Response to Vytenis Babrauskas “Comments on “The Historical Narrative of the Standard Temperature–Time Heating Curve for Structures” by Gales, et al.”

John Gales, Bronwyn Chorlton and Chloe Jeanneret, Civil and Fire
Engineering, York University, Toronto, Canada*

Accepted: 3 August 2021/**Published online:** 19 August 2021

In 2020, we submitted a now published review paper in *Fire Technology* discussing early narratives of fire testing and the origins of the standard temperature and time heating curve [1]. This article is meant to build upon previous work done by Drs. Babrauskas and Williamson as published in the late 1970s [2, 3] given advancements in global digitization and our own digitization efforts. Given the link to their work [2, 3], the authorship team of John Gales, Bronwyn Chorlton, and Chloe Jeanneret are very honoured that Dr. Vytenis Babrauskas provided his feedback on our paper and his opinions on the current and future prognosis of the temperature–time heating curve for structures. In his comments, Dr. Babrauskas raises several valuable points that complement the work we have made, including highlighting the role of computational based methods in fire safety engineering practice, risk, as well as insight into the emergence and gradual acceptance of structural performance-based fire design. Dr. Babrauskas has given a useful perspective of the design situation in the United States in highlighting challenges in making changes to the standards.

We would now like to address some portions of Dr. Babrauskas’ feedback to ensure that our statements are interpreted correctly within their original context in our paper. We note that some feedback raised by Dr. Babrauskas could be considered already acknowledged and explained in our paper. We however acknowledge these may require additional commentary herein for emphasis and further background to avoid any misrepresentation.

*Correspondence should be addressed to: John Gales, E-mail: jgales@yorku.ca

Dr. Babrauskas notes that he disagrees with a statement from our paper, that *“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”* [1]. Within the context of our original publication, this statement is supported by explanation that there is no definitive reference to show how the ASTM committee established these specific time and temperature points, although it is not to say that there is no value to further research and opinions as each review leads closer to the source document. As is discussed in our paper, Ira Woolson stated in ASTM meetings that, *“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 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”* [4]. At the time of the temperature–time curve’s adoption, it was noted by Woolson that the curve is arbitrary and not to be interpreted as a real fire. While there were indeed tests data that to varying extents aligned with points observed on the standard temperature–time heating curve, we (or anyone to date) cannot conclusively, without being subjective in commentary, identify the rationale behind the points of the temperature–time curve unless (or until) further historical literature comes to light. For example, a definitive document would need to be identified describing all time and temperature points, and the rationale as to why each time–temperature value is specified as so. This document has yet to be found by anyone despite modern digitization efforts.

This discussion relates to why Fig. 8 in our paper can only be subjective. Our paper acknowledges within the text and the caption of the figure, that it is a subjective interpretation where references are unavailable to otherwise show. It is noted throughout the paper that these subjective comments require further scrutiny. Figure 8 illustrates the 1896/1897 New York tests, the Henning Standard (1090 °C at 5 h) used for those New York tests, the next standard by Woolson-Miller (927 °C at 4 h), and the adopted ASTM time temperature curve that came after and is still used today, over 100 years later. This can be considered a simplified interpretation of the curve’s evolution. By plotting the standard temperature–time curve used today appears to show a near-linear connection between 927 °C at 1 h (the Woolson-Miller peak temperature and initial hold time) and 1090 °C at 4 h (the Henning Standard peak temperature, although with the Woolson-Miller time). It subjectively appears that all temperature–time points between 1 and 4 h may be a compromise between the Henning and Woolson-Miller durations and peak temperature standards. In addition, the modern standard temperature–time heating curve envelopes the previous New York 1896/97 tests shown in Fig. 8. We also know that Woolson favoured the New York 1896/97 test series as the starting point for cataloging fire tests, so it is within reason that he would ensure that they are considered within the curve’s development. In reference [5], Woolson provides a catalogue of structural fire tests starting with the 1896/97 New York fire tests that followed the Henning test standard. Woolson’s cataloguing of 82 tests is followed by tests which follow the Woolson-Miller test standard up until its date of publication in 1912 [5]. In addressing any notion that the

1896/1897 New York Test series cannot be used as a basis for benchmarking due to corruption; although our paper discusses the corruption that surrounded this test series, it is suggested that these data were deemed credible by Woolson and Miller who note in that reference from 1912, “*Derogatory statements have been published concerning the reliability of the New York tests, the assertion being made that corrupt influences were used to modify results. We wish to correct this impression. [...] we are confident that it is unjust to cast suspicion on the tests*” [5]. Despite the corruption associated with the test series, the evidence from Woolson and Miller suggest that the test series was still considered as valid during the era of the temperature–time curve’s establishment and the original foundation for the tests that followed it. We acknowledge our opinion can be debated but it is not misleading. It is already stated in our original paper that this subjective comparison is worthy of further exploration (“*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*” [1]). In our original paper, we have acknowledged Dr. Babrauskas’ position that the curve represents an envelope of other tests. This perspective is also defensible. There is much credence that harmonization of previous fire tests was evident in the development of the standard. Meeting minutes show the hourly ratings were apparent to be based upon risk concepts, “*Construction should be classified into three or more grades based upon the degree of protection which they would afford when measured by a fire test conducted in accordance with a standard time–temperature curve. For various reasons it was decided that the terms, “Full”, “Partial” and “Temporary Protection,” previously recommended were unsatisfactory. In place of this plan to classify standard of fire resistance by groups, the conference decided to adopt the terms “four Hour Protection” “Two Hour Protection” “One Hour Protection” Etc. This classification harmonizes easily with the fire test work already done under the standard specifications of the American Society for Testing Materials, by the Underwriters’ Laboratories, and other investigators. It is also evident that it will be a simple matter to interpolate other classes as they may become necessary*” [4]. Note that these conversions between protection level and time are direct, full protection meant 4 h to the test and so on. The temperatures specified in that proposal were more closely aligned to the Woolson-Miller standard of 927 °C not of Sach’s specified temperatures though. It appears that the hour, but not the temperature, of the curve is influenced by Sach’s three (if you interpret as risk) categories. For now, all we have are opinions and are lacking that missing link document that clearly defines and states the rationale behind each time and temperature point of the standard curve. The only fact currently available from historical literature is that the standard temperature–time curve is acknowledged by Woolson as being arbitrary and does not have a basis to be interpreted as a real fire with respect to its time and magnitude.

Dr. Babrauskas notes that the conclusion of our abstract is problematic, “*This reinforces contemporary discussion that the heating curve lacks scientific basis in its representation of a real fire*” [1]. In fact, the full statement in the abstract reads, “*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.” This discussion also reflects the considerations regarding combustible materials that were included later in the paper as the authors note that, “*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.*” As discussed above, we do not believe that the basis for the temperature–time heating curve is justifiably shown, which is problematic particularly in light of the test data on timber structures that show significant fire exposures in excess of peak values in excess of that curve [6, 7]—hence renewed contemporary discussion on the basis of the curve. Dr. Babrauskas explains that our paper cites the 1927 Underwriters Laboratories study [8] to show that the temperature–time curve had not been adequately studied and refers us to next cover Ingberg [9]. The authors’ paper does include discussion of Ingberg’s study (as Reference [45] in our original paper), though the point that is being discussed with regards to the 1927 Underwriters Laboratories study is concerning issues of combustible materials, which are not directly addressed by the Ingberg 1928 reference. A companion paper called “*Fire Test of Brick Joisted Buildings*” [10] where the research, also released in 1928 and led by Ingberg, was to seek to “*determin[e] the actual fire behavior ... compared with the assumed fire conditions of the standard time–temperature curve*”. In his “*Fire Test of Brick Joisted Buildings*” study, Ingberg concluded that “*The temperature rise during the initial portion of the test was more rapid than in the standard furnace test, ... indicating temperatures exceeding [1093 °C] at several points within 20 min and maximums at a few points between [1200 °C] and [1300 °C] as obtaining within 40 min*” [10]. We do acknowledge that this companion paper may only strengthen the discussion that the standard time–temperature heating curve lacks scientific basis in its representation of a real fire that is made in 1927 [8].

With regards more to differences of perspective, specific items raised by Dr. Babrauskas will be discussed below.

It is noted in Dr. Babrauskas’ letter that he views the cool down phase of heating to be a non-problem. The authors would like to highlight that there have been experiments where cool down has been shown to be a vulnerability to structures [11–14] and also in real structures [15]. The inclusion of the cool down phase acknowledges the delay in heat propagation through materials (including combustible ones), and this allows for a more thorough analysis of the structural behaviour after the peak fire temperatures has been reached. We do not want to dismiss the importance of a cool down phase, or non-homogenous nature of a real fire exposure to be a vulnerability for all stages of design (for example when resilience may be considered, or where firefighter safety is concerned, etc.). At the time of writing, this is a very active area of academic study for structures, and a cool down stage may be required in practitioner considerations when examining structural post-fire resilience beyond just the concept of in heating fire resistance.

Dr. Babrauskas notes that he has not seen any obvious trends or needs which suggest that changes to ASTM E119 will (or should) occur, and that performance-based fire design can be used instead where appropriate. We feel, however, that there are still barriers to using performance-based fire design, particularly in the North America, and that there have been trends to suggest that changes to ASTM E119 are possible, or that it is possible to at least mobilize the fire community towards new design procedures in other relevant standards. In 2018, ASTM E05 (which maintains E119) held a workshop on *Advancements in Evaluating the Fire Resistance of Structures* in Washington, D.C., that the lead author here co-chaired and that the authorship team helped to organize. This workshop featured several studies in which potential needs for changes to the ASTM E119 standard were discussed, especially in light of the rise of engineered timber structures [16–18] but even steel and concrete structures with the concept of restraint [19]. Each of these topics highlighted relatable aspects to the transition to performance-based fire design for structures. Moreover, although performance-based design may be becoming more common and potentially more accessible, there are still challenges with its uptake and adoption at the time of this writing. For example, these challenges have been identified in Authorities Having Jurisdiction, though able to approve of designs, have differing qualifications and are uncertain of taking on the liability of the approval [20, 21], as well as possible resistance from some of the material industry itself. A need for tools that have pursued adequate validation and verification to be expertly used, as well as a need for available relevant experimental data, have also been identified [21–23]. A need for software that can be capable of modelling the full sequence of fire events, from the fire scenario through to the thermomechanical response has further been recognized [24]. Though performance-based design is certainly possible and occurring, overcoming the aforementioned present challenges can make realization of these designs less accessible. We would like to convey that we encourage the discussions of above topics at standards meetings, especially for those that would like to see change, and this has been happening recently as of the time of writing. Such a discussion amongst all stakeholders can be fruitful in communicating the importance and needs of adoption of performance-based philosophies, or complementary additions or changes to the standards whether they involve the standard temperature–time heating curve or not. Following the aforementioned 2018 workshop, we have observed mobilization towards performance-based initiatives by the attendees of that workshop, though these changes may not directly impact the documentation of the standard itself. It is simply our opinion to include all stakeholders wherever possible in these discussions, and not to circumvent processes or omit consequences to other aspects of building design that may be non-structural in nature. We restate 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 [of plurality] accordingly upon how they may improve the standard in question. This is not limited to the E119 standard alone, but also to the standards and codes that refer to it. We acknowledge that people will differ in opinion based on their experiences with the standards committees, but we still believe a platform of respectful communication is essential and is

achievable as demonstrated by the recent adoptions of ASCE/SEI 7–16 Appendix E within NFPA standards, among other international efforts.

We wish to re-iterate that the primary aim of our paper is to provide practitioners with additional source references that can accurately interpret how this standard temperature–time heating curve framework came to be, providing context for the origins of the curve. The focus of our paper considers original literature between 1890 and 1927, with supporting materials from post-1980 that elaborates on contemporary structural fire design practice which already includes reference to early fire modelling. We believe developments of structural fire design practice and associated fire dynamics beyond the late 1920s should be considered by a future paper (not necessarily by us), where existing publications we have listed in the paper may provide a starting point for that research. Dr. Babrauskas' letter which provides early context to modelling is useful for this endeavour as well. We believe, though not limited: such an endeavour will need to carefully consider the barriers to performance-based fire design as discussed above; that the history of structural modelling in fire is very intertwined with the standard time–temperature curve for their development, and not necessarily linked towards critical material changes that may occur in real fires; and that the slower uptake of performance based methodologies is not completely related to the high processing of a computer but also to the growth of competency of the profession (though a multitude of societal and professional educational programs are emerging today [25] to facilitate adoption, this is still a slow process and has limitations as explored above). For the last example, prominent fire scientist Philip Thomas once remarked in 1986, *“More and more people are using computer codes to make calculations and predictions of the possible outcome of a fire. Who is to certify the use of these? Who knows what is in the Harvard code? (or should I say who in European countries knows what is in the US-Based Harvard code and are they teaching it to other users?). If more and more people outside government are going to be able to design for functional requirements, they will need to be taught the methods that are available and the people who approve them for use will need to be taught what they are, whilst it is true that it may be sensible to de regulate, one must deregulate into a profession which has competence”* [26] (reference 25 in our original paper). By no means is the history of our structural fire engineering field (or fire science in general) comprehensively documented to provide complete context, though this is badly needed.

To conclude, the authors appreciate the contributions and critiques of Dr. Babrauskas in highlighting insights that the authors believe are complementary to our work. We of course do not expect Dr. Babrauskas, nor every reader to agree with our communication in its entirety, however, we do hope that readers will appreciate our statements within the context of our original paper and further explore the history of the field we practice, teach and develop. We aim to have conveyed within our paper and response that unless previously unrealized historical literature comes to light, we (and others) cannot definitively specify the original basis of the standard temperature–time curve without subjectivity (yet). This becomes especially relevant in the contemporary discussion of the applicability of the standard temperature–time heating curve to combustible structures—which is, as of

now, being used as a benchmark for these structures' approval in some international jurisdictions. Though the authors cannot foresee the future of relevant standards and design methods of fire safety engineering, the authors believe that there is justification and momentum to make current design methods more accessible and/or more reflective of the state of knowledge of the twenty-first century.

Declarations

Conflict of interest The authors declared that there are no conflicts of interest.

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