A Twenty-First Century Approach to Fire Resistance

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2.1 History of Fire Resistance Concepts

Most construction types are adversely affected by fire, if it occurs. If the construction is combustible, then the structure may burn down. But even if it is not combustible, a serious fire, especially a post-flashover fire, may result in major damage or even collapse. This is because few materials are available which can stand prolonged application of high temperatures without degradation or failure.

Up through the first half of the nineteenth century, serious fires, conflagrations, and entire towns burning down used to be considered as unavoidable disasters [1]. But in the second half of the nineteenth century, tall buildings started being built in large cities. This focused attention on the fact that major fires involving tall buildings should be considered as a solvable engineering problem. That is, techniques should be developed to limit the damage sustained from fires. Specifically, two primary social objectives became at least implicitly recognized: (1) Efforts should be taken to prevent city-wide conflagrations and (2) Fire safety measures should be adopted to reduce the likelihood of life loss during structure fires. The first objective was generally accomplished legislatively, without requiring overt engineering measures. This typically involved restriction of the use of combustible materials in construction, measures to provide streets of adequate width, and measures to restrict use of the more combustible types of roofings.

But the second objective required development of engineering solutions. Measures to reduce flame spread or to minimize ignition potential had to wait until much later in the twentieth century. What was possible in the nineteenth century was to provide what later became known as *fire resistance*. During the nineteenth century, however, this was known as designing of "fireproof" buildings [2]. The term

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"fireproof" was later deprecated, since it was clearly incorrect—no building can be practicably designed where fires can be staged with impunity and without damage to the building. Instead, the term was replaced with the term "fire resistance," which correctly implied that the building had the ability to withstand some effects of fire, for some time. It was early on understood that fire resistance had two quite different aspects associated with it: (1) When threatened by fire, the building should resist collapse for some agreed-upon length of time and (2) a fire originating in one room of the structure should not readily propagate into other rooms or other floors. The latter requirement implies that a role for walls and floors is to prevent fire from transgressing this barrier for a certain length of time. In modern usage, the first objective is termed *stability*, while the latter one is separated into *integrity* and *insulation*. Integrity indicates that holes should not open up in a barrier allowing flames to move through them, while insulation refers to the ability to prevent fire propagation by means of heat conduction. A steel plate may not collapse and may not open up holes through it, but if no insulation is used, combustible materials on the unexposed face would be likely to ignite quickly.

As we will see later, in the twentieth century it became possible to use engineering design methods to provide fire resistance. But for the first century (1860s–1870s onward), fire resistance could only be demonstrated by testing. Thus, the early history involves solely efforts to intuitively design fire resistant floors, walls, and other building elements, along with the development of testing methods to demonstrate that the expected fire resistance was indeed achieved. The detailed history of how fire resistance testing evolved has been described by Babrauskas [3], by Babrauskas and Williamson [4], and more recently by Gales et al. [5]. Here, we shall summarize just some major highlights below.

During the crucial decades of 1890 to 1910, two individuals were mostly responsible for establishing the concepts of fire resistance testing that have remained in use for over 100 years. In the US, the effort was led by Ira Woolson, who was affiliated with both the National Board of Fire Underwriters and Columbia University. The latter was the first institution in the US to establish a fire testing station. In the UK, the effort was led by Sir Edwin Sachs, who was an architect who founded the British Fire Prevention Committee, BFPC and proceeded to build a fire resistance testing station (Fig. 2.1). In 1903, Sachs proposed, in very imprecise terms, how a fire resistance testing standard might be configured [6]. Sachs and the BFPC became prolific testing engineers in London, publishing numerous fire resistance tests as a series of "Red Books." This inspired later researchers, but did not directly lead to the later—published—standards.

The work of Woolson, Rudolph Miller from the Dept. of Buildings of New York City and other researchers, mostly based in New York City, eventually did result in the first edition (1918) of a published standard, ASTM C 19 [7], later renumbered E119 [8]. The parallel UK standard, BS 476 [9], was not issued until 1932, while the international standard, ISO 834 [10] only emerged in 1975. It may be interesting to note that C 19 had a rather grandiose title of "Standard Specifications for Fire Tests of Materials and Construction," implying that this constituted the only type of fire testing that should be needed. Later tests for different fire properties, however,

Fig. 2.1 The test huts at the first UK fire testing station, built in London in 1899 by Sir Edwin Sachs

were issued as separate ASTM standards. In the UK, however, BS 476 eventually encompassed a hodge-podge of unrelated testing methods. Although even there eventually additional fire test types were issued under separate numberings. The opposite was true of ISO, where fire resistance testing concepts in later editions of ISO 834 devolved into diverse "Parts," published as separate documents.

2.2 Principles of Standardized Fire Resistance Tests

Despite differences in detail, fire resistance tests in all countries evolved in a fairly similar manner. Unlike tests of small products, it is clearly impractical to arrange for true full-scale testing of buildings, since this would involve erecting and burning down of an exemplar building. Instead, two concepts arose:

1. That buildings can be subdivided into a small number of discrete components, e.g., walls, floors, beams, columns, etc.
2. That realistic testing results can be obtained by testing components of large, but not excessive scale, generally somewhere in the range of 8 ft. (2.4 m) to 15 ft. (4.6 m).

It may be noted what this philosophy does *not* encompass:

(a) The performance of joints or connections;
(b) Frame action and load redistribution.

Real building members typically do not involve what the structural engineers refer to as “pinned” connections. In other words, the ends of the member can resist moments and not just axial loads. Much later in the development of fire resistance testing, the concept of “restrained” ratings for floors was adopted [11]. This testing strategy endeavored to simulate a certain amount of moment resistance at the ends of the test specimen. This was a half-way measure since it still does not simulate what would be happening in a real building fire. This concept was added in the 1960s, and since then, fire resistance testing has changed only in minor details.

2.3 Simulation of Fires and Control of Fire Test Furnaces

While the concept of flashover did not originate until the 1950s [12], today we understand that the fire resistance test is a test which examines the post-flashover behavior of building elements. In other words, time $t = 0$ represents flashover, or at least to the extent practicable. But how did the testing concepts originate in the 1890–1910 time period? A modern engineer might consider quantifying heat release rate, heat flux, or possibly several other variables, but, as the adage goes, “When all you have is a hammer, everything looks like a nail” [13]. The “hammer” in 1900 was a temperature-measuring device, typically a thermocouple, which was already invented in the 1820s. There was no other way of characterizing fires in 1900 except by a temperature measurement. What is interesting in hindsight, is that the early developers of fire resistance testing concepts did not go about characterizing real building fires by their temperatures. Instead, they made the tacit assumption that real fires will not be hotter than the hottest fires that they can create in the laboratory, the latter being done by either stoking the furnaces with wood or firing them with gas burners. Here, we can add that the very earliest test furnaces did not much resemble the dedicated fire testing furnaces of today. Instead, they were often ad hoc built huts, where the specimen formed the to-be-tested portion of the hut, e.g., a wall.

In a modern view, the thermal attack upon a building element would more commonly be represented by a heat flux, rather than by a temperature. Due to the importance of radiant heat transfer, the heat fluxes are scale-dependent and would be distinctly lower if the same temperature were maintained, but a burning room would be reduced to a small-scale model. However, there is very little scale effect [14] once the size exceeds 2 or 3 m, thus the instinctive understanding of the early researchers that fire resistance testing should not be done in small scale proved to be prescient.

What may be striking, however, is that a decade had to elapse after the 1918 publication of ASTM C 19 before somebody became curious enough to study the temperatures in real fires. Since the thermocouple was invented in the 1820s, this means that a century elapsed before the profession started learning what fire temperatures really are. The curious researcher was Simon Ingberg, who worked at the US Bureau of Standards, the institution which today is known as NIST, the National Institute of Standards and Technology. In 1928, Ingberg reported on an extensive series of full-scale fire experiments [15], conducted in some buildings in Washington DC. Ingberg extended this original study by additional tests conducted in 1939, but the results were not published until 1967 [16].

2.4 Modern Data on Room Fire Temperatures

These two Ingberg test series are now mainly of historical interest, but modern data on room fire temperatures were published by Fang and Breese [17], working for the same institution as did Ingberg. Figure 2.2 shows some of their results, obtained by testing modern furniture (substantive use of plastics, instead of cellulosic materials). Two important observations can be made from this figure:

1. During the early part of the test (0 – 30 min), recorded gas temperatures are substantially higher than the standard ASTM time/temperature curve.
2. But when averaged over a 60 min interval, average temperatures are similar to, or lower than the standard time-temperature curve. Fire resistance test rating periods for walls, floors, etc. in the US are not shorter than 60 min, but may be 2 h, 3 h, or 4 h. Thus, it can be concluded that, when averaged over a 1 h, or longer, time period, the ASTM E119 standard time/temperature curve is not unconservative.[1]

The comparison is not straightforward, however, due to differences in temperature measurement technology. Unlike ISO 834 or BS 476, the US standard uses very peculiar thermocouples, which are enclosed in a heavy pipe (“thermowell”) [5]. The temperatures registered in fires by thermocouples depend significantly on the physical characteristics of the thermocouples. Notably, increasing diameter leads to lower observed temperatures [18]. But the thermocouples in the ASTM standard are not only of a large size (1.02–1.63 mm wire diameter, but they are enclosed in an 21.3 mm O.D. Inconel (earlier, iron) thermowell. In the early days of the twentieth century, such a protective thermowell was seen as necessary to ensure reliability and longevity for the thermocouples. This was achieved, but at a serious cost of accuracy. Figure 2.3 shows that after about 20 min, there is little difference in temperature readings between small-diameter, bare thermocouples (such as are normally used to measure temperatures in test room fires), and the ASTM thermocouples. But early in the test, recorded temperatures from ASTM thermocouples are up to 550 °C lower than obtained from a more realistic temperature measurement technology (bare-wire thermocouples). This effect was *not* taken into account by Fang and Breese in Fig. 2.2. If this effect were properly taken into account, it would be seen that the

[1] There are other countries which use 20 or 30 min fire resistance ratings. It is understood that the purpose of such ratings is to allow for a minimum time period during which occupants can make a safe escape and fire services can complete their search. Such short ratings do not indicate that fires are expected to be only 20 or 30 min in duration.

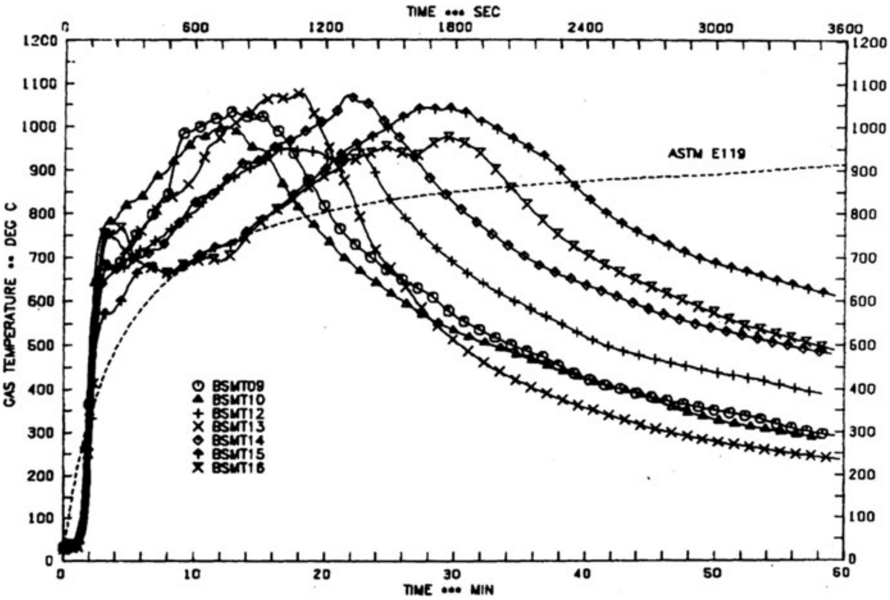

Fig. 2.2 Some example room fire temperature data reported by Fang and Breese [14]

ASTM standard time/temperature curve is notably conservative with respect to real fires in buildings.

Based on the above considerations, the data of Fang and Breese can be compared to "True ASTM" temperatures, with the latter being defined as nominal ASTM temperatures plus the error (difference between bare thermocouples and ASTM thermocouples) presented by Babrauskas (Fig. 2.3). Thus, the "True ASTM" temperatures represent values which would be measured by bare, 0.81 mm thermocouples while the ASTM thermocouples are following the standard ASTM time/temperature curve. It can be clearly seen that, for every test, there are significantly longer times for which the test temperatures fall below the "True ASTM" value, compared to intervals where they exceed this curve (Fig. 2.4).

2.5 Multiple Time/Temperature Curves?

It is very common to find suggestions that the standard time/temperature curve is not right for some purposes, and that different testing curves are needed. One of the earliest such suggestions was by Prof. Boris Bresler [19] in 1972. He observed that by 1972, plastics, and especially foam plastics, were being used in furniture, and that these products, when ignited, could spread fire rapidly and quickly show high peak rates of burning. Thus, he proposed that a Short Duration High Intensity (SDHI) curve be an alternative time/temperature curve for characterizing post-flashover

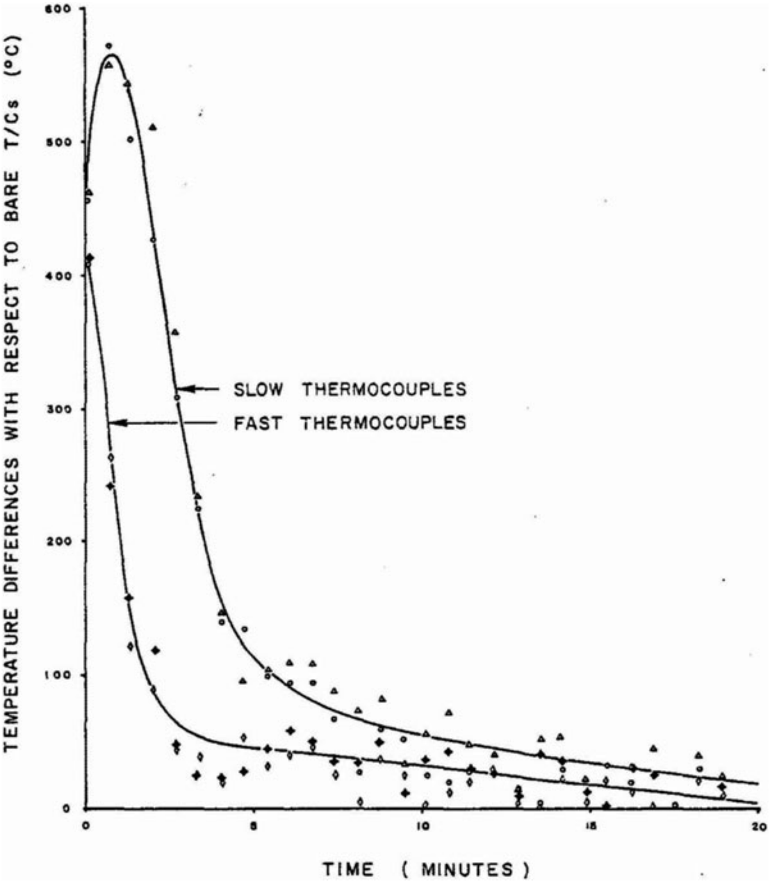

Fig. 2.3 Temperature difference in the ASTM E119 test furnace between bare-wire thermocouples (bare 0.81 mm wires), as compared to standard ASTM furnace thermocouples ("slow thermocouples"), and fast thermocouples (sheathed thermocouples with a 6.35 mm O.D. of sheath); from Babrauskas [1]

fires. Figure 2.5 shows Bresler's SDHI curve, in direct comparison to the nominal ASTM E119 curve. However, it is important to appreciate the context of Bresler's recommendation—he was interested in *modeling*, *not testing* building elements under post-flashover conditions [20]. For modeling purposes, certainly it is just as easy to use one curve, as it is to use another, or an alternative. We further discuss Bresler's work and modeling approaches below. But here, we wish to consider *testing* paradigms, especially since engineers might consider the presentation of such SDHI curves as a suggestion that the ASTM E119 test curve is inadequate, and should be either supplemented or supplanted.

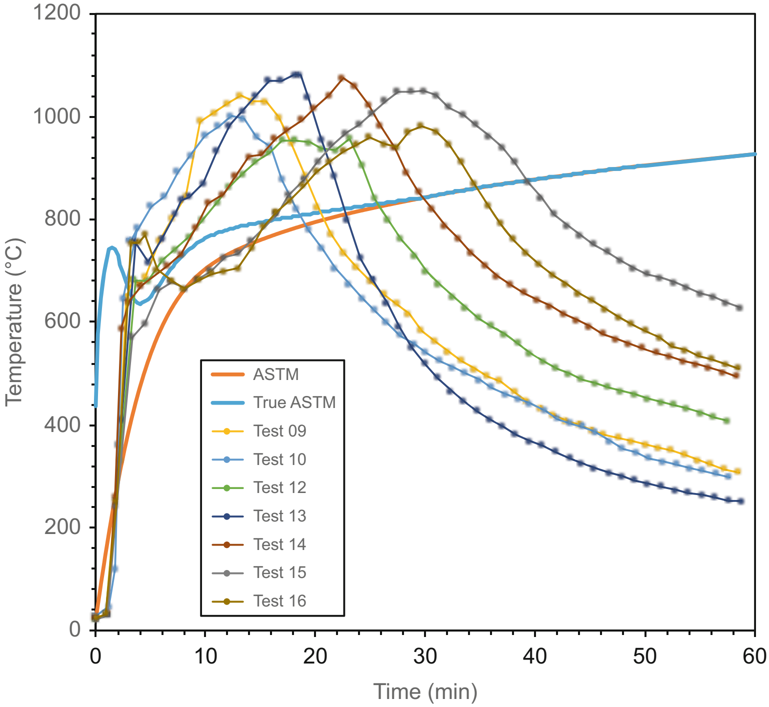

Fig. 2.4 The data of Fang and Breese along with the "True ASTM" time/temperature curve

In a narrow sense, one may consider that the standard time/temperature curve is, in fact, a family of curves, rather than a single curve. This is because the ASTM curve is defined over the interval of 0–8 h, and a product might be tested for 1, 2, 3, or 4 h.[2] Whether this is considered to be multiple curves, or not, is a matter of perspective.

What is important to appreciate in Fig. 2.4 is the area under the curve, which effectively represents the integrated value of the thermal attack from the fire upon the test specimen. It is clear that the area under the SDHI curve is much smaller than the area under the ASTM E119 curve. Thus, if the more appropriate test exposure was considered to be the SDHI curve, and the test was conducted by following the standard ASTM E119 prescription, the results would be conservative.[3]

The main reason why multiple time/temperature curves are not used is practical. Multiple tests of a product would be needed to provide results under the various

[2] No fire tests have been used or reported for durations over 4 h in the modern era, although some very long fire tests were being conducted in the 1890s and early 1900s.

[3] It might be thought that this is not necessarily true, if the response of the test specimen to fire is highly non-linear, in that destruction is disproportionately higher at temperatures which exceed the ASTM E119 curve. However, in practice, no such materials have been identified.

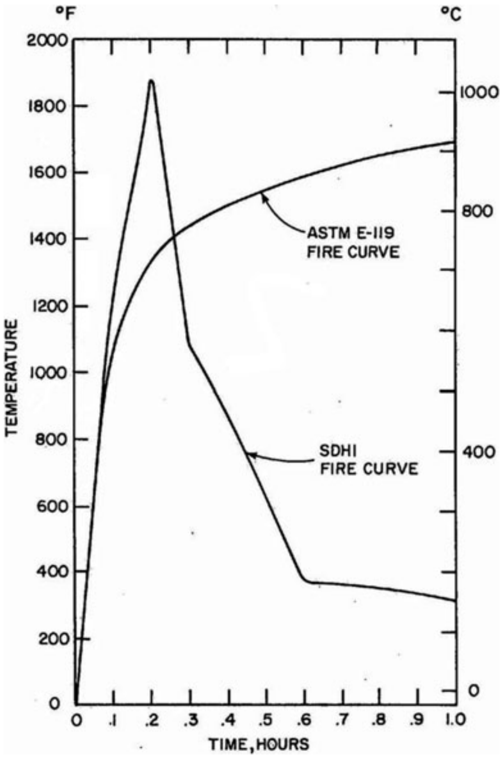

Fig. 2.5 The SDHI time/temperature curve, as envisioned by Bresler [17]

test curves. Fire resistance testing is very different from small-scale reaction-to-fire tests. It is common for the latter to be run at several test conditions, since the tests are relatively inexpensive and quick to run. But fire resistance tests are more expensive by several orders of magnitude, thus, there would have to be an enormous societal benefit for this type of testing, and such benefit has not been seen.

As shown above, for residential occupancies, the behavior of typical fuel loads is such that testing under the standard time/temperature curve is conservative and acceptable. The main exception would be libraries and storage facilities [21], where nearly-unlimited fuel loads may sometimes be encountered. In such cases, fires may indeed burn for many hours, or even days, and building codes do not consider that commensurate fire resistance should be provided. In other words, after a facility has burned for several hours, it is highly unlikely that there are still some unevacuated occupants; meanwhile, the costs of providing such long-term fire resistance would not be economical.

2.6 Petrochemical Industry Tests

2.6.1 Pool Fires

Burning hydrocarbon liquids will tend to show a much higher heat release rate (HRR) than wood materials. But this does not imply higher peak temperatures. The temperature that a flame would exhibit under conditions of no heat losses is the *adiabatic flame temperature*, T_{ad} [22]. Values of T_{ad} for wood and for hydrocarbon liquids are very similar [3]. Yet, operators of petrochemical facilities noted that high thermal assault from hydrocarbon fires can often be expected.

It has been claimed that fires from burning hydrocarbon liquids develop high heat fluxes very rapidly and that, consequently, the ASTM E119 curve, with its gradual rise does not represent the "thermal shock" from those conditions. The importance of this was never demonstrated, nonetheless, ASTM published standard E1529 [23] which is intended to simulate thermal attack from a hydrocarbon pool fire. The furnace control here is done in a peculiar manner, with the primary control being cold-wall heat flux, which, after a 5-min warm-up period, is required to be constant at 158 kW m^{-2} $\pm$ 25%. In addition, the furnace temperature is also to be controlled, being between 1010 °C and 1180 °C after the first 5 min. There has been no significant research justifying such a test method, although some of the ideas were based on an early paper by Castle [24], and unpublished testing was later done by the US Coast Guard and by Sandia National Laboratories.

UL has published a similar, but not identical test as UL 1709 [25]. This uses standard thermal instrumentation, in contrast to the ASTM test, which requires unique instrumentation, generally not used elsewhere. Consequently, this test can be considered to be preferable to the ASTM version. But again, there is no known research detailing how it was developed. Some modeling results using ASTM E119 and UL 1709 thermal exposures do not suggest major differences [26]. IEEE 1717 [27] is an offshoot of UL 1709, intended for testing cables instead of structural members. And, again, background research is nonexistent.

In the EU, a similar concept is defined in EN 1991-1-2 [28]. But here, the hydrocarbon pool fire exposure is defined as a temperature *curve* (the "hydrocarbon curve"), similar to the standard time/temperature curve, but showing more rapid rise.

The main conclusion is that there has been no credible demonstration that "thermal shock" is an important variable in establishing the fire endurance of petrochemical, nor of building, products. In the absence of such demonstration, a slightly greater thermal attack can always be presented in the context of the ASTM E119 standard furnace exposure by providing for a slightly longer required exposure. Conversely, without relevant research, the possibility cannot be precluded, but a possibility alone would not seem to be the ideal way to justify a testing paradigm. If focused research were to establish the need for "thermal shock" testing, then, to be useful, it would also need to identify the categories of materials and the types of circumstances where such extra challenging testing needs to be used.

2.6.2 Jet Fires

Operators of petrochemical facilities observed that fires due to broken piping producing jets of burning hydrocarbon liquids can show exceedingly damaging effects. This is due to the fact that the typical failure incident is likely to produce a jet flame with very high flow velocity, and this jet may impinge on structural components. The heat fluxes created due to high jet velocities and an impinging flow geometry can be very high [29]. Heat fluxes from such heating will not only be greater than what is expected in buildings of other occupancies, but also greater than the thermal attack from pool fires. Thus, industry considered that a separate, specialized test is required.

Unlike for pool fires, the research leading to a jet fire test has been documented at significant length. Parker [30], Roberts et al. [31], and Mather and Smart [32] provide some overviews of the problem and the test development. A large number of detailed research studies have also been published. The basic testing details are standardized in ISO 22899-1 [33], although industry testing in practice often involves deviations [34]. The test is generally intended for testing of fireproofing materials applied to steel piping or equipment products, rather than assemblies from buildings or building frames. Much of the development occurred at the UK Health & Safety Executive, who published the preliminary version of the testing procedures, in cooperation with Shell Research, British Gas, SINTEF NBL, and several other institutions [35]. The scale of these tests is usually 1 m, or less, in contrast to tests of building elements, which are several-fold greater in size.

2.7 What Is the Basis for the Required Fire Resistance Rating?

Some early nineteenth century thinking was based on the idea (but not clearly delineated) that the required fire resistance rating be such that the structure withstand a full burnout. Even in the twentieth century, some authors argued for this concept [15, 36]. An essentially equivalent formulation is that the required fire resistance rating increases proportionately to the fuel load present. However, this notion was never accepted by US building codes. Instead, the building codes effectively espoused a *risk* concept, although not labeling it as such. Within a risk framework, more conservative designs need to be provided, if the consequences of failure are more severe. Single-family homes have few occupants, are short in height, and normally easy to escape from. Thus, in most cases, US codes have not laid any fire resistance requirements on them. Commercial buildings may be taller, and may hold many more persons. Thus, depending on details, 1- or 2-h ratings are typically required. Structural frames and bearing walls may, in the most stringent applications be required to have 3-h ratings [37]. During much of the twentieth century, however, some situations required up to 4-h ratings. Also, within commercial buildings, more important structural components (e.g., columns) require greater ratings than less important ones (e.g., non-bearing partition walls). These are clearly risk concepts, even though the codes do not label them as such.

2.8 Design Practice

During the late 1970s, the fire safety engineering profession considered that standardized tests, of the type represented by ASTM E119, BSI 476, or ISO 834, would be shortly obsolete, due to advances in fire modeling. Babrauskas published the first computer model, COMPF, for predicting post-flashover room temperatures in 1975 [38]. Meanwhile, at the same institution, University of California Berkeley, Prof. Boris Bresler took the next step. He considered that, once the fire temperatures are known, the fire resistance design of a building can be achieved if two more models are available: [1] a model to predict the thermal response of a building's structural elements and [2] the mechanical (thermostructural) response of the structural elements to these temperatures. In short order, he and his graduate students produced two computer models, FIRES-T [39] and FIRES-RC [40], for accomplishing task #1 and task #2, respectively. These were limited to analyzing buildings with concrete frames, since he considered this to be the first priority. These were shortly (1977) followed by expanded versions, FIRES-T3 [41] and FIRES-RC II [42].

There is little evidence that any of Prof. Bresler's models received any significant use. Instead, for the next 20 years, nothing changed within the profession. Eventually, during the late 1990s, the profession rediscovered the potential applications for providing fire resistance to buildings by use of fire modeling and thermostructural modeling.

Fast-forwarding to today, a large or expensive structure is likely to have its fire resistance protection provided by modeling. Fire modeling is generally done by using the FDS [43] program of NIST. This is vastly more capable than COMPF, in that it can treat multiple rooms and encompasses both pre- and post-flashover modeling. Thus, it finds use in other applications, e.g., smoke management, not just as a tool for fire resistance design. There is no single dominant thermostructural model, but common commercial packages are typically used, especially ANSYS and ABAQUS, although there are numerous others also. Some useful references describing useful techniques for providing fire resistance by means of thermostructural modeling include those by Buchanan [44], ASCE [45], and Wang et al. [46] A brief overview of the subject has been published by the (UK) Institution of Structural Engineers [47]. However, most of the books on this topic are written from an academic point of view, rather than that of the practicing design engineer or architect. In the EU, a series of Eurocodes prescribe requirements for structural design, including thermostructural design. Franssen and Vila Real [48] and Narayanan and Beeby [49] have published designers' guides to steel and concrete structural fire design, respectively.

2.9 Hose Stream Testing

The United States and Canada are deviant with respect to the rest of the world, in that a hose stream test [50] is included as an integral part of fire resistance testing (Fig. 2.6). This means that, after the fire test is concluded, water from a hose stream is applied to the specimen according to certain specifications. The test is passed if the specimen does not collapse, and the hose stream does not penetrate the far side of the assembly. The test used to be required for all types of assemblies, but in 1955 it was removed as a requirement for floor assemblies. The reason had nothing to do with appropriateness of the test. Instead, the requirement was deleted due to excessive damage to floor furnaces. Specimens are not handled identically in floor and in wall furnaces. In a wall furnace, apart from early testing activities, the procedure has been to provide a specimen frame into which the specimen is constructed. This gets wheeled (typically by an overhead crane-type device) into the furnace at the start of the test, and wheeled out afterwards, where the hose stream test can be conducted some distance away from the furnace. Specimen frames for floor furnaces, on the other hand, are typically much more massive, and lack provisions for rapidly wheeling out from the furnace at the completion of the fire test. Thus, hose stream testing used to be conducted as shown in Fig. 2.6, leading to significant thermal shock damage to the furnace as a result.

The origin of the test was in the fact that during the 1840s through the 1880s, cast iron used to be a popular material for constructing the facades of commercial

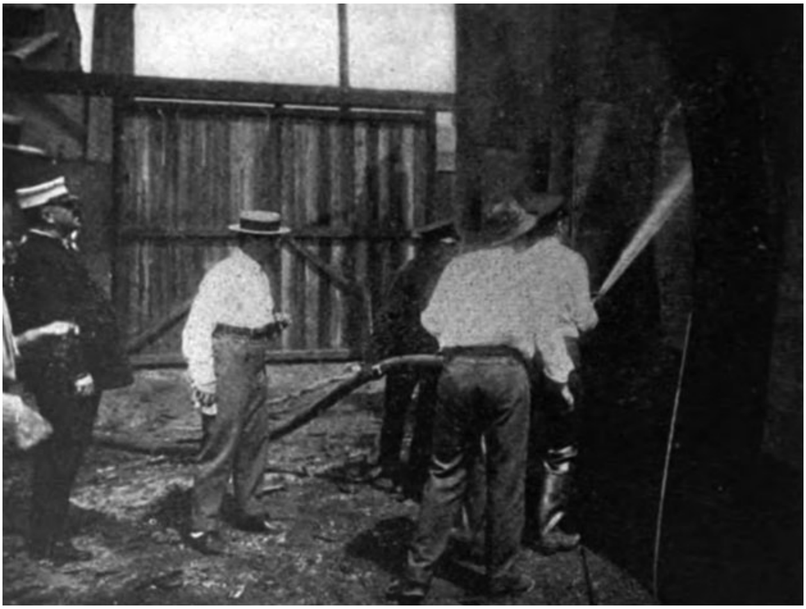

Fig. 2.6 Hose stream testing at the Columbia University Testing Station, ca. 1913

buildings in New York and some other large cities. Cast iron is a very brittle material, and if hot cast iron is hit by a stream of cold water, it is likely to shatter precipitously. Obviously, this would create an unsafe situation for firefighters, since the façade would be likely to tumble down upon them, if they are standing below in the street. Since fire resistance testing was primarily developed in the 1880s and 1890s, it made good sense to establish specific provisions that this would not happen, at least for buildings intended to be fire resistive.

What makes much less sense is that the first edition of the ASTM standard on fire resistance testing did not appear until 1918. By that time, cast iron architecture was obsolete and not used for new building constructions. Furthermore, fire resistance testing has always been seen as a test for the materials or products to be put into new buildings, not as a means of examining the performance of historical buildings. Thus, putting the hose stream provision into the standard made no sense, but put in it was. The hose stream test also appeared in the original 1932 edition of the British standard BS 476, although it was sensibly removed from the next (1953) edition.

So why does the hose stream test still exist as a requirement for wall tests in ASTM E119? The answer is, due to industry influence. The building products industry is extremely loathe to make any changes in the standard for two reasons:

(a) It might invalidate the massive data bank of past tests; and
(b) It might change the marketplace, or allow entry for new competitors.

If the hose stream test were not present, more lightweight wall assemblies could pass the test, leading to lower prices for the product category. This is not advantageous to the existing producers. Fortunately, the rest of the world is not saddled with this unsatisfactory history.

2.10 Additional Issues

The combination of E119 testing and design-by-modeling currently addresses the majority of fire resistance problems for the design profession. Yet there are certain areas that fall outside the scope of these two types compliance mechanisms.

Specialized Fire Resistance Tests ASTM E119 testing encompasses walls (partitions), floor/ceiling assemblies, beams, and columns. But in more recent years, some additional tests have been established by ASTM for certain building components which are sufficiently different from E119 so that they are described in different standards. The hydrocarbon pool-fire test has already been discussed above. The oldest of the specialized fire resistance tests is ASTM E814 [51], a test for firestopping of penetrations ("poke-through") in wall or floor assemblies, originally published in 1981. Such products are small scale, thus, they do not require a full-scale test furnace. As a result, this standard notably differs from ASTM E119 in that a small (typically, 1 m cube) furnace is used. The standard time/temperature curve is followed, using ASTM E119 thermocouples.

Another specialized fire resistance test is ASTM E1966 [52], a test method for seismic or expansion joints, established in 1998. This appears to be a solution in search of a problem. Theoretically, fire could spread in a building by burning through lightweight or flimsy joints. However, no such case incidents have been identified. It can also be noted that the standard is bereft of any references to the scientific literature.

Finally, ASTM E2307 [53] is described as a fire resistance test for perimeter fire barriers. One may begin to view this situation by noting that US building codes and US design practice is such that for most buildings, there is no fire resistance requirement of the façade walls. This can readily be verified by noting that the overwhelming majority of buildings are fitted with windows on their outside walls, and these are made of ordinary window glass, a product which has no fire resistance rating. What the test method actually tests are firestopping products which go between the end of the floor slab and the exterior wall. Now, one might ask, if the exterior wall is not required to have any fire resistance, what benefit is there of making sure that the few centimeters spanning between the end of the floor slab and the wall have a fire resistance rating? Proponents will claim that the 1970 fire in the One New York Plaza building [54] is a good example. In that event, light-gauge aluminum panels were used to span a void space between the ends of the floor slab and the curtain wall, and fire spread upwards by melting through these flimsy barriers. But is that really a robust justification? Fire spread from storey to storey via the façade is obviously a very dangerous situation. This has occurred numerous times in high-rise buildings outside of North America, typically where combustible ceilings are used (we are assuming here that the façade itself is not combustible). The simplest way to guard against this mode of fire propagation is to prohibit combustible ceilings from being used in high-rise buildings. Theoretically, progressive upward fire propagation along a non-combustible façade could also be precluded by using non-combustible spandrel panels. However, to serve this purpose, the spandrel panels would have to be unreasonably high [55], much higher than 3 ft. or 1 m. Thus, it is not at all clear that the One New York Plaza fire could have been prevented by fire resistive blocking of the end-of-floor-slab gap; fire might well have propagated upwards by going directly through the outside, via the glazing. There may indeed be a practical value from fire testing of these barriers, but the situation is unproven, based on currently available research.

Unexplored Areas It may be noted that E1966 and E2307 are the only tests where some form of joint or intersection between structural members is assessed. Both of these are intended for testing firestopping-type materials, i.e., non-structural materials used to fill in some gap and to thereby provide fire resistance. But the actual structural joints are not subjected to testing. These might be inadequately designed, so that they fail prematurely or precipitously. But tests do not exist to examine for this.

Another area of interest that has received very little attention is frame action. Significant buildings are typically designed with a plurality of load-bearing (and moment-resisting) joints. If a fire occurs in one, or a few compartments, heating of one portion of the frame will cause load redistribution around that area, and possibly throughout the whole structure. The research of Prof. Bresler in the 1970s focused on that type of behavior. But in more recent times, there has been little interest in pursuing research on this topic.

2.11 Conclusions

The provision of fire resistance to buildings, structures, or equipment can be done by testing, as has been done for over 140 years now. Conversely, it can be done by computer modeling in the modern era. The primary "driving force" in a fire resistance test or model is the fire temperature. Since this can vary over time, it is usually referred to as the time/temperature curve. In this chapter, we have undertaken to examine how the exposure temperature definition originated, and why there is only one standard time/temperature curve, instead of a family of curves.

The ASTM E119 test is now over 100 years old, yet it has changed surprisingly little over its exceedingly long history. Since the test requirements are driven by industry, this is to be expected. The main reason is that fire resistance tests are hugely expensive and industry would not consider itself to be well-served by any efforts to abrogate the validity of the exceptionally expensive investment in the database of product tests. This is the overriding reason why a family of testing curves has not been found to be practical.

Nonetheless, testing alternatives exist, and some have flourished. The petrochemical industry is substantially different from the building products industry, and they have elected to develop different tests, notably comprising pool-fire and jet-fire arrangements. The ASTM test for pool-fire exposures, ASTM E1529, requires some quixotic instrumentation whose necessity has never been justified. Consequently, the later UL 1709 test is preferred nowadays, since it utilizes standard thermal instrumentation. Jet fire testing is typically done under guidance from the ISO test, although, due to the nature of the industry, tests often require deviations.

When fire resistance is provided by means of computer modeling, there is of course no restriction as to the nature of the thermal attack to be simulated. Typically, in such cases, no standard time/temperature curve is employed. Instead, designers model fire temperatures, and then use these data to compute the thermal and mechanical performance of the building assemblies being studied. Despite great progress in both computer hardware and computer fire models, such an approach is still time-consuming and expensive. Thus, this approach has been primarily used for the design of unusual or high-value projects, such as airport terminals, sports arenas, and train stations.

It is unlikely that computer modeling approaches will start being used for low-cost, mundane projects anywhere in the near future. But what is likely to happen, is that the use of this approach will gradually spread downward into mid-cost projects.

This may well entail some automation or simplification of the computer modeling design process.

Finally, in view of the enormous costs of providing fire resistance for buildings, one might surmise that there exist good benefit/cost analyses. One would be wrong. In general, there have been no significant studies on case histories of failures of fire resistance. Without good knowledge of failures, it is impossible to rationally assess how much expenditure is economically justifiable to avert such failures. It should be self-evident that providing fire safety features should not be mandated, if they are not cost effective. Yet this topic is painfully neglected in the codes, standards, and regulations [56]. Instead, both industry and regulatory officials tend to pursue the philosophy that more safety is better, and cost is irrelevant. This is not societally responsible regulation.

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