The Historical Basis of Fire Resistance Testing — Part II

VYTENIS BABRAUSKAS* and
ROBERT BRADY WILLIAMSON
Department of Civil Engineering
University of California, Berkeley

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.

THE FIRST part of this paper described the beginnings of fire testing and discussed the testing of floors and columns. Here we will discuss testing of walls and doors and other opening protection as well as the development of the standard time-temperature curve.

TEST OF WALLS

The first controlled tests of walls can be dated from 1891 in Germany. The fire test facility of the Königlichen Technischen Versuchsanstalt zu Berlin was established in 1884 in Charlottenburg; the first published report[36] gives results of a pair of tests conducted in 1891 by Professor Böhme.

The tests were designed to compare the performance of wood walls against a proprietary wallboard system. Two identical test huts were erected, each containing a burn room 2.01 m by 2.63 m by 2.63 m high. The burn room was surmounted by a chimney and fueled by manually stoked fir logs soaked in petroleum. Each test hut contained a smaller adjoining observation room. The test wall was erected as a partition between the burn room and the observation room. In addition, the same wall material utilized in the test partition also lined the ceiling and other walls of the burn room. The test houses carried a fire window plus a loaded cast iron column and a timber column, both protected with wallboard.

Gas temperatures were monitored by multiple melting point indicators. Wall thermal performance was determined by several methods. A peak registering thermometer was attached to the unexposed face, sheets of thin paper were hung on the wall to check for ignition, and the wall was

* Now at the Center for Fire Research, National Bureau of Standards, Gaithersburg, Maryland.

touched to determine if it was too hot to the touch. The temperatures underneath the column protection were determined by a buried peak thermometer plus samples of two low melting point materials.

A total of 275 kg of fuel was used for each test. Gas temperatures averaged 1000° C and the length of the test was one hour. Observations mentioned the window glass bursting at 5 min and eventual slight cracking and crumbling of the walls. One column collapsed at 50 min; the other lasted a full hour. At the end of the test, fire was extinguished by a feeble hose stream applied to both the inside and outside of the burn room, causing some falloff inside.

The Vienna column test[27]* of 1893 also incorporated some test of wall panels. These panel tests cannot be considered quantitative building component tests, since the panels were small and not erected in the manner of intended use.

Work was resumed at Charlottenburg in 1895. By 1900, Gary could report[36] a series of eleven wall tests. In each case, an ad hoc test hut was erected and divided into two rooms by the test wall. For most of these tests, the hut was framed with wood studs, since it did not need to be reused. The inside dimensions varied in each case, and the fuel was petroleum-soaked fir burned on a brick checkerwork.

In the new series, gas temperature measurement was improved, with both Seger cones and thermocouples used. Only the maximum temperature was reported, and it varied in the range of 1000° C to 1100° C for the series. A hose stream was applied after each test and was first directed at the test partition. Unexposed face conditions were recorded as they were earlier. In one case, curtains were also hung on the back face. Observations included note of cracks and falloff as well as the back-face heating. The assemblies tested in the second series were mostly proprietary wallboard systems, many of them based on gypsum planks. They were not intended for fire resistive buildings but were viewed as more modern replacements of traditional plastered wood walls. The tests were all conducted for 1 hr. Successful systems were generally issued approval to be used as equivalent to plastered wood walls in residential occupancies.

The British Fire Prevention Committee testing of walls began in 1899, shortly after its initiation of floor testing. A nonload-bearing specimen 3.0 m wide and 2.1 m high was constructed,[37] dividing the space of one of the test huts. Temperature control was similar to that used for floor tests; a hose stream was applied after the test. Burn-through and structural stability appear to have been the main criteria. By the next year,[38] temperature readings of the unexposed face were being taken, and shortly thereafter recording of deflections was also begun. At times, a match would be held to the unexposed face to see if it would ignite.

In the United States, testing of nonload-bearing walls (generally called "partitions") was started by the New York Department of Buildings.[39] In 1901, thirty walls were tested in fifteen separate huts by W. W. Ewing.

* References 1–34 appear in Part I, August 1978.

Each hut was 4.4 m long, 2.9 m wide, and 2.9 m high. The test walls were erected in the long side. Most of the tests involved two slightly different assemblies by the same manufacturer. Underneath the hut was a grate on which kerosene-soaked wood fuel was burned.

Furnace temperatures were measured with platinum-rhodium thermocouples. The temperature control consisted of trying to reach 926° C at 30 min, then maintain that level until the end of the test. All tests were 1 hr in duration. A hose stream was applied to the fire side after the test. The criteria for success were that neither the fire nor the hose stream passed through the assembly.

The systems tested included plaster block, tile block, and concrete block walls and plaster on metal lath constructions. The walls that passed the test were approved for use wherever the New York Building Code allowed "other fireproof material." Those systems containing organic materials, however, were barred from use for shafts in tenements, since the 1901 law specifically prohibited any combustible material there. The New York City testing was continued by Woolson when his station was built.

The U.S. Geological Survey had a mission at the turn of the century to evaluate building materials used in construction of government buildings. As part of that program, they set about to evaluate the fire resistance of walls. A series of wall tests were conducted in 1907 by the USGS at the UL facility, and Humphrey reported the results[40] in 1909. These tests were intended to explore the physical properties of the materials rather than to be directly used for regulatory purposes. Nonetheless, the tests were standardized and the results are of interest.

The furnace used at UL (Figure 3) was their first fire test furnace, erected in 1903 for testing doors and windows. It may be considered the first modern furnace, more resembling current furnaces than the huts predominantly used then. The furnace was a gas-fired chamber, only 32 cm deep inside and approximately 2.7 m wide by 3.7 m high. Gas was fed through burners in the floor, while forced air was supplied through holes in the front. Furnace temperature was monitored with stubby shielded platinum-iridium thermocouples. A vertical specimen panel 1.8 m wide by 2.1 m high was tested for 2 hrs at a temperature which rose to 926° C in the first half hour and was then held at that level. A hose stream test was applied immediately after the test. The panels were not loaded during testing, since the furnace was not so equipped, but were taken out and load tested the following day. Thirty panels in all were tested; bricks, concrete blocks, tile, concrete, and stone specimens were included. Backface temperatures were measured, and, in addition, some internal temperature readings were taken.

The UL conducted its own series of tests on gypsum block walls[41] during the years 1909–1918. At first, the furnace described in the preceding paragraph was used. Starting in 1915, a new larger furnace[42] was constructed. It was also gas fired, as had become customary in the United States. The inside chamber was 0.4 m deep by 3.6 m wide and 4.5 m

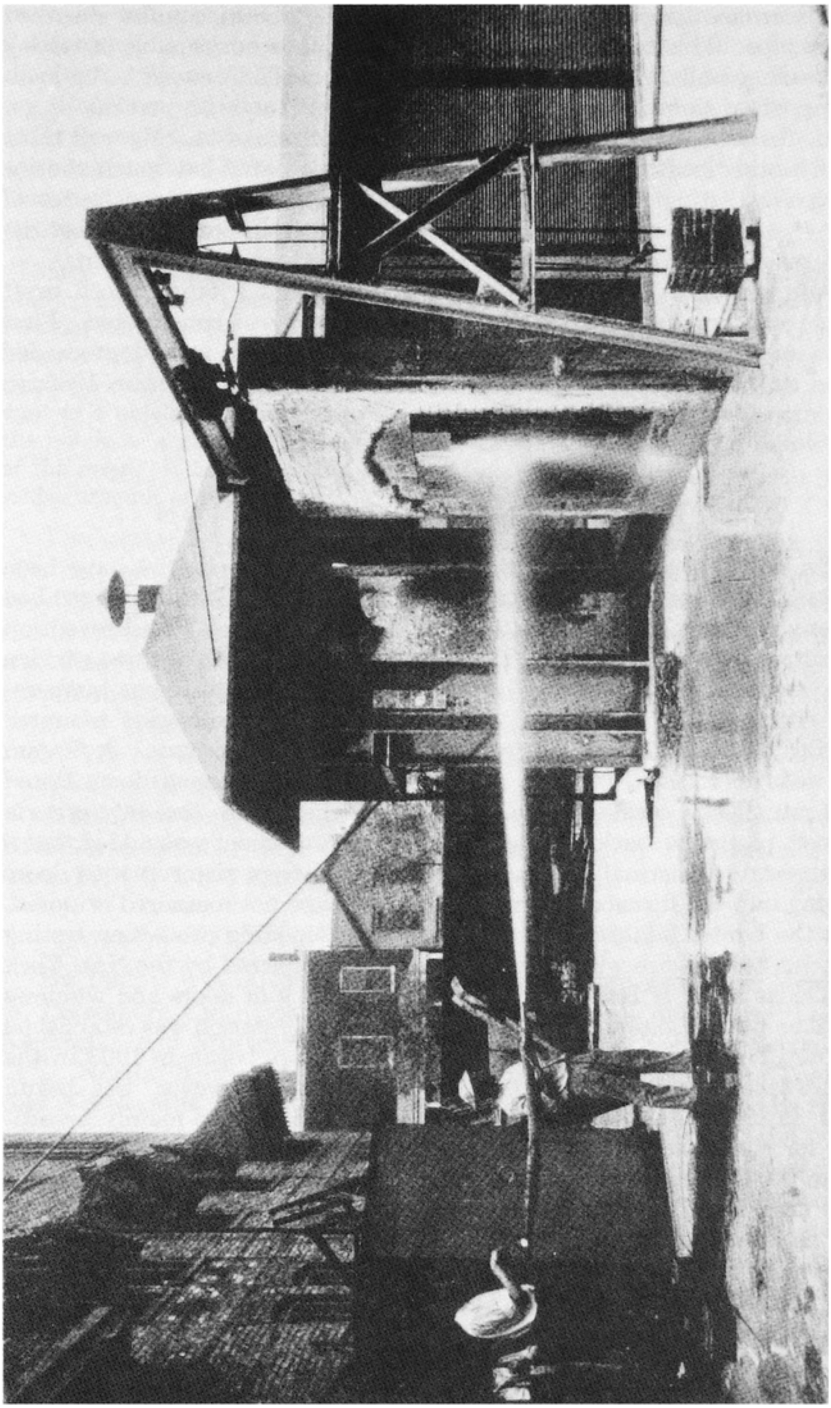

Figure 3. Wall panel furnace at Underwriters Laboratories.

high. Furnace temperatures were measured by thermocouples sheathed in steel pipe. This furnace, like its predecessor, was not capable of testing load-bearing walls. If the UL wanted to test walls intended to be load-bearing, they simply tested them unloaded, but for a 25 percent longer period. In 1927, a test frame was built to perform load-bearing wall tests. As with other building components, UL did not carry out much routine testing and listing of walls until the 1940s. Occasional large series of tests[43,44] would be sponsored at UL by trade associations, but most detailed ratings emerged from the Bureau of Standards test program.

Wall testing at NBS began around 1915 when a large forced draft furnace accommodating 3.3-m by 4.9-m specimens was constructed. First results were not published until 1929,[45] although testing had proceeded during the intervening years. The furnace was reconstructed in 1930, in the course of which it was converted to gas operation.

TESTS OF DOORS AND OTHER OPENING PROTECTION

The 1892 investigations of fire door performance in Berlin have been discussed previously in connection with floor tests. The first controlled fire tests on doors can be dated to 1899 when the British Fire Prevention Committee began door tests.[46] The initial series consisted of three wooden doors, mounted in the exitway of one of the test huts, tested at temperatures rising to 900° C–1100° C until failure. The doors were mounted swinging outwards but failed by collapsing into the furnace. A 50-mm solid teak door lasted 60 min, while standard pine paneled doors lasted 19–20 min before burn-through or collapse, which were the only criteria involved. Later, a back-face temperature measurement was added, but a hose stream was normally not used. Some tests were also run with doors swinging into the furnace. Furnace pressures were not measured or noted.

In the United States, the earliest record of opening protection testing is of some tests of fire windows and shutters[47] conducted by the New York City Department of Buildings. Systematic testing of doors and windows was taken up by Columbia University when its test station was established in 1902. Testing by the UL of doors and windows began in 1903 in the wall furnace already described. Rating of doors, however, was begun earlier, in 1901. This was possible because the doors were mainly investigated for conformance to the various prescriptive specifications set forth by the NBFU and the National Fire Protection Association (NFPA), rather than being tested as a fire barrier. Very similar prescriptive specifications were adopted in Britain by the Fire Offices' Committee.[48] Woolson's report of 1912[16] states that by then the UL had already tested 209 doors and 273 window frames. Despite this extensive activity, Freitag[49] could not list any American test results as having been published by that year. The first description of the UL testing program appeared in 1917. Carr[50] described how these tests were conducted in the wall testing furnace. A test was of 1-hr duration with a hose stream applied afterwards. An interesting set of additional measurements was involved; at distances of 81 cm, 162 cm, 243 cm, and 324 cm horizontally away from the center-point of the unexposed face, thermometers and cloth test strips were hung. It is not stated, however, what use was made of these measurements, which were taken after 1903. From a committee report[51] of 1915, it would appear that positive furnace pressure was maintained at that time. Woolson is quoted as saying,

> "I have been much interested during the past year or more in studying laboratory reports on tests of various types of fire doors, and I find that it is not unusual during a test of a device of that kind that flames anywhere from four inches to three feet issue from around the edges of fire doors. It seems to me that is a very decided danger point, and we ought to provide for it in some way by a regulation keeping combustible material away from the door. I think the public as a general thing expects that any fire door is going to keep fire out of the room. It is certain that a single door will not do it if there is a considerable amount of pressure on the fire side."

The testing of doors by the UL was not coordinated with the testing of other components. While other components were tested and rated for varying time periods, the pervasive influence of the early prescriptive specifications fixed these door tests to be 60 min in duration. The testing was changed in 1938 under the impetus of New York City Building Code Requirements, which provided for three rating periods:

(a) ¾ hr for doors with glazing of greater than 645 cm^2 in area,
(b) 1½ hrs for exterior doors and vent shaft doors, and
(c) 3 hrs for doors in fire walls.

A standard door test was not available until the first edition of ASTM E152[52] was adopted in 1941. A parallel standard by Underwriters Laboratories, UL 10b,[53] was adopted the following year.

OTHER EARLY TEST EFFORTS

By 1903 it was reported[54] that a fire test station existed in Russia at St. Petersburg and occasional testing was being done at Ghent,[55] Leipzig, Karlsruhe, and Stuttgart. An initial test had also been conducted[56] by C. L. Norton of the Massachusetts Institute of Technology. The next year Norton was associated with the founding of the Insurance Engineering Experiment Station by the Boston Manufacturers' Mutual Fire Insurance Company. This station conducted several fire tests, then closed within a year's time. Ad hoc testing was occasionally done in other U.S. cities. These tests were generally not as well controlled as the ones in New York, and little record remains of their results.

DEVELOPMENT OF THE STANDARD TIME-TEMPERATURE CURVE

Until 1903, each test laboratory used its own specifications for temperature, generally a prescription saying that the temperature will be maintained, on the average, above a certain level. As the most active testing organization, the British Fire Prevention Committee was the first to propose a widely accepted standard method. Their standard, as developed by Sachs, was issued at the 1903 International Fire Prevention Congress,[55] where its use was adopted by a resolution of the delegates. The standard consisted essentially of only a table, which is shown slightly condensed as Table 1.

Three main classes of endurance were established:

(a) Full protection
(b) Partial protection
(c) Temporary protection

These terms were, perhaps, somewhat ill-chosen. Temporary did not apply to temporary structures, but rather to endurance that would not be sufficient to endure a burnout of the contents. Full protection, on the other hand, was envisioned as providing such assurance. The main classes were each divided further into subclasses A and B. Prescribed temperatures for both classes were identical, but specimen size and loading and duration of hose stream application varied. The subclasses entailed quite different requirements, but no record remains explaining the necessity for such subdivision.

In the United States, the first test standard was promulgated as part of the New York Building Code in 1899.[57] It was not intended to be national in scope. A nationwide attempt at standardization came from the efforts by the American Society for Testing and Materials (ASTM). Prompted by the Baltimore conflagration of 1904, ASTM organized Committee P on Fireproofing Materials, which first met in May 1905. The Committee, which was soon redesignated C-5 and later E-5, produced its first standard, "A Standard Test for Fire-Proof Floor Construction,"[58] in 1907. Ira Woolson was the chairman of Committee P and R. P. Miller, the New York Superintendent of Buildings, was its secretary. Thus, it is not surprising that its recommendations consisted mainly of a rewording of the New York procedure.

The test conditions envisaged a test hut similar to the ones used in

TABLE 1

FIRE TEST STANDARD OF THE BRITISH FIRE PREVENTION COMMITTEE

Classification	Sub-Class	Duration of Test	Minimum Temperature	Length of Hose Stream Test	Floors		Partitions		Doors	
					Load	Minimum Area	Maximum Thickness	Minimum Area	Maximum Thickness	Minimum Area
		(min)	C	(min)	(kg/m²)	(m²)	(m)	(m²)	(m)	(m²)
Temporary	A	45	816	2	not required	9.3	0.051	7.43	0.051	1.86
	B	60		2		18.6	not limited		not limited	
Partial	A	90	982	2	547	9.3	0.063	7.43	0.063	1.86
	B	120		2	820	18.6	not limited		not limited	
Full	A	150	982	2	1094	9.3	0.063	7.43	0.018	2.32
	B	240		5	1367	18.6	not limited		not limited	

New York and London. The grate area, flue construction, hut wall thickness, and inside clear height were all specified. The clear span of the floor was to be 4.3 m and the floor was to be loaded to 750 kg m^{-2}. A hose stream was to be applied afterwards. When cooled, the floor was to be loaded to 3000 kg m^{-2}.

The temperature control was the same as the New York tests — an average of no less than 926° C was to be maintained for 4 hrs. Criteria consisted of the following:

(a) No flame-through or passage of smoke,
(b) No collapse, and
(c) A permanent deflection of no more than 1/96 the length.

In 1909 a separate test for walls was added, "Standard Test for Fireproof Partition Construction."[59] With a few exceptions, this test was to be conducted in a manner similar to the floor test. Only nonload-bearing partitions were considered; following New York practice, the specimen was to be at least 2.9 m high and 4.4 m long. The temperature was raised to 926° C in the first half hour and then maintained at 926° C until the end, the standard endurance being 2 hrs. Criteria consisted of the following:

(a) No flame-through or passage of smoke,
(b) Sustain the hose stream, and
(c) No "warp or bulge, or disintegration under the action of the fire and water to such an extent as to be unsafe."

Meanwhile, in other countries the 1903 BFPC standard was being adopted. Woolson, at that time, was also the chairman of a similar standards committee of NFPA. Influenced by the increasing prestige of the BFPC standard, this NFPA committee recommended[60] in 1914 that, instead of further developing an American standard, the 1903 International Standard be adopted in the United States but with certain modifications. These modifications consisted of:

(a) Deleting the subclass A,
(b) Lowering the temperature requirements to 926° C in the "full" and "partial" classes,
(c) Increasing the duration of the hose stream up to a maximum of 10 min for floors with "full" protection, and
(d) Some modifications in specimen thickness, area, and loading.

This recommendation was not approved by NFPA.

Instead, in 1916 and 1917 two meetings were held for the purpose of determining U.S. fire test standards. These conferences were made up of representatives from ASTM, NFPA, UL, NBS, NBFU, Factory Mutual, American Institute of Architects, American Society of Mechanical Engineers, American Society of Civil Engineers, Canadian Society of Civil Engineers, and American Concrete Institute. The new standard, ASTM C19 (later renumbered E119), was issued at the 24 February 1917 meeting of that conference.

The most striking innovation of the new standard was its prescribed time-temperature curve. That curve, shown in Figure 4, was first published in the 1916 description[61] of the proposed UL column tests and has not been changed since then. For years, it had been called the "Columbia Curve" in honor of Woolson.

Its origin stemmed from the realization that it is not adequate to merely specify that the temperature must, on the average, be greater than some value. A furnace does not heat up instantaneously; for reproducible results, this initial heating rate should be quantified. Figure 4 gives some results of early time-temperature curves and shows a rather gradual rising characteristic. At the conference, the members examined about a dozen such curves. The resulting standard curve was basically an idealization of these previous curves. It differed only because, at the insistence of William C. Robinson, who was in charge of fire testing at UL, the rise in the initial 10 min was made faster than in the earlier curves.[62] Robinson believed that in some occupancies a more rapid rise can be expected, and the test should reflect that fact. It is likely that this more rapid rise was made possible by the more modern gas-fired furnaces that had come into use. Earlier tests in the United States, having used manually stoked wood fuel, could not have produced a sufficiently fast rise. Of the existing curves, the one adopted was closest to those of the New York/Columbia tests after 1902, when the average temperature was dropped from 1093° C to 926° C. Thus, the designation "Columbia Curve" was appropriate. The curve was specified for a period of 8 hrs. Standard

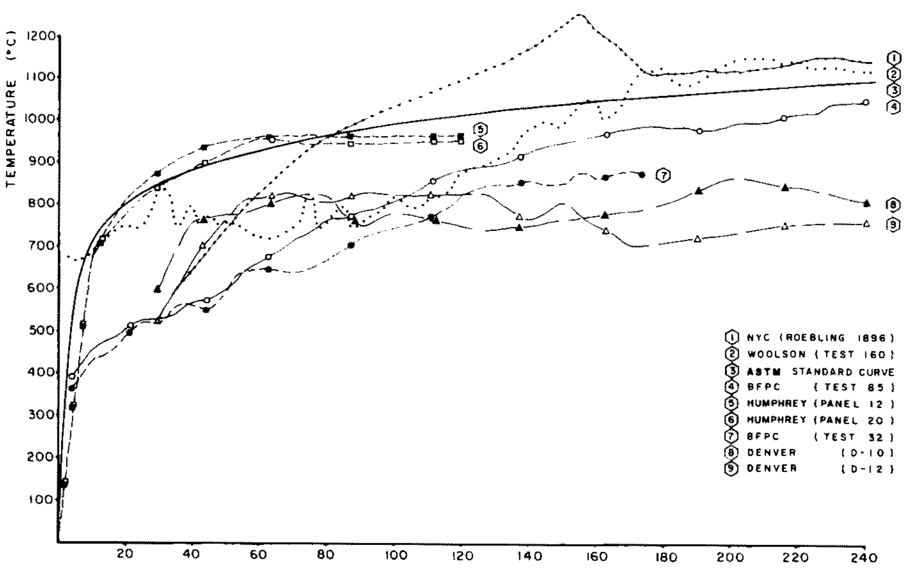

Figure 4. The standard ASTM curve compared to some earlier test curves.

tests prior to 1916 were normally not over 4 hrs. To leave an option for future testing, however, the curve was defined up to 8 hrs, with a constant rise of 41.7° C per hour prescribed after the first 2 hrs. Ingberg[63] later reported some furnace tests up to 14 hrs long.

CRITERIA

The 1918 standard provided criteria for two types of assemblies — floors and partitions. Unlike the earlier standards, no minimum floor loading was specified, only that the design load was to be applied. Besides carrying the load, a floor had to successfully pass a reloading test, pass the hose stream test, and exhibit no flame-through.

Partitions had to be successfully hose stream tested, not show flame-through, and also "not warp or bulge, or disintegrate under the action of the fire or water to such an extent as to be unsafe." The interpretation of this requirement was certainly vague, and it was dropped from later editions. The practice, however, of recording — but not limiting — deflections has continued to this day.

A completely new criterion for partitions was also incorporated in the 1918 standard. The unexposed surface of the partition could not exceed a temperature of 149° C. The criterion apparently stemmed from a study[64] of wood ignition that had been done at the Forest Products Laboratory in Madison,Wisconsin and reported to the NFPA three years earlier. In that study, piloted ignition temperatures for nine species of wood ranged from 157° C to 195° C.

Another unique feature of the 1918 standard was the inclusion of a safety factor. Both floors and partitions were to be tested for 25 percent longer than the desired rating period. The safety factor was dropped from the next edition.

A detailed history of the changes in the E119 criteria is available elsewhere.[2] It bears noting, however, that the hose stream criterion is still retained for walls, that the unexposed surface temperature criterion is present in only a slightly modified form, and that reloading is still required.

ATTEMPTS TO VALIDATE THE CURVE

It is important to realize that the standard curve was prescribed in 1917 without the knowledge of what actual temperatures in building fires might be. Although burnout experiments had already been conducted in Europe, as discussed previously, Woolson and his fellow committee members were not aware of them. None had been conducted in the United States, and the variables controlling fire temperatures were not known.

The first systematic effort at the measurement of fire temperatures was started by S. H. Ingberg at the National Bureau of Standards with the construction of their first test burnout building in 1922. Tested the next year, the building was furnished with furniture and papers resembling office occupancies. Fires were started and their development noted; temperature measurements were made with thermocouples, sometimes bare but usually sheathed in heavy iron pipe. The program continued for many years. Some of the questions investigated included the differences between the fire behavior of steel and wood furniture, the temperatures of smoldering debris piles, and the fire damage to papers in safes and metal cabinets. Ingberg was particularly interested in the latter problem and worked, under the auspices of the NFPA, towards developing standards for fire testing of safes.

Some preliminary findings from the burnouts of the simulated offices were briefly given in 1927.[65] The main results, published in 1928,[66] included the first presentation of Ingberg's equal area severity hypothesis. The actual data from the burnouts were not published; only a single illustrative curve and the overall average curve were given. Burnout work continued at NBS in the 1930s and 1940s. Fires in residential occupancies were studied in 1939[67] and into the late 1940s. These results were not published.

The early New York City philosophy of fire testing basically implied that there was no difference among fires. An assembly either withstood it or it did not. The 1903 International Standard proclaimed that it was desirable to have six different categories of protection. It was not based on six different possible expected fires. Instead, the distinction was mainly economic — how good a protection can you afford? Later such a quantized scale of protection would be incorporated into building codes. In 1903, however, Sachs's work, done in London, was not even used by the London County Council.[54]

In the same year, Woolson was using 926° C as the test fire temperature,[54] since as he stated, "This particular temperature was chosen because it is given by the New York Building Code as approximately the heat of a burning building." To complete the circle, one only needs to know that the New York Building Code used 926° C as the temperature of a burning building because Constable ran his fire tests at that temperature.

What emerges from this discussion is that fires were considered to have a single representative temperature and last for, perhaps, 4 hrs. A building assembly passing a test under these conditions could withstand a fire burnout. An assembly qualifying for some lower classification could be used if failure would not be intolerable.

Ingberg's major contribution to fire endurance theory consisted of recognizing a quantitative variable important in determining the expected fire, namely, the fuel load. His burnout results indicated that the expected fires could have temperatures quite different from the standard curve. In support of the fuel load theory, Ingberg organized fuel load surveys, the major results of which were reported in 1942 in Report BMS 92,[68] which summarized some 25 years of fire endurance studies at NBS. If different building occupancies had different fuel loads and these, in turn, determined different time-temperature curves, then the direct consequence would be a multiplicity of fire resistance tests for an assembly using different curves. Ingberg realized the impracticality of that approach. The simplest solution was to reduce the dimensionality of the problem (two — temperature and time) by one. There was no physical basis for doing that, so he provided a hypothesis: What mattered was not the entire time-temperature curve but merely the integral under it. He defined this integral as the "severity" of the fire. The problem was now reduced to a single dimension, the severity.

Some of Ingberg's findings[68] are summarized as follows: The fuel load is the sole variable governing the intensity of room fires. This intensity can be interpreted as a type of "severity." All fires of the same severity have approximately the same effect on a structure. An "a posteriori" justification for having a single time-temperature curve was thereby produced. The severity concept became the "golden rule" of fire endurance and its validity was not questioned until the 1960s.

CONCLUSION

Until the 1880s the concept of fire resistance was generally not distinguished from noncombustibility and was not measured. Testing started in the 1880s in Europe and in the 1890s in the United States. Systematic testing started in 1899. The first edition of the present governing test standard, ASTM E119, was issued in 1918. The test method was not based on a knowledge of the intensities of building fires. Ingberg's research led to an identification of one variable governing determination of the intensities. The remaining variables were not identified until some four decades later. While a realistic replacement for the "standard" fire is available in some countries (notably Sweden), the United States testing approach has not materially changed since 1918.

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