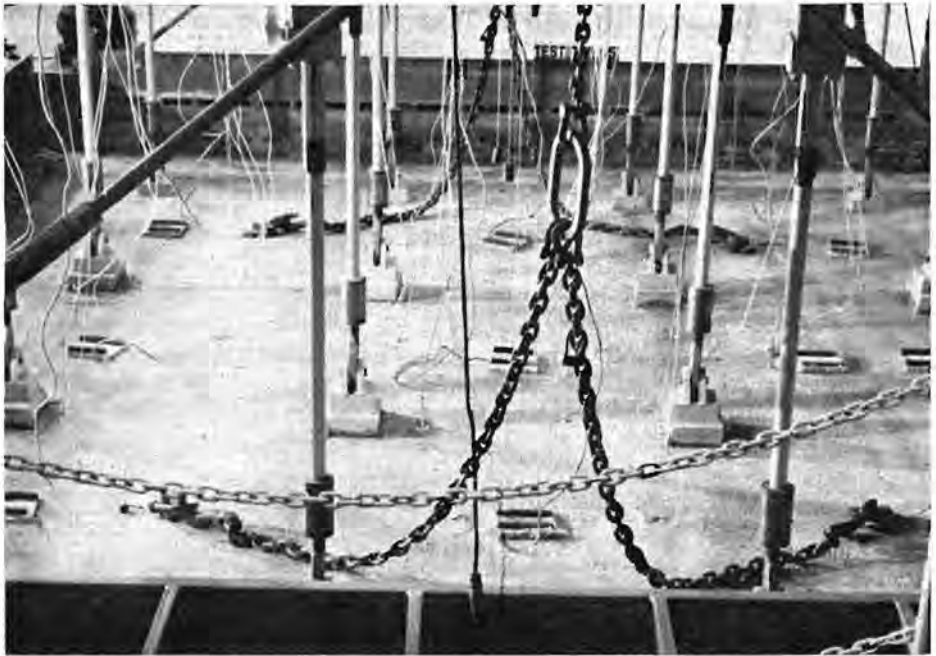


Fig. 4—Thermocouple arrangement for measuring unexposed surface temperature of floor assemblies in the United States

surface increases even in protected locations. Thus unexposed surface temperatures measured by thermocouples which are bare will tend to be lower than temperatures measured by covered thermocouples. In some unreported studies of the fire resistance of masonry partitions in which the ASTM method for measuring the unexposed surface temperature was compared with other systems, temperatures registered by thermocouples under felted asbestos pads were more than 80 F higher than temperatures from uncovered thermocouples. This difference was recorded at about the end point of a fire test as determined by the unexposed surface temperature criteria of ASTM E 119. In terms of endurance time, the difference amounted to about 30 min, that is, the end point as established by the ASTM method occurred about 30 min sooner.

In fire tests of constructions of concrete or other materials which may contain a measure of moisture at the time of the exposure, it is important that the insulating efficiency of the ASTM standard thermocouple pad be maintained. It has been observed in many fire tests that moisture within specimens tends to migrate to the cooler, unexposed surface where it may accumulate beneath thermocouple pads in sufficient quantity as to actually cause them to become damp to wet. Tests of flat floor or roof assemblies present a particularly difficult problem because water may collect in puddles around a pad during the "boiling" interval.

Pads which become wetted are changed for dry ones as soon as the "boiling" stage has passed. Some American laboratories have designed special equipment for replacing wetted thermocouple pads on horizontal

specimens which avoids the hazards of direct handling during fire tests. Wet pads can cause depressions in the unexposed surface temperature of as much as 50 F. Evidently, this

problem is not present in the British system nor in other systems which employ bare thermocouples for measuring the unexposed surface temperature.

MOISTURE CONTENT OF SPECIMEN

The moisture content of a construction at the time of exposure to the standard fire test is highly important to the results. Constructions of concrete are obviously no exception. The effects of moisture in concrete on fire resistance are discussed by other contributors to this symposium. Excessive moisture in concrete at the time of testing can lead to disruptive spalling and early failure in some cases, and to endurance periods of unwarranted length in others. In most standards reviewed, the moisture aspect is covered by a statement requiring that the moisture content of the test assembly be brought to a state which simulates that which the prototype is likely to attain in service.

Various interpretations have been applied to the above instructions. Until only recently the problem of mois-

ture control was dealt with in this country by observing weight changes in the specimens being conditioned for the fire tests or in representative samples of these specimens. A specimen was regarded as ready for the fire test when no appreciable weight change occurred during five successive days of drying under conditions favorable to good drying.

Equilibrium relative humidity

In 1955 Menzel⁶ proposed the relative humidity test for ascertaining the proper time for testing with respect to moisture content. His method is based on the premise that moisture in all elements comprising a building will eventually come into equilibrium with the average year-round climatic relative humidity of the area in which the building is to be located. From United States

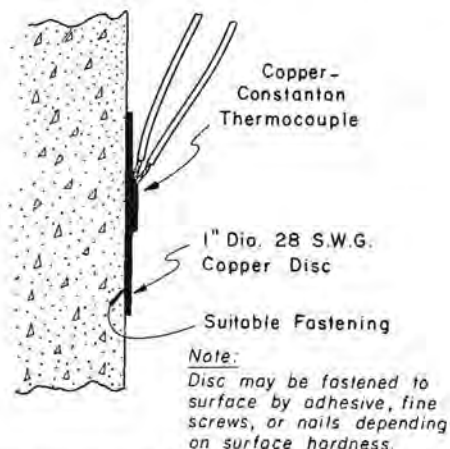
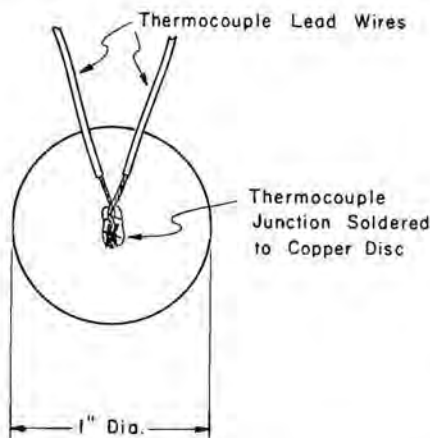


Fig. 5—British method for measuring unexposed surface temperature

Weather Bureau data it was found that the average year-round relative humidity for various areas of the country ranged from 40 to 85 percent. The average for the greater proportion of the country, however, ranged from 60 to 75 percent.

As a working application of Menzel's thesis a tentative amendment to the instructions of ASTM E119 on the conditioning specimens for fire testing was proposed which requires that the building element or assembly be dried until the equilibrium relative humidity in the dampest portion is 70 percent or less. Artificial drying is allowed provided that no damage or undue structural change is wrought by the process.

Fig. 6 shows an application of the relative humidity method for measuring the moisture content of concrete slabs. In this case it was found more convenient to observe the moisture changes in representative samples rather than in the test slabs themselves. The relative humidity of the concrete is measured by means of an electric hygrometer which is sealed for a period within a steel-lined well (Fig. 7), the bottom of which is open at the particular level of the section being measured.



Fig. 6—Specimen with Menzel's device installed

The well is formed at the time the concrete is cast by placing a thin walled tube at the desired location in the forms and plugging the bottom end with a foamed plastic material which is easily removed later with a rotary cutting tool to expose the concrete.

It is the opinion of many that the relative humidity method provides a truly rational means for measuring the moisture content of concrete specimens being conditioned for fire tests. It has been observed in many fire tests of structural concrete elements and assemblies that the occurrence of spalling is greatly reduced when the equilibrium relative humidity of the concrete has been

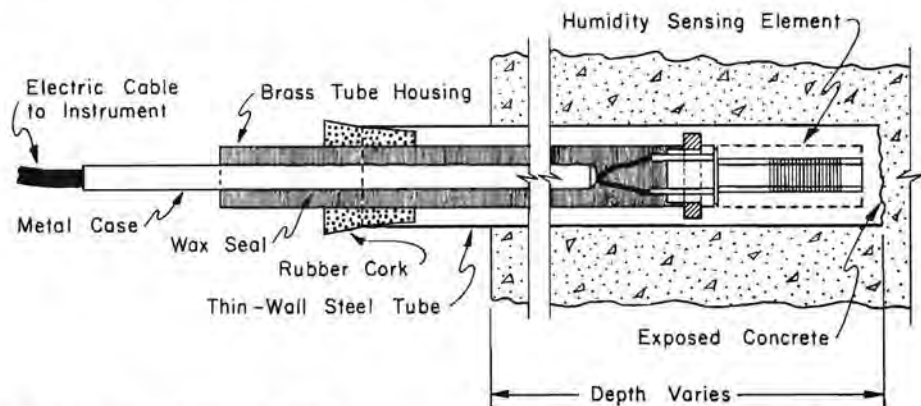


Fig. 7—Menzel's method for measuring moisture in concrete fire test specimens

lowered to about 70 percent or less. This is even true with higher strength concretes and restrained specimens. Weight change from a moisture level equivalent of 85 percent relative humidity, where the likelihood of spalling is acute, to 70 percent relative humidity would hardly be detectable by practical weighing methods.

RESTRAINT IN FIRE TESTS

The effect of axial and moment restraint on the fire resistance of structural elements and assemblies is recognized by most of the standards but the provisions for its application vary, even among testing laboratories in the same country. As yet no evaluation has been made of the forces and stresses that are generated when concrete construction (or any other type) is restrained against thermal expansion arising from a fire exposure.

The standards treat the subject in broad terms which in essence recommend that service conditions be simulated. As a result, the restraining frames which are used in tests of partitions, floors, roofs, and beams vary according to the experience and judgment of the testing agencies. This is not to say that any of the restraining methods are in error. Actually, each system provides a realistic measure of restraint in a fire

exposure. Since they vary in design, they can not produce identical restraining effects, all other things being equal.

Fig. 8-12 shows in section some restraining frames in use in America and in Europe. The capacity of a frame to restrain is governed, of course, by the size and stiffness of the steel members which make up the frame and the manner in which they are joined at corners.

Exploratory fire tests which have been conducted on concrete floor assemblies under design loads with the variable restraining system of Laboratory E (Fig. 12) have indicated that full restraint (i.e., zero expansion under the heat of the fire) can lead to heavy spalling and early structural damage. The spalling which occurs under this circumstance is believed to be due to differential compressive stresses which develop between heated layers of concrete

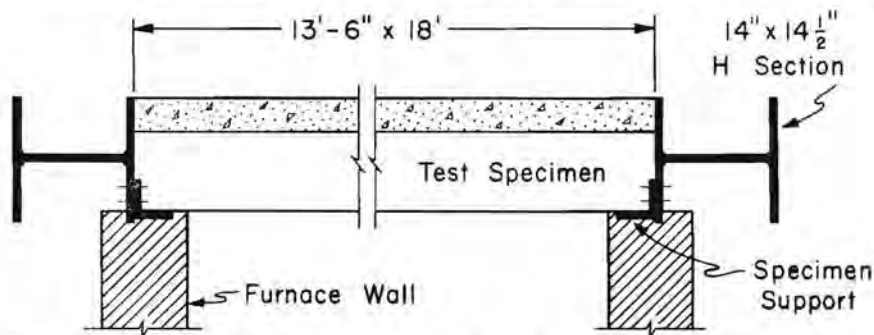


Fig. 8—System for applying restraint to floor assemblies (Laboratory A)

and the cooler mass behind. On the other hand, if little or no restraint is applied to the loaded specimen during the fire exposure, substantial deflections may be anticipated but little or no spalling. This assumes that the moisture level has been reduced to 70 percent relative humidity or less.

The restraint which may develop in actual building assemblies under fire conditions lies somewhere between zero and full restraint. Just what magnitude of restraint may develop in a building fire depends upon a multitude of factors. It appears quite certain, though, that only under very rare circumstances can full restraint be attained as the forces and

stresses attending its development are much too large to be contained for protracted periods. Some portion of the construction must yield.

Concrete construction has a unique ability for adapting itself to restraints which do not induce stresses beyond its capacity. Some measure of restraint will improve the fire resistance of concrete construction over that which may be realized with no restraint or full restraint. It is therefore important to note in any review or comparison of fire test data whether restraint was imposed in the tests and the approximate magnitude judged by the stiffness of the restraining frame members.

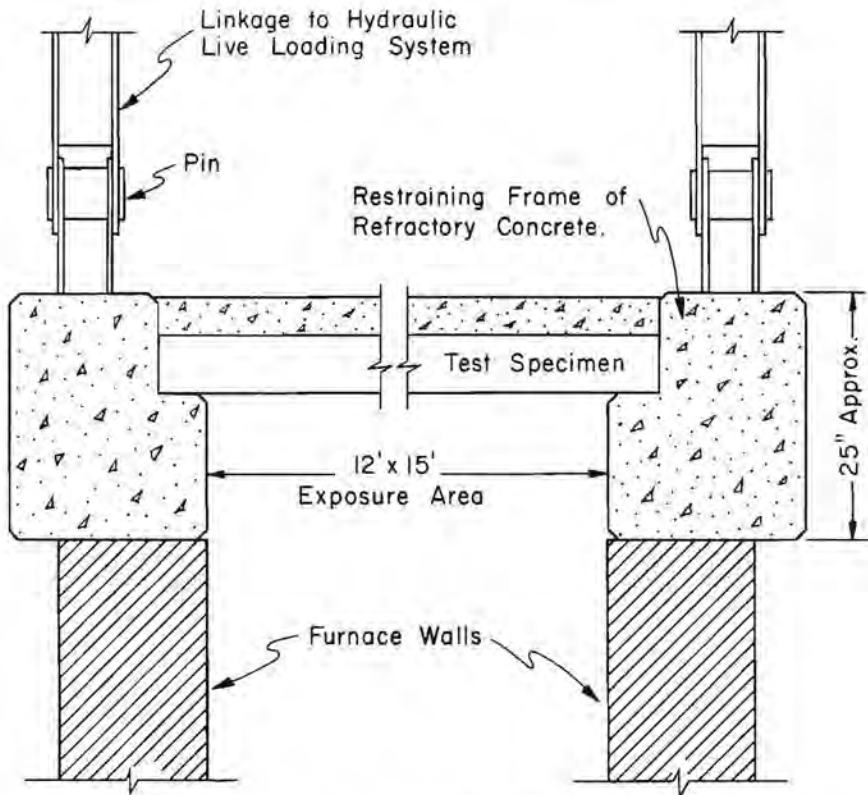


Fig. 9—System for applying restraint to floor assemblies (Laboratory B)

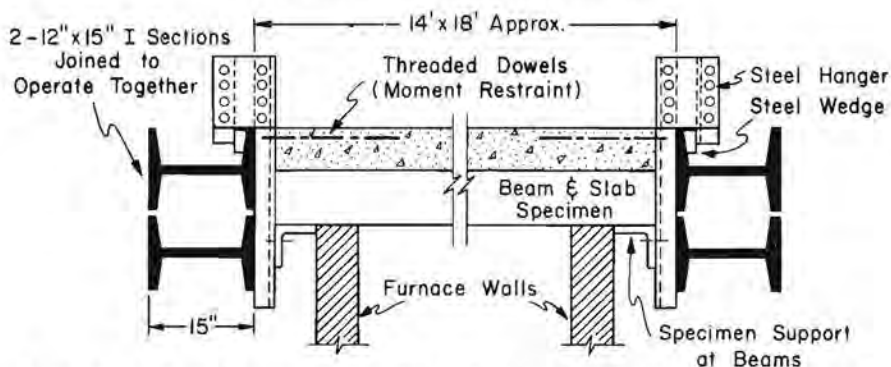


Fig. 10—System for applying restraint to floor assemblies (Laboratory C)

SUMMARY AND CONCLUSIONS

In general, the standards which govern the testing procedures for ascertaining the fire resistance of building construction in the countries studied are about the same. There are differences in the details of their application, however, which can affect in varying degree comparisons of fire test results produced by different countries. The following conclusions were reached regarding these differences:

1. In the heating of fire testing furnaces, the time-temperature relationships are practically the same in American and European laboratories. The differences in thermocouple positions and the use of shielded thermocouples by American laboratories poses questions as to the direct com-

parability of foreign and American test data from the standpoint of specimen heating.

2. The methods for firing testing furnaces vary in laboratories in the United States as well as in Europe. In fire tests exceeding 1 hr in duration, it appears that the type of fuel and the flame that results from its burning are not of important significance. A fire test specimen might be heated somewhat more rapidly under bright, radiant flame conditions than under a colorless flame condition in tests under 1 hr. This is a point that can be resolved only by research.

3. The size of the fire test specimen representing a building construction has an important influence on its structural behavior during the

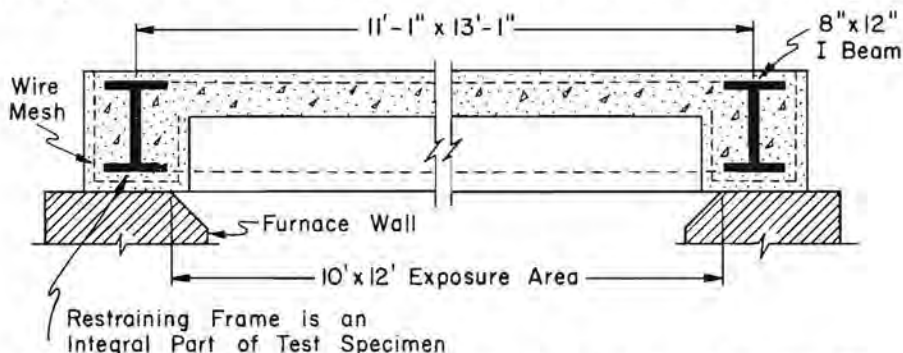


Fig. 11—System for applying restraint to floor assemblies (Laboratory D)

fire exposure. If results of fire tests involving structural considerations of similar building constructions are to be compared, the sizes of the test specimens must be reasonably similar.

4. In any comparison of foreign and American fire test data dealing with similar load bearing constructions, it is important to have knowledge of the stress level due to the imposed load. Accurate comparisons cannot be made where load induced stress levels differ appreciably.

5. In any comparison of the fire endurance of walls, partitions, floors, and roofs which have been determined on the basis of unexposed surface temperature criteria, it is important that the methods for measuring unexposed surface temperature be the same. Endurance periods for similar constructions determined by

unexposed surface temperature criteria will be shorter when the thermocouples are covered by insulating pads.

6. The moisture content of the specimen at the time of exposure to the fire test has influence on its fire endurance. The relative humidity method developed by Menzel appears to be a truly rational and realistic means for resolving questions of moisture content in constructions of concrete or other materials being prepared for fire tests.

7. Structural concrete fire test assemblies which are restrained against thermal expansion to a degree somewhat less than full restraint will usually exhibit greater structural endurance in a fire test than when there is no restraint. Comparisons of fire test data should give careful consideration to the conditions of restraint.

REFERENCES

1. "Fire Tests on Building Materials and Structures," *British Standard 476*, British Standards Institution, London, Part 1, 1953.
2. "Combustibility, Inflammability and Flame Spreading Properties of Structural Materials. Fire Resistance of Structures," *Dutch Government Standard NEN 1076*, June 1957. (in Dutch). (Available from American Standards

Association, New York. Chapter D, "Fire Resistance," translated by Library of Research and Development Division, Portland Cement Association. Translation available from SLA Translation Center, John Crerar Library, Chicago.)

3. See Kamp, Horst, "Fire Tests of Heavily Reinforced Concrete Columns. Report on Tests Conducted at BAM, Berlin-Dahlem," *Bulletin 132*, Deutsch-

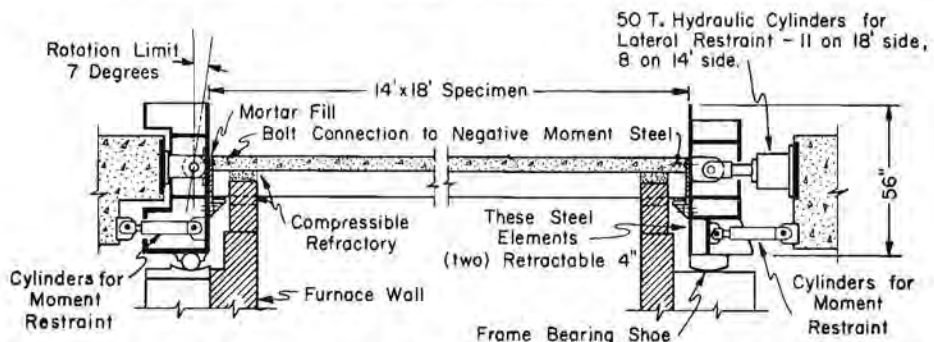


Fig. 12—System for applying variable restraint to floor assemblies (Laboratory E)

er Ausschuss für Stahlbeton, Berlin, 1959. (in German). (Translated by Margaret Corbin, Library of Research and Development Division, Portland Cement Association. Translation available from SLA Translation Center, John Crerar Library, Chicago.)

4. Davey, Norman, and Ashton, L. A., "Investigations on Building Fires, Part V, Fire Tests on Structural Elements," *Research Paper No. 12*, Building Research Station, Watford, Herts, England, 1953, 273 pp. (Available from Her Majesty's Stationery Office, London.)

5. Ashton, L. A., and Bate, S. C. C., "Fire Resistance of Prestressed Concrete Beams," *ACI JOURNAL, Proceedings* V. 57, No. 11, May 1961, pp. 1417-1440.

6. Menzel, Carl A., "A Method for Determining the Moisture Condition of Hardened Concrete in Terms of Relative Humidity," *Proceedings, ASTM*, V. 55, 1955. (Also *Bulletin D-4*, Research and Development Department, Portland Cement Association.)

7. Bergstrom, M., Johannesson, P., and Larsson, G., "Fire Research, Some Results of Investigations at States Testing Laboratory," *Bulletin 66*, States Testing Laboratory, Stockholm, 1957. (in Swedish). (Chapter 3, pp. 11-32, translated by Toby Larsen, Library of Research and Development Division, Portland Cement Association. Translation available from SLA Translation

Center, John Crerar Library, Chicago.)

8. Bakke, H. A., "Fire Resistance of Prestressed Concrete," *Teknisk Ukeblad* (Oslo), V. 105, No. 28, July 1958, pp. 651-658 (in Norwegian). (Translated by Dr. Gunnar Viguerust, Library of Research and Development Division, Portland Cement Association. Translation available from SLA Translation Center, John Crerar Library, Chicago.)

9. Murashev, V. I., "Methods Adopted in the USSR for the Study of Fire Resistance of Structural Elements and Some Results Obtained to Date," *Report 6530*, National Bureau of Standards, Sept. 1959, 21 pp. (English translation of paper in French by Bernard H. Fouguet available from Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C.)

10. Kristen, T., and Wierig, H. J., "Effect of High Temperatures on Prestressed Concrete Structural Units," *Der Bauingenieur* (Berlin), V. 35, No. 1, 1960, pp. 6-11. (in German). (Translated by Library of Research and Development Division, Portland Cement Association. Translation available from SLA Translation Center, John Crerar Library, Chicago.)

11. "Directory of Laboratories and Research Establishments, Fire Research," European Productivity Agency, Organization for European Economic Cooperation, Paris, Mar. 1960.

Examines the effect of thermal and structural factors on the fire endurance of normal reinforced concrete. The effects on fire endurance of such variables as type of aggregate, moisture content of the specimen, and the ability of cover to remain in place are discussed.

Fire Resistance of REINFORCED CONCRETE

By I. A. Benjamin

THE PURPOSE OF THIS PAPER IS TO review the available knowledge on fire tests of reinforced concrete, and to specifically list those fire ratings which have been established for concrete structural elements for buildings.

References to both United States and European test data have been used. However, since the European testing procedures are different from those listed in ASTM E 119, the voluminous data developed by foreign laboratories cannot be used for rating purposes in this country. Nevertheless, many of the relationships and observations published in Europe are pertinent to an over-all understanding of the performance of reinforced concrete structural elements.

The proposed ASTM definition of fire endurance is as follows: "A measure of the elapsed time during

which material or an assembly continues to exhibit fire resistance under specified conditions of test and performance. As applied to elements of buildings, it shall be measured by methods and criteria defined in the 'Methods of Fire Tests of Building Construction and Materials' (ASTM E 119)." The term fire endurance will be used throughout this paper to designate the resistance of constructions which have been subject to a standard fire test.

During the period of the fire test, two criteria are used to evaluate the performance of the structural element. First, the thermal transmission through the floor or wall construction must be such that it will not allow the average unexposed surface temperature to rise above 250 F, or to rise above 325 F at any individual location. Second, the structural performance must satisfy the condi-

tion that it will carry its full design load during the period of the test. These criteria are independent of each other; either one may determine the end of the test.

Before reviewing the fire endurance of reinforced concrete structures, some of the factors which affect their behavior under exposure to fire will be discussed. Fire endurance is influenced by both the thermal and physical properties of the structural element. Factors affecting

the thermal performance are: type of aggregate in the concrete; free moisture in the concrete, both absorbed and capillary; and volume of concrete per square foot of exposed area. Factors affecting the structural performance are: stress level in both the concrete and the steel, cover over the reinforcing bars, tendency of aggregate and free moisture to cause spalling, and lateral restraint conditions.

THERMAL FACTORS

Type of aggregate

For solid concrete slabs, the fire endurance, insofar as heat transmission is concerned, is roughly proportional to the square of average concrete thickness, where the constant of proportionality depends upon the thermal properties of the concrete. The effect of the thermal properties of the concrete is illustrated in Fig. 1, which compares the performance of 4¾ in. thick solid concrete slabs made from siliceous, calcareous, slag, expanded shale, and expanded slag aggregates. In changing from siliceous to expanded slag aggregate, the fire endurance of the slab will more than double.

A limited amount of data has been compiled in tests on concrete slabs of variable thicknesses using common commercial types of aggregates. The available data is shown in Fig. 2. For fire endurance values of less than 90 min, the relationship to the

thickness of slab is curvilinear. For longer periods, the relationship is reasonably proportional to the square of the thickness. The normal weight concretes (over 140 lb per cu ft density), with the exception of air cooled slag, have been represented by a single curve. These aggregates shown negligible differences for 4¾ in. thick slabs, but significant differences for 6 in. thick slabs. Further tests are needed to determine whether these differences are consistent.

Air cooled slag, expanded shale, and expanded slag lie on separate curves and show increasing fire en-

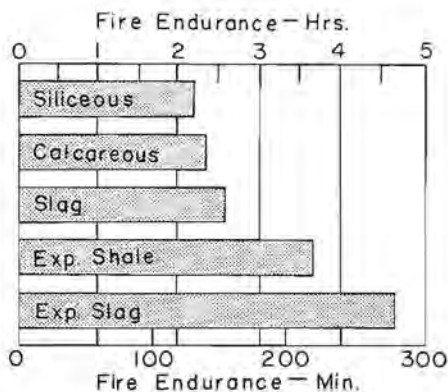


Fig. 1—Effect of various types of aggregate on the fire endurance of 4¾-in. slabs

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duration for a given thickness of concrete in the order named. The required thickness of concrete slabs for a 3-hr fire endurance, a common rating requirement, would be from 4¼ to 5½ in., depending on the type of aggregate used.

Moisture effect

Another factor which affects the fire endurance of a concrete slab is the moisture content. The process of drying out concrete in preparation for the fire test is an extended one, particularly for large volumes of concrete. The unexposed surface temperature will rise to about 212 F and then remain constant for a period of time depending upon the amount of moisture in the concrete to be evaporated. After all the moisture has been driven off by conversion to vapor, the temperature on the top surface will start to rise again. This time lag, while the moisture is being evaporated, may have a definite effect in prolonging the over-all fire endurance period when the top surface temperature rise is the governing criterion. For this reason, ASTM E 119 was amended in 1959 to pro-

TABLE 1 — EFFECT OF MOISTURE ON RELATIVE FIRE ENDURANCE¹

Aggregate type	Fire endurance, min		
	Storage time		Retest
	1 mo (A)	12 mo (B)	
Calcareous	180	196	150 (A) 159 (B)
Expanded shale	486	383	196 (A) 201 (B)

vide for a more accurate measure of the moisture content.

The effect of moisture on the fire endurance of some 6-in. slabs is shown in Table 1. Separate small scale slabs of both calcareous and expanded shale aggregates were tested¹ after storage for 1 month and 12 months. Each slab was then retested. Although moisture content had little effect on the fire endurance of the calcareous slab, there was a marked decrease in the fire endurance for the expanded shale slab after the slab had been dried out.

The difference between the effects of curing on the calcareous and the expanded shale slabs may be attributed to the large difference in initial water content between the two con-

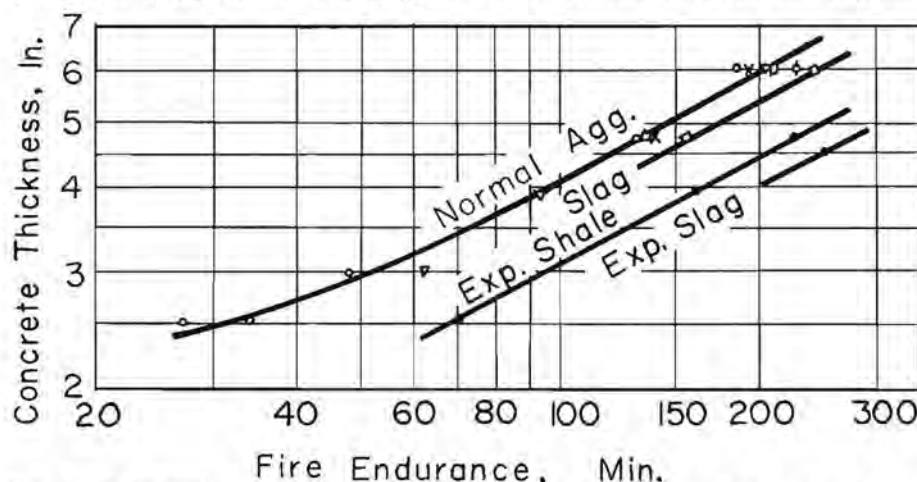


Fig. 2—Relationship of slab thickness and type of aggregate to fire endurance