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Fire Resistance Of Steel Deck Floor Assemblies

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Fire Resistance of Steel Deck Floor Assemblies

H. Shoub and S.H. Ingberg

Building Research Division
Institute for Applied Technology
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Contents

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Tests were conducted to determine the resistance to fire of welded steel plate and beam floor assemblies with various conditions of floor covering on the plates, and ceiling protections beneath the beams. The trials included fire exposures from the burnout of combustible materials ranging from 10 to 40 lb/ft^2 on the floor surface as well as standard fire endurance tests in which the ceiling of the structure was exposed to fire.

The results of the tests indicated that the use of steel floor structures was practical from considerations of fire safety. For the test conditions established, fire exposure on top of the floor did not heat the structural steel supporting members sufficiently to cause load failure or collapse, and did not produce untenable conditions in the room below. In tests involving fire exposure to the underside of floors, the fire endurance times, based solely on heat transmission criteria, ranged from 1 hr 24 min to over 4 hr. Temperature levels attained by the structural members and deflection of the floor assemblies are also reported.

Key words: fire endurance, steel plate floors, burnout tests, floor tests, fire severity.

1. Introduction

Steel deck floors supported by protected steel beams and girders have been used in multistory buildings in the past because, with their relatively light weight compared to some other types of fire-resistive floors, the structural load on the girders, columns, and foundation of a building could be reduced, with consequent increase in allowable live loads. Further advantages were the ease of framing the steel decks into irregularly-shaped panels, and the rigidity which the floors, when suitably attached to structural members, could impart to the building as a whole.

The tests described in this paper were designed to determine the fire endurance performance of such floors under design load. Trials were made with the fire either above or below the floor assembly. The work was performed between 1931 and 1933 with the cooperation of the American Institute of Steel Construction. The apparent promising future for steel deck floor systems at that time failed to materialize because of the development of other lightweight steel products such as open-web joists and light-gage decking.

This report is being issued with the purpose of making generally available the large body of still pertinent data secured in the tests. In some of the tests, the floors were subjected to fire exposure by means of controlled burnout of combustible materials from above the floor. It appears that these are the only laboratory tests so conducted. In the tests with the fire conventionally below the floor, the performance of the ceiling structures and floor toppings are of interest in the design of floor assemblies now in use.

For the purpose of the tests, the steel deck floors were installed in a specially built furnace, and subjected to 16 separate trials of fire endurance, 10 with fire exposure below the floor, and 6 burnout tests of combustible furnishings typical of office occupancies placed on the floor.

The 10 tests with the fire below the floor were conducted under requirements for fire tests substantially the same as those of the currently applicable standard [1][1]. In two of the set of 10 tests, however, a hose-stream application was made on the floor assemblies subsequent to the fire exposure. This is not listed as a requirement or an option in the standard now in use. As steel in itself has little resistance to the effects of exposure to high temperatures, the floor systems were necessarily protected with various insulating coverings applied as a ceiling beneath the beams, and also in most cases on top of the steel floor deck.

The purpose of the six burnout tests where the fire was above the floor was to determine if heat from fires in combustibles in several concentrations representing the furnishings, supplies, and records of office-type occupancies would be transmitted through the floor to an extent sufficient to weaken the plates, beams, and other structural members to the point of failure under the applied load. In four of these tests, insulating floor-covering materials were applied to the steel deck surfaces to retard the passage of heat to the structural members.

[1] Figures in brackets indicate the literature references at the end of this paper.

2. Materials and Construction of Test Floors

The floors were constructed of materials of commercial grade supplied by the manufacturers or purchased in the open market. The workmanship was representative of that normally obtained in construction. Welding and plastering operations were carried out by skilled craftsmen in the employ of local contractors. Certain special materials such as linoleum, mastic floor finishes, and ceiling tiles were installed by representatives of the manufacturers. Casting and finishing of ordinary concrete on the floor surfaces were done by regular employees of the National Bureau of Standards.

The floors are described, together with sketches of the various constructions, in table 1 (Tests 1–6, fires above floors), and table 2 (Tests 7–16, fires below floors). All of the floors were approximately 13½ ft wide by 18 ft long and were built in place in the floor furnace.

2.1. Floor Structure

In every case, the floor structures were ¼ in steel plates 18 ft long attached to the upper flanges of small section I- or H-beams by either continuous or intermittent welds along their longitudinal edges. From the tables it will be noted that the steel beams varied in size and spacing. In Tests 1–14, seven beams, either in 4-in, 7.7-lb, or 5-in, 10-lb size, were used on 24-1/16 in centers. The floor assembly for Test 11 was also used in Tests 13 and 14. In Tests 15 and 16, four beams were spaced 48-5/16 in on centers. Two of these were 5-in, 18.9-lb I-beams placed near the centerline of the panel, with side support furnished by two 5-in, 10-lb I-beams, each about 8 in distant from the restraining frame of the furnace. The same structure sufficed for the two tests.

Steel girders were used in six of the tests. They were 12-in, 31.8-lb I-beams spanning the width of the floor 5 ft from one end of the furnace restraining frame. Thus the girder divided a test floor into two sections, one having a supported clear span of 13 ft, the other consisting of a 5-ft span cantilevered from the girder. In one test, No. 10, the floor beams were carried over the top flange of the girder. In the other tests, shelf angles welded to the girders supported the beams, placing the tops of the beams and the girder in the same plane.

In floor assemblies designed with restrained or fixed end supports, the beams were welded along both sides of the lower flanges where they rested on supporting angles securely bolted to the furnace frame. Additional welds were made under the flanges at the edge of the supports. Other restraining angles, bolted to the furnace, were welded to the top of the plate above the beam supports. The beams of freely supported floors were not welded to the shelf angles, although temporary tack welds were used to secure proper spacing of the parts during assembly of the floors.

2.2. Floor Finish (Surface Insulation)

Three of the tests (1, 2, 15) were conducted without a covering of any kind on the steel plates. The floor in Test 3 was covered with 3/16-in thick battleship linoleum while that in Test 4 had a ½-in coating of an asphalt emulsion concrete. The floors for the remaining tests had from 1 to 3 in of concrete, or concrete base and topping. Concretes had gravel or cinder aggregate, or were gas-expanded. Toppings, where used, were ½ in thick, and principally of cement and sand mix, although limestone concrete and mastic were also used. Wherever a concrete flooring was to be applied, except in Test 7, an expanded metal reinforcement binder was tack welded to the steel plates at 2-ft intervals, and raised from the surface between welds. Details are given in tables 1 and 2.

2.3. Ceiling Protection

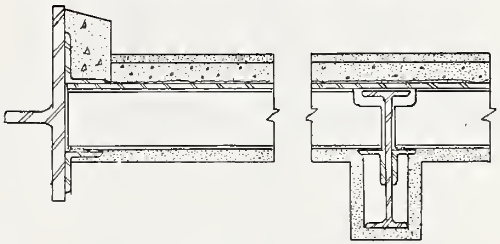
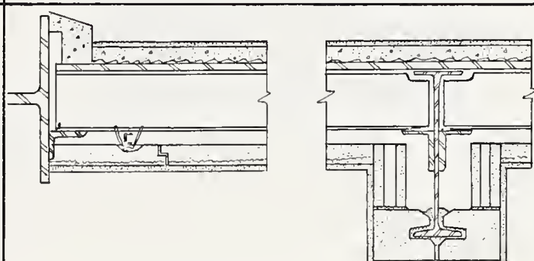
Details of lathing, plastering, and application of ceiling tile on the underside of the floors are also given in tables 1 and 2.

Metal lath, with or without reinforcing rods, was used in all tests except Nos. 6, 10, 12, and 15, which had 2-in precast gypsum ceiling tile. This was usually supported on 1-in hot rolled channels with wire ties or clips, but in Test 12 was installed directly on the lower flanges of the beams.

Plaster was applied to plain diamond mesh metal lath (3.4 lb/yd^2) or to lath reinforced with stamped ribs or welded wires (3.4 or 4.2 lb/yd^2). The ceiling protection varied in materials and thickness for the several tests. Two-coat sanded gypsum plaster ⅞ in thick was used in Tests 1, 3, 4, 5, 7, while an average thickness of 1⅜ in (range 1 to 1⅝in) was applied for Test 2. For the ceiling in Test 13, three different materials were used, portland cement, hair-fibered gypsum, and wood-fibered gypsum. Other ceilings had three-coat plaster built up to thicknesses of 1 to 1½ in.

Heavier insulation was provided in the four tests in which 2-in gypsum ceiling tile was used. For these, an application of ½ in of unfibered sanded gypsum plaster was applied to the tile, producing a total thickness of 2½ in. Where the girders were protected by 2-in (Tests 6, 10) or 3-in (Test 11, 13, 14) hollow gypsum tile installed along the web, approximately ½ in of sanded gypsum plaster was

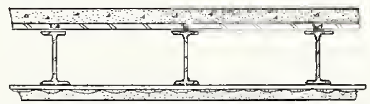
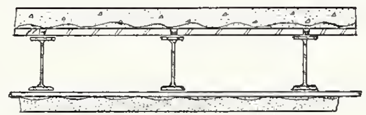
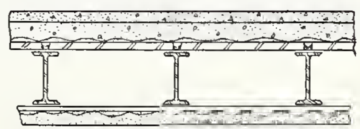
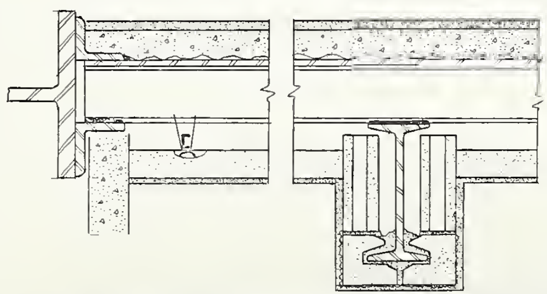
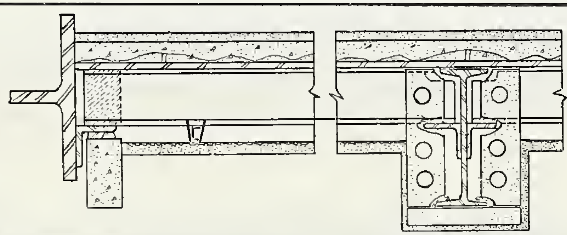
TABLE 1. *Description of structures for fire exposure tests of steel plate floors—fire above floor.*

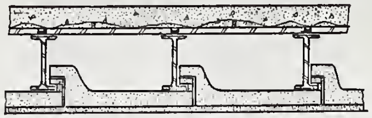
Test No.	Floor Construction	Restraint	Beam	Plate to Beam Weld	Girder Protection[1]	Floor Finish	Ceiling Protection[2]	Load: Floor	Load: Combustible lb/ft²	Load: Total Live lb/ft²	Load: Total lb/ft²
1		Restrained at ends and sides	4-in. 7.7 lb.	Continuous		Bare plate	1/4-in. rods, 16 in. o.c. wire clips to beam flanges; exp. metal lath; 7/8-in. 1:2, 1:3 gypsum-sand p' ster	24	10	81	105
2		Freely supported	4-in. 7.7 lb.	Continuous		Bare plate	Ribbed metal lath clipped to beam flanges; 1 to 1 5/8-in 1:2, 1:2 1/2 fibered gypsum-sand plaster	26	10	46	72
3		Restrained at ends and sides	4-in. 7.7 lb.	Continuous		3/16-in. battleship linoleum	Reinforced metal lath clipped to beam flanges; 7/8 in. 1:2, 1:3 fibered gypsum-sand plaster	25	15	80	105
4		Restrained at ends and sides	5-in. 10 lb.	Continuous		1/2-in. asphalt emulsion concrete 1 1/2:2:3:2 cement, sand, limestone, asphalt emulsion	Metal lath clipped to beams; 7/8-in. 1:2, 1:3 gypsum-sand plaster	50	20	115	165
5		13-ft span restrained; other end 5-ft cantilever	4-in. 7.7 lb.	Continuous	Exp. metal lath; 7.8-in. 1:2, 1:3 fibered gypsum-sand plaster	Expanded metal floor binder; 1 1/2-in. gas-exp. concrete; 1/2-in. concrete topping	Exp. metal lath fasted to beams with clips; 7/8-in. 1:2, 1:3 fibered gypsum-sand plaster	38	30	165	203
6		13-ft span restrained; one end; 5-ft span cantilever	4-in. 7.7 lb.	Continuous	2-in. gypsum shoe tile bottom; 2-in. gypsum hollow tile sides; 1/2-in. 1:3 gypsum-sand plaster	Exp. metal floor binder; 1 1/2 in. 1:2:4 gravel concrete; 1/2-in. gypsum-cement asphalt topping	1-in. channels, 18 in. o.c., clipped to beams 2-in. reinforced gypsum tile; 1/2-in. 1:3 gypsum-sand plaster	53	40	131	184

1/ Where protection is indicated, a 12-in., 31.8-lb. girder was used in the assembly.

2/ No white coat finish was applied in any of these six tests.

TABLE 2. *Description of structures for fire exposure tests of steel plate floors—fire under floor.*

Test No.	Floor Construction	Restraint	Beam	Plate to beam weld	Girder protection 1/	Floor finish	Ceiling protection 2/	Load Applied lb/ft^2	Load Total lb/ft^2
7		Restrained at ends	4-in. 7.7 lb. "I"	Continuous		1-in. 1:1 1/2:3 gravel concrete	1/4-in. rods, 12 in. o.c., wire clips, exp. metal lath; 7/8 in. fibered gypsum-sand plaster	68	105
8		Freely supported	4-in. 7.7 lb. "I"	Continuous		Expanded metal floor binder; 1 1/2-in. 1:1 1/2: 3 gravel concrete	1/4-in. rods, 12 in. o.c. tack welded to beams; exp. metal lath; 1 1/2 in. fibered gypsum-sand plaster	22	70
9		Restrained at enda	5-in. 10.0 lb. "I"	Continous		Exp. metal floor binder; 1 1/2 in. gas-exp. concrete, 1/2-in. limestone cement topping	1/4-in. rods, 12 in. o.c, tack welded to beams; exp. metal lath; 1 in. portland cement-sand plaster	125	165
10		Restrained one end; other end 5-ft. cantilever	4-in. 7.7 lb. "I"	**Continuous**	2-in. gypsum shoe tile bottom; 2-in. gypsum hollow tile sides; 1/2 in. 1: 3 gypsum-sand plaster	Exp. metal floor binder; 1 1/2 in. 1:1 1/2:3 gravel concrete; 1/2-in. gypaum-asphalt	1-in. channels, 18 in. o.c. clipped to beam; 2-in. reinforced gyp-sum tile; 1/2 in. 1:3 gypsum-sand plaster	145	200
11		Freely supported; one end 5-ft. cantilever	5-in. 10.0 lb. "I"	3 1/2-in., 12-in. o.c.	2-in. gypsum block bottom; 3-in. gyp-sum tile sides; 1/2-in. gypsum-sand plaster	Exp. metal binder 1 1/2-in. 1: 1 1/2:3 limestone concrete; 1/2-in. cement-sand top-ping	1-in. channels, 18 in. o.c. clipped to beams; ribbed metal lath; 1 1/4-in. 1:2 wood fibered gypsum-sand plaster	240	292

Test No.	Floor Construction	Restraint	Beam	Plate to Beam Weld	Girder Protection 1/	Floor Finish	Ceiling Protection 2/	Load Applied lb/ft²	Load Total lb/ft²
12		Restrained at ends	4-in. 7.7 lb. "I"	3 1/2 in., 12-in. o.c. 4/		Exp. metal floor binder; 2-in. 1: 1 1/2:3 gravel concrete	2-in. gypsum ceiling tile, integral cast lugs attach to beams; 1/2 in. 1:3 gypsum-sand plaster	48	105
13	Similar to 11; ceiling modified	Freely supported; one end 5-ft. cantilever	5-in 10.0 lb. "I"	3 1/2-in., 12-in. o.c.	Same as 11, but plaster 1 side 1: 2 1/2 portland cement-sand	Reused from test 11	1-in. channels, 18 in. o.c. 1 1/2-in. below beams; ribbed metal lath; ceiling in thirds; 1-in. cement, hair- or wood-fibered gypsum plaster	240	292
14	Similar to 11; ceiling modified	Freely supported; one end 5-ft. cantilaver	5-in. 10.0 lb. "I"	3 1/2-in., 12-in. o.c.	Same as 11	Reused from 11 and 13; rehydrated	1-in channels, 18 in. o.c. clipped to beams; ribbed metal lath; 1 1/2-in. 1:2 hair fibered gypsum-sand plaster	235	292
15		Freely supported	center-5-in., 18.9 lb. "H"; outer-5-in. 10.0 lb. "I" 3/	6 1/4-in., 12-in. o.c. 5/		None (bare plates)	1-in. channels, 18-in. o.c.; 1-in. below beam; 2 in. reinforced gypsum tile, special clips; 1/2-in. gypsum-sand plaster	90	122.4
16		Restrained at ends	center-5-in. 18.9 lb. "H"; outer-5-in. 10.0 lb. "I" 3/	6 1/4-in., 12-in. o.c. 5/		3/16-in. wire, 3 1/2 by 12-in. mesh; 2 1/2 in. cinder or gas exp. concrete; 1/2-in. topping	1-in. channels, 18 in. o.c. 1-in. below beams; 3/16-in. rods 12-in. o.c.; exp. metal lath; 1 1/8-in. gypsum-sand plaster	94.3	149.7

1/ Where protection is indicated, a 12-in., 31.8-lb. girder was used in the assembly.

2/ The indicated thickness of plaster included a white coat finish, except in test 9, where one coat of cement paint was applied.

3/ Beams 4 ft. 5/16 in. o.c.

4/ Plates 47 3/4 in. wide; holes 1 in. diameter; 12 in. o.c. on longitudinal axis for welding to overlaid beams.

5/ Center plate 48 in. wide; outer plates 54 in. with 1 1/16 diameter holes 12 in. o.c. on line approximately 6 in. from edge for welding to outer beams.

also applied to the tile. In Test 5, the girder was protected by 7/8 in of sanded gypsum plaster on metal lath, similar to that provided on the ceiling.

The floors were conditioned about a month prior to their test for the purpose of drying plaster and concrete. In many cases the drying was accelerated by application of heat below the floor. However, it seems unlikely that the conditioning procedures used were adequate to dry the concrete floors to the moisture content levels typical of thoroughly seasoned concrete.

3. Test Equipment

3.1. Furnace and Burnout Room

The tests were conducted in a furnace and associated burnout room accommodating a floor structure 13½ ft wide and 18 ft long (see fig. 1). The design was such that either the top or under surfaces of test floors could be subjected to fire exposure. The furnace consisted of a masonry and concrete structure enclosing the lower side of a horizontal and independently suported steel restraining frame made of 30-in, 240-lb H-section girders fastened at the corners through a system of angles and plates and supported by steel columns. The girders of the restraining frame were mounted with their webs horizontal and the centerline 4 ft 7 in above the building floor or 6 ft 10 in above the bottom of the furnace pit. The inner flanges of the girders were flush with the interior face of the furnace walls. Holes were provided in the lower half of the girder for bolting the shelf angles supporting a test floor assembly. Steel plates were welded to the girder web and flanges for additional rigidity. To prevent distortion of the frame girders during a test, they were cooled by using the upper portion of the girder outside the furnace walls as reservoirs for water. As shown in figure 1, the space above the furnace was enclosed with brick walls permanently built over the restraining frame so that the top surface of test floors could be subjected to fire exposures from the burning of combustible materials on the floor. Louvers near the top of the burnout room could be used to regulate the amount of air admitted and so give some control over the rate of burning.

Figure 2 shows a portion of the furnace restraining frame during construction and before erection of the furnace walls. The system of corner fastening and column support can be seen. The burnout room with a bare steel deck floor in place is shown in figure 3. In figure 4, the furnace space can be seen, with a steel deck-and-beam floor in place, prior to installation of the protective ceiling assembly beneath the floor.

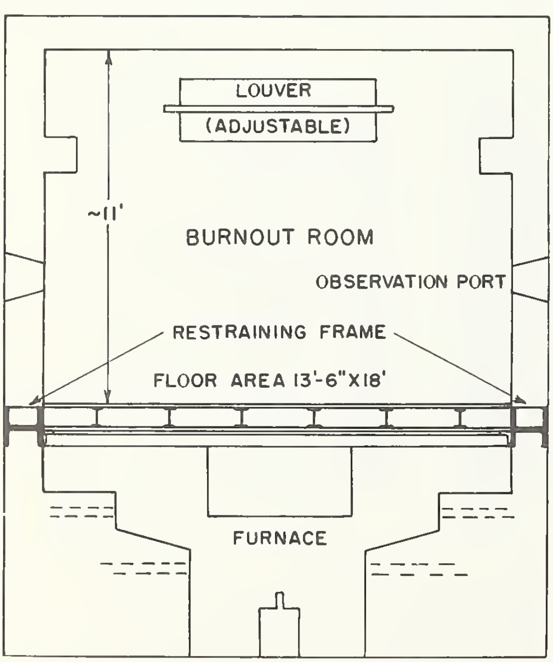


Figure 1.—*Sketch of furnace and burnout room for fire tests of floor assemblies.*

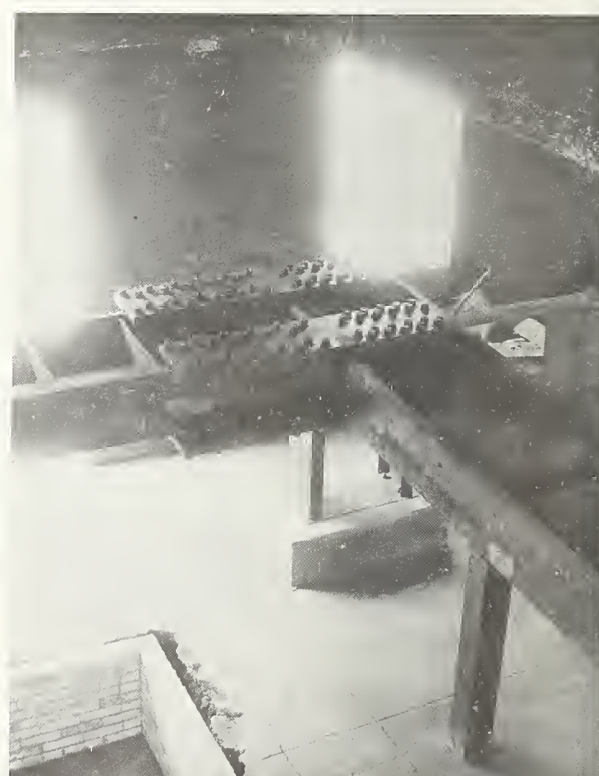


Figure 2.—*Floor test furnace during construction; corner fastening and column supports visible.*

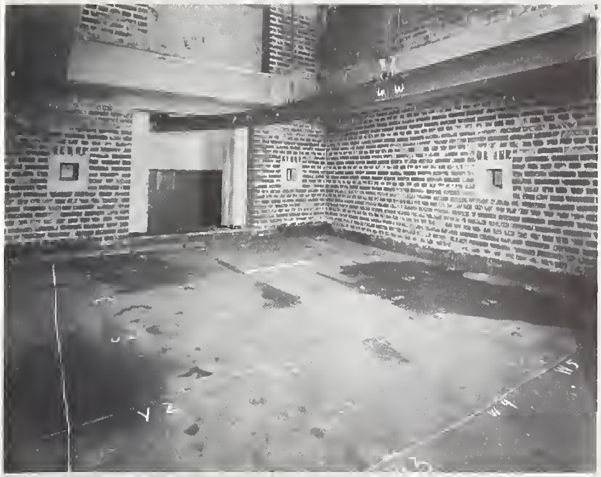


FIGURE 3.—*Upper furnace space; bare steel-deck floor.*

The furnace was gas fired, with 48 venturi-type burners, arranged in two rows on each side. The burners on each side of the furnace were housed in a plenum chamber supplied with low pressure air. An auxiliary air supply was provided in the combustion chamber of the furnace through six air inlets in line with each bottom row of burners. Three 9-in diam flues on each side served to carry off the combustion gases. Some of the burner, air, and flue openings are visible in figure 4.

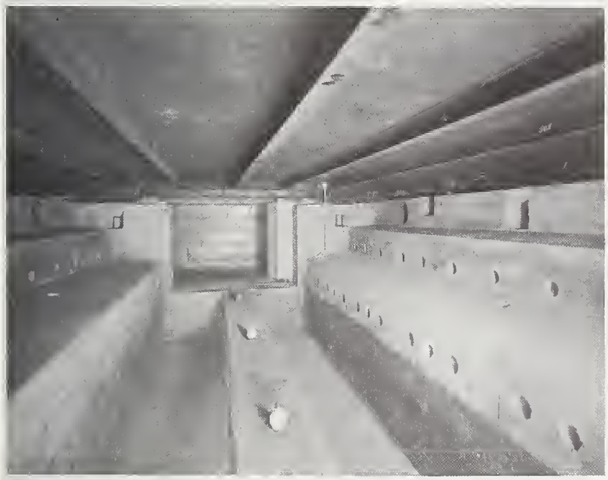


FIGURE 4.—*Lower furnace, steel deck-and-beam floor in place, prior to installation of protective ceiling.*

3.2. Temperature-Measuring Equipment

All temperature measurements, except those in the furnace space in the room burnout Tests 1–6, were made with chromel-alumel thermocouples.

For Tests 7–16, the temperatures in the furnace were determined with 12 thermocouples, mounted in iron pipes and located 12 in below the ceiling of the test floor. Where the fire exposure consisted of a burnout of combustibles above a floor (Tests 1–6), temperatures in the burnout room were measured by 13 thermocouples, similarly protected in iron pipes and suspended nine at 3 ft and four at 7 ft above the floor. In these tests, total immersion thermometers, suspended approximately 1 ft below the ceiling, were used for temperature measurement in the furnace space below the fire room. It is probable that the ceiling temperatures were not high enough to cause appreciable radiation error in the readings of these thermometers.

The temperatures of the bottom flanges of the beams and girders, and also of the floor plates (lower side), were measured with thermocouples peened into the steel. Thermocouples were placed near the center of the span of these structural elements, and also at locations approximately 1 ft from their ends.

The temperatures on the upper or "unexposed" surface of the floors which were subjected to fire exposure on the under side were measured with 12 thermocouples symmetrically located over the floor area. Their bare junctions were placed in contact with the floor surface, and were protected by weighted asbestos felt pads 6-in square and 0.4-in thick. No measurements were made on the surface of test floors which were subjected to burnout of combustibles above the floor.

Thermocouples, usually three or four, with bare junctions, were also installed in the air spaces between the steel floor plates and the ceiling assembly. They were located at the center of the floor span between the beams.

Iron pipes protecting thermocouples in the furnace may be seen in figure 5, and in the burnout space above the floor in figure 6. Figure 7 shows the weighted asbestos pads covering the bare thermocouple junctions in contact with the unexposed surface of a floor.

FIGURE 5.—*Lower furnace showing iron pipes for protection of furnace temperature-measuring thermocouples.*

FIGURE 6.—*Burnout space above the floor; thermocouples contained in suspended iron pipes; showing arrangement of combustible materials.*

3.3. Deflection-Measurement Equipment

The deflections of the floors were measured by means of graduated invar tapes attached to the floor components. Readings on the tapes were made by use of a transit mounted on a stable support external to the floor. For floors subjected to top fire exposure, the tapes were fastened to pins welded to the beams or under sides of the floor plates, and brought down through the celing plaster. In those tests having bottom fire exposure, the tapes were attached to pins screwed into the top of the steel plates and extended up to wires running over pulleys (see fig. 7). In all cases, the tapes were held vertical by weights.

Location of deflection measurements varied according to the structure of the floor. Readings were taken at the centers of spans, and also at some quarter-points. Where a cantilever construction was used, deflection at the extreme end of the cantilever span was noted.

4. Test Method

4.1. Loading

For the fire tests, load was applied to each floor to the extent required to produce an extreme fiber stress of approximately 18,000 lb/in^2 in the beams. Where girders were used. they were only loaded to a small fraction of their design load and were considered to be suitably protected, so that the fire exposures could be taken as critical tests of only the beam and steel plate assemblies. As noted later, this was not always true.

The average weight of the steel in the 13½- × 18-ft floor panels ranged from 14 to 15.2 lb/ft^2. A maximum of 28 lb/ft^2 was added by the concrete floor covering. Ceiling assemblies ranged in weight from 10 to 15 lb/ft^2 in the tests with the fire above the floor and 10 to 18 lb/ft^2 for the remaining tests of the series. For all the floors, the total dead load due to structural steel, floor covering and ceiling construction ranged from 24 to 57 lb/ft^2.

Part of the applied load in Tests 1–6 consisted of combustible materials in the form of office equipment, supplies, and records placed on the floor in amounts varying from 10 to 40 lb/ft^2. The furnishings were of the same general nature in all burnout tests, with increased combustible loadings achieved by the addition of paper in the required amounts. The remainder of the applied load was supplied by pig iron placed in rows. In Tests 1 to 4, there were four rows, located 3 ft and 6 ft from each end support. In Tests 5 and 6, there were three rows, one at or near each quarter-point of the 13-ft span and one at the center of the cantilever span.

In the tests with the fire exposure below the floor, the applied loads consisted entirely of pig iron placed in rows on the floor surface, except in Test 15, where the weights were uniformly distributed over the entire floor. The weights used in all of the tests, except that of Test 15, were raised from the floor surface by means of iron pipes placed directly on the floor. This established definite points of loading at the beginning of the test and permitted air circulation under the weights. In the later tests, upright sections of pipe were installed to form a small gap at the center of each row, thus preventing arch action of the stacked weights due to deflection of the floor. The arrangement is illustrated in figure 7.

4.2. Fire Exposure

The tests with the fire exposure above the floor were conducted as burnout tests, for which no performance standards or criteria have been established. The fires in the combustible portion

FIGURE 7.—*Top of floor for standard fire test, showing asbestos pads covering surface thermocouples, deflection measuring tapes, and method of loading with pig iron.*

of the applied loading in these tests were representative of fire hazard severities nominally equivalent to 1 to 4½ hr in a standard fire-endurance test. The fires were ignited by the use of kerosene-soaked cotton waste placed at several locations in the furnishings assembled as office occupancies, and allowed to continue until the fuel was exhausted. The burning rate was controlled, but to an indefinite extent, by regulating the admission of air through louver openings in the top of the burnout room.

Tests made with the fire exposure below the floor were generally in accordance with the requirements of the Standard Methods of Fire Tests of Building Construction and Materials, ASTM Designation E119. By this procedure, the underside of a floor structure is exposed to a fire controlled to conform as closely as possible to a time-temperature schedule defined by the following points:

1000 °F at 5 min
1300 °F at 10 min
1550 °F at 30 min
1700 °F at 1 hr
1850 °F at 2 hr
2000 °F at 4 hr.

The fire endurance of a floor is determined by the earliest time to one of the following criteria of failure:

1. Failure to sustain the applied load.
2. Passage of flame or gas through the floor hot enough to ignite cotton waste.
3. A temperature rise of 250 degrees F, average, or 325 degrees F, one point, above the initial temperature of the unexposed surface.

For the fire and hose stream tests (13 and 15), the fire exposure was stopped after 1 hr and the hose stream was applied through the furnace door to the heated under surface of the floor. The water was applied through a 2½-in hose with a 1⅛-in nozzle at a pressure of 40 lb/in^2 in Test 13 and 45 lb/in^2 in Test 15. For Test 13, the duration of water application was 6 min 5 sec, equal to a 2½ min application for a 100-ft^2 ceiling, and for Test 15, the duration of water application was 12 min 9 sec, equal to a 5-min application for 100-ft^2 of ceiling area.

Fire exposures under the floors were usually continued beyond the time to reach a criterion of failure, in order to develop additional information on the behavior of the steel structure under fire conditions. Particular note was taken of the time to reach an average temperature of 1000 °F or a one-point temperature of 1200 °F in the structural steel members. In addition to recording temperatures and deflections, visual observations were made of the effects on the floors during the fire tests.

5. Results of Tests

5.1. Burnout Tests 1–6

The maximum temperatures and deflections recorded in the tests with the fire exposure above the floor are indicated in table 3. More complete temperature data for these six tests, in the form of time-temperature curves recorded in the burnout space and floors are available in figures 8–13.

The fires burned with varying intensities and with considerable flaming that lasted until 3 to 6 hr after the start of the test. The highest one-point lower flange beam temperature, 885 °F, occurred in Test 3 at approximately 6 hr. The highest average temperature, 729 °F, occurred at the centrally located thermocouples on one of the beams in Test 2. The time was 3 hr 10 min. It should be noted that in Test 2 the floor was bare while in Test 3 it was covered with a thin sheet of linoleum. The maximum one-point and highest average temperatures in the plate also occurred in Test 3 (1170 °F at 5 hr 20 min, and 891 °F at 6 hr, respectively). The corresponding temperatures in Test 2 were almost as high but were reached at 3 hr after the start.

In all tests of this group, the full applied load was supported during the entire test period. The average deflection at the center of the beams due to initial application of load was approximately 0.3 in. The greatest deflection observed in any of the tests was 5.80 in (Test 3). However, the maximum permanent set, (2.62 in), was noted after the cooling period for Test 2.

The concrete floor coverings (Tests 4–6) appeared to maintain a bond to the steel floor plates, although cracked through in many places to the steel surface.

Table 3. *Fire Exposure above steel floor—results of tests*

Test No.	Equivalent Std. Fire Exposure	Max. Deflection in Test				Permanent Set		Max. One Point Temp. Steel						Highest Av. Temp. Steel [2]						Highest Av. Temp. in Floor (airspace)		Max. One Point Room Temp. (in fire space)		Max. Av. Room Temp. (in fire space)	
		Beam		Girder		Beam	Girder	Beam [1]		Plate		Girder [1]		Beam [1]		Plate		Grider [1]							
	hr:min	in.	hr:min	in.	hr:min	in.	in.	° F.	hr:min	° F.	hr:min	° F.	hr:min	° F.	hr:min	° F.	hr:min	° F.	hr:min	° F.	hr:min	° F.	hr:min	° F.	hr:min
1	0:35	3.10	3:53	------	------	1.40	------	615	4:00	882	0:50	------	------	[3] 536	3:40	[3] 828	0:50	------	------	484	0:55	1,321	0:30	993	0:40
2	0:43	2.92	22:00	------	------	2.62	------	864	3:10	1,108	3:00	------	------	[3] 729	3:10	[3] 864	3:00	------	------	766	3:00	2,100	0:15	1,486	0:15
3	1:03	5.80	6:19	------	------	1.36	------	885	6:00	1,170	5:20	------	------	[3] 621	6:50	[3] 891	6:00	------	------	763	6:30	1,634	0:20	1,411	0:20
4	1:21	3.50	9:01	------	------	1.37	------	615	9:00	822	9:20	------	------	[3] 498	9:40	[3] 689	9:00	------	------	552	9:20	1,771	0:25	1,445	0:30
5	1:40	0.87	29:00	0.35	95:00	0.35	0.17	511	17:00	651	16:00	327	19:00	[4] 468	17:00	[4] 642	16:00	318	19:00	415	20:00	1,767	0:20	1,323	0:20
6	3:06	2.38	26:40	0.41	68:30	1.18	0.33	741	18:40	869	19:00	433	22:20	[3] 615	22:00	[4] 750	17:00	428	25:30	646	21:00	1,695	0:45	1,447	0:45

[1] Temperatures measured on lower flange of beam or girder.
[2] Determined from a group of thermocouples located at center or ends of a plate, beam or girder, and in test Nos. 5 and 6 on a plate or beam near the girder.
[3] Thermocouples at center of plate or beam.
[4] Thermocouples near girder location.

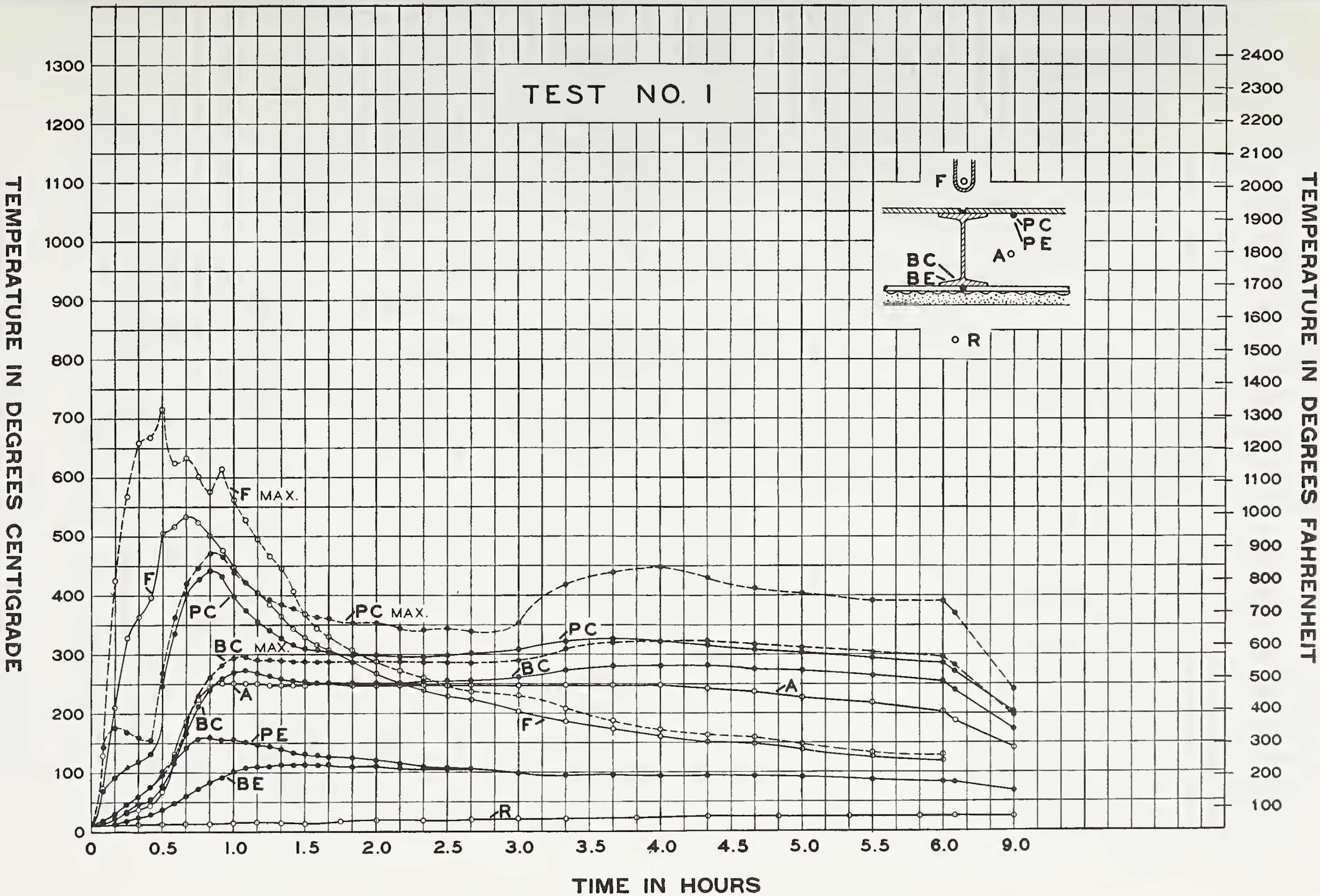


FIGURE 8.—*Time-temperature curves, Test 1.*

Location of temperature measurements: A, air space; BC, bottom flange of beam, center of span; BE; bottom flange, end of beam; PC, plate, center of span; PE, plate, end; F, furnace or burnout space; R, room below. Solid lines represent highest averages at a particular location on a structural element: broken lines represent highest individual readings, not necessarily on the same element.

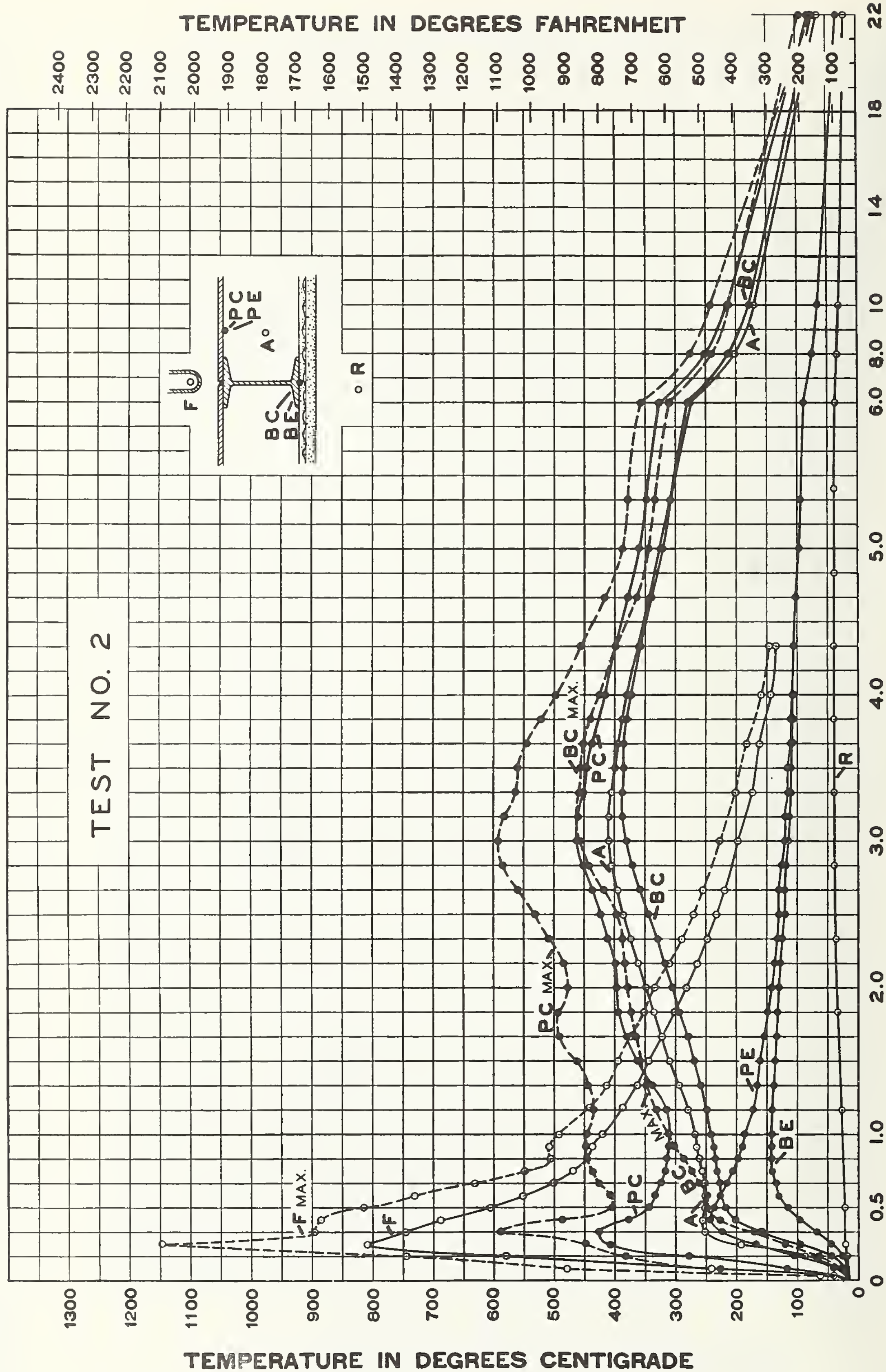


FIGURE 9.—*Time-temperature curves, Test 2.*
For temperature measurement locations, see figure 8.

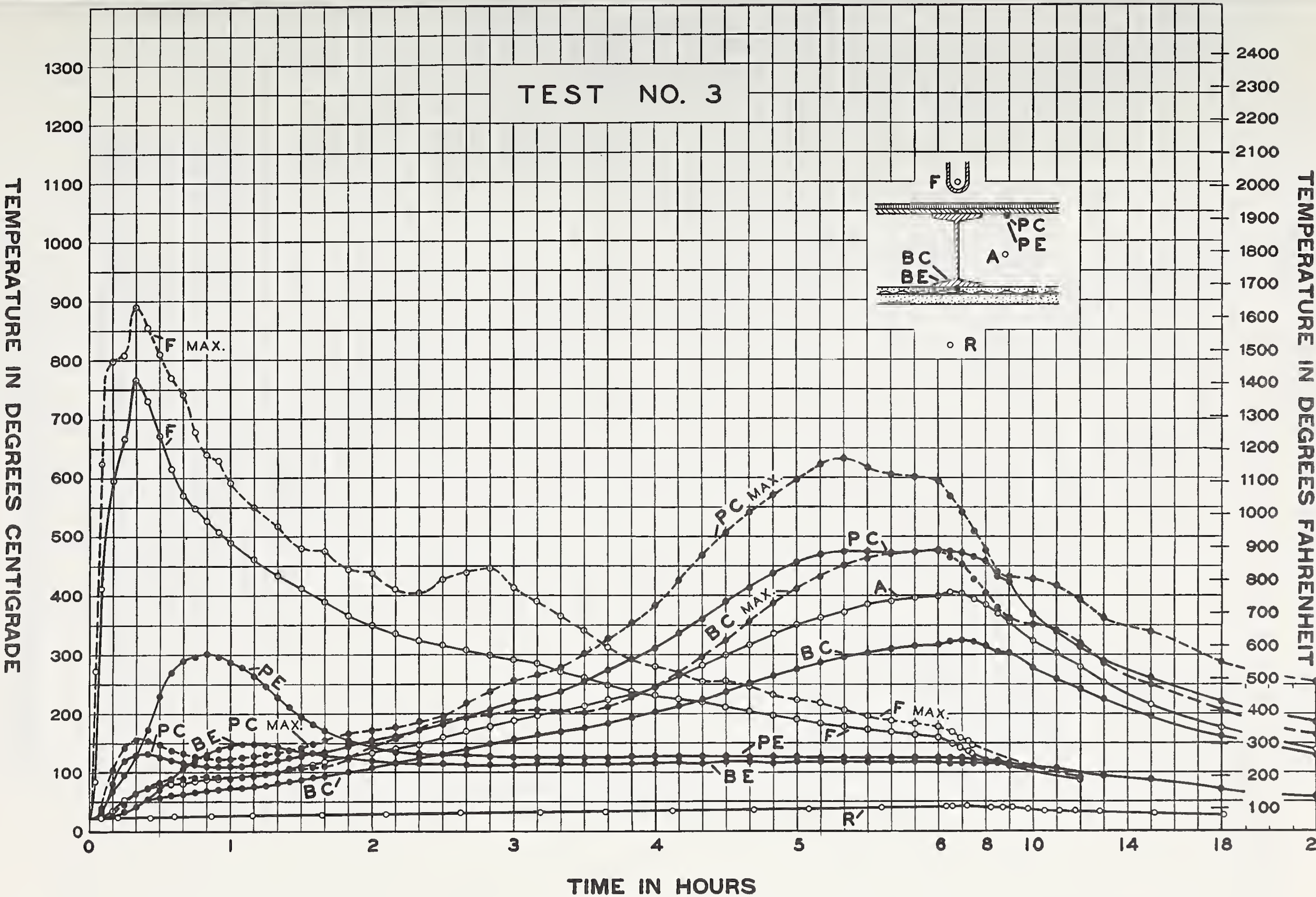


FIGURE 10.—*Time-temperature curves, Test 3.*
For temperature measurement locations, see figure 8.

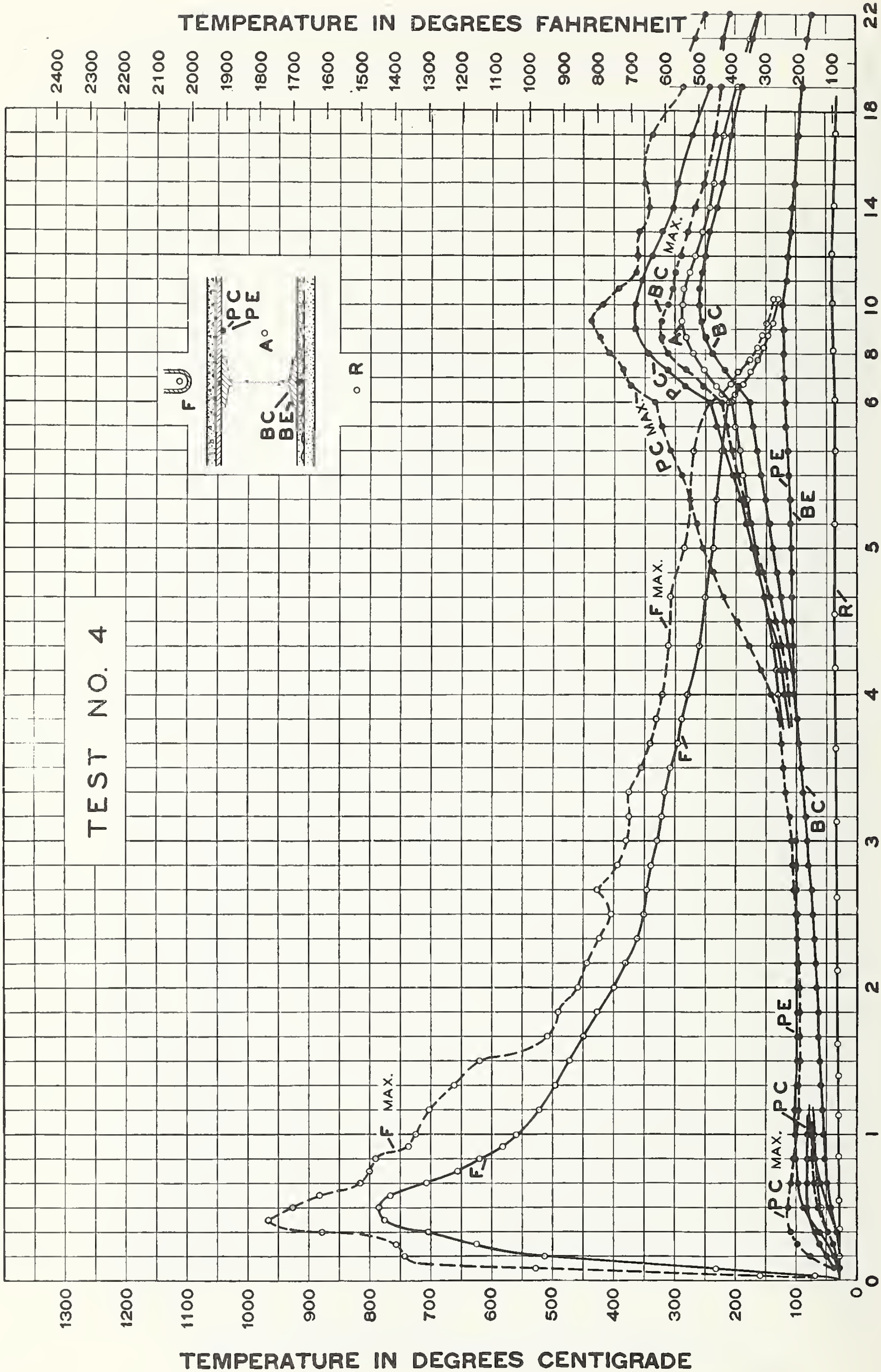


FIGURE 11.—Time-temperature curves, Test 4.
For temperature measurement locations, see figure 8.

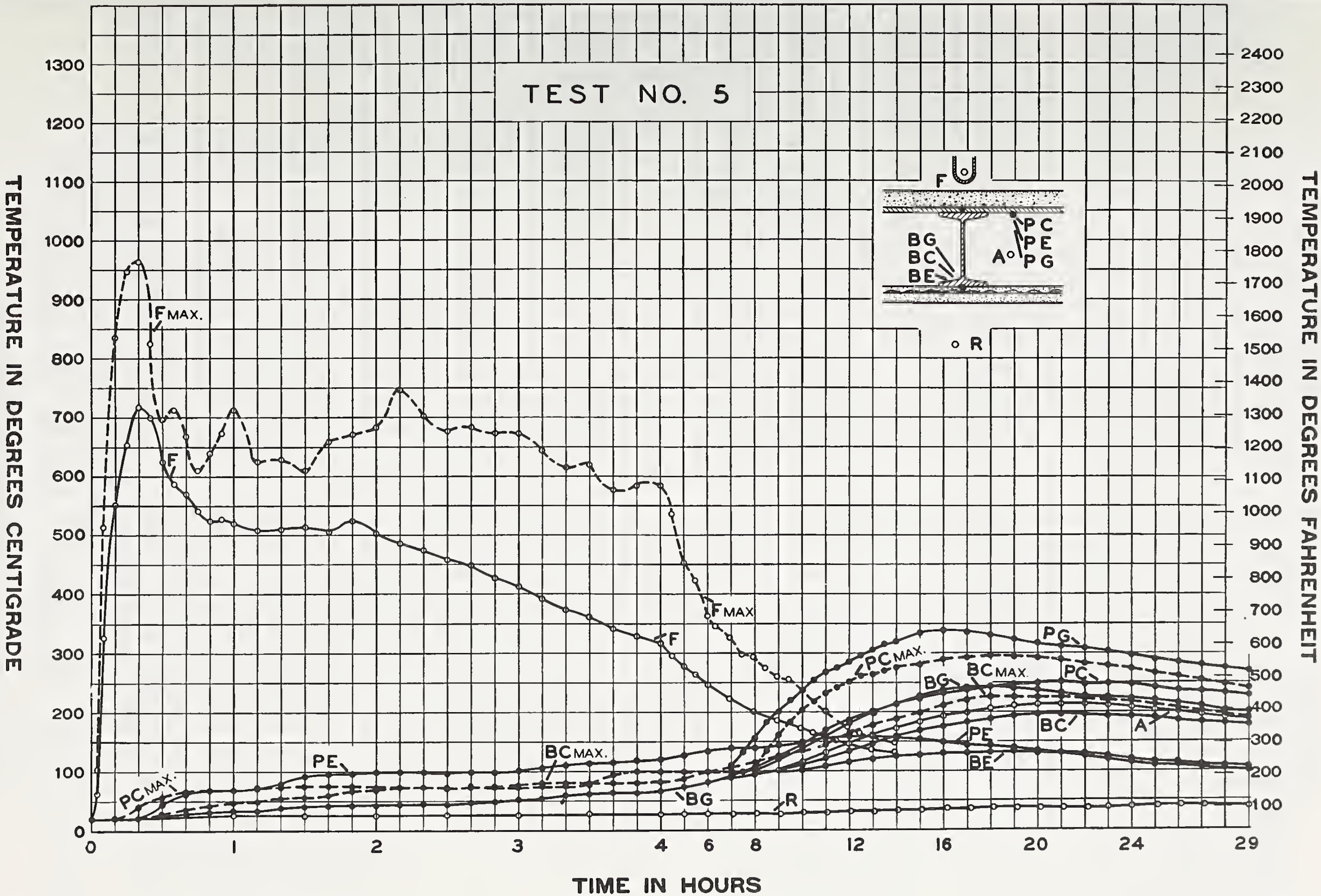


FIGURE 12.—*Time-temperature curves, Test 5.*

Location of temperature measurements: A, air space; BC, bottom flange of beam, center of span; BE, bottom flange, end of beam; PC, plate, center of span; PE, plate, end; BG, bottom flange of girler, center of span; PG, plate, above girder; F, furnace or burnout space; R, room below. Solid lines represent highest averages at a particular location on a structural element; broken lines represent highest individual readings, not necessarily on the same element.

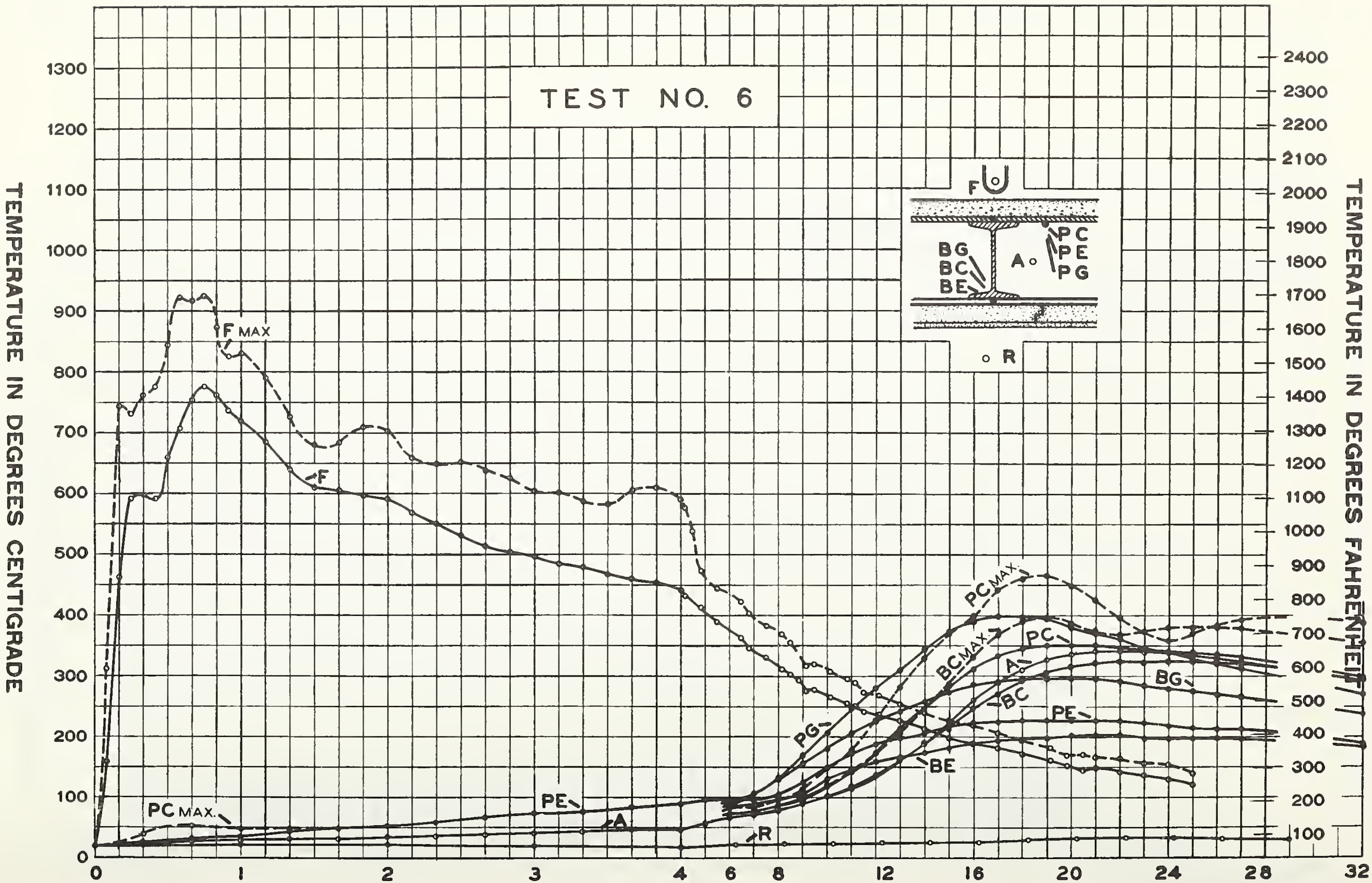


FIGURE 13.—*Time-temperature curves, Test 6.*
For temperature measurement locations, see figure 12.

The welded joints withstood distortion of the structures caused by the fire exposure, except for breaking of some of the fillet welds at beam supports and several ruptures in the plate seams. No failure in the welds was such as to prevent the floor sustaining its applied load.

Some cracking and separation of ceiling constructions occurred, principally from failure of iron wire ties. There were no serious ruptures, and the ceilings generally remained fairly close to their original positions.

5.2. Fire Endurance Tests 7–16

Data for floors tested under the conventional method of fire exposure beneath the floor, are given in table 4.

The temperatures recorded for the furnace were usually in fair agreement with those of the standard time-temperature curve. Where required by the extent of the deviations of the furnace temperatures from those of the standard, corrections were made in the times to limiting temperature rises on the unexposed surface of the floors. The fire test exposure severity, shown in table 4, is defined as the ratio of the area under the curve of average furnace temperature to the area under the standard time-temperature curve, each from the start of the test to the end or time of failure, and measured above a base temperature of 68 °F.

The fire endurance of the floors, as determined by rise of temperature on the unexposed surfaces, ranged from 1 hr 24 min (Test 8) to 4 hr 55 min (Test 10). Times to reach an average temperature of 1000 °F in the beams were as low as 1 hr 42 min, ranging up to 4 hr 46 min. Maximum one-point temperatures of 1200 °F were attained at times comparable to those required to reach the 1000 °F average. In Test 11, the specified average and one-point maximum temperatures were not reached in the beams, although the fire exposure period was 3 hr. In Tests 13 and 15, confined to 1-hr duration followed by application of a hose stream, limiting temperatures on the unexposed surface as well were not reached.

Fire exposure periods in the other tests were from approximately 2 to 5 hr. In these periods maximum average temperature in the beams reached levels ranging from 860 °F after 3 hr in Test 11 to 1742 °F at 2 hr 43 min in Test No. 8. In Tests 10 and 14, girder temperatures in excess of 1000 °F were recorded after 2 hr 36 min and 4 hr 2 min, respectively.

Excluding Tests 11, 13, and 15, which were terminated before critical temperatures were attained in the steel, the maximum deflections observed in the floor beams ranged from 7.8 in reached 30 min after the end of the 5 hr fire exposure period in Test 14 to approximately 13 or 14 in near the ends of the respective fire exposure periods in Tests 8, 9, 12, and 16. Maximum deflections in the beams and girders usually occured at the center of span. Permanent set in the beams ranged from 3.2 in in Test 7 to 13.2 in in Test 16.

The ceilings used in the floor assemblies in which the underside was subjected to fire exposure began to disintegrate in the first few minutes of each test, but with wide variations in behavior thereafter. The ceiling in Test 11 did not rupture to an extent causing it to fall. Gypsum ceiling tile used in Test 10 remained intact for about 4½ hr, but was almost completely down in the next half hour. In Test 14, the tile protection fell from the lower flange of the girder just before the end of the fire exposure. The ceiling in Test 16 functioned well for almost 4 hr, when it began to fall in large sections. Generally, the ceilings remained fairly well in place for a considerable time after an average temperature of 1000 °F was exceeded.

All of the floor coverings in these tests showed considerable cracking and some spalling. However, disintegration occurred only in the floor of Test 12. The concretes adhered well to the steel deck after the fire exposure, except in Test 7 where no expanded metal floor binder was used. In four of the Tests (7, 9, 12, 16), cotton waste applied to the surface of the floors became ignited in approximately 2 to 4 hr after start of the fire exposure. The floor covering in Test 11 was sufficiently intact to be reused in the hose stream Test 13, and after rehydrating, in Test 14.

The welding retained satisfactory strength in nearly all cases, with five of the floors exhibiting no weld fractures. Only two failures occurred in floor plate seams, in locations where welds 3½ in long were used. In Tests 8 and 9, 75 percent of the fillet weld joints of the plates to the exterior (side) beams indicated failure although the welding on the five interior beams of the panel was in satisfactory condition after the test. The welding failures were in no case of an extent to impair the ability of the floors to support the applied load throughout their respective fire exposures.

TABLE 4. *Results of tests with fire exposure under floor*

Test No.	Fire Exposure Period hr:min	Exposure Severity %	Deflections: Maximum: Beam in.	Deflections: Maximum: Beam hr:min	Deflections: Maximum: Girder in.	Deflections: Maximum: Girder hr:min	Perm. Set: Beam in.	Perm. Set: Girder in.	Highest Average Temperatures: Beam ° F.	Beam hr:min	Plate ° F.	Plate hr:min	Girder ° F.	Girder hr:min	Unexp. Surf. ° F.	Unexp. Surf. hr:min	Time to Limiting Temperature: Steel [4]: Beam hr:min	Steel [4]: Plate hr:min	Steel [4]: Girder hr:min	Unexposed Surface [5] hr:min	Fire Endurance hr:min
7	2:03	95.6	8.5	2:00			3.2		1,022	2:05	946	2:05			781	2:30	1:51 avg	N.R.		1:37 avg	1:35
																	2:01 max			1:35 max.	
8	2:45	94.0	13.0 (est)	2:40			9.8		1,742	2:43	1,747	2:40			1,018	3:15	1:42 avg	1:48 avg		1:47 avg	1:24
																	1:45 max	1:49 max		1:24 max.	
9	3:23	99.1	14.4 (est)	3:20			9.9		1,625	3:25	1,785	3:20			477	4:20	1:45 avg	1:52 avg		3:22 avg	3:20
																	2:03 max	2:17 max		3:20 max.	
10	5:00	99.7	8.9	5:30	14.0	6:00	8.0	13.9	1,576	5:03	1,603	5:02	1,839	5:04	628	6:00	4:46 avg	4:46 avg	2:36 avg	5:12 avg	4:55
																	4:43 max	4:45 max		4:55 max.	
11	3:00	101.4	3.8	3:15	1.4	3:15	2.0	0.5	869	3:10	801	3:10	545	4:00	480	4:00	N.R.[6]	N.R.	N.R.	2:57 avg	2:45
																				2:45 max.	
12	3:40	95.6	13.6	3:40			7.1		([7])		([7])				798	4:00	2:35 avg	([7])		2:47 avg	2:31
																	2:10 max			2:31 max.	
13	[1] 1:00	98.5	1.3	1:00			0.7		554	1:00	471	1:00	208	1:00	205	2:00	N.R.	N.R.	N.R.	N.R.	
14	5:00	100.2	7.8	5:30	11.7	6:15	6.7	9.9	1,141	4:50	1,051	5:05	1,967	4:50	728	5:40	3:29 avg	4:29 avg	4:02 avg	2:34 avg	2:34
																	N.R. max	N.R. max	4:18 max	2:34 max.	
15	[1] 1:00	101.8	1.9	1:00			1.1		156	0:40	147	0:50			([8])		N.R.	N.R.	N.R.	([8])	
16	4:45	98.7	14.0 (est)	4:30			13.2		1,486	4:10	1,477	3:50			[2] 594	5:55	2:12 avg	2:05 avg		4:12 avg [2]	[2] 3:43
																				3:43 max.	
															[3] 507	6:15	2:20 max	2:18 max		4:49 avg.[3]	[3] 4:42
																				4:42 max.	

[1] Fire and hose-stream test, 1 hour.
[2] Cinder concrete.
[3] Gas-expanded concrete.
[4] 1,000° F. average of thermocouples.
1,200° F. maximum on one thermocouple.
[5] Average temperature rise of 250 degrees F. on all thermocouples, or maximum rise of 325 degrees F. on one thermocouple.
[6] N.R. = Not reached.
[7] t.c's out due to rapid deflection.
[8] No data.

6. Discussion of Results

6.1. Burnout Tests (Tests 1–6)

In these tests, which may be considered as burnout exposures, the combustible loading above the floor provided the only fuel for the fire. Such loadings have been related to equivalent exposures in standard fire endurance tests [2]. The fire severities in these tests, when calculated as the area of the exposure time-temperature curves, including cooling curves, above a base of 150 °C (302 °F), were lower than those established on the basis of earlier burnout tests [3]. A comparison of the observed severities and those determined from the results of the other burnout tests can be seen in the following table:

Avg. Weight Combustibles	Severity by Ref [2]	Observed Severity
lb/ft [2] floor area	hr:min	hr:min
10	1:00	0:39 [1]
15	1:30	1:03
20	2:00	1:21
30	3:00	1:40
40	4:30	3:06

[1] Average of two tests.

The lower than generally accepted values observed in these six tests were possibly due to differences in the amount and type of ventilation provided and the location of thermocouples, as well as the size and construction of the burnout room.

Damage to the steel plates of the floors from the fire exposure above varied with the amount of protection over the surface of the plates and the intensity of the fire. The bare plates in Tests 1 and 2 were subjected to high expansion stresses caused by the temperature differential between them and the beams to which they were welded. This caused buckling and fracture of the welds, more in evidence in Test 1 where the beams were restrained at the ends than in Test 2 with a freely supported floor structure. The 3/16-in battleship linoleum of Test 3 appeared to offer some protection with consequent reduction in buckling. With ½ in of asphalt emulsion concrete, only slight distortion of the plates was noted (Test 4). Floors covered with 2 in of concrete, even under rather severe exposure, showed practically no distortion of the plates and no fracture of plate-to-beam welds. With concrete covering (Tests 4, 5, 6), the average of the maximum temperatures in the steel plates was about 70 deg F lower than in the first three tests, even though the concretes showed considerable cracking and the fire exposures were greater.

In cases of standard fire tests where structural loading has been impractical, an average temperature of 1000 °F has often been applied as a limit for structural steel members exposed to fire [1]. At this temperature, the steel is considered to have lost approximately half its strength, so that where the usual safety factor of two applies, the structural members will be critically stressed. Although this temperature was not reached in the beams in any of the six burnout tests, there was considerable deflection of the beams and some permanent set. It should be noted that, of the four floors made without cantilevered beams, the one that was freely supported (Test 2) had the greatest permanent set, although the maximum deflection of its beams during the fire exposure was less than that of any of the other three. The smaller deflections in Tests 5 and 6 were probably due to both the reduced length of the main floor spans and to the insulating effect of the thicker floor covering, which limited the increase in temperature in the beams. In these tests, the cantilevered beams also showed only small deflections at their ends, probably as a result of the lower temperatures prevailing at the extremities of the fire space.

The greater deflections noted in the beams of the fully restrained floors were probably due to the bowing of the floors resulting from their expansion under exposure to heat. In Test 2, the freely supported beams had some space for movement on the shelf angles of the supporting frame on which they rested. Thus, in this case, the defection of the floor represented principally the actual deformation of the unrestrained beams under the applied load, which may be taken as the explanation of its greater permanent set.

In a paper proposing criteria for defining load failures [4], formulas are given for limiting total deflection and hourly rate of deflection based on the length of span and the depth of the structural component or assembly. For floors with 4-in beams on an 18-ft span, this would allow a maximum deflection of 13.7 in, and a maximum rate of deflection of 73 in/hr. For 5-in beams over the same span, the values are 11.1 in and 59 in/hr. These limits were not approached in the tests with the fires above the floor. The greatest deflection, 5.8 in, occurred in test 3, which also exhibited the greatest rate of deflection, approximately 1.3 in/hr.

While it is generally accepted that a loaded floor may deflect up to 1 in for 30 ft of span without the formation of cracks in the ceiling, somewhat greater deflections were obtained in these fire tests before damage to the plaster was visually noted. In Test 3, a deflection of 2 in occurred at the center of the span before cracking in the plaster was observed. With deflections above 3½ in, the wire ties holding the metal lath were overstressed, and some were broken.

The rise in air temperature in the space below the floor never exceeded 30 deg F in any of the burnout tests. In every case, the maximum temperature was attained at a time considerably past the peak of flaming on the surface of the floor, and was not such as to make the space untenable. Thus, these burnout tests support the premise that above-floor fires do not produce excessive structural damage to the floor, or untenable heat conditions in the room below.

6.2. Fire Endurance Tests (Tests 7–16)

In the 10 tests in which the ceiling of the floor assembly was exposed to a fire beneath the floor, the structure and composition of the ceiling largely determine the fire endurance of the floor. The steel components transmit heat quickly and will themselves soon reach their yield point in the event of failure of the protective materials below them. In this condition, there are several interacting effects. Heat from the fire causes eventual calcining of the ceiling plaster. However, enough plaster generally remains in place to offer insulation to the beams. This, of course, cannot be complete, and the expansion of the beams as they are heated, especially if restrained, causes their deflection with consequent deformation and partial or total failure of the ceiling structure. When this occurs, the beams become exposed to the fire, and quickly undergo progressive yielding as their temperatures rise.

The relationship between the time to an average temperature of 1000 °F or to 1200 °F at one point and that of several phases in the destruction of the celing protection in these tests can be seen in the following table:

Test No.	Time to Cracking of Ceiling	Hole in Ceiling	Critical Temp. in Beams
	hr:min	hr:min	hr:min
7	0:40	2:02	1:51
8	0:38	1:44	1:42
9	0:36		1:45
10		4:30	4:43
11	No destruction of ceiling.		Not reached.
12		1:46	2:10
13	No destruction (1-hr test).		Not reached.
14	1:40	3:25	3:29
15	No destruction (1-hr test).		Not reached.
16	1:10	2:00	2:12

With destruction of the ceiling, transmission of heat through the floor plates also will follow rapidly, and if the floor has not already failed structurally, there will be failure by excessive rise of temperature on the floor surface. The time to such failure will be governed, in part, by the insulating properties of the floor covering material. Those with poor insulating characteristics will quickly transmit the heat required to give the limiting unexposed surface temperature rise. Surface finish materials that are good insulators, however, will slow the temperature rise on the unexposed surface, but can at the same time cause the steel members of the structure to attain higher temperatures, so that failure under the applied load may occur.

Differences in the effect of floor covering on the fire endurance of a floor assembly can be observed by comparison of Tests 8 and 9. Both of these showed an average temperature of 1000 °F on the plates at almost the same times (1 hr 48 min and 1 hr 52 min respectively). Their fire endurance, however, as determined by rise of temperature on the unexposed surface was 1 hr 24 min in Test 8, in which the floor consisted of 1½ in of gravel aggregate concrete, and 3 hr 20 min in Test 9, where the floor was 1½ in gas-expanded concrete with a ½-in limestone-cement topping. In Test 16, in which the time to limiting temperature rise on the steel plates (2 hr 5 min) was comparable to that in Tests 8 and 9, the floor covering was in two sections consisting of 2½ in of gas-expanded concrete or a like thickness of cinder aggregate concrete, both with a ½-in cement-sand topping. Here, the extra inch of gas-expanded concrete apears to have contributed significantly in raising the endurance to 4 hr 42 min. Under the same conditions of test, however, the limiting temperature rise was attained on the surface of the section made with cinder aggregate concrete in only 3 hr 43 min.

Unlike the burnout test results, rather large deflections were observed in the fire-endurance test series. In Tests 8 and 12, in which 4-in beams supported the floor, maximum deflections of 13.0 and 13.6 in, respectively, were observed. These approached the limit, previously described in the discussion of the results of Tests 1–6, of 13.7 in deflection for floors consisting of beams 4 in in depth plus ¼-in thick floor plates and spanning a length of 18 ft. The times required to reach these maximum deflections, however, were in each case more than an hour in excess of those at which failure by temperature rise on the unexposed surface had occurred. The maximum rate of deflection for any of the trials was noted in Test 12, where the downward movement of the floor reached a rate of approximately 18 in/hr between 2 hr 20 min and 2 hr 40 min after start of the test. This is only about one-fourth the limiting rate proposed in the floor failure criterion [4].

Maximum deflection of 14.4 and 14.0 in occurred in the floors of Tests 9 and 16, respectively. These had 5-in beams, and under the conditions of these tests, the proposed limit of deflection would be 11.1 in. This amount of deformation was reached in 2 hr 30 min in Test 9, and 3 hr 45 min in Test 16. However, the highest rate of deflection in these two tests was approximately 7 in/hr (Test 16), or less than one-eighth the limiting rate, so that imposition of the deflection criteria of failure was not warranted in any of these tests. It is reasonable to assume that the restraining action of the steel plates welded to the beams served to limit the rate of deflection of the structural members.

The deflections of the end of the cantilevered beams were affected by the type of floor structure as well as by the heat of the fire. In Test 10, where the beams were continuous over the girder, the cantilevered ends showed considerable upward movement as the center of the long span moved downward. At the end of the test, however, the cantilevered beams were down approximately 14 in, following the large deflection of the girder. In Tests 11 and 13, in which the deflections at the center of the main span beams were small, there was only a small upward movement of the cantilevered ends, about 1 in maximum. The ends of the cantilevered beams in Test 14 also moved upward in the early phases of the fire exposure, but shortly after the completion of the test, exhibited a downward deflection of approximately 11 in, about the same as the maximum deflection of the girder. In these tests, it appeared that the displacement of the cantilevered beams was more a function of the movement of the supporting girder than the effect of heat on their unsupported ends. The comparative deformation, after test, of a girder and cantilever beams supported on it can be observed in figure 14.

FIGURE 14.—*Deformation of girder and cantilever beams after 5-hr fire exposure (ceiling and girder covering removed).*

7. Summary

An examination of the results of fire exposure tests of steel plate floors supported on steel beams may be summarized as follows:

First, steel deck floors are practical for use from a fire safety standpoint. In tests made with the fires in combustible materials above the floors, burnout of combustible loading of 10 lb/ft^2 caused no appreciable damage or impairment of load-carrying capacity of the floor structures, even those with no protective covering on the surface. Exposure to fires in greater concentrations of combustibles, up to 40 lb/ft^2, were sustained by floor assemblies having only moderate surface coverings not exceeding 2 in of concrete.

In the tests with the fire exposure conventionally below the floor, all of the floor assemblies had fire endurance periods, as determined by the permissible rise of temperature on the unexposed surface, of more than 1 hr, with several structures over 4 hr. Thus, most building code requirements for fire resistance could be met by the choice of one of the tested floor assemblies.

The values of equivalent standard fire exposure derived from the burnout tests of this series, did not correspond to those usually assigned to burnout of given weights of combustibles. The usual equivalents are 1 hr standard fire exposure for each 10 lb/ft^2 of combustibles, up to 30 lb/ft^2, plus 1½ hr for each additional 10 lb/ft^2. In these tests the equivalent exposures based on the area under the time-temperature curves, were somewhat lower than those based upon the results of earlier burnout tests, and this may be due to differences in the amount and type of ventilation provided and the location of thermocouples, as well as the size and construction of the burnout room.

Finally, the fire endurance of steel floors, where the fire is below the structure, appears to be largely a function of the protection provided by the ceiling and the insulating properties of the floor covering material. The fire endurance is usually stated as the time to reach a limiting temperature rise on the unexposed surface of the floor, but the endurance may also be limited by failure of the structure to sustain the applied load. A good insulating covering on the floor may retard the temperature rise on the surface, but, in so doing may cause higher temperatures in the structural elements, thus hastening their deformation and the rate of deflection of the floor assembly. There are, however, no established criteria by which failure by excessive deflection may be determined. It would appear, that to insure uniformity in the interpretation of test results and in the assignment of fire resistance ratings necessary for implementing the requirements of building codes, a criterion such as the one proposed [4] and referred to in this paper, should be adopted to define the deflection conditions under which a floor assembly may be considered to have experienced load failure. Preferably, this point should be reached before the structure has fallen completely into the test furnace.

8. References

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