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The Rise and Rise of Fire Resistance

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Abstract

Fire resistance is one of the most enduring ideas in fire safety design. This paper charts the emergence of *fire resistance*, and its rise to ubiquity – with a focus on British codes and standards. Beginning as a method for independent testing of 'fireproofing' systems, *fire resistance* was formalised in the USA, and subsequently in the UK. Minimum *fire resistance* periods were defined that would allow a structure to resist burnout of the fuel in a compartment; these minimum periods became legislatively empowered in the 1950s. Over subsequent decades the required periods of *fire resistance* evolved in response to uncertainties and competing motives. It is shown that within UK guidance, where statutory guidance recommends 30 minutes as a period of *fire resistance*, such buildings are not expected to resist burnout. Where guidance recommends more than 30 minutes *fire resistance* (for offices or residential buildings), it *is* intended that such buildings should resist burnout. This paper aims to assist those with responsibility for meeting the requirements of the building regulations to consider for themselves whether following the guidance in the approved documents (or technical handbooks in Scotland) is likely to be sufficient to discharge their responsibilities as construction professionals.

Keywords

Fire resistance; regulation.

1. Introduction

On the afternoon of 6th August 1857, Isambard Kingdom Brunel attended a party. The occasion was the wedding of Florence Saunders and Frederick Stopford, and the celebration took place in the grounds of Westbourne Lodge [1]. The venue was owned by Charles Saunders, general secretary of the Great Western Railway. At the end of the garden, trains on the Great Western rumbled past. At this time, the railway was still new – the lodge close to, but unaffected by, its new neighbour. However, this elegant stone building ultimately succumbed to the industry spawned by its inhabitants. Westbourne Lodge was demolished in around 1910 to make way for a railway siding. Today, an imposing red brick building stands at the former entrance to Westbourne Lodge; a car park now sits atop the gardens where the newlyweds celebrated their nuptials.

Brunel is of course an engineer of great renown, frequently cited as one of the most prolific figures in engineering history. His achievements are wrought in iron, stone, and brick; they have physically shaped the geography of the United Kingdom and stand as the most permanent physical monument it is perhaps possible for a human to leave behind. However, it is little known that also from the gardens of Westbourne Lodge emerged an idea that has proven just as enduring as Brunel's great physical legacy; an idea that has spread far beyond the shores of the United Kingdom; an idea that is so deeply embedded within engineering convention that it has created its own language; an idea that thrives in virtually every building code in the world; and an idea that has proved so powerful that even the most revered minds in fire science have found themselves unable to kill it.

The idea, of course, is *fire resistance*.

2. The Trigger

Nearly half a century after the wedding of Florence and Frederick, the gardens at Westbourne Lodge became home to the British Fire Prevention Committee's testing station [2]. The landscaping was replaced by several small brick buildings. Each of these was linked by pipework which supplied a series of gas burners. There would, periodically, be a frenzy of activity as workers built a wall, or a floor, or fitted a door. Once each detail of the construction was complete, members of the Committee would officiate over the ritual firing of the burners. The temperature in the furnace would rapidly rise to greater than 500°C and, over the course of a few hours, would eventually exceed 1000°C. At any point during the test the construction might fail, sending debris tumbling into the furnace below. The representatives of the Committee would then diligently document their observations. The test report would be bound together with photos from before, during, and after the test. This would then be published as a 'red book'.

The British Fire Prevention Committee (BFPC) was set up in the wake of the devastating 1897 Cripplegate warehouse fire, and was led by Edwin Sachs. The Cripplegate fire occurred at Jewin Street in London on 19th November 1897, and by January 1898 Sachs had already assembled a list of some three hundred interested individuals who together would form the Committee [3]. Even before the first meeting, it had already been identified that of particular interest was the question of independent testing of 'fire-proof' construction to prevent fire spread. It was proposed to draw widely on knowledge and experience from the USA and continental Europe. Shortly after it was formed, the committee began systematically testing 'fire-proof' construction. A testing station was established at Regent's Park – however, the nature of the committee's activities soon led their landlord to terminate their lease agreement [4]. Thus, by 1903, the BFPC had relocated to the gardens of Westbourne Lodge, where their activities continued until in around 1905 when they moved again back to different premises near Regent's park [2]. In around 1910, Westbourne Lodge and its gardens were subsumed into the infrastructure of the Great Western Railway.

Although the frenetic activity of the BFPC lasted less than two decades, their impact on fire safety design and regulation persists to the present day. The colourful life of Sachs is well documented [5] by his son (the Lord Justice Eric Sachs). Sachs' many achievements include the founding of the Concrete Institute – which would later become the Institution of Structural Engineers [6]. However, of more interest to the subject of this paper are Sachs' ideas regarding the performance of structures in fires, and the degree to which he and others were able to successfully promulgate these.

3. Initiation

In 1903, Sachs and the BFPC turned their attention to the organisation of an International Fire Prevention Congress. Held in London, this would be the first meeting of its kind. The most comprehensive account of this conference is given by Ira Woolson, at that time representing Columbia University (USA) and the United States [7]. The culmination of the conference was a paper presented by Edwin Sachs on 'suggested standards for fire resistance'. Sachs' paper (for which he made great effort to share the credit with other members of the committee) contained four seminal ideas [8].

First, he suggested that the term 'fireproof' should be avoided. Sachs noted that the term 'fireproof' was used by 'fraudulently-disposed traders' to 'try to palm off on unwary builders, architects and landlords spurious materials and unsafe systems of construction' [9]. He suggested instead that 'fire-resisting' was more 'applicable for general use, and that it more correctly describe[d] the varying qualities of different materials and systems of construction'. This echoed earlier reservations about the use of the term 'fireproof'– notably by Charles Fowler who in 1871 observed that the word fireproof 'may be considered a misleading one' [10].

Second, he suggested that building systems should be 'classified' in terms of their fire resisting qualities. He suggested that (as previously noted by Babrauskas [11] and Hamilton [12]) there should be three classifications, namely: temporary protection, partial protection, and full protection.

Third, he linked these classifications to durations of exposure to a fire. He suggested that:

- temporary protection implies resistance against fire for at least three-quarters of an hour;
- partial protection implies resistance against a *fierce* fire for at least one hour and a half; and
- full protection implies resistance against a *fierce* fire for at least two hours and a half.

However, in outlining these classifications, neither Sachs nor the other conference delegates appear to have defined which classes, occupancies, heights, or sizes of buildings ought to be designed to meet which classifications. Similarly, there does not appear to have been any specific consideration of what qualities a fire resistant structure required; Sachs did not set performance requirements but only devised the framework within which performance might be assessed, and against which requirements could subsequently be set.

Finally, Sachs suggested the thermal conditions within a fire testing furnace under which *fire resistance* should be verified. He described the duration of exposure, minimum temperature, required loading, and minimum specimen size that should be used for each classification of construction.

Sachs followed his paper by expressing his vision for a common international approach to fire testing. His vision was that every test station in the world should execute its test on 'identical lines' to a test that had been conducted *the previous afternoon* within the gardens of Westbourne Lodge [8].

The congress was held from 6th to 11th July 1903, and was apparently regarded as a great success. However, subsequent attempts by the BFPC to standardise the concept of 'fire resistance' had little immediate impact in English legislation; the ideas that had been presented at the congress found much more accepting audiences overseas. Prof Woolson, who had attended the conference as a US delegate, led the National Fire Protection Association (NFPA)'s (USA) subsequent attempts to standardise 'fireproof' construction.

In 1914, Woolson's NFPA committee on 'fire-resistive' construction resolved that the term 'firepoof' should be discontinued and that the term 'fire-resistive' should be adopted instead [13]. They also noted that 'in considering the question of standards of fire resistance [Woolson had been] invaluably guided by the standards adopted by the International Fire Prevention Congress held in London in 1903' [13]. Woolson's NFPA committee consulted widely and, in 1917, determined that the BFPC's terms for a three-tiered approach to *fire resistance* ratings, i.e. 'full', 'partial', and 'temporary', were unsatisfactory [14]. Instead, they decided to modify the terminology – and the associated *fire resistance* periods – to 'four-hour protection', 'two-hour protection', and 'one-hour protection'.

At the same time, Woolson proposed a tentative standardised temperature versus time definition for the gas phase temperatures to be followed within standard fire testing furnaces. Being acutely aware of the significance of this tentative proposal to standardise heating exposures for assessment of *fire resistance*, Woolson explicitly highlighted the challenges being faced – stating that 'we are feeling our way in an entirely unknown field. Nothing of this character, so far as I know, has yet been done and in this we are at least trying to base the requirements upon fundamental principles' [15]. In 1917, he presciently observed that 'we want to get it as nearly right as possible before it is finally adopted, because, after it is adopted… it will be pretty hard to change it' [14].

Woolson was, of course, correct. The standardised temperature versus time curve that was the subject of intense debate between 1914 and 1917, once adopted, has come to almost completely dominate the fire testing of elements of structure internationally. Indeed, the 'standard fire' remains today, essentially unchanged after more than a century since it was first set out in 1917, as ASTM E119's [16] original curve. The similarity with the testing curves that were recorded by the British Fire Prevention Committee during the period 1897-1903 is both remarkable and, in a sense, inevitable – given the approach that was agreed by the BFPC in 1903. Figure 1 shows the temperature versus time curve that was measured during one specific test at Westbourne Lodge on the afternoon of 12th August 1903 [17] – this is plotted together with the current ASTM E119 temperature time curve.

It took a further decade for the standardisation of *fire resistance* to be formalised in the UK. In 1929, the Royal Institute of British Architects (RIBA) Science Standing Committee wrote to the British Engineering Standards Association (the precursor of the British Standards Institution (BSI)) suggesting that it should consider the desirability of standardising *fire resistance* and 'incombustibility' in building materials, and providing a specification for tests to assess elements of structure against attack from fire. The intent was to prevent mis-interpretation of building by-laws [2]. The result, in 1932, was the publication of the first edition of BS 476 [18]. This document presented a standardised testing method for establishing the 'fire resistance' of elements of construction. During the development of this standard, the committee considered various temperature versus time curves for use in the fire testing furnace (including one of the BFPC curves). Ultimately however, they settled on 'the American' curve – which had in fact been derived from Sachs' work in the UK at the beginning of the 20th century [2], as already noted.

The acceptance criteria for the new British Standard was a thermal insulation criterion (250°F or 139°C on the unexposed face, following a precedent established in the 1926 American standard which appears to have been originally based on tests for piloted ignition of wooden blocks tested in a tube furnace [19]), an integrity criterion (that 'cracks, fissures or other orifices through which flame can pass shall not develop'), and a stability criterion (that ‘the structure shall remain rigid and not collapse’). *Fire resistance* was defined as the duration (in minutes) during which an element of construction met one these criteria when exposed to the standard fire in a *fire resistance* testing furnace.

To perform these new standard *fire resistance* tests, a new testing station was constructed at Borehamwood, near Watford. This location was chosen on the basis of its convenient access to London [2]. Just as Westbourne Lodge had the Great Western railway running at the end of the gardens, the new fire testing facility was directly adjacent to the Midland main line. Over the course of the next 60 years this site would grow to become the Fire Research Station (FRS) and, eventually, part of the Building Research Establishment (BRE).

The *fire resistance* test, as envisioned by Sachs and formalised by Woolson and BSI, has subsequently drawn significant technical criticism, as discussed later in Section 6. However, at the time of its development the discipline of fire science did not exist in any form that would be recognised today. The behaviour of room fires had yet to be elucidated and – as was highlighted by Woolson – the committee members were feeling their way in a largely unknown field. While the technical aspects of the *fire resistance* test can now be judged against the current state-of-the-art, the motivations and decisions that led to the standard fire should be judged within their historical context; Sachs and Woolson were doing their best, with the knowledge that was available to them at the time, and openly communicated their uncertainties.

Figure 1 Temperature time curve from the afternoon of 12th August 1903 [17], and today’s ASTM E119 [18] temperature time curve.

3.1. Full, Partial, and Temporary

The previous discussion has shown how the terminology ‘full protection’, ‘partial protection’ and ‘temporary protection’ originated from the BFPC and were agreed at the 1903 congress. They were then picked up and modified in North America – whereupon the terminology was changed to ‘four hour’, ‘two hour’ and ‘one hour’ protection when tested under exposure to the standard fire. This story thus far, however, fails to fully elucidate the fundamental intent of the terminologies adopted.

What was it that Sachs meant when he suggested, at the 1903 International Fire Prevention Congress, that any given structure ought to be ‘fully protected’, ‘partially protected’, or ‘temporarily protected’?

Sachs had identified that a ‘fully protected’ structure should provide the ‘fullest protection obtainable in practical circumstances’ [9]. Babrauskas [11] interprets this to mean that the structure should be able to withstand burnout of the fire compartment’s contents without intervention by the fire and rescue services. In contrast, temporary protection provided a notional level of *fire resistance*, but not to a degree wherein resistance to burnout of all the available fuel could be assured. Sachs’ definitions were based on a combination of *fire resistance* tests and experience obtained from actual fires. Further insight into his intent can be gleaned from the discussion that follows his seminal 1903 paper [8]. One conference delegate (Major Huleatt from The War Office) noted his satisfaction with the proposal on the basis that it was sometimes difficult to get people to go ‘the whole hog’, but that there was significant value to be attached to temporary protection – as it ‘makes all the difference if you can hold a fire for three-quarters of an hour’.

These minuted discussions suggest that Sachs was indeed intending that ‘full protection’ should allow a structure to resist burnout of a severe fire. Similarly, he appears to have intended that ‘temporary protection’ should not be expected to resist a burnout fire – but should have utility, in particular, for undertaking fire brigade operations. The utility of ‘temporary protection’ was also discussed in NFPA’s meetings [13] with one contributor observing that this classification ‘is presumably intended for the kind of protection that is required, for example, around a stairway, especially in a non-fireproof building, for the purpose of making enclosure of that stairway a safe means of escape in case of fire’ [13].

However, at least in the UK, the appropriate level of protection (i.e. *fire resistance*) that ought to be provided by particular buildings had not yet been defined with clarity, nor set out by regulations.

Looking back from the 21st century, the fundamental intent of these different levels of protection (i.e. *fire resistance*) could be clearer. However, review of the available documentation yields a strong impression that structures that were ‘fully protected’ were intended to resist a burnout fire, and that partial and temporary protection were required only to provide notional *fire resistance* – that might have some utility in terms of fire-fighting or evacuation.

3.2. Equivalence

The outbreak of World War I led Sachs and the BFPC to focus their efforts on fire prevention measures in the new military camps and hospitals that sprang up across the country. By this time Sachs’ health was failing and, in September 1919 at the age of only 49, he died of renal failure and pneumonia [5]. After the war, and without Sachs’ leadership, the BFPC never returned to the topic of *fire resistance* with the same vigour. Nevertheless, Sachs’ vision of an internationally recognised approach to *fire resistance* had been realised. In North America, a standard temperature versus time curve had been established, and various interested organisations in the USA had begun to assess structural elements against this new standard.

One such early adopter of the standardised testing procedures was Simon Ingberg of the US National Bureau of Standards (NBS). Ingberg, in conjunction with representatives from the US insurance industry, undertook a series of standard fire tests at Underwriters Laboratories (Chicago) between June 1917 and December 1918 [20]. This allowed systematic comparison of how much *fire resistance* could be provided by different forms of construction and different methods of fire protection. In his role as Chief of the Fire Resistance Section at the NBS, Ingberg became increasingly interested in the character and physics of real – rather than standard – fires.

Previously, Sachs had relied on experience and observation from real fires to decide that a ‘fully protected’ structure should be able to resist a ‘fierce fire’ for two and a half hours; Ingberg took a more methodical approach. During a series of fire tests performed with real contents in real compartments, Ingberg attempted to define and measure the ‘severity’ of fires that resulted from the ‘burning out’ of contents of buildings. He did this with the intent of understanding how much *fire resistance* would be required for a structural element in order for it to be capable of withstanding a real fire in any given building. His key motivation was to ‘place the whole structure of fire resistance requirements on a rational basis’ [21].

Ingberg’s 1928 [21] work has been much discussed by other authors (e.g. [11,22,23]). The key idea contained within his paper was an attempt to link the severity of a real fire to an equivalent period of exposure in the standard fire test. Ingberg hypothesised that two fires could be said to be equivalent when there were equal areas under the gas phase temperature versus time curves (with a few caveats that we omit for brevity). Ingberg noted that this was only an approximation, but that he had not yet found a better measure of comparison that could be conveniently applied. The limitations of this hypothesis are perhaps most succinctly summarised by Drysdale, who notes that ‘there is no theoretical justification for the hypothesis’ [24]. Nevertheless, unable to propose a better justified approach, Ingberg took a further step and suggested that the severity of a fire was proportional to the fuel load density within a building – i.e. the mass of combustible building contents per unit floor area. This allowed him, for a given fuel load density, to define the amount of *fire resistance* (i.e. the period of *fire resistance*) that a building would need to resist burnout of the available fuel load within a fire compartment.

4. Rise to Domination

By the mid-1930s, Sachs had conceived of ‘fire resistance’ – setting out the key parameters; Woolson had formalised a standard fire and promulgated it within the United States; RIBA had instigated the creation of a new British Standard for *fire resistance* testing, also adopting the ‘American’ standard fire; and Ingberg had linked real fire behaviour to an equivalent period of exposure in a standard fire – thus suggesting the concept of a ‘fire resistance rating’. Sachs, Woolson, and Ingberg had identified that the objective for *fire resistance*, at least for ‘fully protected’ structures, should be to resist a burnout fire.

The final step needed to cement the rise of *fire resistance* was the adoption of a legislative system to explicitly link the required standard of performance with a period of *fire resistance* – i.e. to define how much *fire resistance* was needed for a given element in any given building. In the UK, the first tentative steps along this path were taken in 1935 when London County Council proposed to grade buildings by height; they suggested that buildings above 120 feet should have a *fire resistance* standard of six hours, and buildings that were below 30 feet should have a *fire resistance* standard of 30 minutes [25]. However, these proposals were perceived as onerous (particularly for structural steelwork) [25], and in 1938 London

County Council formally incorporated the idea of fire resistance into their local by-laws [12]. The 1938 by-laws defined that the *fire resistance* of construction should be based on a list of defined construction types (e.g. a prescribed thickness of brickwork as a deemed-to-satisfy design detail). Alternatively, the by-laws allowed the use of results from the recently developed BS 476 test to show that a building could achieve an appropriate *fire resistance* classification. For example: dwellings or office buildings below 50 feet in height were required to have a *fire resistance* standard of 30 minutes; manufacturing premises with a volume less than 250,000 cubic feet were required to have a minimum *fire resistance* standard of one hour; and manufacturing premises with a volume of greater than 250,000 cubic feet were required to have a minimum *fire resistance* standard of two hours [12].

Although the idea of *fire resistance* was introduced to London's statue book in 1938, the outbreak of WWII meant that the various clauses were not extensively used [26]. It took the Post War Building Studies (PWBS) 'fire grading of buildings' report [27] to promote the link between a required standard of building performance and a period of *fire resistance* as measured in the furnace test. Writing in 1946, the members of the Fire Grading Committee reviewed Ingberg's results. They also analysed results from the Building Research Station and decided, based on this combined work, that the equivalent *fire resistance* required to resist burnout could be directly linked with the fuel load density within a compartment (i.e. the quantity of combustible building contents). They determined that 'we have thus obtained the necessary basis on which to formulate requirements for that grade of building which should resist a complete burn-out without failure'. Drawing on the terminology of Sachs from some 40 years earlier, they proposed to call this 'fully protected construction'.

The Fire Grading Committee observed that in selecting the period of *fire resistance* required to resist burnout for a particular occupancy, it was necessary to make a decision about how much fuel was likely to be present in that occupancy. They settled on three grades, these being low, moderate, and high fuel loads. Occupancies were grouped into these three categories based on survey results from real buildings. For example, offices and flats were determined to have a low fuel load, and would therefore require a one hour period of *fire resistance* in order to resist burnout – in accordance with Woolson's revisions to Sachs' original terminology. In making these statements it was noted that these were 'average results obtained for a number of occupancies' and that there would inevitably be 'instances where the severity of the fire would be greater'.

Having established a system to ensure that structures could survive burnout of the compartment fuel load, the Fire Grading Committee then moved their attention to structures where burnout resistance was *not* required, but where some *fire resistance* could have utility with regard to, for example, fire-fighting operations. Again adopting the language of Sachs, they suggested that 'partially protected' structures could be considered one such construction type. They suggested that it might be known that a particular structure should require 4 hours *fire resistance* in order to resist collapse – but that a lesser period of 2 hours of *fire resistance* could instead be provided on the basis that fire-fighting operations might 'mitigate' the risk of collapse. The Fire Grading Committee therefore introduced the 30 minute *fire resistance* period, with the intent that structures requiring this level of *fire resistance* did *something*, but were not expected to resist burnout of a fully developed fire.

In relation to combustible elements of structure, the Fire Grading Committee noted that some elements of combustible construction could be relied upon to provide a 'high standard of fire resistance'. However, they noted that if combustible elements of construction were not protected (or if they ignited during the fire) then the structure itself could burn and lead to a ‘complete burn-out’ – i.e. consumption of the fuel *and* the structure. They therefore recommended that structures required to resist burnout ‘should be of incombustible material’.

The research that was conducted for Fire Grading of Buildings was drawn upon in the creation of the UK’s new model by-laws [28]. The model by-laws were an attempt by the national governments to draft ‘model’ legislation – that could then be adopted by individual jurisdictions at a local level (e.g. London, Liverpool, Glasgow, Edinburgh). When implemented, this legislation [28] defined the required minimum *fire resistance* periods for elements of construction. The model by-laws required that offices or dwellings with a lower fire load should have a *fire resistance* period of one hour. However, for residential buildings where the height was less than 50 feet (15.2 metres), the by-laws required a minimum period of *fire resistance* of only 30 minutes. Where the building height was two storeys or less – no *fire resistance* was required. Thus, with the introduction of the by-laws in the UK, the cumulative work of Sachs, Woolson, and Ingberg was enshrined within a legislative framework based on *fire resistance* periods – and imbued with the power of legislation. This was no longer simply research; this was law.

It must be understood that the two periods of *fire resistance* that were defined in this first legislative power represent two *entirely different* concepts in terms of the expected outcomes in a fully developed fire. The longer period of *fire resistance* was an attempt to ensure that the structure was able to resist total burnout of the fuel load; whereas the shorter period of *fire resistance* was intended to facilitate egress, and with a *hope* that the fire service might be able to safely intervene before structural collapse occurred. Confusingly however, these two different intents were expressed using the same nomenclature and metric – that is, minutes of exposure to the standard fire in a *fire resistance* testing furnace. Even more confusingly for buildings with a higher fuel load (e.g. storage facilities), neither 30 minutes nor one hour of *fire resistance* would be sufficient to resist a burnout fire – the relevant physics (for example, the data collected and disseminated by Ingberg [21]) clearly indicated that a significantly longer period of *fire resistance* would be required in many cases.

4.1. Legislative Promulgation

Now firmly established in the by-laws, the *fire resistance* framework was subsequently incorporated into the national building regulations that were first introduced in the UK in the 1960s. First in Scotland [29], and then in the rest of the UK [30], the national building regulations set out the required *fire resistance* periods that structures – or rather elements thereof – should be required to achieve when exposed to the standard fire. In Scotland, the Guest Report [31] was explicit that the minimum *fire resistance* periods for buildings should consider prevention of fire spread to other buildings in addition to ensuring the safety of life.

The new national building regulations introduced a subtle change to the approach that had been suggested by the Fire Grading Committee. In England, an additional performance category was introduced – office or residential buildings over 90 feet (27.4 metres) were required to have a higher period of *fire resistance* of 90 minutes. The precedent was set in Scotland; and England’s Building Regulations Advisory Committee used the Scottish standards as the starting point for their first draft of the English regulations [32]. The 90 minute period was justified by Scotland’s Building Standards Advisory Committee on the basis that it ‘gave substance’ to the more precise classification of buildings in the new standards (when compared against the previous bylaws) [33] – i.e. that the greater number of area classifications allowing greater precision in the *fire resistance* requirement. It appears, therefore, that the 1965 Building Regulations for England may have simply copied the Scottish approach in order to maintain consistency across the UK [32].

In England, between 1965 and 1985, the Building Regulations were repeatedly revised. Similarly, after 1985 with the introduction of the Approved Documents (e.g. [34]), the required periods of *fire resistance* were transposed into the format of the newly developed statutory guidance. Table 1 and Figure 2 show the periods of *fire resistance* that were required (or, latterly, recommended) within the applicable regulatory instruments to meet the requirements of the building regulations in England. In the interests of brevity, these have been presented only for residential (i.e. flats) and offices. These tables also represent a simplification of the guidance since, in many cases, the regulations also imposed limitations on building areas which are not discussed here.

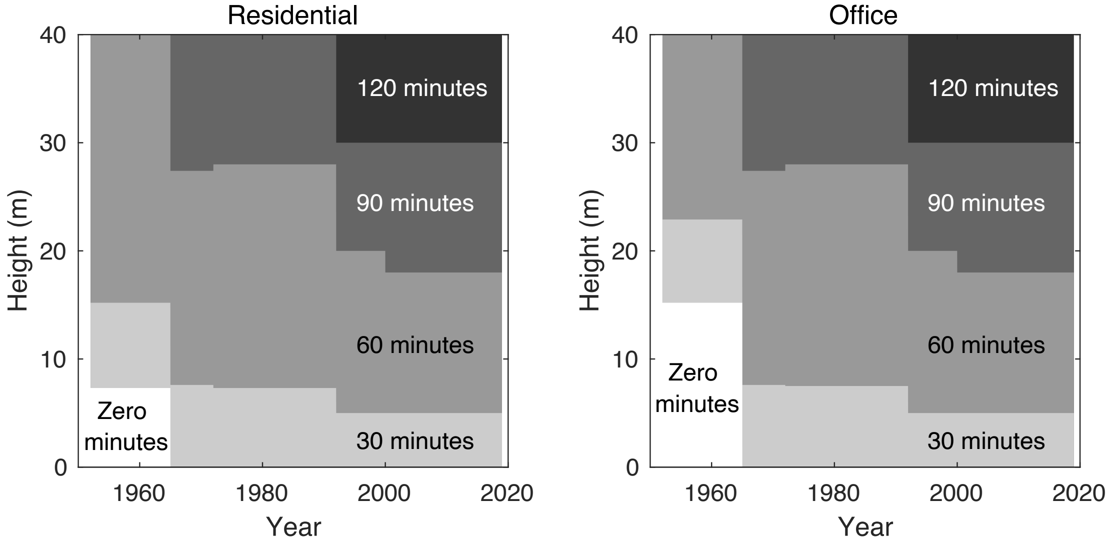

Figure 2 Changes in the required or, latterly, recommended periods of *fire resistance* in English legislation and guidance since 1952. Note that where building size was expressed in terms of storeys (e.g. the 1972 residential regulations), these plots were created on the assumption of 12 feet (3.66 metres) per storey.

The 1992 revisions to Approved Document B [35] introduced the most significant changes to the recommended *fire resistance* periods since the demise of the Model By-laws. At the time, the most controversial appears to have been the recommended use of sprinklers as a trade-off to allow a reduction in the recommended period of *fire resistance* [36]. However, also notable was the introduction of a new 120 minute performance category for buildings with a storey height over 30 metres. The 'trigger height' for 90 minutes *fire resistance* was also changed to 20 metres.

The rationale for these changes sat firmly within the logic presented in Fire Gradings. Writing in 1990, Ian Smith noted that 'one would expect fire resistance to increase with building height in order to ensure the stability of the framework for people escaping, or for those who might remain in a building designed with phased evacuation' [37]. Notably, Smith also stated that 'fire severity is independent of building height' and therefore the 'increase in fire-resistance period as a consequence of height achieves an increased factor of safety' [37].

However, the recommendation for buildings above 30 metres to provide 120 minutes of *fire resistance* originated not with a rigorous analysis of the fire risks and associated safety factors. Rather, it appears to have originated with an attempt to reach a compromise between the Building Regulations Advisory Committee (BRAC) and London's District Surveyors. While England's Building Regulations were national, London's Local Acts and By-laws had allowed for local variations in some aspects of fire safety design. By 1991 the London Building (Constructional) By-laws [38] had been repealed, but the London Building Act [39] still allowed local authorities to require additional fire safety measures to be specified in buildings that were taller than 30 m [40] (or previously 100 feet). At the time there was a desire to synchronise the national and local approaches – and to reconcile the differences between the national and local expectations [41,42].

The London Building (Constructional) By-laws had required that, irrespective of height, the external wall with an adjoining building should have a period of 120 minutes *fire resistance* – and that 'party walls' should provide four hours of *fire resistance* (defined additively as two 120 minute walls). This requirement originated with the Fire Grading Committee (see paragraph 182 of *Fire Grading of Buildings*). Similarly, Greater London Council guidance to section 20 had required that office buildings over 100 feet (30.48 m) should have a *fire resistance* of 120 minutes (for elements other than floor slabs) [43]. However, the Approved Documents recommended that separating walls should have a period of *fire resistance* equal to that of the other elements of structure – and that this should change with height. At the time of the redraft in 1991, ADB therefore specified a lower standard of *fire resistance* for offices or for building separation than previously required by London's legislation. The 120 minute period of *fire resistance* in ADB therefore originated as an attempt to find a compromise between BRAC and the London District Surveyors association; this being that, for tall buildings, the former London By-law requirements in relation to *fire resistance* for building separation would be maintained.

Hinting at this lack of technical rigour when summarising the periods of *fire resistance* in the proposed revisions to the approved document, Smith noted that the new revisions 'do not provide any clue to the level of safety which is required to meet the criterion of "stability for a reasonable period"' [37].

Nevertheless, despite Smith's apparent uncertainty about true performance (i.e. 'levels of safety'), the periods of *fire resistance* that were/are enabled by English fire safety legislation continue to support the key ideas first set out by the Fire Grading Committee. The key evolution in the performance requirements for elements of structure in different types, heights, areas, and occupancies of buildings, appears to have been that, over time, legislators have sought a higher (albeit unquantified) level of certainty that buildings would, in fact, endure a burnout fire. Thus, the 60 minutes of *fire resistance* that was originally proposed as being sufficient to endure burnout of an 'average' home or office fire was increased to achieve some higher factor of safety. The higher the building, the more regulators apparently hoped to protect against fires that were not 'average' – whether they recognised that this is what they were doing, or not.

In Scotland – where the promulgation through national regulation was first initiated – a similar process of evolution followed. The individual tables in the relevant legislation have a greater number of categories, so do not lend themselves to presentation in the manner of the English guidance (i.e. as in Figure 2). However, it is notable that in 2001 a rationalisation process was undertaken whereby the *fire resistance* requirements stated within the Scottish Technical Standards [44] – the Scottish statutory guidance that serves a similar purpose as the approved documents in England – ceased to be expressed as a period of minutes, but rather as one of three categories, namely ‘short’, ‘medium’, and ‘long’. These changes originated with Paul Stollard, who at the time of the changes was a senior civil servant at the Scottish Executive. His changes resulted in a regulatory system that bears a striking resemblance to the three categories originally proposed by Sachs (temporary, partial, and full protection). Stollard’s use of ‘words’ rather than ‘numbers’ to express the required structural fire performance also represented a reversal of the approach advocated by Woolson. Stollard’s logic was that ‘we must get away from numbers’ because of the confusion this generated about how long a structure would last in a real fire [45].

Thus, in Scotland, the requirements were greatly simplified and the widely – and falsely – perceived direct link between *fire resistance* time, and time in a *real* fire was weakened. Buildings below 7.5 metres were recommended to have a ‘short’ *fire resistance* duration; buildings between 7.5 and 18 metres were recommended to have a ‘medium’ *fire resistance* duration; and buildings between 18 and 60 metres were recommended to have a ‘long’ *fire resistance* duration. Above 60 metres, no recommendation was made, since such buildings were (and still are) considered to be explicitly outwith the scope of the Scottish Technical Standards/Handbooks.

Table 1 Changes in the required or, latterly, recommended periods of *fire resistance* in English legislation and guidance since 1952. Note the change in units for *fire resistance* period in 1992 is as per the change in the relevant regulation/guidence.

	Residential				Office		
Date	Height in feet (up to)	Height in meters (up to)	Height in storeys (up to)	*Fire resistance*	Height in feet (up to)	Height in meters (up to)	*Fire resistance*
1952 [28]			Two	0	50	15.2	0
	50	15.2		0.5	75	22.9	0.5
	Over 50	Over 15.2		1	Over 75	Over 22.9	1
1965 [30]	-	-	-	-	25	7.6	0
	25	7.6		0.5	25	7.6	0.5
	90	27.4		1	90	27.4	1
	Over 90	Over 27.4		1.5	Over 90	Over 27.4	1.5
1972 [46]	-	-	-	-	24.6	7.5	0
			Two	0.5	24.6	7.5	0.5
			Three	1	49	15	1
	91.9	28	Any	1	91.9	28	1
	Over 91.9	Over 28	Any	1.5	Over 91.9	Over 28	1.5
1976 [47]			Two	0.5	24.6	7.5	0.5
			Three	1	49	15	1
	91.9	28	Any	1	91.9	28	1
	Over 91.9	Over 28	Any	1.5	Over 91.9	Over 28	1.5
1985 [34]			One	0.5	24.6	7.5	0.5
			Three	1	49	15	1
	91.9	28	Any	1	91.9	28	1
	Over 91.9	Over 28	Any	1.5	Over 91.9	Over 28	1.5
1992 [35]	16.4	5		30	16.4	5	30
	65.6	20		60	65.6	20	60
	98.4	30		90	98.4	30	90
	>98.4	>30		120	>98.4	>30	120 (requires sprinklers)
2000 [48]	16.4	5		30	16.4	5	30
	59.0	18		60	59.0	18	60
	98.4	30		90	98.4	30	90
	>98.4	>30		120	>98.4	>30	120
2019 [49]	16.4	5		30	16.4	5	30
	59.0	18		60	59.0	18	60
	98.4	30		90	98.4	30	90
	>98.4	>30		120 (requires sprinklers)	>98.4	>30	120 (requires sprinklers)
2020 [50]	16.4	5		30	16.4	5	30
	36.1	11		60	36.1	11	60
	59.0	18		60 (requires sprinklers)	59.0	18	60
	98.4	30		90 (requires sprinklers)	98.4	30	90
	>98.4	>30		120 (requires sprinklers)	>98.4	>30	120 (requires sprinklers)

4.2. Trigger Heights

In documenting how the ‘trigger heights’ for the required *fire resistance* standards has changed over time, there are various ‘magic numbers’ that occur – and recur. The origin of these numbers is not always clear and (as shown above) is often the result of some compromise. However, there are some numbers whose origin is well documented. In many cases, the key consideration for defining trigger heights appears to have been the capacity of the fire and rescue service to effect occupant escape using external ladders.

Sixty feet does not appear directly in Table 1; however its metric equivalent, 18 metres, appears in 2000 and had been a recurring feature of codes and legislation for many years (e.g. see CP 3 Chapter IV 1971 [51]). The 1861 Tooley Street fire, during which James Braidwood (the head of the London Fire Establishment) was killed, is commonly cited as being the origin of a cube of 60 feet (216,000 cubic feet) as the ‘maximum size for a compartment that could be safety fought with any degree of success’ [52]. However, the 216,000 cubic feet rule actually predates Tooley Street and was enacted in the 1855 Metropolitan Building Act [53] as a result of lobbying by Braidwood [54,55]. Sixty feet was used in the London Building Act 1894 [56] in relation to the height above which additional measures should be required to facilitate egress ‘at the top of high buildings’ [57]. At the time, it appears that the logic was that above this height rescue by the fire service would not be possible and that the fire would be difficult to fight given the size of the building. Domestic buildings above this height were also required to be constructed from ‘fire-resisting materials’ [58].

However, while 60 feet was initially the trigger height for the London Building Acts, it was recognised that this number had little practical value for egress – as the wheeled fire escape ladder that was used by London Fire Brigade was 55 feet long, and could only reach up to a vertical height of 50 feet (15.2 metres) [59]; fire fighters were therefore unable to effect rescue from the uppermost storeys of a 60 foot high building. Accordingly, the trigger height was reduced to 50 feet in subsequent amendments [60]. These two values were picked up in 1952 by the Fire Grading Committee which noted that the length of a contemporaneous wheeled fire escape ladder was only 50 feet long, and it could therefore only be used for affecting from a maximum height of 42 feet (12.8 metres) – because it would need to be placed at an angle [61]. Eighteen metres as a trigger height is therefore historically tied to fire-fighting techniques and equipment of 1850s – and the original 50 feet from the 1952 by-laws appears to be directly linked to the height of a wheeled escape ladder.

The London Building Acts are (as described in Section 4.1) also the origin for the 30 metre trigger height that is present in current guidance. However, the early London Building Acts set this thresholder at a lower level. In 1894 buildings were allowed to rise vertically from street level to a height of 80 feet high, with an additional two storeys in a diagonally sloped roof. This approach intended to ensure that there would be sufficient light and air at street level, and was motivated by a desire to temper the ‘increasing mania of putting up immense blocks of lofty buildings’ [62]. In total, this meant that the practical height that was achievable under the 1894 Act was 100 feet [63]. Buildings rising vertically more than 80 feet were not permitted without special consent from the Council [64].

By the 1920s there was significant commercial pressure for the maximum height of buildings to be increased [65]. In addition to aesthetic objections, one recurring obstacle to allowing taller buildings was that the fire service were not able to ‘throw an effectual jet’ more than 100 feet high [63]. Indeed, in 1920 the then president of the RIBA remarked that ‘it is grotesque that architecture and its development should be restricted by the height to which the Fire Brigade can squirt a stream of water’ [66]. Nevertheless, the 1930 London Building Act (which was essentially a consolidation of previous legislation) retained the previous height limits [67]. It was not until 1935 that a review committee determined that maximum height should be increased to 100 feet [39]. The basis for the new height limit was, again, related to the environment on the street rather than any particular fire concerns. Indeed, the committee stated that ‘the indictment “danger from fire” always sounds impressive, but on examination will not bear the tests of analysis’ [68]. They opined that ‘in modern fire-resisting buildings risks have been reduced to a minimum’ and that ‘the extreme hazards to life attributed to possibility of fire are therefore unlikely to materialise so far as new buildings are concerned’ [69]. Having set the limit at 100 feet to ensure adequate light to the street below, it was then conceded that if buildings were proposed above this height, additional fire safety measures could be sought by the council.

5. Critics and Detractors

The narrative thus far has illustrated the origin and rise to dominance of prescribed periods of *fire resistance*. However, over the course of its history there have been many criticisms made of this approach to fire safety design of structures. These fall into three categories:

1. criticism of the standard heating curve (i.e. it doesn’t look like a real fire, it lacks a decay phase, etc.);
2. criticism of standard fire testing furnaces (i.e. the furnace is a poorly controlled and variable test method, the thermal and mechanical boundary conditions are unrealistic, system effects and interactions are ignored, etc.); and
3. criticism of the equivalent severity method (i.e. Ingberg’s approach was physically wrong, and fails to account for a range of relevant factors which are now well understood to influence fire dynamics in compartments, and structural outcomes in real buildings).

All of these criticisms are, of course, justified. Over decades, much research effort has gone into attempting to correct these maladies whilst avoiding more substantive or fundamental changes to the existing *fire resistance* framework for structural fire design. For example, the plate thermometer was introduced (in Europe [70] but not in the USA [16]) as a method of furnace control in an attempt to better harmonize thermal exposures in furnaces, and innumerable so-called ‘time equivalence’ methods [22] were developed and codified in an attempt to address various deficiencies with Ingberg’s original ‘equal area' equivalent fire severity approach.

However, perhaps even more notable than the specific criticisms of standard furnace testing is the list of esteemed individuals of who have voiced them. Many of the ‘luminary’ figures in fire safety science and engineering have, at various points in their careers, taken issue with one or more aspects of the standard testing framework and method of prescribing periods of *fire resistance*. The names Harmathy, Lie, Kawagoe, Thomas, and Law command unrivalled reverence within the fire science community, yet they all strongly criticised the concept of *fire resistance*.

> ‘... in a strict sense standard ‘fire resistance’ is not a measure of the actual performance of an element in fire, and it is not even a perfect measure for comparison… the fire load concept must be abandoned; the fire test must

> become a truer representation of the conditions that probably will be met under particular circumstances.'
>
> - Harmathy & Lie, 1970 [71]

> '…(my future ambition is) to abolish the fire resistance test.'
>
> - Kunio Kawagoe (likely 1970s, via Phillip Thomas) [72]

> 'The standard temperature-time curve is not representative of a real fire in a real building – indeed it is physically unrealistic and contradicts available knowledge of fire dynamics.
>
> The required duration of fire exposure in the standard test (or the time-equivalent exposure) is open to criticism on a number of grounds and should be revisited.
>
> The loading and end conditions in the standard test are not well defined – and clearly cannot represent the continuity, restraint, redistribution, and membrane actions in real buildings.'
>
> - Margaret Law (1981) [73]

> 'It is suggested that time equivalent is not a useful parameter for design purposes'
>
> - Margaret Law (1997) [22]

6. A Test of Endurance

Despite the objections of these luminaries, the concept of *fire resistance* remains as firmly embedded in UK regulation (and indeed in regulations around the world) as it has ever been. Although virtually every aspect of the *fire resistance* framework's approach can be (and has been) legitimately challenged, *fire resistance* is an idea with such strong inertia that it has proved extraordinarily resilient to reasoned and legitimate criticism. The possible reasons for this persistence are rooted in a combination of factors.

6.1. High Severity

Sachs and Woolson explicitly designed the standard furnace test and selected the standard temperature versus time curve to generate what they considered to be an extreme scenario. In doing so, the intention was to make the conditions in the fire testing furnace very challenging for any structural element. Many authors have subsequently demonstrated that the gas temperatures in real compartment fires can be higher (e.g. [74–76]), or that differing rates of heating can have significant impacts on structural performance for different structural systems (e.g. [77]). Nevertheless, the furnace test is sufficiently extreme that, if a structure is able to endure a substantial period of heating in a *fire resistance* test, then it is usually fair to say that it has some beneficial fire resisting qualities that will be of use to a structure experiencing a real fire. It is also true that a structural element that has more *fire resistance* in a furnace will very likely exhibit better performance in a real fire, all other factors being equal, and provided that the structure itself would not contribute fuel during a real fire.

Thus the standard furnace test, for all its failings, does provide a form of proxy assessment of the qualities from which a structure would be likely to benefit in a real fire. For many common structures there is therefore an inherent utility embedded within the *fire resistance* framework.

6.2. Validity through Usage

More than a century of testing with the standard temperature versus time curve in standard fire testing furnaces internationally means that a huge volume of both proprietary and research literature exists regarding the performance of different structural materials and configurations in a furnace test. This literature has spawned a litany of design and 'simplified' methods for structural fire 'design'. While these data have numerous limitations, they are clearly not devoid of value; a century of experience with the furnace as a proxy for real fires means that engineers have learnt *something* about how to protect structures from severe fires.

Furthermore, while there have been instances of significant structural failures in fires – these have historically been rare. It is possible that this is partly because building fires themselves are comparatively rare (and severe fires even rarer), but the isolated cases of catastrophic structural failures in fires suggest that, much of the time, the lessons learnt from the proxy test may be *good enough*. There are, of course, the exceptions where the real fires have brought the failings of the proxy test into sharp relief – element interactions leading to catastrophic failure at World Trade Center towers 1, 2 [78], and 7 [79], unconventional load paths in the Broadgate Phase 8 fire [80], and cooling behaviours leading to structural failure (and loss of life) of a car park in Gretzenbach, Switzerland [81], to name only a few examples.

The case for *validity through prolonged usage* suggests that if both the structure and fire are not too unusual, uncommon, or innovative, then the lessons learned from the proxy test may well suffice in practice.

6.3. Burnout

As has been described in this paper, the *fire resistance test* is only one part of the broader *fire resistance framework*. The idea of resisting a burnout fire has been a central philosophical aspect of the endeavour of *fire resistance* since its inception in the gardens of Westbourne Lodge. Subsequent steps in the story of *fire resistance* have periodically reinforced the idea of designing high consequence structures to resist burnout. In the UK, legitimate uncertainty over how much *fire resistance* was required to resist burnout – and the desire of regulators to ensure that burnout could be achieved, and spread of fire avoided – has led to the gradual ratcheting up of the recommended periods of *fire resistance*, particularly for ever taller buildings.

Similarly, Sachs' idea that for certain buildings *some fire resistance* was better than no *fire resistance* has also endured to the present day. The idea of 'temporary' or 'partial' protection is firmly embedded within UK statutory guidance. Thus, the concept of *fire resistance* can be used to service two *very different* objectives – both of which have a useful function in building design.

6.4. Proxy Metrics of Structural Behaviour and Performance Specification

The fact that the test is a proxy for useful structural qualities also contributes to the inertia of the *fire resistance* test. The test does not directly measure structural behaviour but relies on deflection as a proxy for all aspects of mechanical performance. As a consequence, it is difficult to assess whether a *fire resistance* test does (or does not) adequately represent the performance of a structural element within a real system.

Similarly, while the qualitative objective for structural performance is clear based on the discussion above (that it should resist a burnout, or that it should do *something*), the quantification of these objectives is much less clear. In the absence of a clear expression of what constitutes *adequate* structural performance in a fire, the fire resisting framework provides a mechanism by which those with responsibility for meeting the requirements of the regulations can avoid addressing this more fundamental question; indeed they are unlikely to be equipped to even begin to answer it. Inertia is therefore generated as a function of uncertainty about the true objective for structural performance.

7. Conclusion

Edwin Sachs' idea of *fire resistance* has proved extraordinarily powerful and resilient within the collective psyche of regulators and the construction professions. Its power has grown with time – initially derived as a means of comparing candidate fire protection systems, it was standardized in the USA by Woolson, and then given the appearance of scientifically quantified underpinnings by Ingberg. Empowered by the legislative and regulatory systems that emerged during the post-war period, *fire resistance* appears to now be fundamentally immovable within the UK's fire safety regulatory frameworks.

Some of the sources of *fire resistance*'s power have been discussed in this paper, leading to the conclusion that *fire resistance* may serve one of two fundamental, yet different, objectives in relation to building designs, namely:

1) that a structure should resist total burnout of the available fuel load – this is Sachs' definition of 'full protection'; or, alternatively,
2) that a structure should not resist burnout, but should do *something* to facilitate occupant evacuation or support the fire and rescue service's activities – this is Sachs' definition of 'temporary' or 'partial protection'.

In the UK, where statutory guidance recommends 30 minutes as a period of *fire resistance*, it appears to be implicit that these buildings are not generally expected to resist burnout. Where statutory guidance recommends more than 30 minutes *fire resistance* (for offices or residential buildings), it is implicit that burnout resistance is 'expected'. Higher periods of *fire resistance*, such as 90 or 120 minutes, are intended to ensure, with ever greater confidence for greater durations of *fire resistance*, increased factors of safety accounting for inherent uncertainties in the available fuel load and fire dynamics.

Beyond these general statements of intent, the specific numbers (or durations) that are defined with UK guidance for *fire resistance* do not represent a careful balancing of risks, or a detailed consideration of fire scenarios or structural responses. Rather, they are a knowing approximation; the product of uncertainty and compromise between competing interests and motives. Over time, the recommended periods of *fire resistance* have evolved – each evolution simply reflects the need for a new compromise or a changed set of motivations or political or economic circumstances. The most explicit regulatory embodiment of this approximation is the relatively recent evolution of the Scottish regulatory approach – the use of 'short', 'medium' and 'long' in place of minutes to describe requirements for *fire resistance*.

That the *fire resistance* periods defined in UK guidance represent the product of uncertainty and compromise is not intended to be read as a criticism – this is merely a factual statement based on a historical review of their origins. Indeed, despite the numerous criticisms levelled against *fire resistance* by various luminaries of fire science, the evidence suggests that for *most* buildings and for *most* fires – the *fire resistance* framework has been good enough. It is only for *unusual* buildings, or *unusual* fires that the flaws in the *fire resistance* framework may become acutely evident. The challenge for designers is to identify which buildings may result in structural behaviours or fire dynamics that are not adequately addressed by the approximations and compromises of the *fire resistance* framework. This challenge is compounded by the fact that the *fire resistance* framework provides no explicit definition of what kinds of buildings are *usual*, nor does it suggest to a designer the conditions under which a fire (or a structure) should be considered *unusual*. Which design proposals fall outwith the scope of the available guidance is therefore difficult to define; even harder, perhaps, is to identify which design proposals fall *within* the scope of the available guidance.

It is hoped that this paper may help to 're-establish the rationale behind the rules' [82], and assist those with responsibility for meeting the requirements of the building regulations to consider for themselves whether following the guidance in the approved documents (or technical handbooks in Scotland) is likely to be sufficient to discharge their responsibilities as construction professionals.

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