Fire Technology 57, 529–558 (2021)

Manufactured in The United States
https://doi.org/10.1007/s10694-020-01040-7

The Historical Narrative of the Standard Temperature–Time Heating Curve for Structures

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Received: 15 July 2020/**Accepted:** 2 September 2020/**Published online:** 22 September 2020

Abstract. This review aims to provide additional context to the historical narrative of the development of the standard temperature–time heating curve used for the determination of the fire resistance of structural elements. While historical narratives of the development of the standard temperature–time heating curve exist, there are portions of the timeline with missing contributions and contributions deserving of additional examination. Herein, additional newly available contributions (owing to recent digitization efforts) from the original standard development cycle not distinctly covered by existing historical narratives are introduced and reviewed. Though some engineers have long been recognized for their contributions to the curve's development, lesser-recognized influences are re-examined. These include contributions to fire resistance testing from Sylvanus Reed, that are acknowledged for the first time in a contemporary light. Practitioners will find discussion from the temperature–time heating curve's development period that is useful for current philosophical discussions pertaining to the curve's use for combustible material testing. This study identifies that no currently available historical literature can support the definition of the temperature points which describe the standard temperature–time heating curve. This reinforces contemporary discussion that the heating curve lacks scientific basis in its representation of a real fire.

Keywords: Fire resistance, Standard fire test, Timber, Concrete

1. Introduction

The standard fire test is a common and globally applied fire resistance metric. Its advantage lies in its simplicity, convenience in repeatability, and the fact that it has been used for more than a century. It therefore has a wealth of experience for testing performance of structures and building products. This allows the construction industry to move at a fast pace based on precedent. Historically however, questions have been posed by practitioners and researchers on the applicability of the standard temperature–time heating furnace test as a single qualification metric for structural fire resistance design purposes. Questions were primarily derived from the unrealistic nature of the standard temperature–time curve as a fire and

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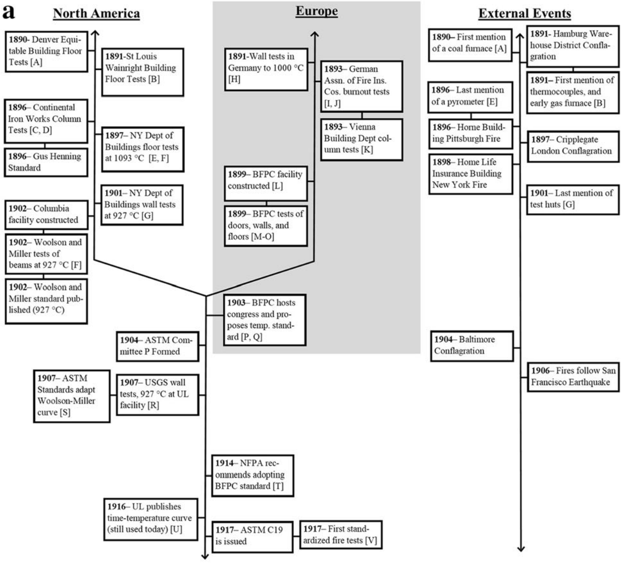
the potential limitations to this [1, 2]. For example, not considering cooling phases have been shown to be detrimental for certain structural configurations such as connections [3] or for passive fire protection products such as gypsum boards [4]. Other researchers have argued that non-uniform fires may indeed lead to a different and more onerous structural responses. In intumescent paint application to steel structures, slower heating regimes have been shown sometimes to be more detrimental as the paint may not always activate [5]. All these limitations need to be considered by standardization committees when developing guidance specific to structural design and/ or complementary testing of fire protection systems.

More recently, the questions about the use of the standard fire resistance framework has been directed towards its application to timber members [6, 7]. This is due to timber's combustible nature which provides additional heating fuel in the furnace, which consequently affects the actual applied fuel needed to control the temperature–time curve (see Fig. 1). The subsequent considerations have led to recent debates on how the fire resistance of timber and even concrete structural elements can be compared using the same standard when fundamentally, the thermal input (or boundary condition) is different between incombustible to combustible materials. Therefore, this above discussion raises a renewed interest in the historical basis of the framework of the standard temperature–time heating curve that permits its use on timber elements. Because the standard temperature–time heating curve has not been changed significantly since its conceptual definition in 1916, it is important to understand what data it was created upon, and if the founders envisioned this modern boundary condition paradigm in standardization. That knowledge can help determine the standard temperature–time heating curve's applicability to current designs and in identifying if an evolution could be necessary for standardized testing in the future.

Herein, the authors attempt to complement the historical narrative of the standard temperature–time heating curve that is used within the current fire resistance structural element test. Within the current ASTM standard [8], a brief historical narrative is provided in its commentaries and the reader is directed to an original historical review of fire resistance testing that was presented in the Fire Technology journal over forty years ago [9, 10]. That two-part paper represents a historical narrative of standard fire resistance testing by Babrauskas and Williamson, titled: *The Historical Basis of Fire Resistance Testing* [9, 10]. These papers referenced in the standard examined the multitude of tests upon which it is assumed the standard temperature–time heating curve is based upon. The Babrauskas and Williamson study reviewed tests undertaken between the 1880s and 1918 which show the development of standardized fire testing of floors, walls, columns and doors. These papers had a focus on those occurring in North America, however, some reference is made to European tests which also had an impact. That research outlined the lack of changes to the temperature–time heating curve, the basic test apparatus, and some of the testing criteria as it was created in 1916 and conferred upon for standard use in the 1917 column test program. Babrauskas and Williamson attribute the development of the standard fire curve as a consensus of stakeholders examining previous tests and developing an appropriate temperature–time envelope. They detail the history of the attempts to create universal

Figure 1. Standard fire resistance test of a wooden floor (at test conclusion—author's photos).

exposure and test standard citing the European works of Edwin Sachs and the BFPC (British Fire Prevention Committee) test criterion (discussed herein). It became apparent in NFPA and ASTM meetings that followed that North America intended to modify that test criterion for use, however, the adaptation was rejected as noted in the two-part paper. No commentary is directly given by Babrauskas and Williamson in their paper regarding the BFPC's use of multiple fire intensities to define protective classes, though such an effort is often applied in international structural fire design by considering a structure's response to a fam-



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A. *The American Architect and Building News, Vol. 31 (March 28, 1891), pp. 195-201.*
B. *Engineering Record, Vol. 23 (May 7, 1892), pp. 376-377.*
C. *Sachs, E. O, "Fire Tests with Unprotected Columns," Red Book No. 11; British Fire Prevention Committee, London, 1899.*
D. *Engineering News, Vol. 36 (August 6, 1896), pp. 92-94.*
E. *Engineering Record, Vol. 35 (January 2, 1897), pp. 93-94; (May 29, 1897), pp.558-560; also Vol. 36 (September 18, 1897) pp. 337-340; (September 25, 1897), pp. 359-363; (October 2, 1897), pp. 382-387 and pp. 402-405.*
F. *Woolson, I. H., and Miller, R. P., "Fire Tests of Floors in the United States," Proceedings, Sixth Congress; International Association for Testing Materials, New York, 1912.*
G. *Engineering News, Vol. 46 (December 26, 1901), pp. 482-486 and 489-490.*
H. *Bohme, Mittheilungen, K. Tech. Versuchsanstalt, Berlin, Vol. 9 (1891), pp. 268-270.*
I. *Deutsche Bauzeitung, Vol. 27 (May 6, 1893), pp. 224-227; (May 13, 1893), pp. 241-242; (May 20, 1893), pp. 246-248.*
J. *Engineering Record, Vol. 26 (October 7, 1893), p. 300; (October 14, 1893), pp. 317-318.*
K. *Engineering News, Vol. 32 (September 6, 1894), p. 184.*
L. *Sachs, E. O., "The V. F. P. C. Testing Station," Red Book No. 13; British Fire Prevention Committee, London, 1899.*
M. *"Fire Tests with Floors -- A Floor by the Expanded Metal Company," Red Book No. 14; British Fire Prevention Committee, London, 1899.*
N. *"Fire Tests with Partitions," Red Book, No. 22; British Fire Prevention Committee, London, 1899.*
O. *"Fire Tests with Doors," Red Book, No. 24; British Fire Prevention Committee, London, 1899.*
P. *The Official Congress Report, First International Fire Prevention Congress; British Fire Prevention Committee, London, 1903.*
Q. *Woolson, I. H., Report of Proceedings of the International Fire Prevention Congress; Martin Brown, New York, 1904.*
R. *Humphrey, R. L., "The Fire-Resistive Properties of Various Building Materials," USGS Bulletin 370; Government Printing Office, Washington, 1909.*
S. *"Standard Test for Fire-Proof Floor Construction," ASTM Proceedings, Vol. 7 (1907), pp. 179-180. 69*
T. *"Report of Committee on Fire-Resistive Construction," NFPA Proceedings, Vol. 18 (1914), pp. 216-219.*
U. *NFPA Quarterly, Vol. 9 (1916), pp. 253-260.*
V. *Underwriters Laboratories, Fire Tests of Building Columns; Chicago, 1920. Also issued as Bureau of Standards Technical Paper 184.*

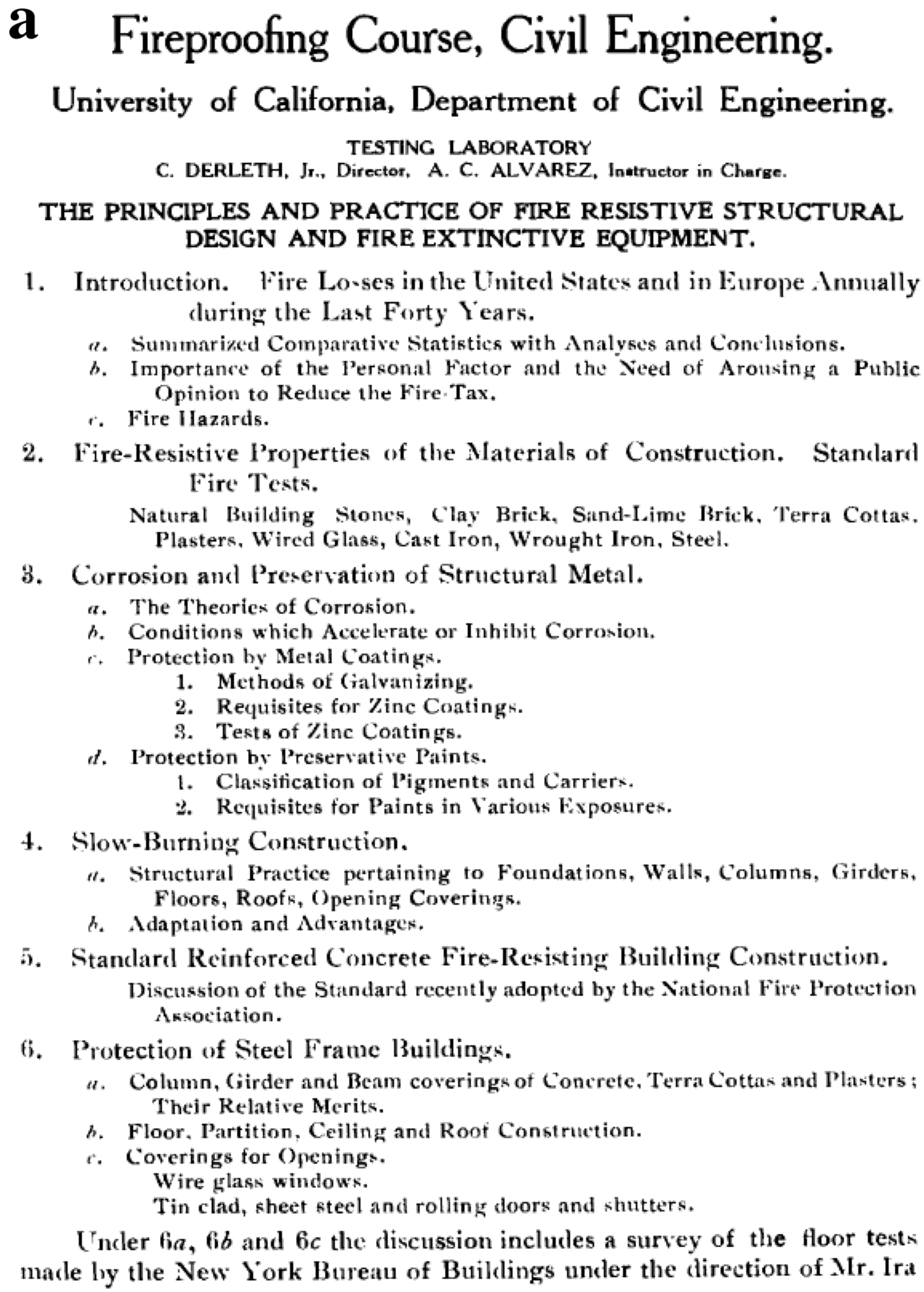
◂Figure 2. (a) 1890–1917 timeline of the development of the standard time and temperature curve (as adapted from source material presented in Babrauskas and Williamson [9, 10]). (b) 1890–1917 reference material for the development of the standard time and temperature curve (as adapted from source material presented in Babrauskas and Williamson [9, 10]).

ily of fires. Herein, we will also show Edwin Sachs' efforts were not the first attempt to consider a range of fires to assess building materials. In their papers, Babrauskas and Williamson focus on providing a historical narrative leaving interpretation largely to the reader. Figure 2 illustrates the historical narrative of key publications that were identified by Babrauskas and Williamson. The narrative is not completely exhaustive and there are portions of the timeline with missing contributions or contributions which have profound influence and are deserving of additional examination.

To place that two-part historical narrative paper [9, 10] within context, it is necessary to highlight the study's origins. This two-part paper mainly derives from Babrauskas' doctoral thesis published in 1976 [11]. Within that thesis the goals of the work are quite clear; that Prof. Brady Williamson believed "... that fire protection can and should be an engineering discipline, not just a technology guided by traditional roles and ad hoc methods" and more specifically the work was to: "... attempts to examine the major aspects of fire endurance in buildings and provide a self-consistent rationally based framework for design and analysis. Four broad areas of concern are developed. These are the physics of compartment fires, test requirements, design procedures, and history of fire endurance requirements and standards. The latter is pivotal for the understanding of the status quo, since it will be shown that the present building code provisions are founded largely on studies reported in the 1920's and earlier—their relationship to the present state of engineering and economics knowledge is not notably strong".

The goal of our paper's review is to provide further context to the standard temperature–time heating curve's origins and is within similar motivation of those that precede it in their studies over 40 years ago. This communication will examine the now available literary sources that were not necessarily available (see Sect. 2) to Babrauskas and Williamson, and the effect of combustible materials to extend the historical narrative. In addition, this paper only considers standard temperature–time heating curve, not other fire resistance test methodologies, procedures and controls reviewed elsewhere.

Herein, it is not attempted to debate merits and pitfalls, nor rationalize consistent crudeness paradigms of fire resistance testing and the introductions of contemporary resilience definitions. The authors' primary aim is to provide practitioners with additional source references that can accurately interpret how this standard temperature–time heating curve framework came to be to provide context for the origins of the curve. We specifically focus on (forgotten) literature from within the time period that the curve was developed. This paper was developed to more thoroughly complete the historical narrative and direct other researchers to where the narrative is incomplete. The authors leave others with the



Fireproofing Course, Civil Engineering.

University of California, Department of Civil Engineering.

TESTING LABORATORY
C. DERLETH, Jr., Director, A. C. ALVAREZ, Instructor in Charge.

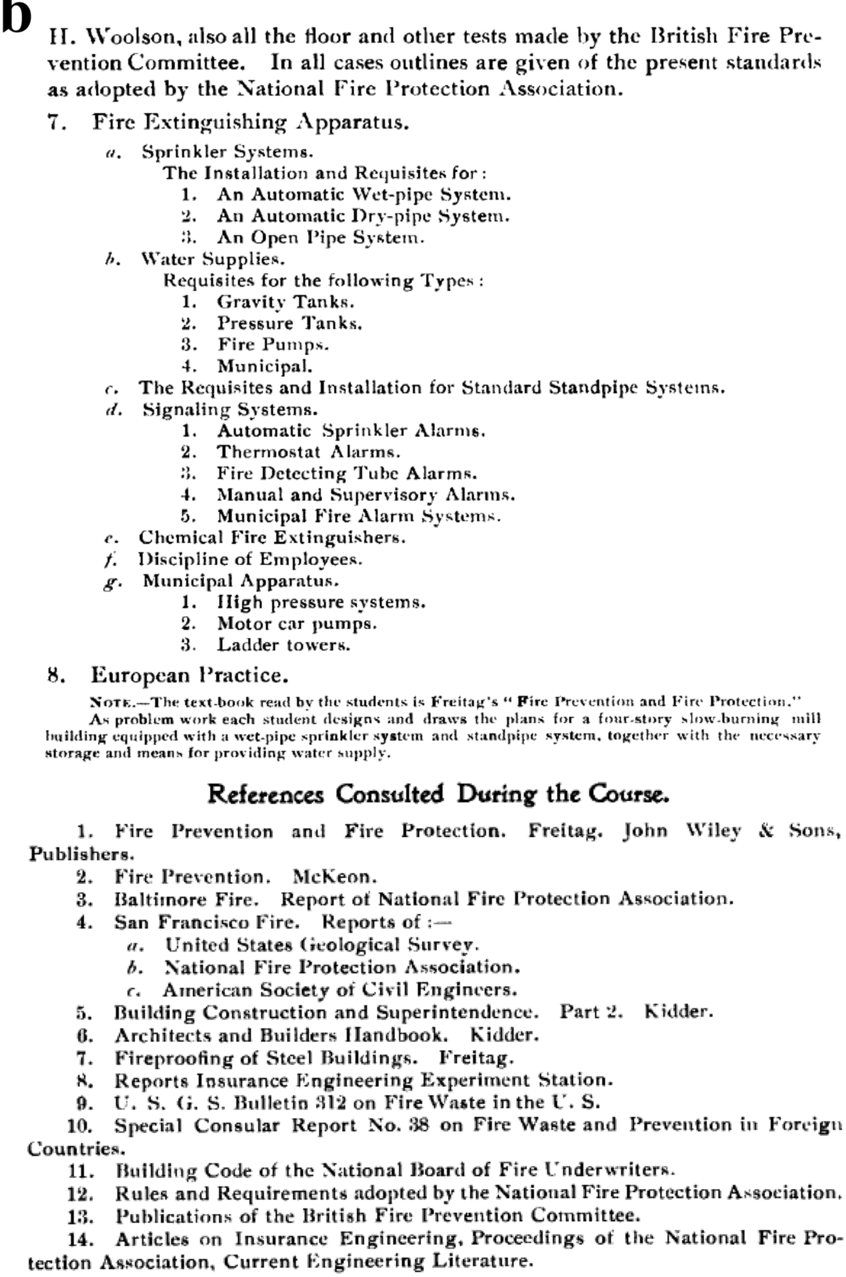
THE PRINCIPLES AND PRACTICE OF FIRE RESISTIVE STRUCTURAL DESIGN AND FIRE EXTINCTIVE EQUIPMENT.

1. Introduction. Fire Losses in the United States and in Europe Annually during the Last Forty Years.
    - *a.* Summarized Comparative Statistics with Analyses and Conclusions.
    - *b.* Importance of the Personal Factor and the Need of Arousing a Public Opinion to Reduce the Fire-Tax.
    - *c.* Fire Hazards.
2. Fire-Resistive Properties of the Materials of Construction. Standard Fire Tests.
    - Natural Building Stones, Clay Brick, Sand-Lime Brick, Terra Cottas, Plasters, Wired Glass, Cast Iron, Wrought Iron, Steel.
3. Corrosion and Preservation of Structural Metal.
    - *a.* The Theories of Corrosion.
    - *b.* Conditions which Accelerate or Inhibit Corrosion.
    - *c.* Protection by Metal Coatings.
        1. Methods of Galvanizing.
        2. Requisites for Zinc Coatings.
        3. Tests of Zinc Coatings.
    - *d.* Protection by Preservative Paints.
        1. Classification of Pigments and Carriers.
        2. Requisites for Paints in Various Exposures.
4. Slow-Burning Construction.
    - *a.* Structural Practice pertaining to Foundations, Walls, Columns, Girders, Floors, Roofs, Opening Coverings.
    - *b.* Adaptation and Advantages.
5. Standard Reinforced Concrete Fire-Resisting Building Construction.
    - Discussion of the Standard recently adopted by the National Fire Protection Association.
6. Protection of Steel Frame Buildings.
    - *a.* Column, Girder and Beam coverings of Concrete, Terra Cottas and Plasters; Their Relative Merits.
    - *b.* Floor, Partition, Ceiling and Roof Construction.
    - *c.* Coverings for Openings.
        - Wire glass windows.
        - Tin clad, sheet steel and rolling doors and shutters.

Under 6*a*, 6*b* and 6*c* the discussion includes a survey of the floor tests made by the New York Bureau of Buildings under the direction of Mr. Ira

Figure 3. (a) University of California fire course reading list part 1 (1914) (from [12]). (b) University of California fire course reading list part 2 (1914) (from [12]).

b



H. Woolson, also all the floor and other tests made by the British Fire Prevention Committee. In all cases outlines are given of the present standards as adopted by the National Fire Protection Association.

7. Fire Extinguishing Apparatus.
   - *a.* Sprinkler Systems.
     The Installation and Requisites for:
     1. An Automatic Wet-pipe System.
     2. An Automatic Dry-pipe System.
     3. An Open Pipe System.
   - *b.* Water Supplies.
     Requisites for the following Types:
     1. Gravity Tanks.
     2. Pressure Tanks.
     3. Fire Pumps.
     4. Municipal.
   - *c.* The Requisites and Installation for Standard Standpipe Systems.
   - *d.* Signaling Systems.
     1. Automatic Sprinkler Alarms.
     2. Thermostat Alarms.
     3. Fire Detecting Tube Alarms.
     4. Manual and Supervisory Alarms.
     5. Municipal Fire Alarm Systems.
   - *e.* Chemical Fire Extinguishers.
   - *f.* Discipline of Employees.
   - *g.* Municipal Apparatus.
     1. High pressure systems.
     2. Motor car pumps.
     3. Ladder towers.

8. European Practice.

NOTE.—The text-book read by the students is Freitag's "Fire Prevention and Fire Protection."

As problem work each student designs and draws the plans for a four-story slow-burning mill building equipped with a wet-pipe sprinkler system and standpipe system, together with the necessary storage and means for providing water supply.

References Consulted During the Course.

1. Fire Prevention and Fire Protection. Freitag. John Wiley & Sons, Publishers.
2. Fire Prevention. McKeon.
3. Baltimore Fire. Report of National Fire Protection Association.
4. San Francisco Fire. Reports of:—
   - *a.* United States Geological Survey.
   - *b.* National Fire Protection Association.
   - *c.* American Society of Civil Engineers.
5. Building Construction and Superintendence. Part 2. Kidder.
6. Architects and Builders Handbook. Kidder.
7. Fireproofing of Steel Buildings. Freitag.
8. Reports Insurance Engineering Experiment Station.
9. U. S. G. S. Bulletin 312 on Fire Waste in the U. S.
10. Special Consular Report No. 38 on Fire Waste and Prevention in Foreign Countries.
11. Building Code of the National Board of Fire Underwriters.
12. Rules and Requirements adopted by the National Fire Protection Association.
13. Publications of the British Fire Prevention Committee.
14. Articles on Insurance Engineering, Proceedings of the National Fire Protection Association, Current Engineering Literature.

Figure 3. continued.

task of rationally evolving fire tests that fulfill the safety and property protection of various international building and construction codes though this paper may provide useful context to those discussions. Therefore, this study's primary use is to be built upon by others. While it is acknowledged that in some cases subjectivity is required for interpretation of events, the authors have made effort to minimize this where possible and present only factual discussions that have been found to be recorded in literature. The authors therefore encourage the reader to examine the sourced and referenced articles where possible. To the authors' awareness no formal framework defining intent was developed throughout the evolution of the temperature–time heating curve.

Additional contributions from the original development cycle not distinctly covered by existing historical narratives are explored for the first time herein. While in the past some have believed to have found the foundations of the temperature–time heating curve (including that it corresponds to the rate at which wood could be stocked in a fire; and to the melting points of metals) the authors have found no evidence to support these claims. The authors will identify that no literature is (currently) available that supports a basis for the points which describe the standard temperature–time heating curve. The contributions to fire resistance testing from Sylvanus Reed will be acknowledged herein in a contemporary light, particularly his contribution towards integrating real fire dynamics for different building types. Practitioners will find, presented herein, discussion from the temperature–time curve's development period that is useful for current philosophical discussions pertaining to the curve's use for combustible and incombustible structural elements.

2. Literary Search Methodology

There is a significant resource (the previously mentioned two-part study led by Babrauskas and Williamson, then of the University of California) that practitioners utilize when discussing the origins of the standard temperature–time heating curve and likewise the concept of the historical basis of fire resistance testing [9, 10]. By far, those papers are thorough investigations into the subject. Since their publication, however, questions have emerged regarding missing detailing (for instance, in regards to what the temperatures within the curve represent leading some to believe unverified claims). The complete narrative of the curve's evolution is missing. The authors believe that due to the lack of resources available to Babrauskas and Williamson at the time of writing their manuscripts, their narrative could be further expanded. Digitization (as we know today where articles are freely accessible online) did not exist in the 1970s and this can have restricted those authors [9, 10] to provide a complete narrative. Today, a large portion of the source literature cited in [9, 10] are available online and digitized by the University of California for public access. Furthermore, it can be examined that these sources digitized reflect the curriculum of the first fire course that was offered at the University of California (to the authors' knowledge).[1] It reflects very accurately the time period during which the standard temperature–time heating curve was being developed (1890–1916). The course calendar of that fire course taught at University of California (1914) is provided herein as adapted from the NFPA Quarterly series [12] (see Fig. 3).

Today, with the novel efforts to improve digitization technology, it is possible to expand upon the above literary search performed previously by Babrauskas and Williamson [9, 10] by looking at articles beyond the California library collection. With every year, new documents related to the fire engineering research field are digitized by various university and industrial catalogues. These new documents provide a clearer picture on the origin of the standard temperature–time heating curve, the standardization test motivation and the philosophy behind its development. Herein, the authors aim to discuss additional period sources that complement previous historical paper compilations on this subject. The authors will restrict the literary search to post-1870 aligning with the various city conflagrations in North America, which are generally accepted as the prompt for the creation of fire resistance philosophies as opposed to fire proofing design. The interested reader is directed elsewhere for structural fire testing historical information for the period of 1770–1870 when the first documented tests are recorded (see [14–17]), or where relevant within the footnotes of this manuscript are provided.

While parallel efforts to developing standardized fire resistance test procedures for construction elements were mirrored in Europe largely led by the architect Edwin Sachs, the authors will restrict most discussion to North America, and will only discuss the European influences that affected the evolution of the original 1918 ASTM temperature–time heating curve for fire resistance testing.

For this study, an examination of the papers utilized for the Babrauskas and Williamson literature review [9, 10] was first conducted. Most of these articles were readily available online and, as aforementioned, they were digitized by the University of California for the *Google Books* and *Hathi Trust* projects. It is of note that these archives also include resources from other university libraries thereby expanding the capabilities of a modern literature search on the subject. The combined institutional search of these libraries (online) conducted were provided for examination: the complete works of *NFPA Quarterly*, partial collections of *Engineering News and Record*, *ASTM committee notes*, American Society of Civil Engineers article database, American Society of Mechanical Engineers article database, American Concrete Institutes database, Canadian Society of Civil Engineers article database, various newspaper archives (*New York Times, New York*

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[1] The Armour Institute of Technology in Chicago, Illinois was the first post-secondary institution in North America to offer courses in fire protection engineering. First offered in 1903, the fire engineering program ran until the 1980s, surviving the merging of the school with the Lewis Institute to form the Illinois Institute of Technology. The program was promoted by insurance companies who were seeking specialists in the new methods for fire prevention [13].

Tribune, Chicago Tribune etc.), various pamphlets pertaining to fire proof construction, as well as numerous textbooks on fire protection, and building standards and codes. It should be extended that most professional societies in this time period produced meeting minutes in annual transactions. These were reviewed where available (NFPA, ASCE, ASME, ACI etc.).[2] The resulting literature search considered mainly materials between 1870 and 1927 (1927 as an end date for current copyrights for public posting of digital material at the time this manuscript was prepared but also correlates to the death of Ira Woolson who instigated the first ASTM fire resistance standard).[3] While the literature search herein generally considered materials between 1890 and 1927, with supporting materials from post 1980 that elaborate contemporary structural fire design practice, the following decades (1930s to the 1980s) garnered significant research interest and developments into fire dynamics, and eventually in fire modelling [21]. Developments of structural fire design practice and associated fire dynamics beyond the late 1920s should be considered by future work, where existing publications (such as [21, 22], and [23]) may provide a starting point for that research endeavor.

3. The Origins of Contemporary Fire Resistance

The contemporary definition of “fire resistance” was termed in the late nineteenth century. This came from an evolution of moving from defining building materials as fire-proof (restriction of combustible materials exposed to high temperature) to fire resistant (how any material performs in a fire—i.e. materials, even incombustible ones, will eventually fail and other metrics of analysis are needed beyond just stability—integrity and insulation for example). The terminology evolved from the aftermath of various city conflagrations. Examination of any major city illustrates these conflagrations, particularly those seen in Chicago in 1872, and

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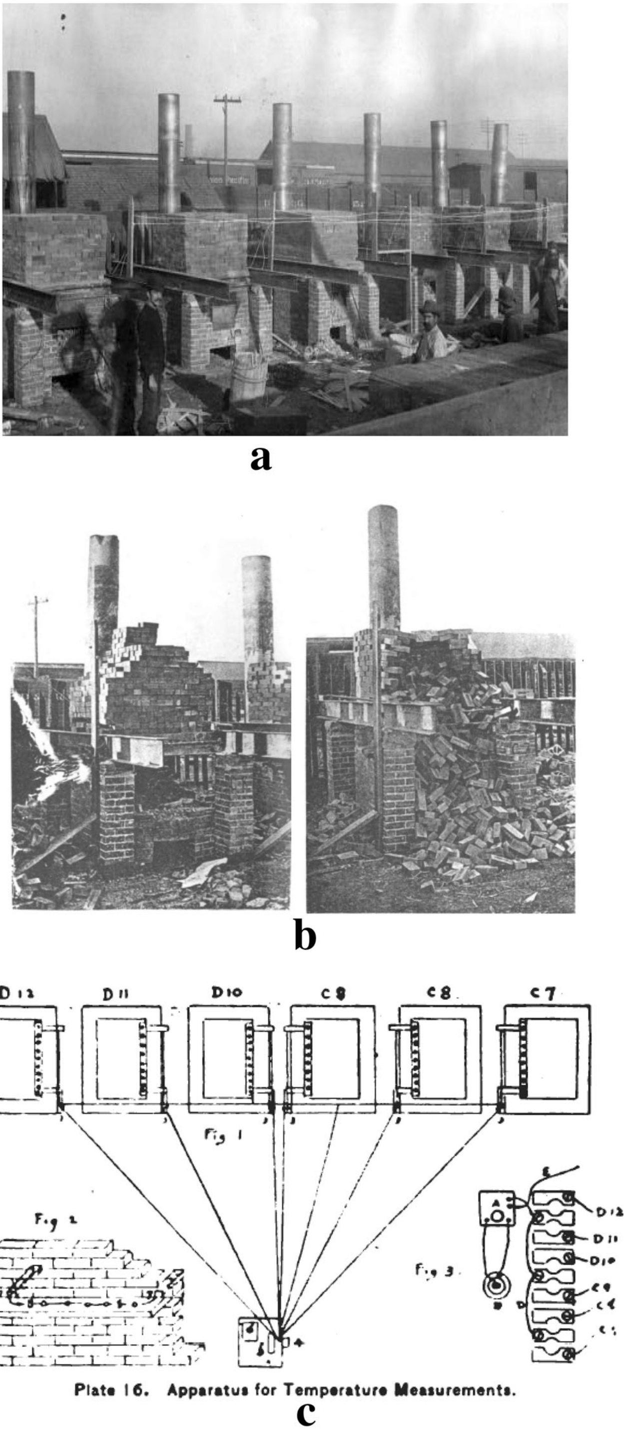
[2] Several of the figures herein stem from publicly available digitization’s from the sources discussed. As such, the quality and resolution of the figures is limited to that of the existing digitization. Many of these documents were digitized as a part of a mass digitization process, for instance through HathiTrust or Google Books. In this process, the document owner will scan the document and send to the organization or loan the document to the organization for them to scan. The documents may be scanned using book scanners that feature high quality cameras, with recommendations in place with regards to image quality (though not always strict requirements). Scans may be processed to eliminate noise on the image, and for optical character recognition.

[3] Babrauskas and Williamson note historical papers relating to building materials and fire dating back to the 1700s. Contemporary searches can also show literature dating into the 1600s speaking to building material behavior in fire and fire-fighting technologies. These sources however seem not to speak to standardized fire testing of building materials. Some of the earliest calls for fire testing involve the Barrett–Fox composite floor system in in 1854 in RIBA proceedings [18], which resembles a reinforced composite concrete flooring system. The floor was advertised as being fire-proof, however when presented publicly, criticism highlighted that the new material concrete had questionable performance. In the author’s professional experience, when these floors are found in heritage structures, they are found to be unreliable due to the poor quality of the concrete used and often need to be removed. Those in attendance at these historical meetings stated that the debate could only be resolved with testing of these flooring systems. Thomas Thyatt Lewis (1865) presents a comprehensive overview of Victorian era papers on building materials in fire. In his review, he notes the contributions of James Braidwood to the aspect of materials losing strength in fire though little experimental evidence was available to quantify the effects [19, 20].

Boston in 1874. The outcome of these city fires led to a surge in ad-hoc (ad-hoc meaning that they were demonstration in test design not necessarily following an established test methodology) fire tests of building elements that were often not trusted by the scientific and greater community.

These ad-hoc tests primarily considered new reinforced concrete elements (beams and slabs) which had emerged in the building market in the North East (mostly after the Chicago fire). Between 1870 and 1890, the terminology called ‘‘fire-proof’’ was adopted in practice, where fire-proofing was strictly being defined as incombustible construction [24]. These fire-proof tests were not qualitative in nature and were often performed as a public spectacle. They consisted of a building element by a material manufacturer (constructed in-situ), supported on stilts. The material would then be ‘‘burned’’ using timber logs in random placement and number. Often, they were unloaded, and measurements (temperature and deflection) during these tests were not recorded. Confidence in the building element was achieved by the non-appearance of a ‘‘failure-collapse’’. These tests had little science to validate the manufacturer’s claims, and there exist little scientific articling or reports that survive today on these tests.

By the 1890s, ad-hoc testing was decreasing. This appears initiated by architects when assigning competing assemblies for design that were being claimed to be fireproof [25]. This led to the emergence of the concept of fire resistance. Testing began that now considered quantitative performance and attempted to rank competing materials on the basis of a test standard of equivalent thermal assault. Researchers measured temperature (and deflection) in these tests, and the tests of building elements were then compared on these bases. Measurement of deflection of a building element was used to define failure criterion, while collapse after a measurable exposure time was deemed defining failure. One of the first ‘‘fire-designed’’ buildings using early principles of fire resistance, the Denver Equitable Building, was constructed in the 1890s. Prior to its construction, the responsible architects were faced with choosing three competing flooring (arch) systems made of terra-cotta, which were said to be fire-proof by their manufacturers [25]. The manufacturers of these competing flooring systems each debated that their products were superior to the other—leaving the architects to resolve this. The architectural firm Andrews, Jaques and Rantoul organized a test program to settle the debate where they would rank each flooring system in a comparative coal-stocked fire test. The test utilized the same target temperature of assault for each specimen tested. They specified and recorded gas temperatures. These were measured with platinum wire where temperature was calibrated to electrical resistance. Each platinum wire has its own circuit of copper wire which was connected to a Wheatstone bridge and galvanometer. The temperatures measured were approximately peaking at 815 °C (1500F) with variability (note experimental accuracy of this time period cannot be relied upon in assessing thermal performance of the materials) and the flooring systems were ranked accordingly to time of collapse. Note that these tests were extensively documented in a test report [25]. They were highlighted briefly in [9, 10], though they were not placed in the context of their significance in attempting to create comparative and standardization principles. Even today, a 17-photo set of loading and failure conditions survives in the


a
b
D12
D11
D10
C9
C8
C7
Fig 1
Fig 2
Fig 3
D12
D11
D10
C9
C8
C7
Plate 16. Apparatus for Temperature Measurements.
c

◀**Figure 4. (a) Denver equitable building fire tests pre-test (as adapted from [25]). (b) Denver equitable building fire tests post-test (as adapted from [25]). (c) Denver equitable building fire tests instrumentations (as adapted from [25]).**

Denver Public Library, see Fig. 4 for a few sample images illustrating the repeated test procedure with instrumentation.

4. A Simplified Narrative for the Standard Temperature–Time Heating Curve Definition

In 1896, two very different test series were organized and reported by the New York Department of Buildings, which involved researchers from the Mechanical and Mining Engineering Department at Columbia University. It is well known that Ira Woolson is credited with the test series that eventually led to the standard temperature–time heating curve, or rather the Columbia curve as it is sometimes referred to [9, 10], but what isn't well known is the parallel research which was being done at Columbia in gas-furnace development at this time. The missing information in the existing narrative of the development of the standard temperature–time heating curve is the test series that was developed to utilize a controlled gas-furnace for various building elements. This was reported by mechanical engineer Sylvanus Reed in 1896 [24], predating Edwin Sachs' efforts in gas controlled element tests that used a range of fires for material assessment. The more well-known test series utilized a testing procedure similar to the aforementioned Denver tests, though now wood-stocked for specific floors [26].

Today, Sylvanus Reed's historical contributions largely mention his role in the creation of the modern metal aircraft propeller and note a relatively large absence in his career, with an apparent inactivity in the early twentieth century prior to his aircraft propeller research. There is a lack of information recorded showing his contributions to define fire resistance testing and very little information about his contributions provided in existing references [9, 10]. It is important to consider Reed's contribution (correctly or wrongly) in his efforts to develop material element testing. Reed established principles were very similar to the ASTM standard temperature exposure that would be proposed by Sachs in 1914 and followed in 1918 led by Ira Woolson—as well as some contemporary themes of fire severity argued today in element testing. Reed's fire resistance tests relied on using a gas fueled furnace to take advantage of the control of temperature. Reed documented various limitations for establishing test simplicity despite the broad objective of his test: "steel or iron columns, girders, and beams, must be made on a full working scale and under the actual conditions, as far as possible, which would be obtained in a fire" [24]. Reed went so far as to establish three different fire severities based on occupancy type (the fuel which would be expected in each that would control the severity of the fire), which were established as the metric for this series. Reed argued that the tests' objective should be: "To be a standard it must contemplate all fire possibilities, even the most remote, pertaining to those conditions….to establish a datum level from which allowable variations may be determined" [24]. This may be considered alike to the modern-day viewpoint of creating acceptable solutions. The fire defined on the material would be controlled in a furnace as one of three cases: (1) 1371 °C for six hours—warehouses; (2) 648 °C for 1 h—commercial store; or (3) 371 °C for thirty minutes—office building or house. He does not detail how he arrives at these temperatures and his text is filled with instances that demonstrate a provisional understanding of fire dynamics presenting a correct qualitative view of radiative heat, but a flawed quantified account of its calculation. These tests were performed under an applied service load, using a pyrometer to measure temperature, and his predominate concern was the testing of columns. Reed justified that all buildings should be expected to resist a conflagration, as to quantify what expected damage state would occur. This was to inform the insurance industry which is more interested in recent discussions pertaining to fire resiliency. Reed's test program can be found documented in the *Journal of the Franklin Institute* and is readily available to the interested reader today [24].

At this time, practitioners attempted to influence and debate the creation of these early tests and their merit when applied to real construction. Abraham Himmelwright (a practitioner who dealt primarily in developing concrete material systems during this time period) publicly advocated that "The object of all tests of building materials should be to determine facts and develop results that may be of practical value in future designing. In order that such facts and results may have real value, three conditions are necessary: first, that the materials tested shall be identical with what is commercially available in the open market; second, that the conditions, methods, and details of constructions conform exactly to those obtainable in practice; third, that the tests be conducted in a scientific manner." [27]. Himmelwright also stated that the design of structures had to resist thermal loading caused by fire: "The actual and relative expansion of the materials due to heat and deflections caused by unequal heating must receive careful consideration… The limit of safety is in some cases dependent upon temperature and in other cases upon expansion." [27].

Of note, both Reed and Woolson studied under Frederick Hutton of Columbia University in their young adulthood. Hutton was an expert in gas-furnace design [28] and it is natural to see that these researchers (Reed and Woolson) would eventually follow Hutton's combustion background influence in the development of their own test procedures.[4] While Woolson would start using wood stocked furnaces (it is documented he resisted gas furnaces due to their control difficulty and that they could not mimic the radiative heat seen in real fires), he would eventually advocate the use of a gas furnace by the inception of the standard fire resistance test (see below). The tests performed by Reed were largely intended to be for informing the insurance industry and public interest. They were not meant for proprietary testing or material development, which is the clear distinction

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[4] The authors were unable to find any evidence that Hutton contributed directly or that his work was referred to in the defining of the standard temperature–time heating curve.

between how his tests evolved and how the tests of Woolson would later evolve to meet material competition. This, however, is not explicitly stated as the reason Reed's tests ceased (Reed's departure in developing fire resistance test philosophy correlates to the passing of his partner). The authors hypothesize that the lack of funding may have also contributed as a result of omitting the proprietary aspect of testing. It is interesting that Woolson's tests were more aligned to ranking proprietary systems where the material manufacturer often paid to test their systems—Reed's materials were not financed, to the authors' knowledge, by the material manufacturers. Ira Woolson's tests would eventually form the basis of contemporary fire resistance test as defined by qualification (standardized) testing as per below. Ira Woolson oversaw the parallel test series [29]. Those tests considered primarily flooring systems at first, with the original test criterion calling for a steady state temperature of 1093 °C (the precision owing to conversions of Fahrenheit).

Although we credit Woolson in most historical papers (the 'Columbia' curve for example), careful examination will show that the test temperatures that Woolson originally defined were proposed in 1896 by the engineer Gus Henning, the chief engineer of the New York Department of Buildings [26]. Temperatures of over 1090 °C, were reached by feeding a wood fire furnace which was beneath the loaded flooring assembly and the duration of heating was meant to be held for over 5 h (Fig. 5 illustrates schematics of the test hut used). Feeding rates were not specified but viewed as the speed necessary to reach the peak temperature as fast as possible. Post-test confirmation of peak temperatures would be performed that considered the presence of various metals that were confirmed melted.

In 1902, after the New York fire tests (1896–1897), it was decided to specify a less severe fire exposure in terms of temperature. This new test standard [29] (a collaboration between Ira Woolson with Rudolph Miller) called for a sustained 'average' gas phase temperature equivalent to 927 °C (1700°F) for 4 h (with peaks still allowed to 1093 °C (2000°F)), hose stream cooling, and residual testing to higher loads (4 times the sustained fire service load) for a further 24 h. If after this test, the floor's deflection (measured via surveying) did not exceed 1.4% of its span, the element was assumed to have 'passed'. The test still used a wood-stoked furnace since the thermal scenario was intended to be more severe than a real fire. In 1902, Woolson and Miller advocated in the New York Tribune, that "no ordinary room would have enough inflammable material in it to maintain a 1700°F fire". and that the basis for this heating regime was firefighters' qualitative experience in New York. In 1912, a complete catalogue of nearly 80 flooring systems tested (between 1896 and 1912) with this and previous test controls was published by Woolson in the proceedings of the International Association for Testing Materials conference in 1912 [29] (a precursor organization somewhat absorbed to the modern-day ASTM).

These standard fire tests by Woolson were often criticized during this period [30–33] because, at this time, the floor tests were not nationally standardized and were not widely adopted outside of New York. They were also a subject of the Mazet Inquiry of 1899 which alleged corruption in the fire tests. Aspects of the alleged corruption and Mazet hearings are detailed by Wermiel (2007), where she

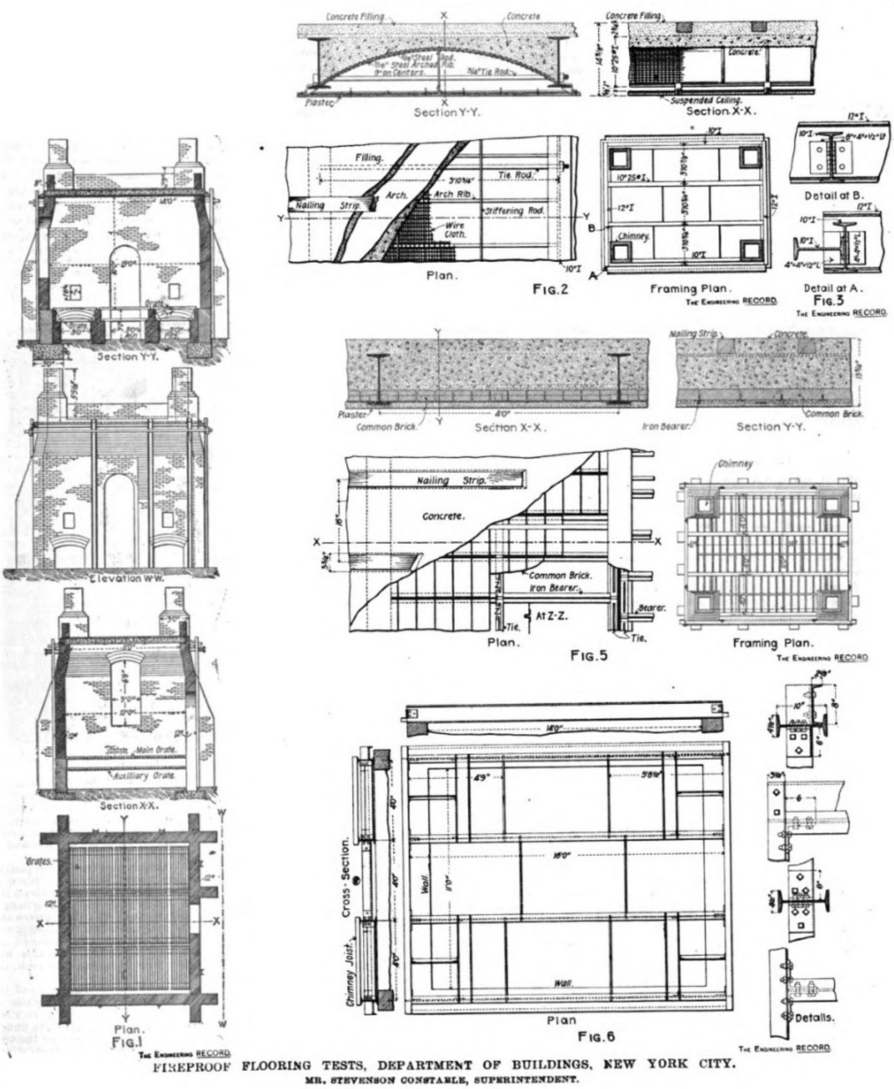

Figure 5. 1896–1897 New York fire tests by the department of buildings [26].

notes that the Mazet hearings led the chief counsel and interrogator "to conclude that all concrete floors were dangerous", with the committee ultimately recommending "a new Building Code Commission be appointed to revise the city's code" [34]. For a small example of what was viewed as corruption, each test had to employ a night watch to prevent tampering of specimens for each test. These tests were followed by decreased influence of the city in the tests, and more control by research bodies to ensure their test integrity. In what appears timed to the response to the change in leadership in the momentum of the test series evolution, Gus Henning (see above) penned an open editorial in the New York Times where he publicly criticized the current test procedure being used by Woolson [31]: "Other fakes I desire to call attention to are the fire tests now being made in New York City at temperatures of only 1700°F. I herewith wish to declare fire tests of materials made at average temperature of 1700°F as shams and frauds. They do in no sense of the word determine the fire proof qualities of materials". Henning's reference to 1700°F (927 °C—the 1-h mark used in the standard fire today), in the authors' subjective opinion appears in relation that real fires have more severity and that materials would behave differently under this severe heating though the exact reasons for the public statement are not well documented in available literature.

Following criticism towards the New York building structure fire test series, various construction material agencies lobbied for change. This change was mobilized by Ira Woolson at the American Society of Testing of Materials (ASTM) as a new fire test standard evolved and was proposed in 1916 [32] (Fig. 6). The test philosophy then had the intention to shift away from floors and to consider columns (concrete, steel and timber). There exists no publicly available nor digitized documentation that explicitly defines the origins of the standard temperature–time heating curve that was created in 1916 and still used today to assess fire resistance. Some have claimed (see [33, 35–37]) that in 1963, Bieberdorf et al. defined the curve's origins on the basis of metal melting points of metals,[5] a theory that is common to hear in our practice, but has no evidence to the authors' awareness. The authors' personal examination of the Bieberdorf paper shows that it does not state this directly. Woolson himself does provide some commentary to the curve's origin being recorded as stating the curves intention as follows [38]: "When you say it is a partition which will give two-hours' protection, it means it will resist a fire two hours according to the standard control curve given. That curve, which was presented last year (1917) purely as an arbitrary curve, has had a year's service by the Underwriters' Laboratories and by the Bureau of Standards at its laboratories in Pittsburgh".

The authors have prepared a subjective simplified interpretation of the temperature–time heating curve's origin (in the absence of other data available). The examination is of the test curve itself, previous linear set point standards, and the raw temperature data collected at the New York fire tests in 1896–1897 (extrapolated from reference [26]). The temperatures recorded from these tests utilized a

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[5] Past historical papers on fire science have experienced these pitfalls. The historical review by Cooper and Steckler provides a factual critique of the standard fire tests origins [36]. They attempt to find the primary source document which rationally explains where the curve comes from. They trace the origins from a secondary reference by a paper by Ryan which claims the fire's origins are in a paper written by Bieberdorf [33]. Cooper and Steckler were unable to locate the Bieberdorf's paper to continue the search. That paper was found by the authors in the University of Edinburgh's BRE fire science library. The paper does not point to the origins of the temperature–time curve—it does not even reference an origin, it does confer upon the statement given by Shoub [37]. The study by Shoub indicates that it "… apparently was based on temperatures found in the various stages of growth of actual fires in buildings using references such as the observed time of fusion of materials of known melting points." [37]. Both references do not provide a reference for melting points.

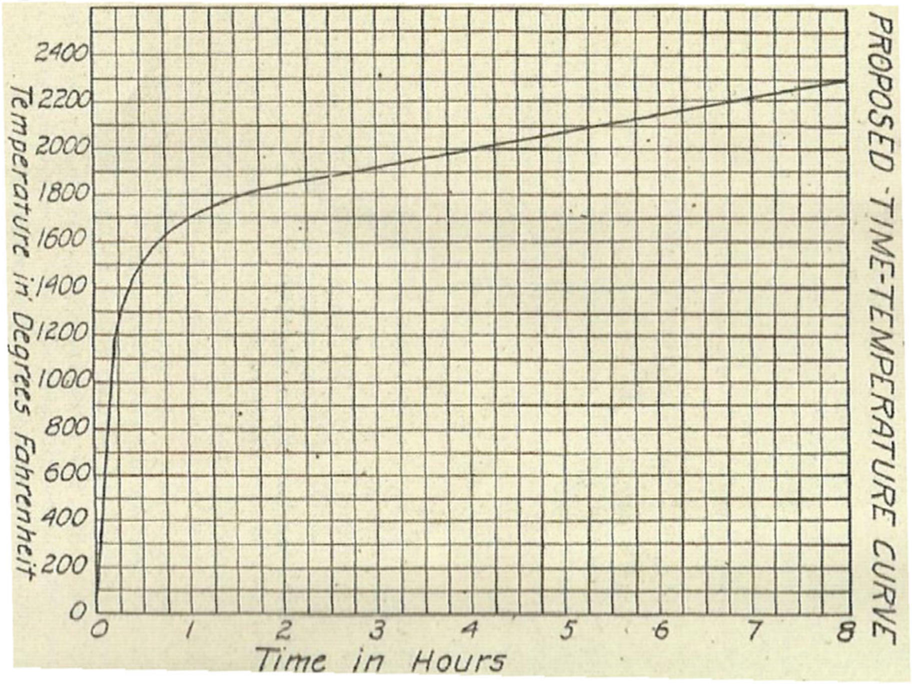

Figure 6. Temperature–time curve proposed in 1916 [32].

pyrometer which have experimental inaccuracies of ± 300 °C (even acknowledged at that time). This is a subjective error as attributed to temperatures being recorded via human interpretation, as shown in Fig. 7 as taken from reference [27]. The resulting comparison in Fig. 8, illustrates what appears to be a linear linkage of the Henning 1896 and Woolson-Miller 1902 proposed temperature–time heating curve standards (a linear line between them at two set points up to 4 h). Careful plotting of test data from the 1896–97 tests (see reference [26]) illustrates that the contemporary standard fire curve intercepts these points well, and achieves a linear fit between 1 and 4 h of the Woolson-Miller curve adopted in 1902 and the Henning Standard from 1897. This information is plotted in Fig. 8 and requires continued research to definitively answer whether it is a best fit curve to test data and not real building fire data. Values are reported in Fahrenheit because they were measured in this unit at that time. Barbrauskas and Williamson do a similar comparison, only showing all test curves used prior to the 1916 standard proposal. They also indicate that the heating curve had seen no change in its defining plots since inception which carries true to today. The authors hypothesize herein that the standard temperature–time heating curve was developed along a more subjective rationale to link previously accepted time and temperature heating curves (specifically the Henning Standard and the Woolson-Miller Standard) and to ensure previous tests performed could still see acceptance under the new pro-

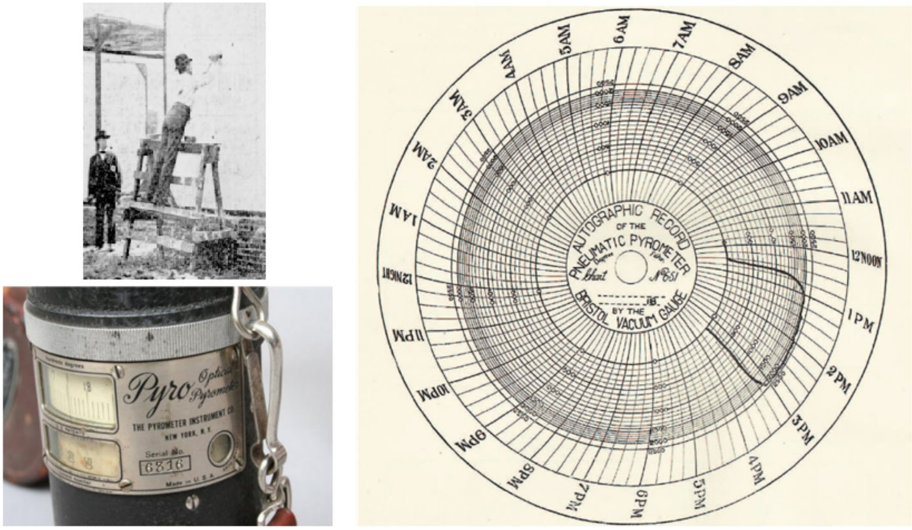

Figure 7. Pyrometer temperature recorded measurement (see [27]).

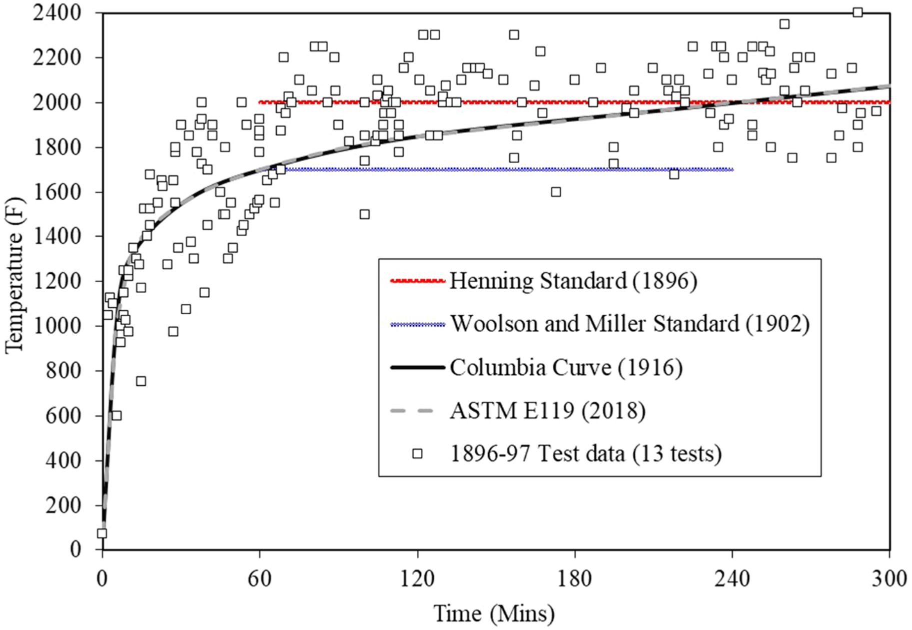

Figure 8. Author's subjective evolution of fire temperature–time curves as adopted by ASTM [39].

Table 1
Edwin Sachs BFPC Universal Time and Temperature Exposure (advocated for ASTM use in 1914)

Classification	Sub-class	Duration of test at least (mins)	Minimum temperature (°C)
Temporary protective class	A	45	816
	B	60	816
Partial protective class	A	90	982
	B	120	982
Full protective class	A	150	982
	B	240	982

posed heating curve. This hypothesis requires further scrutiny but nevertheless agrees with the currently available digitized literature from that time period at the time of the writing of this paper.

5. European Efforts Towards Standardization

Careful examination of literature will show similar initiatives for heating test control development, heavily influenced by architect Edwin Sachs, were underway in Europe at the same time as Woolson. It is important to note the influence these efforts had on the standard temperature–time heating curve development. As aforementioned, the Universal Standard was originally proposed with modification as the ASTM standard time and temperature thermal boundary condition in 1914 (see Table 1). This standard heating control was considered for some time in the Americas. That temperature condition was introduced at the International Fire Prevention Congress held in London in 1903 chaired by Edwin Sachs and his BFP committee. Also in attendance was an American delegation which included Ira Woolson. It was Woolson who would advocate the use of this temperature condition in ASTM meetings that would follow after 1903. During these meetings, demonstrations of gas furnace design and use were also shown to the American attendees. Woolson would report on the conference upon his return in brevity in 1904, however, the conference proceedings were more accurately published officially and in more detail in what was called the RedBooks [40]. The RedBooks periodical was internationally distributed (at times translated in French and German), and arguably the first scientific fire journal. These proceedings were summarized where relevant in Babrauskas' work. Edwin Sachs health did not maintain in his later years and he passed away in 1919, after which his committee saw little growth and disbanded. Figure 9 details the Redbooks and Edwin Sachs' gas-fired furnaces demonstrated at the 1903 conference. These photos are extracted from the Red Book conference proceeding from 1903.

After the conference, Sachs and Woolson continued correspondence and there are details of their meetings together aiming to develop a Universal Standard until at least 1912 [29]. The Universal Standard would be significantly criticized in

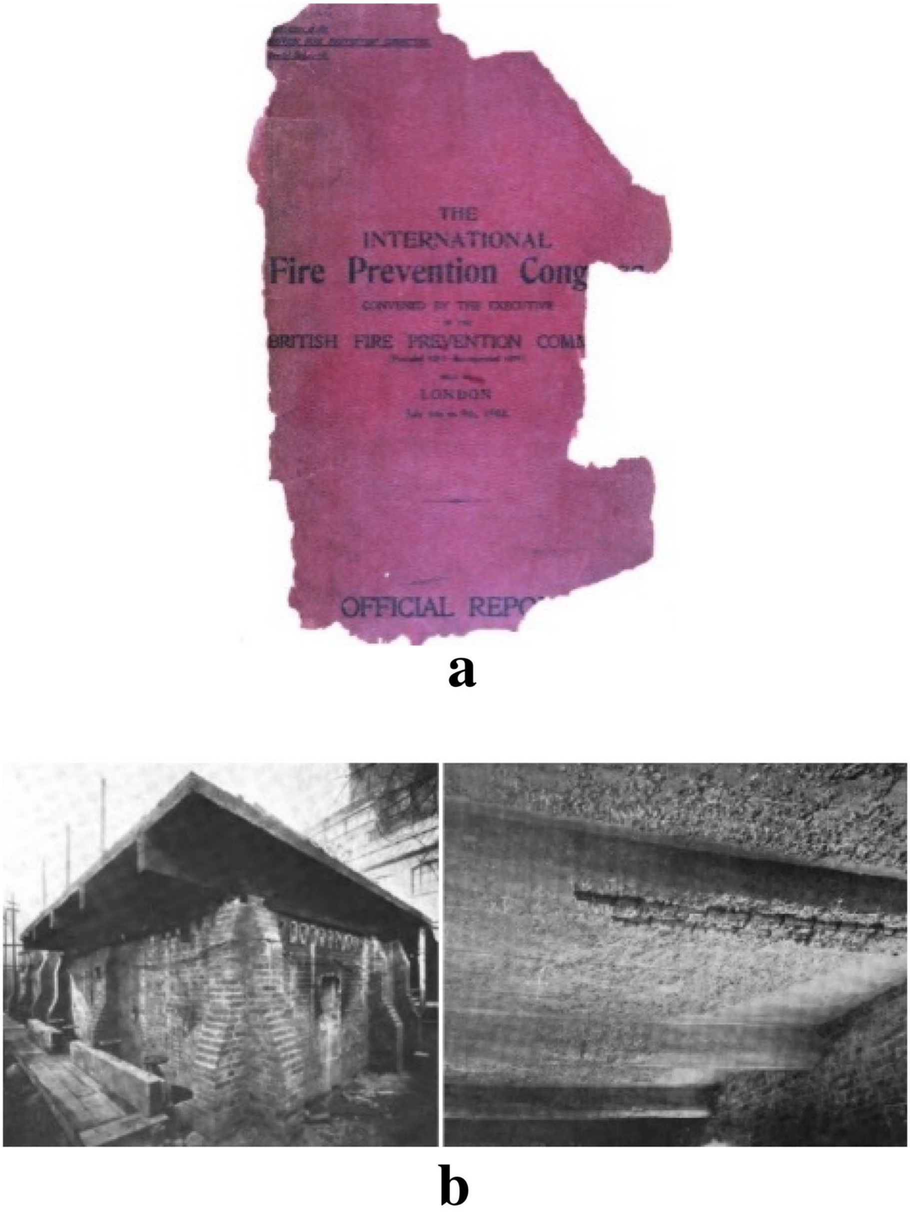

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Figure 9. (a) Edwin Sachs' RedBook Proceedings [40]. (b) Edwin Sachs' gas controlled furnaces with Specimens [40]. (c) Edwin Sachs' Gas Controlled Furnaces [40].

North America and was not received well and subsequently not adopted. NFPA meeting minutes specifically targeted the standards more laxed criterion for its inclusion of a temporary building condition. While these meetings were not very

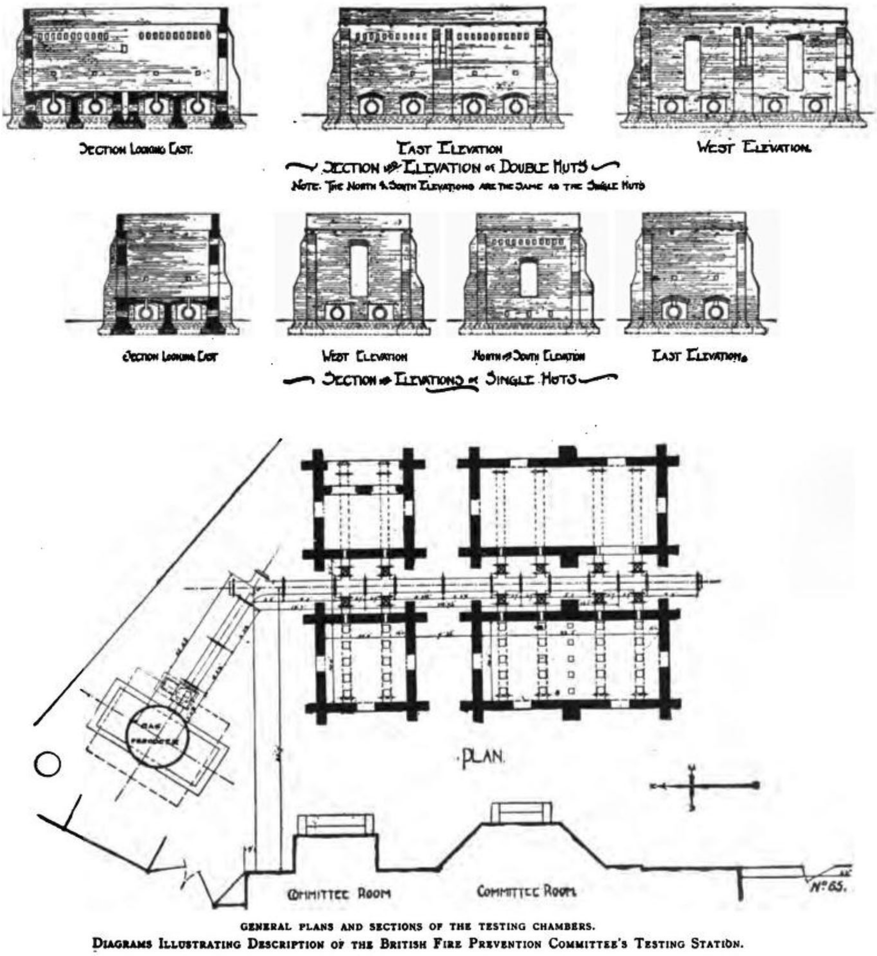

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Figure 9. continued.

specific to why the standard ultimately was rejected, the lower severity of fire was critiqued in NFPA meeting minutes specifically due to implications to exit use where partitions would be present. ASTM would mobilize conferences afterwards (recorded as two meetings) to determine the character of the standard temperature–time heating curve, and the familiar curve was then presented in NFPA Quarterly in 1916 [32]. Provisions of temporary, partial, and full were dropped and hourly ratings were recommended instead with one heating curve to be used [38].

After Sachs' death, momentum for developing standardized fire testing in Europe appeared slow, and it would not be until 1932 where the British Standards Institute revisited the subject. In that year, BS 476 was created which laid down the test procedure for assessing structural elements by means of a standard test, which adopted the time temperature heating curve from ASTM [41]. It would not be until BS 476 was adopted in the 1930s, which largely mirrored the ASTM fire standard from that time in its initial conceptions but deviates today in test control.[6] BS 476 would later evolve into ISO 834.

By the late 1970s and into the early 1980s, over-reliance on standard fire resistance testing was widely recognized as limiting innovation in architecture and construction, and technical papers began to appear which openly questioned the applicability of these tests. In 1981, practitioner Margaret Law remarked [1]: "The standard temperature–time curve is different from the temperature time exposure likely to be encountered in real fires which will depend on the amount and type of fire load, the ventilation, size and shape of the building, and the activities of the fire brigade." Fire engineering researcher David Jeanes commented in 1982 [42]: "although the traditional approach of assigning time for a given structural element or assembly allowed for a comparative measure between different types of construction; it is hard pressed to represent actual structural performance in a real fire due factors of restraint, redistribution of loads, moment resistance, as these are difficult to quantify and duplicate in tests". It is the authors' opinion that the standard today recognizes fire resistance as the time duration that a 'mock-up' building element is able to withstand furnace heating based upon standard fire testing requirements and acceptance criterion defining test end.

6. After the Time Temperature Heating Curve

The 1916 temperature–time heating curve was used for the first time in June 1917 to test a series of steel, and concrete columns; though six timber column tests were performed [43]. The criterion for the standard fire resistance test was then published by National Bureau of Standards (NBS) in the 1921 document: Fire Tests of Building Columns [43]. The test procedure used was very similar, albeit without technological control and procedural advances, to the modern ASTM E119 fire test standard [8]. Overall, the tests considered using a controlled temperature–time heating curve on loaded columns using gas-controlled furnaces. Gas furnaces could better control the temperature–time heating curve in linear fashions. The tests were performed with manual control of temperature with consideration to temperature lag of the furnace and generally suggest poor resemblance to the standard temperature–time and heating curves. For example, Fig. 10 illustrates the temperatures recorded for a concrete column test in 1917. For timber, temperatures exceeded 927 °C after 30 min in most tests where timber was left exposed (temperature plots in the original reports are too poor quality to reproduce herein). In those tests series, six timber columns were tested (Pine and Douglas firs with measured moisture contents of 13–22%) with four columns tested without encapsulation technologies. The averaged charring rates of the unencapsulated members can be extrapolated (they did not report charring rates only time and

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[6] Today, the ISO 834 fire resistance test is specified to use plate thermometers as opposed to the ASTM E119 that specifies thermocouple. Both instruments govern the test control differently.

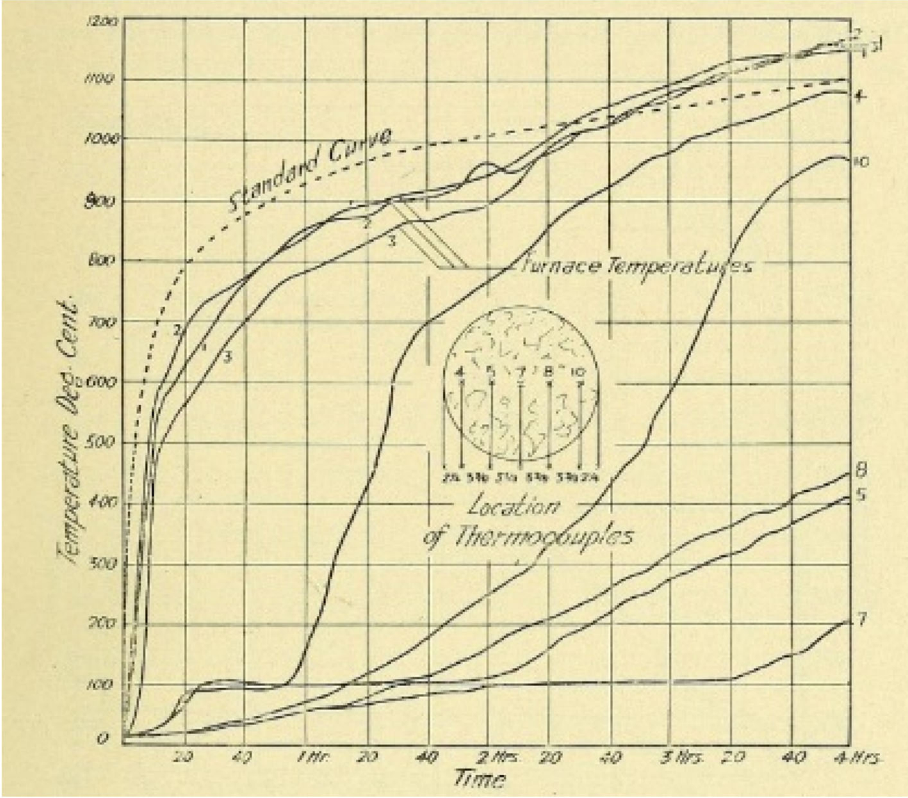

Figure 10. As-measured versus control temperatures of a standard fire resistance column test circa 1917 [44].

char depth) to 1.13 mm/min which is on the higher end of what would be expected from a modern furnace test controlled to contemporary ASTM standards.

The NBS documentation [43] does not describe the origins of the time and temperature heating curve, but it does provide comparison to versions of the Woolson-Miller Standard, US Geological Society, and a version of the BFPC time and temperature heating curve illustrating that it envelopes each in that it is of higher peak temperature with time.

Even in the 1920s, it was widely known that the standard temperature–time heating curve was by no means indicative of a real fire. Simon Ingberg reported that "it is necessary to assume maximum probable conditions both with regard to building contents and air supply, as considered with respect to intensity and duration of a possible fire. Compensations and adjustments between intensity and duration may be necessary under some conditions in order to approximate a fire duration having intensity equivalent to that of the exposure of the fire test" [45]. Efforts principally by Ingberg [45] began to correlate a fire severity—using measurements from real burn out compartment tests—to the standard fire curve based on the "Equal Area Concept.". This concept was suggested in the aforementioned column test series above for which Ingberg contributed. Other researchers continued with the development of new concepts of equivalent fire severity based other severity metrics ("Maximum Temperature Concept", "Minimum Load Capacity Concept", and "Time-Equivalent Formulae"). Buildings could then be re-classified, not only by fire activation risk, but also by functions of fuel load, and 'equivalent' standard fire resistance times could then be specified for building elements.

Minimal if any changes to the standard temperature–time heating curve were made through the years in various iterations of ASTM standards that were produced after 1918. The test procedure itself showed increasingly less emphasis on residual capacity of the elements after a fire and to rather refine technological advances for test control (ensure more uniformity in heating for example). Overall, the fire community has largely followed the original testing procedure for construction materials and elements.

7. Contemporary Challenges and Conclusions

In recent times, concerns have been posed in the fire safety community regarding the degree of heat provided in the fire resistance test. That being, the fuel provided to the furnace is reduced to compensate for the heat given off from the timber during the combustion process resulting in a reduced fire severity when compared to other building materials. Currently, in the interim of other approaches not being available, these challenges are addressed by fire safety engineers by lining the exposed timber areas of compartments, increasing the required duration of fire resistance tests (aiming to achieve an equivalence for the additional fuel load) and bespoke testing of timber frames. Additional research in timber fire dynamics is necessary to explore further any potential risks or opportunities.

There is no question that standard associations struggled and continue to struggle with these facts from creation of the temperature–time heating curve to contemporary times. In 1903, Ira Woolson when studying lumber specified the thermal boundary temperature simply to read 927 °C as was per his criterion for the Woolson-Miller Standard [46]: "This particular temperature was chosen because it is given by the New York Building Code as approximately the heat of a burning building". There was no differentiation then for the thermal exposure varying between combustible and non-combustible materials by him at this time, because that was the state of the art for fire dynamics knowledge then—a subjective maximum temperature a building could see. For contextualization, Babrauskas [11] makes a statement that "The current standard for fire testing reflects adequately the knowledge of compartment fires of 1918 but incorporates few of the later findings". When the test was first developed, it was used for timber columns in 1917. Nowhere in the reports issued of those tests was the combustion effect on the test control discussed, yet examination of the report shows deviations from the standard temperature–time heating curve. Nonetheless, it was clearly recognized a decade later that timber had additional complications for fire testing, with the creation of various sub-committees within ASTM to undertake its study in fire. As the standard fire resistance test evolved, however, ASTM committee membership expanded, and funding was allocated for the study and standards creation for combustible materials such as lumber. This occurred in the late 1920s, followed by the creation of sub-committees to engage the issues of combustibility. In 1927, an ASTM meeting discussion emerged which began to question the credibility of the standard temperature–time curve for the assessment of timber (in fact all materials), "Standard Fire Tests for Combustible Building Materials" [47]. It was stated by Pierce of UL Underwriters: "We do not know with exactness what are the temperatures characteristic of conflagration exposures nor do we know what are high and ordinary temperatures as applied to building fires. It is in such difficulties as this that the chief obstacles lie in developing the test methods on a scientific basis. We have our standard method of fire testing for materials; whether it is suited to the testing of combustible materials as well as non-combustible is certainly open to question. The method is somewhat arbitrary in that we apply a standard method of fire, standard rate of rise of temperature, to the test specimen and observe the results without wasting time in discussing whether the temperatures and times involved are those that would exist in Louisville, Ky., or Chicago or Boston in an actual fire. Our art-of-fire-prevention study has not reached that point" [47]. Later in the same discussion, Simon Ingberg noted that "I want to second what has been said here relative to the necessity for proper interpretation of results. Using our regular fire testing procedure we are at present testing combustible or partly combustible constructions and obtaining certain results without any generally accepted interpretation as to what they mean when the constructions are applied in buildings" [47].

The discussion spoken of today [6, 7] regarding the temperature–time curve's usage on combustible construction is not new, but we do have better measurement tools to quantify it and investigate its implications [6, 7]. The temperatures given off by timber during a standard fire resistance test are not fully understood, nor are all building materials when real fires are considered as the field of fire dynamics is still evolving. It is merely that the standard temperature–time heating curve was framed as a unified gas temperature independent of any other fire because it was meant to be (at that time) the credible worst-case fire on concrete and steel materials that were tested.

The nature of timber, and even concrete compartments, can create temperatures in real fires that exceed this time temperature heating curve, merely illustrating that the design philosophy of equivalence against this benchmark is a very debated topic that can polarize the approach to the design we are attempting to solve today. To suggest the standard temperature–time heating curve still serves its original purpose to this day is to argue that no advancements have been made in fire science, instrumentation, or even structural engineering since 1916—which is not correct.

For example, calculated temperature–time design curves have been accepted and can be used in design practice in recent years. These include Parametric heating curves [48], and more recently, there has been use and acceptance of the Travelling Fire Methodology [49–51] for the design of structures. These have been devel-

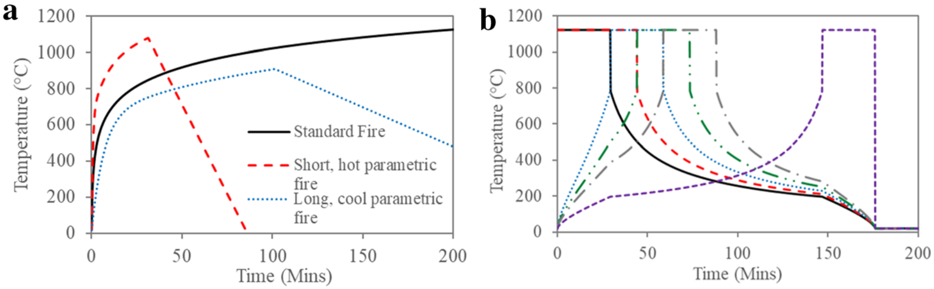

Figure 11. Different design fire examples including (a) the standard fire, two sample parametric fires and (b) a sample travelling fire as it progresses through a fixed dimensioned compartment of 20 × 20 m. These calculated design heating curves utilize arbitrary inputs for illustrative purposes only.

oped as an acknowledgement that the standard temperature–time heating curve is not representative of the current understanding of fires and cannot represent expected deformations of building elements as would occur in reality—particularly representing a cooling phase. These design curves have led to numerous contemporary and densely instrumented compartment fire tests both completed and planned. An arbitrary example of these heating curves is illustrated in Fig. 11. These are shown with comparison to the standard temperature–time heating curve. These different curves used for design allow for more consideration of contemporary fire dynamics theory such as allowing for consideration of fuel and ventilation effects to name a few. These curves, as well as calculated realistic fires, in design are also continually being adapted by researchers and practitioners for structural fire engineering design. With consideration being on larger compartment spaces or even different construction materials beyond just concretes and steels.

We as an industry can respect the standard temperature–time heating curve's origins. But at the same time, we need to use our contemporary knowledge of fire dynamics and structural response to build upon it to create the next generation of standards. This review largely limits recommendations for the readership on steps forward other than that all practitioners should engage in the standardization meetings and discussion. The authors advocate that, if the standard curve is still considered unacceptable to some, it is of critical nature that those individuals participate within the standardization process and convince these committees accordingly how upon they may improve the standard they have in question [52]. Such discussion and development will also have to show consideration to a range of building elements such as ducts, dampers, doors, fire stopping etc.

The authors have aimed to provide additional context to the historical narrative of the development of the standard temperature–time heating curve to add background and the thermal boundaries context for today's contemporary discussions. Herein, additional contributions from the original development cycle not distinctly covered by existing narratives were explored. The contributions to fire resistance testing from Sylvanus Reed are acknowledged in a contemporary light and it is illustrated that the themes discussed were aligned to today's contemporary discussions. For example, the concept of examining building materials under a family of fires (different thermal boundary conditions to examine the most conservative design) for which, in some jurisdictions, we are returning to this concept in practice. This being in part due to acknowledgement that a structure may have more fuel load (contents or otherwise exposure to its combustible elements) and ventilation conditions to produce a thermal state that can evoke critical damage that a standard time and temperature heating curve cannot otherwise evaluate on its own. However, unlike the past, the state of knowledge of structural and fire dynamics has improved where we know uniform thermal boundary exposures are not necessarily the more critical heating to an assembly, where cooling (after heating) can be important for certain structural arrangements like steel connections or the invocation of cracking in concrete. The authors have also identified that no literature is (currently) available that supports a basis for the temperature–time heating curve points. Practitioners will find discussion useful for current philosophical discussions pertaining to the temperature–time heating curve use for combustible construction.

Acknowledgements

The research herein is inspired through a multitude of research discussions with Dr. Maluk, Dr. Bisby and Dr. Torero and support of all of the lead authors previous university affiliations. The manuscript has been extensively reviewed by members of the York University Fire Group including but not limited to Ben Nicoletta.

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