The Historical Basis of Fire Resistance Testing — Part I

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This review summarizes the history of fire resistance testing and its impact on the formulation of the present standard. It focuses on studies from the 1880s to 1918.

FOR NEARLY the last six decades in the United States, fire endurance design for buildings has been based on Standard E119 of the American Society for Testing and Materials (ASTM).[1] While numerous minor changes have been made, the time-temperature curve, the basic test apparatus, and some of the criteria have remained unchanged. Component test methods established in other parts of the world have, until recently, likewise been modeled on E119. Engineering advances in the calculation of expected fires in buildings have been made continually over the last two decades.[2] Engineered design methods have also come to be available; yet the sixty-year-old methodology incorporated in most U.S. building codes has not been supplanted. Thus, it becomes important to carefully review the data on which the fire test standard was based. A thorough examination of the basis for traditional fire testing can then be used to analyze any benefits of more recently available design procedures.

BEGINNINGS OF FIRE TESTING

The first edition of ASTM Standard E119, then numbered C19, was issued in 1918. For most intents, it marked the end of experimental and ad hoc testing procedures. While additional experimentation and research continued after 1918, their results rarely made significant impact on the test standard or on building codes. Thus, the large-scale fire experiments conducted prior to 1918 played the principal role in shaping the standard test. Tests that did not model a realistic use condition or

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that were not quantitative will generally be excluded from this review. Research after 1918 will be examined here in only a few special cases.

The precursors to fire testing can be traced to the 1790s. Quantitative work began in Germany in the 1880s and in the U.S. and England in the 1890s. The latter 1890s saw intensive efforts in exploratory testing, leading gradually to standardization in the early 1900s. Efforts were also going on in other countries; but, with a few exceptions, they will not be considered here since they were not influential in the English-speaking world and their records are not easily accessible.

Today, the distinction between fire resistive and noncombustible construction is clear. The fire resistive assembly is engineered to withstand some specific effects of fire for a given time, while a noncombustible material is any which will not have a significant heat of combustion at temperatures that can be expected in a fire. In the last century, the two terms were initially presumed to be synonymous. Thus, the early history of designing fire endurance into buildings began with efforts to find useful noncombustible materials.

Load-bearing masonry systems were proving to be too costly for the increasingly high multistory buildings in the 1870s. Their replacement was the skeleton frame construction. Developed in the 1880s, it replaced the heavy bearing masonry with skeletons of iron columns. Meanwhile, floors had been evolving in the 1870s from heavy all brick arches, which generally had good fire performance, into significantly lighter brick or terra-cotta arches sprung on iron beams whose fire behavior was variable. There arose a lucrative field of designing and manufacturing ingenious patented floor systems and systems for fireproofing of columns.[3] Their merits were touted in florid terms, yet no basis existed for comparing their fire resistive performance. Indeed, not all owners were convinced that any fireproofing really needed to be added to iron columns so long as combustible materials were not used. One of the popular methods of construction involved the complete covering of all iron members with terra-cotta tile, but in some cases, the terra-cotta would fall off very quickly in a fire. In other cases, the assembly held together during the fire but shattered in a brittle manner as soon as fire fighters started applying water.

Records of fires were the principal evidence used in the 1880s and 1890s to evaluate fire performance of different components of buildings. After major fires, such as the Horne Building in Pittsburgh[4] or the Home Life Insurance Building in New York,[5] extensive analyses were published showing what went wrong with their fire protection. The fires following the San Francisco earthquake of 1906 provided a veritable catalog[6] of fire protection lessons. Only a limited number of buildings experienced large fires, so comparative discussions of related firesafety of various systems were still putative rather than factual. Codes were phrased in prescriptive, but vague, terms. For instance, prior to the inception of testing efforts in New York City, the City Building Code required floors in fire resistive buildings to be of brick or stone, "sectional hollow brick, hard-burnt clay, porous terra-cotta or some equally good fireproof material." There was a clear need for methods of predicting fire performance.

Efforts at fire resistance testing started with floors and columns and gradually included walls, doors, and other components. This emphasis was only natural in view of the importance of preserving the main load-carrying capacity of multistory frame buildings. Since the test methods for the different components followed different lines of evolution, their development will be considered separately.

TESTS OF FLOORS

One of the earliest records of a test for fire resistance was one conducted in London in the 1790s. An informal club of architects, The Associated Architects, conducted tests[7] to determine the relative merits of two floor fireproofing systems — one consisted of iron plates, and the other, of stucco covering. A fuel load of wood shavings and barrels was introduced, and tests were run for 1 to 2 hours. The results showed that fire, but not smoke, was successfully contained. The test, of course, preceded the availability of equipment to measure fire temperatures.

Concrete was slowly coming into use in the 1870s. Thaddeus Hyatt was a strong exponent for the use of reinforced concrete as an engineered construction for floors in fire resistive buildings. Widespread acceptance of concrete floors was not to come until two decades later, but in 1877, Hyatt published[8] a remarkable treatise on the design of reinforced concrete members. In addition to performing mechanical property tests and evolving a way of calculating their strength, Hyatt also performed fire tests on concrete floors. First he cast small blocks of concrete, heated them in a furnace for 6 hrs, then plunged them into water. Concrete specimens did not disintegrate, while brick did. Then he built a wood-fired furnace over which a specimen of about 0.6 by 1.6 m clear span was tested for 12 hrs. The test specimen represented three sections of a floor slab, iron reinforcing bars covered by 5, 7.5, and 10 cm of concrete, respectively. Hyatt had no way of recording the furnace temperature, but he did obtain the iron (back face) temperatures by several means — melting of tin and lead squares, bulb thermometers, and, afterward, immersion calorimetry. The results were surprisingly well characterized temperature plots of the back face. A second test was then made to determine the load-bearing behavior. A 19-cm-thick floor was loaded to 1,500 kg m^{-2} and tested for 10 hrs. Afterward, a hose stream test of 15 to 20 min was conducted. Load was held, and no collapse or significant deflection occurred.

By 1890, it was becoming clear in the U.S. that tests rather than mere philosophical discussions were needed to compare the merits of various fireproofing systems. The pioneering work here was a series of tests on floors that was conducted in Denver[9] in that year. The architects for the

Denver Equitable Building wanted to determine which of three competing floor systems was best in both structural and fire considerations. To determine their fire performance, 1.2- by 1.5-m specimens of the three floor systems were given fire and hose stream tests. Two kinds of fire tests were conducted. In the first type, the floors were built up over a pit and loaded down to 1,500 kg m^{-2}. A coal fire was stoked, and its temperature taken by measuring the resistance of a platinum wire strung through the furnace pit. A temperature averaging 815° C was maintained for 24 hrs. The second test entailed conditions similar to the first one, except that every 90 min a hose stream was applied for 3 min. Both tests continued until destruction. The hose stream was recorded as being a very feeble one from a 6-mm nozzle. The floors lasted between three and fourteen such cycles.

In 1891, a similar test was made in St. Louis[10] by the architects for the Wainright Building. Only one type of specimen, 1.4 m by 2.4 m, was tested. The construction involved a concrete arch floor protected by a separately hung clay tile ceiling. The fire test was performed only on the ceiling with the beams, but not the arches, installed. The specimen surmounted a furnace 27 cm deep, which was fed by eighty-four gas burners. This test thereby constituted one of the first known gas-fired tests. Furnace temperature was recorded with a thermocouple protected in iron pipe. A thermcouple was used also for measuring the exposed surface temperatures. The exposure temperature was around 815° C for 6½ hrs, not including an initial period when readings were not taken. Immediately afterward, three cycles of hose stream testing, alternating with reheating, were applied. The water was from a garden hose and apparently of low pressure.

The next series of tests marked the inception of floor fire testing in Germany. During 1893, the Vereinigung von Feurversicherungs-Gesellschaften (The German Association of Fire Insurance Companies) organized a series of tests[11, 12] in a building to be demolished in Berlin. Several floors, doors, wired glass windows, and other components were tested. This series was notable mainly for the fact that doors were begun to be tested. The test conditions were not intended to be uniform enough to be considered standard tests, but were closer to what would now be considered burnout tests. Realistic furniture was used as fuel, and temperatures in the range of 1,000 to 1,300° C were recorded using Seger cones. (Seger cones are small ceramic indicator cones that soften at a known temperature and slump to one side.)

An isolated floor test, one of 4 hrs in duration and fueled by "a fierce wood fire," was conducted in 1894 in Trenton.[13] That same year, a German fire test of a Monier arch floor[14] was recorded. A 0.70-m-wide by 2.0-m-long specimen was heated for 2 hrs in a fire fueled by wood, coal, and coke. Temperatures, noted only with melting point indicators, stayed below 700° C.

The inception of systematic fire testing of floors was not begun until 1896. In that year and the following one, Stevenson Constable, then

Superintendent of Buildings in New York, conducted sixteen tests[15, 16] to determine quantitatively the merits of the various available floor systems and to obviate the need for subjective judgment by the Board of Examiners.

The tests were conducted in different ad hoc brick huts, usually 3.4 m by 4.3 m inside and 3.0 m high. Wood fuel was used, since it was felt to more closely model actual fires. The tests were run for 5 hrs, the first hour being considered warm-up time, while the temperatures in the last 4 hrs were to average 1,093° C. The poor control achieved with manual stoking of wood fuel was the main reason for the long required warm-up time. In this first series of tests, the temperatures were measured with a single pneumatic pyrometer, supplemented by melting point indicators. The floors had a load of 750 kg m^{-2} applied. After the test, a hose stream was applied for 15 min. (Unlike previous tests, this involved a rigorous test with a hose stream pressure of 0.4 MPa.) The load was then raised to 3,000 kg m^{-2} and had to be carried for 24 hours. Deflection, which was not allowed to exceed 6.3 cm, was recorded; falloff or disintegration was noted.

At the same time, the New York Building Department also conducted four tests on small, 1.2-m square, specimens of wood floors,[8] such as typically were used in mill construction. These lasted until flame-through occurred, periods of 29 min to 1 hr and 35 min.

There appears to be a gap in floor testing in the U.S. between 1897 and 1902, when it was resumed in New York. Starting in that year, a measurement of temperatures on the steel of the floor beam was occasionally added. Readings were taken with a special glass bulb thermometer, yet no corresponding criteria for failure were added. Furnace temperatures were then being measured with from two to five platinum-rhodium thermocouples, and the average temperature required was lowered to 926° C.

Although ad hoc tests[16] were still being conducted, 1902 marked the establishment of the first permanent station in the United States for testing fire resistance of building components. Professor Ira H. Woolson, a graduate of the School of Mines at Columbia University, first built fire testing facilities on the Columbia campus in Manhattan, then shortly afterward relocated them to the Greenpoint section of Brooklyn. The work performed there was not basic research, but rather was conducted as a service to the New York Bureau of Buildings. Two large-scale furnaces[16] were erected — a floor furnace 5.5 m by 6.7 m long and a wall furnace 3.0 m by 4.6 m wide. Woolson left Columbia after a few years to join the National Board of Fire Underwriters (NBFU), but work at the station was continued for several more decades. In addition to fire resistance testing, tests for fire retardancy of wood[17] were also developed at Columbia. Little published research resulted from the later efforts.

In Britain, meanwhile, the history of fire testing reads like the biography of Edwin O. Sachs. Trained as an architect and specializing in theater design where firesafety is of utmost importance, Sachs soon realized that official British efforts for firesafety were weak and sporadic. Thus, in 1897 at the age of 27, he organized a group of public-minded citizens and formed the British Fire Prevention Committee. As happened time and again before and since, the precipitating event was a tragic conflagration, in this case the Cripplegate fire of November 1897. In two years time, a facility containing three multipurpose furnace "huts" was erected in London[18], and the first floor test was conducted.[19] The average life of a test hut was said to be about ten tests,[20] even though the walls were 36-cm-thick masonry, and the brickwork was repaired frequently. Figure 1 shows this testing facility. By the end of 1899, thirty-six publications, later called "Red Books," had been issued and twenty-nine tests had been reported. In 1901, the facility was razed to make way for railroad construction, and a new test station,[21] comprising four furnaces, was erected.

Initially, the temperature curve for the producer-gas-fired furnaces was not standardized. Tests began with a slow simulation of a smoldering period and then climbed to the vicinity of 1,093° C. A hose stream test of several minutes then followed. The criteria for success consisted of avoiding collapse and flame-through. In 1906, deflection measuring was started, although deflection was not required to be limited.

In 1912, Woolson[16] reported that Underwriters Laboratories (UL), which were started in 1894 in Chicago to test electrical devices and had gradually expanded to other tests, had already tested six floors. No record appears to exist of the furnaces or the test method. It is known that, in 1920, two identical floor furnaces were constructed. These could accommodate 16.7-m^2 specimens. In 1924, these furnaces were reconstructed but very shortly fell into disuse. Floor testing was then discontinued at UL until 1939. The extensive ratings for building components now being published by the UL in fact did not come into being until the 1940s and 1950s. Previously, only tests of fire doors and windows were routinely being tested and listed. UL's reluctance to routinely test and rate other types of components stemmed from the fact that they were not factory manufactured. Unlike a door assembly, a floor did not leave a factory complete, inspected, and labeled. Thus, in the early days, the UL listings for building components tended to be simple, single material systems from large manufacturers.

By 1920, a floor furnace was already in use at the National Bureau of Standards (NBS) in Washington.[22] Descriptions of the early work have not been published, but summary results were published two decades later.[68]

The British Fire Prevention Committee lost its momentum when Sachs died in 1919, and the following year it was merged into the National Fire Brigades Union. Testing in Britain was continued when the Fire Offices' Committee (FOC), analogous to the NBFU in the United States, which had already been conducting sprinkler, extinguisher, and fire door tests since 1908, built a furnace at Cheetham Hill, Manchester, in 1927. Later, in 1935, the FOC erected a fire testing station at Borehamwood (Elstree), equipped with three furnaces for wall, floor, and column tests.

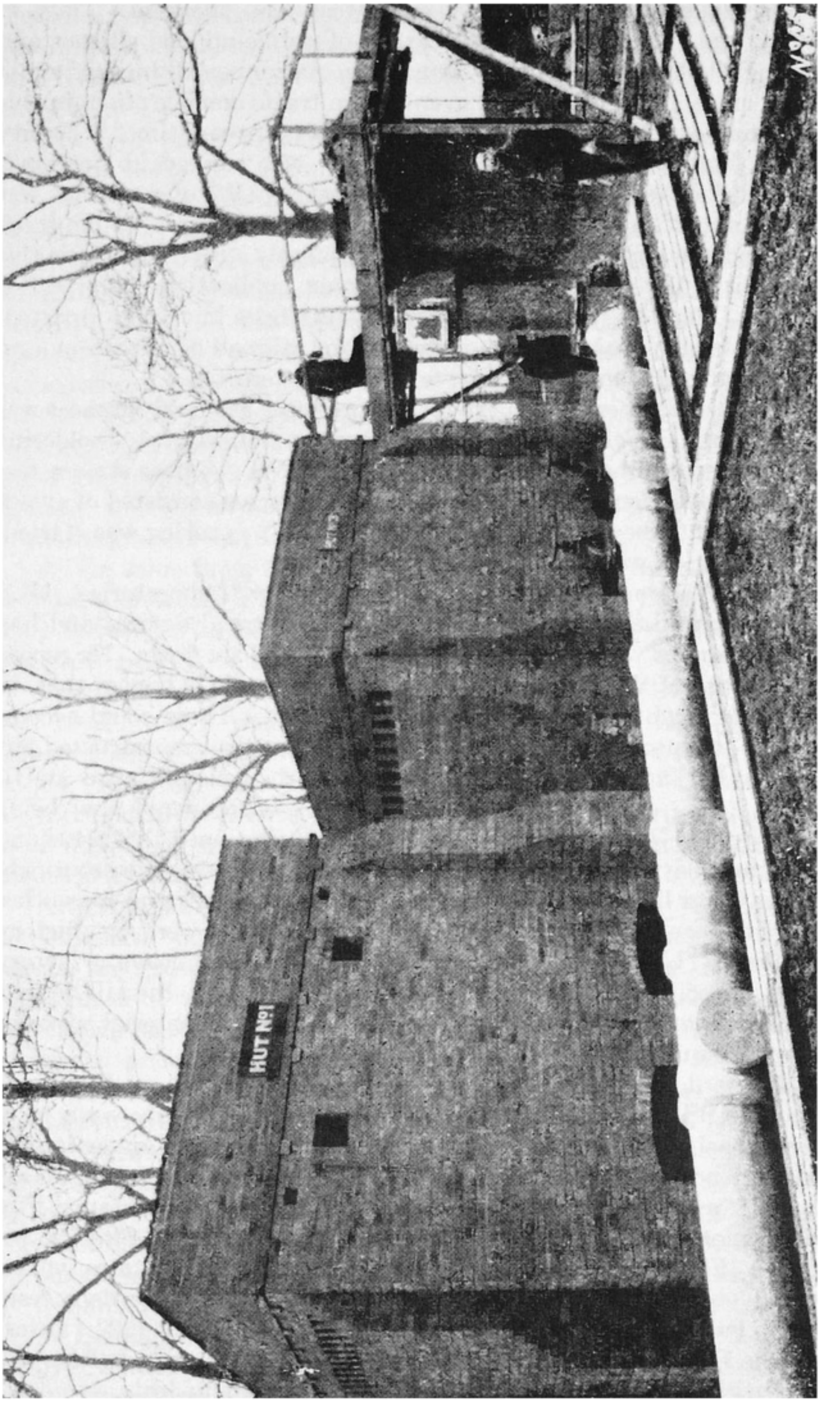

Figure 1. The first British Fire Prevention Committee Testing Station.

TESTS OF COLUMNS

Column testing was first recorded in Germany and Austria. During 1884, Professor J. Bauschinger, famed for his research in materials science, conducted tests [23, 24] in his laboratory at the Technische Hochschule of München on eleven unprotected cast or wrought iron columns and twelve brick, stone, or plain concrete columns. The testing procedure consisted of heating the loaded columns in a horizontal position in a wood-burning furnace. Figure 2 shows a cross section of this primitive furnace. Three successive fire and water tests were to be conducted. An unusual feature of these tests was that, instead of measuring the fire temperature, Bauschinger measured the surface temperature of the columns, using low melting point alloy probes. A column was heated until its surface reached 300° C, then doused with water, then raised to 400° C or 500° C and then doused, and finally doused after reaching 600° C. The columns were loaded and their deflections measured while being heated. After the columns were removed from the furnace, a complete stress-strain curve was run on them. A second series of twelve iron column tests[25] was run in 1886 under similar conditions.

In 1887, Möller and Lühmann conducted a series of tests[24, 26] in Hamburg, described by them in a paper that won a prize from a German construction promotion council. The fire test aspects were only secondary to a general structural column investigation, so an adequate description of the fire tests was not given. A coke- and wood-fired furnace, possibly similar to Bauschinger's, was used, but it was reported that the flame exposure was not solely on one side of the column. Unlike Bauschinger's procedure, only a single cycle of fire and hose stream testing was performed. The times were reported when the columns got red hot and when they failed. The tests were intended mostly to compare the differences between unprotected cast and wrought iron columns. The differences were slight, with most columns lasting between ½ and 1½ hrs.

The next recorded column test was conducted by the Building Department of Vienna[27] in 1893 and represented an advance in furnace building. A single wrought iron column, 3.5 m long and protected by brick masonry, was erected in a furnace hut fired with wood fuel. The column was subjected to load and fire tested for 2½ hrs. Column temperatures were measured with low melting point alloys, but furnace temperatures were not recorded. A hose stream was applied afterward.

Testing activity continued in Hamburg. A municipal committee, under the direction of F. Andreas Meyer, concerned with fire problems after the conflagration in Hamburg's warehouse district in 1891, organized two series of tests[24, 28–30] of protected and unprotected iron columns, which were conducted in the period from 1892 to 1894 and in 1895. The columns were full size, representing a distance of 3.5 m between floors. They were loaded in a hydraulic testing machine, and a 1.0-m high split oven was clamped around the middle portion; illuminating gas was supplied to twelve

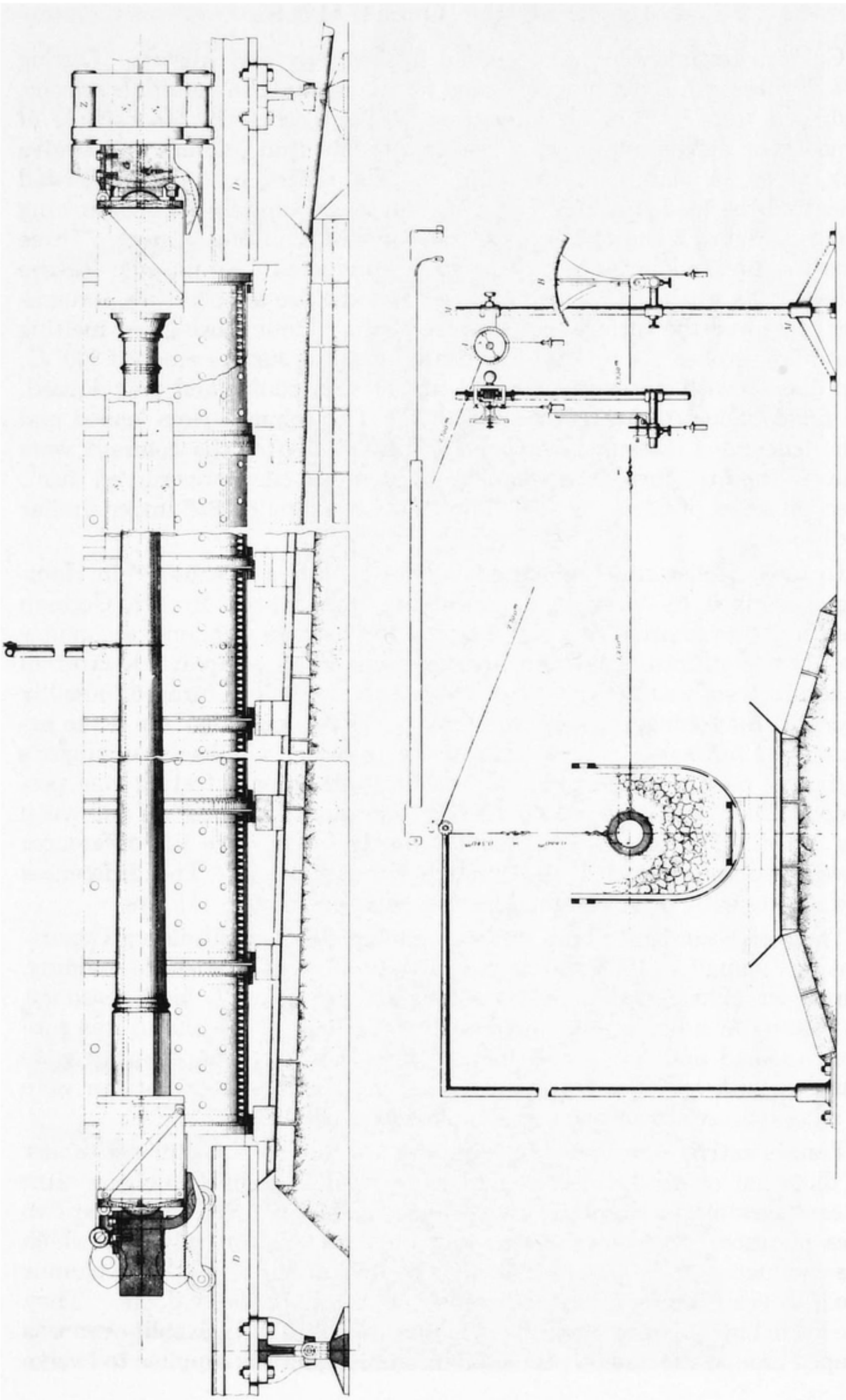

Figure 2. Bauschinger's column test furnace (1884).

burners at the bottom of the oven. Furnace temperatures were monitored with both Seger cones and thermocouples. Unlike in earlier investigations, the column was erected upright and heated symmetrically. A standardized temperature curve was not used. The columns were heated to 1,200 to 1,400° C for up to 7 hrs if there was no failure. Both axial and eccentric load applications were used. Most specimens failed much sooner than 7 hrs with unprotected iron ones tending to last only ½ to 1 hr, at which time the furnace temperature was 800 to 850° C and the specimen was at 800° C. Other specimen temperatures were measured but not published. A hose stream portion was included, but it was not meaningful since most columns had already failed from the heat. For comparison, several 30-cm square timber columns were tested at the same time. When unprotected, they lasted just over 1 hr at temperatures of 900 to 1,000° C.

In the United States, column testing dates from 1896. A committee,[31, 32] representing the Architectural League of New York, the American Society of Mechanical Engineers, and the Tariff Association of New York, arranged to have a furnace fueled by manufactured gas constructed at the Continental Iron Works in Brooklyn. Five unprotected columns, two of steel and three of cast iron, were tested. The test procedure was not standardized. Tests lasted from 25 min to more than 2 hrs, and temperatures ranged up to 840° C. Some columns were subjected to several cycles of fire and hose stream testing.

Column tests were again conducted in New York in 1902, this time by the Guy B. Waite Company[24] for the New York Building Department. In this series, floors, partitions, and columns were tested simultaneously. Tests were conducted for 4 hrs, with the temperature averaging 930° C. The same hose stream test that was prescribed for floor tests in New York was applied. Some additional hose stream tests were also performed.

Reinforced concrete columns were coming into use at the turn of the century. These were first tested in 1904 by the National Fire Proofing Company[33] in Chicago. Three columns were tested unloaded in a wood-burning furnace for 3 hrs, with furnace temperatures ranging around 800 to 1,000° C. A hose stream was applied afterward, and the next day the load carrying capacity was measured.

The next series of column tests, the first standardized ones, was the famous series of 1917 to 1920 conducted at the Underwriters Laboratory in Chicago.[24] In addition to UL, the Factory Mutual companies, the National Board of Fire Underwriters (NBFU), and NBS participated in the effort. Simon H. Ingberg, from NBS, was in charge of the program. These tests represented the first major fire testing effort for both Ingberg, who became the American authority on fire testing, and NBS, which had started its fire testing program in approximately 1912 and had primarily studied material properties prior to this series.

More than 100 steel, cast iron, reinforced concrete, and timber columns were tested, making it the largest testing effort to date in the United

States. The results are still being used in building codes; this acceptance was due mainly to the fact that furnace temperature control had been standardized. Platinum-rhodium furnace thermocouples sheathed in 2.0-cm O.D. porcelain tubes were used. The column specimens were 3.9 m long and were tested vertically under load in a furnace fired by city gas. A load 10 percent greater than the design working load was maintained for 8 hrs or until failure resulted. Some specimens were also subjected to a hose stream test afterward. Temperatures of the column itself were also measured using thermocouples attached to the metal load-bearing portion in the columns containing iron or steel. This technique was much advanced over Bauschinger's crude use of low melting point alloys to indicate specimen temperatures.

Few additional column tests were performed at the UL facility, and the furnace was torn down about 1944. Column testing at UL resumed in 1946, at first in a furnace normally used for testing fire resistant safes. In addition to participating in the joint column test series at UL, NBS conducted a series of reinforced concrete column tests in their own furnace during the period from 1917 to 1919.[34] The furnace facility was at that time located in Pittsburgh and had been taken over by NBS from the U.S. Geological Survey in 1910. The furnace was gas-fired and equipped with similar instrumentation, using similar criteria as in the cooperative series. The specimen length, however, was only 2.7 m.

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