Fire Performance of Heritage and Contemporary Timber Encapsulation Materials

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Abstract

Cultural heritage buildings are often recognized for holding significant heritage value; however, too often these structures are lost to fire. Timber is a building material commonly found in cultural heritage buildings, and for centuries encapsulations have been used in an attempt to improve the fire performance of timber. The research examines the history and evolution of encapsulating timber to improve its fire performance, through analysis of archival literature dating to over 200 years ago, as well as, for the first time, evaluate the fire performance of bench scale samples of these historic and reproduced encapsulations with controlled and repeatable fire testing. The purpose of these tests is to truly understand successes and failures of these protective measures and to assist architects and engineers who may encounter these dated protective coating measures on timber. Plasters, metal plates, lime-based paints, and gypsum boards were all tested using a Cone Calorimeter apparatus, following an adaptive ASTM E1354 procedure. Heat release, material decomposition, charring, and ignition of timber were all analyzed. Results show that the plasters and gypsum board performed similarly, although historic plasters did not stay attached to the wood substrate post-testing, making them impractical for building applications. The iron plate still allowed heat transfer into the timber, provoking measurable char depth. Finally, the lime-based paint delayed timber ignition by only 20 seconds. These results indicate that none of the historic encapsulations significantly improved fire performance, and they therefore cannot be relied upon for fire protection if they are found in a heritage structure. While such encapsulations may still need to be left in-place from a heritage conservation perspective, other passive and active strategies might need to be implemented into the structure to ensure its fire performance and enable its successful conservation.

Keywords: Cultural heritage, architectural engineering, timber, encapsulation, historic materials, gypsum board, plaster, metal plates, fire performance, coatings

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1. Introduction

Cultural heritage buildings can be found worldwide and are often recognized for their heritage value, cultivating a high amount of public interest. Frequently, these buildings serve as excellent exemplars of historic construction methods or may be tied to a historically important person, event, or lifestyle. Furthermore, heritage buildings may hold cultural, social, spiritual or scientific importance [1]. These buildings pose a unique challenge to fire safety, as along with the usual considerations (such as life safety and operational resilience), the conservation of the heritage structures themselves is also very important. Historic buildings are often vulnerable to fire as the fire protection system may be reflective of the technologies used at the time of construction. They are also frequently subjected to renovation and conservation projects, which pose an additional fire risk to the building. Occasionally, they are not as well-maintained as they could be, prompting acts of arson. Since 2008, there have been several high profile losses of heritage structures. A small sample of these are documented in Table 1. It can be seen from this compilation of fires that arson and accidental fires are major causes for concern for heritage buildings, with several notable losses of buildings that are hundreds of years old and hold heritage value. It should be noted that while the Notre Dame Cathedral was constructed in the 12th-14th century, significant changes and restoration work occurred in the 19th century to portions of the building that were involved with the 2019 fire.

Table 1. Recent fires within heritage buildings

Name	Location	Construction Year	Fire Year	Fire Cause
Alma College	St. Thomas, Canada	1878	2008	Arson
Namdaemun gate	Seoul, South Korea	1398	2008	Arson
Quebec City Armoury	Quebec City, Canada	1887	2008	Accidental
Provo Tabernacle	Provo, United States	1898	2010	Accidental
Glasgow School of Art	Glasgow, UK	1909	2014	Accidental
Glasgow School of Art	Glasgow, UK	1909	2018	Unknown
National Museum of Brazil	Rio de Janeiro, Brazil	1803	2018	Accidental
Notre Dame Cathedral	Paris, France	1163-1345, with significant changes and restoration in the 19th century	2019	Under investigation

From a heritage conservation standpoint, it is advantageous to avoid altering a heritage building in a way that changes elements that define the character of the place (known as character-defining elements). The character-defining elements are unique to each particular heritage building but often includes the structural system. Furthermore, early fire safety strategies may be seen as representing the technology of the time period and may have heritage value in their own right. Heritage guidance suggests against the removal or covering of the character-defining elements and heritage value of a building where ever possible [2].

Timber is especially vulnerable to fire due to its combustible nature. For centuries, building owners and engineers have been implementing methods meant to make timber buildings more secure from fire. Often these strategies involved covering up (encapsulating) the timber with another material meant to improve its fire performance. While the encapsulation materials may have changed through time, this practice is still done today, examples being gypsum products in North America that are commonly recommended for enhancing the fire performance of a timber assembly [3]. A sample of commonly encountered historic encapsulation materials include plasters, metal plates, and lime-based (whitewash) paints. See Fig. 1 for example of an 18th century mill plated with metallic plates covering timber. Note that the plates in this building are by heritage designation not to be removed in renovation.

Fig. 1. Metallic plates installed since the 18th century structure, believed to make the structure incombustible

The primary purpose of the research herein is to investigate and understand commonly found encapsulation technologies in historic timber buildings. This will be achieved, for the first time, through a comprehensive recovery and analyses of primary literature created during the time period these encapsulation materials were originally developed (majority of articles dating over 200 years ago, and subsequently not transcribed until today). Recognizing that fire testing was in its infancy in terms of scientific quality when these coatings were installed, for those that encounter these protection systems the authors seek to introduce how these historic and contemporary encapsulations perform in high temperature conditions. This will be done with controlled and repeatable experiments of reproduced samples bench marked to common day gypsum encapsulation technologies following the ASTM E1354 standard [4]. We conclude our study with preliminary guidance and research needs forward for the engineering conservationists who encounters these coatings in practice. These findings will help in understanding the progression of the use of timber encapsulations through history, explaining how we have arrived at current practices today, and to assist current architects and engineers who may have to comment on the coatings relative inefficiencies or efficiencies.

2. Background and History of Timber Encapsulations

For centuries, encapsulation materials have been used with the intent of improving the fire performance of a timber assembly. They do this by creating first an incombustible barrier to the timber, but later evolving to perform as a heat transfer barrier. A number of these encapsulation technology methods will be reviewed in the following section; including metal plates, plasters, whitewash paints (chosen as they are found in heritage constructions), and gypsum board (chosen for contemporary bench marking). A timeline of early mentions and descriptions of these encapsulations is seen in Fig. 2.

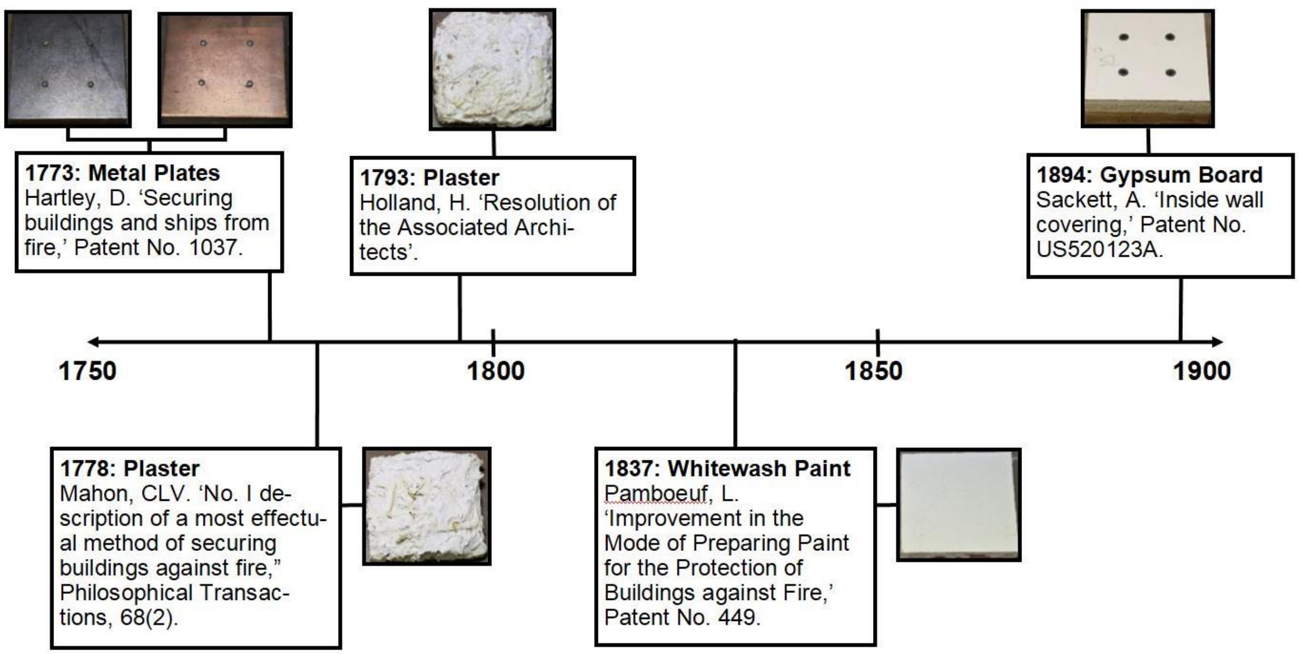


Fig. 2. A timeline of early mentions of encapsulation methods for improving the fire performance of timber assemblies

It is of interest to the reader that many other early 18th and 19th century fire protection technologies can be found in early construction (for example the Roebling System, the Barret-Fox floor), our paper's scope is to consider technologies that were explicitly used for timber-based systems, and those that the authors have encountered in practice. It is by no means a full comprehensive listing of all possible coatings, our procedures may be adaptable should the conservationist encounter alternative technologies.

Prior to the use of documented encapsulation methods, timber buildings have long been left exposed. An exposed heritage timber building is seen in Fig. 3. In the late 18th century, a group of well regarded architects formed a committee (known as the Associated Architects) to deal with the fire problem that they believed was disrupting London, UK, and other cities [5], this committee was formed in response to a recent theatre fire. This association would be later viewed as the precursor to Royal Institute of British Architects (RIBA). Led by Henry Holland, they aimed to identify the causes of the recent conflagrations, as well as methods of preventing similar fires from occurring in the future. The Associated Architects, as they called themselves, described and instructed the use of metal plates and plasters for use as fire protection encapsulations.

Holland also tested and reported on encapsulation methods such as Hartley's metal fire plates and Mahon's plaster, performing six fire tests on each encapsulation. The tests generally consisted of applying the encapsulation to walls, floors, or staircases, and exposing the setup to a seemingly arbitrary fire severity [5]. Holland then described the post-fire state of the assemblies, mentioning the extent and location of the charring. A comprehensive tabulation of Henry Holland's experiments, for the first time to the knowledge of the authors, may be found in Appendix A. Due to insufficient quantification in Holland's reports, and as the testing procedures were not of a standardized nature and ad-hoc in principal, the information included in Appendix A is included for historical interest only and should not be construed as test results that can be applied in practice. In the following centuries, other encapsulations were created, including whitewash paints and, more recently, gypsum board.

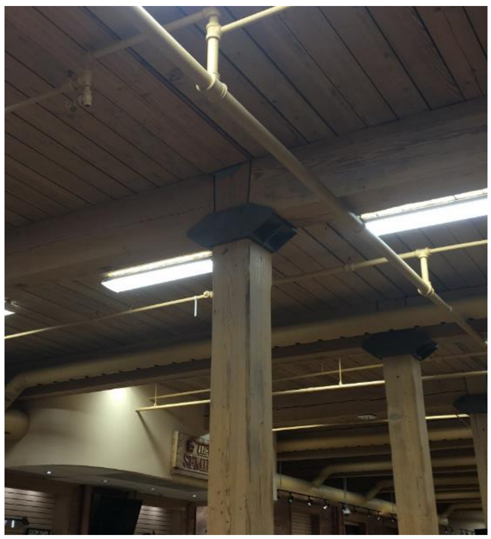


Fig. 3. An exposed timber building, with a timber ceiling, as well as timber beams and columns connected by a cast iron cap. This structure is located in Toronto, Canada, and was constructed in 1902 as a warehouse (but is currently being used for commercial retail purposes)

2.1 Metal plates

The use of metal plates as an encapsulation for improving fire performance was described by David Hartley in 1773 in his English patent, "Securing buildings and ships from fire" [6]. In his method, Hartley describes the use of metal plates to prevent fire and air currents from reaching the encapsulated material. Hartley's suggesting fire plates of iron, as well as copper as a more expensive option that he believed would not rust [7]. Arguably, Hartley can be credited as receiving the first governmental grant to study fire protection systems as he was awarded as a member of the UK Parliament. Fire testing of the metal plates occurred more pronouncedly by Hartley in 1792, largely consisting of lining timber elements and buildings with the metal fire plates, exposing them to a fire of arbitrary severity, and observing the damage

[5,8]. By 1793 the metal plates are deemed 'effectual' by the Associated Architects [5]. Today, there is a monument (consisting of an obelisk with inscription) commemorating the site where Hartley performed his first fire tests – arguably the first documented fire tests in 1776. This monument is seen today in Fig. 4 and is a grade 2 heritage structure. The structure in which he tested his plates is no longer in existence.

Fig. 4. Monument on the site of Hartley's fire plate tests at Putney Heath (authors site visit)

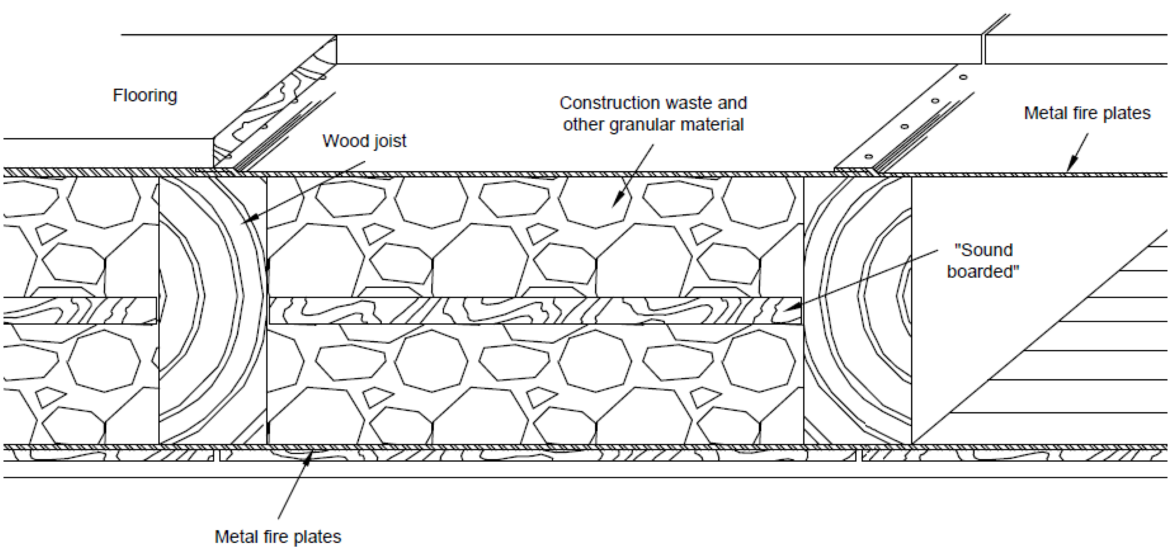


Fig. 5. An alternative configuration of installing metal plates on wooden joists (as adapted from [9])

2.2 Plasters

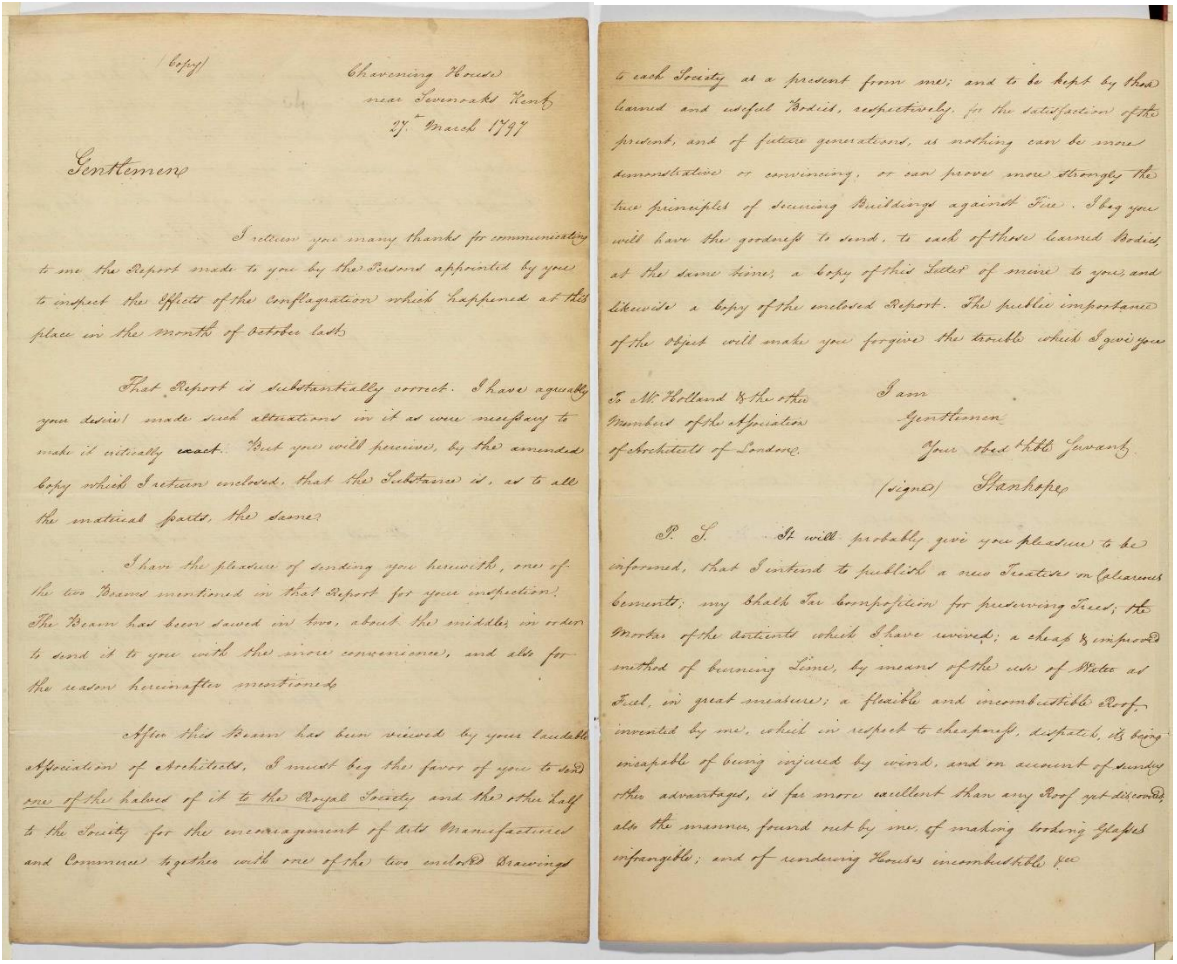
The use of plaster as an encapsulation material was also discussed by the Associated Architects [5]. The use of plaster was originally proposed by Charles Mahon (3rd Earl Stanhope) and was later recreated and modified by Henry Holland. The plaster by Mahon was first published in the Philosophical Transactions Journal in 1778 [10]. Mahon carefully outlines the proportions and ingredients of the plaster, as well as the proper method of application in a house, by "underflooring, extra lathing, and inter-securing" [10]. Mahon also performed fire tests of his plaster, and the results of the experiments were also published in 1778. Similar to Hartley's tests, they mostly comprised of using the encapsulation to cover timber members and exposing the assembly to an arbitrary fire [10]. Henry Holland and the Associated Architects deemed Mahon's plaster to also be 'effectual', but believed there was more liability for injury than Hartley's metal plates as it seemed to fall off in most tests performed (see Appendix A) [5].

After the release of Holland's report in 1793, Mahon forwarded a letter to the Royal Society via the Associated Architects in 1796. This letter can be seen in Fig. 6. The letter was in response to a fire at Mahon's residence, Chevening House where Mahon's plaster was used (which still stands today). Charles Mahon was prompted to forward a beam with attached plaster from Chevening House fire for their inspection. The letter and beam were sought to be lost, indeed the beam has since been discarded; however, the letter was found by the authors for digitization and contemporary analysis.

The letter explains that Mahon forwarded with his letter a beam from Chevening house that had been cut in two, about the center. He asked the Association of Architects to forward half of the beam to the Royal Society and the other half to the Society for the Encouragement of the Arts, Manufactures and Commerce. Mahon hoped that these societies would keep these beams for the education of the society members, present and future, to prove his method of securing buildings from fire.

Henry Holland, in the report of the Associated Architects, expands upon the Mahon's plaster through the suggestion of several additives in 1793. The possible additives suggested include "plaster of Paris, brick rubbish, coal ashes, or any other materials that will form a cement when mixed with hair or chopped hay" [5].

Following Holland's study of these technologies, in 1794, both Mahon and Hartley's technologies were used in the construction of the floors and stairs in the mostly timber-framed Drury Lane Theatre (Theatre Royal) in London, UK designed by Henry Holland as architect [11]. The Drury Lane Theatre was considered the most advanced fire-proofed building of the time. Four water reservoirs were also installed on the roof in order to suppress fire should it occur (akin to a sprinkler system). However, during theatrical performances, these reservoirs served another purpose: the tanks were used to produce real waterfalls and lakes on stage – at the expense of fire-fighting. In 1809, the theatre caught fire while its water tanks were empty and the installed technologies were insufficient to protect the building. The building collapsed before 30 minutes – there was no reported life loss (Fig. 7). Following this fire, the authors have seen limited evidence that these technologies were used in buildings following 1810.



(Copy)

Chevening House
near Sevenoaks Kent
27th March 1797

Gentlemen

I return you many thanks for communicating to me the Report made to you by the Persons appointed by you to inspect the Effects of the Conflagration which happened at this place in the month of October last.

That Report is substantially correct. I have agreeably (to your desire) made such alterations in it as were necessary to make it critically exact. But you will perceive, by the amended Copy which I return enclosed, that the Substance is, as to all the material parts, the same.

I have the pleasure of sending you herewith, one of the two Beams mentioned in that Report for your inspection. The Beam has been sawed in two, about the middle, in order to send it to you with the more convenience, and also for the reason hereinafter mentioned.

After this Beam has been viewed by your laudable Association of Architects, I must beg the favor of you to send one of the halves of it to the Royal Society and the other half to the Society for the encouragement of Arts Manufactures and Commerce together with one of the two enclosed Drawings to each Society as a present from me; and to be kept by those learned and useful Bodies, respectively, for the satisfaction of the present, and of future generations, as nothing can be more demonstrative or convincing, or can prove more strongly the true principles of securing Buildings against Fire. I beg you will have the goodness to send, to each of those learned Bodies, at the same time, a Copy of this Letter of mine to you, and likewise a Copy of the enclosed Report. The public importance of the object will make you forgive the trouble which I give you

To Mr. Holland & the other
Members of the Association
of Architects of London.

I am
Gentlemen
Your obed.t hble Servant
(signed) Stanhope

P. S. It will probably give you pleasure to be informed, that I intend to publish a new Treatise on Calcareous Cements; my Chalk Tar Composition for preserving Trees; the Mortar of the Ancients which I have revived; a cheap & improved method of burning Lime, by means of the use of Water as Fuel, in great measure; a flexible and incombustible Roof, invented by me, which in respect to cheapness, dispatch, its being incapable of being injured by wind, and on account of sundry other advantages, is far more excellent than any Roof yet discovered; also the manner, found out by me, of making looking Glasses infrangible; and of rendering Houses incombustible &c

Fig. 6. Letter from Mahon dated 1796, to the Royal Society and Associated Architects, in response to a fire at Chevening House

Fig. 7. Drury Lane Theatre Fire (Prints from 1825)

2.3 Whitewash (lime-based) paints

Lime based paints, which will herein be referred to as whitewash paints, were another encapsulation technique used to enhance fire performance. Whitewash paint, which in its most basic form is the mixture of water and lime, was widely used in the 18th century, though there is little evidence that it was used for fire purposes at that time [12]. To the author's knowledge, the first documented use of whitewash paint for fire performance purposes appears in the 19th century. In 1837, Louis Paimboeuf filed a United States patent titled, “Improvement in the Mode of Preparing Paint for the Protection of Buildings Against Fire” [13]. In this patent, Paimboeuf describes a mixture primarily of water and slaked (hydrated) lime, with other possible additives such as alum, potash, and salt, as well as plaster of Paris if the whitewash is desired to be white, to help render wood incombustible [13].

2.4 Gypsum board

The precursor to gypsum board was first documented in the late 19th century and was then known as Sackett Board. In 1894, Augustine Sackett patented his inside wall covering [14]. In his patent, Sackett describes a board which is to be applied to the interior walls of rooms, made up of multiple layers of paper and calcined gypsum, which makes a firm and durable wall surface. Sackett also claims his invention to be fire-proof and discourages the use of any materials that soften when heated in the creation of the boards (such as ozocerite and bitumen) [14]. The images included in Sackett’s patent are seen in Fig. 8. Gypsum board is still used for fire purposes today, usually considered as a board with a non-combustible core (usually primarily of gypsum), with paper on the outer surfaces [15]. Today, current code provisions in Canada (the authors jurisdiction) allow for the use of multiple layers of Type X gypsum board to provide a fire resistance rating of 15-60 minutes to timber elements (provided that requirements for joints fastening are adhered to) [3]. In the 1921 column test series led by Simon Ingberg, gypsum board technologies were assessed for the first time to the standard fire [16]. While the academic community is still studying this technology with respect to installation and fall off in fire, it is relatively understood to its performance, and therefore the authors utilise this technology herein as the bench mark for evaluation of the previous technologies.

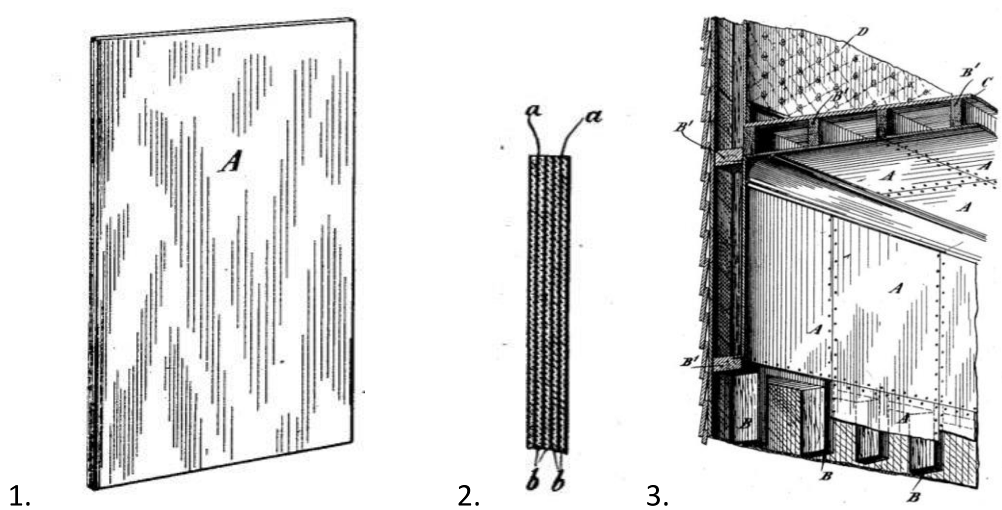


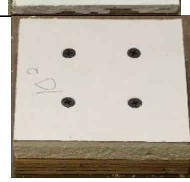
Fig. 8. Images from Sackett’s patent for an interior wall covering, 1. plan view, 2. cross-section view, showing built up layers of paper and calcined gypsum, and 3. possible applications of the boards. In this figure, ‘A’ denotes Sackett Board, ‘B’ and ‘B’ ’ denote vertical and horizontal framing respectively, ‘C’ is the floor, ‘D’ is a decorated wall, ‘a’ is layers or paper, and ‘b’ is layers of plaster [14]

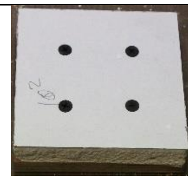
3. Experimental Methodology

The research herein will begin to look at how these encapsulation materials perform in fire using contemporary test methods. As mentioned in the previous sections, many of the historic encapsulations were not tested using any type of standardized method during their creation and have had dubious performance when considered in real installation and real fires. Six encapsulations were created or obtained and tested herein. Each of these encapsulations was applied to a 12 mm piece of plywood, of dimensions of 100 x 100 mm as required by the test apparatus in the ASTM E1354 standard. Plywood was chosen as a substrate for the encapsulations, as it is a contemporary material used today in wall and ceiling constructions. Solid wood could have alternatively been used as a substrate. The evaluation of the encapsulation systems is relative to the performance of the control, so the important element is that the substrate is kept common between all samples. All materials were allowed to acclimatize to laboratory conditions, and all plywood substrates had a moisture content of near 10% at the time of testing. For the metal plates and the gypsum board, the encapsulations were screwed into the plywood using one screw at each of the four corners, 30 mm from each side. An additional unencapsulated piece of plywood was also tested for comparison. The encapsulation compositions and original measurements are summarized in Table 2.

Table 2. Encapsulation compositions, photographs, and original measurements

Sample ID	Encapsulation Name	Photo	Thickness (mm)	Mass (g)
1A	Control		12.2	61.9
1B			12.0	61.9
2A	Mahon Plaster		23.9	202.2
2B			28.9	212.2

3A	Holland Plaster		27.4	219.9
3B			29.6	219.9
4A	Iron Plate		15.0	320.0
4B			15.0	320.0
5A	Copper Plate		15.0	364.8
5B			15.0	364.6
6A	Whitewash Paint		12.0	67.0
6B			12.0	70.0
7A	Gypsum Board		28.8	178.3

7B			27.8	164.0

Assumptions needed to be made in creating and procuring materials since the original inventors did not always provide all of the required information necessary to reproduce their materials and technologies. In creating the plasters, ratios of some of the materials were stated but it was not clarified whether the ratios were by volume or by mass – the authors made the assumption. It was decided to assume the ratios were by volume, as hay had the largest ratio but was the lightest material, and therefore it seemed unreasonable that the compositions would be by mass. Other materials included in the plasters were not assigned a ratio (particularly in the Holland plaster). It was decided to arbitrarily add half of one measure of each of the ingredients that was not assigned a ratio. Furthermore, the Hartley fire plates were described as being thin without an exact specified thickness. The thickness of the metal plates was therefore taken as 3 mm, correlating to the plate thickness found in a heritage building which used this method.

The whitewash paint was created by soaking the (hydrated) lime in 500 ml of water. The salt was also dissolved in 415 ml of water. The two mixtures were then combined. As previously mentioned, the gypsum board tested represents a modern gypsum board used today, rather than attempting to the replication of an original. The gypsum board can therefore be considered a contemporary encapsulation method (hence bench mark). The original descriptions of the encapsulation materials as compared to the materials tested is seen in Table 3.

A Cone Calorimeter apparatus was used for testing, following the ASTM E1354 standard. The Cone Calorimeter is an apparatus that uses a coiled radiant heater to expose a test sample to the desired heat flux [17]. This test setup can be seen in Fig. 9. The Cone Calorimeter apparatus is useful in allowing for controlled and repeatable tests. Each of the test specimens was exposed to heat for 5 minutes, at a heat flux of 50 kW/m^2. The heat flux was measured by the water-cooled heat flux meter of the Cone Calorimeter apparatus, calibrated according to ASTM E1354. The test severity was determined through trial and error, as an upper limit of what an unencapsulated piece of plywood can withstand before charring completely though its depth. After testing, the char depth was measured under the encapsulations. It is of note, that for practicality the authors did not extend testing beyond 5 minutes or at more severe testing, the authors utilised a material specific test to rank performances, further research could be done to explore performance of these materials against more severe testing, however as will be described in Section 4, most heritage material coatings performed rather poorly in short duration and low heat flux testing.

Table 3. Original descriptions of historic materials and the composition of materials tested

Encapsulation Method	Documented composition	Author's composition
Mahon Plaster	One measure rough sand Two measures slacked lime Three measures chopped hay Well mixed with water	300 ml Hydrated lime 150 ml Sand 175 ml Water 600 ml Hay
Holland Plaster	Mahon Plaster; with possible additions of: Plaster of Paris Brick rubbish Coal ashes Hair or chopped hay Any other materials which form a Cement	300 ml Hydrated lime 150 ml Sand 75 ml Brick 75 ml Plaster of Paris 75 ml Seashell 240 ml Water 600 ml Hay [1]
Iron Plate	Unvarnished or Varnished plates of metal	3 mm thick iron
Copper Plate	Unvarnished or Varnished plates of metal	3 mm thick copper
Whitewash Paint	1 Gallon Slaked Lime with Water 20 Pounds Alum 15 Pounds Potash 1 Bushel of Salt	500 g Hydrated Lime 965 ml Water 150 g Salt
Sackett Board/ Gypsum Board	4-10 Alternating layers of Manila paper or builders sheathing paper, and calcined gypsum or Plaster of Paris	1 layer 15.9 mm Type X Gypsum Board

[1] – Measures were taken by volume not by mass to replicate older procedures.

Fig. 9. Cone calorimeter apparatus, with flaming on the surface of a test specimen

4. Results

A summary of post-heating photos of all of the specimen is seen in Table 4. This table also describes the flaming behaviour, as well as the char depth recorded after testing. The char depth was determined visually by colour, by subtracting the depth of uncharred wood from the original sample depth. The charred portion of the wood was taken to be any portion that was black in colour.

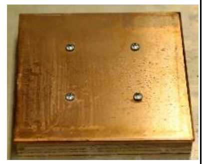
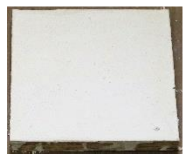
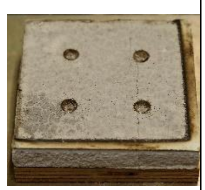
Other properties which were recorded include the heat release rates over time. These heat release rates can be seen in Fig. 10. This figure shows the heat release rates of the control sample, gypsum board, and whitewash paint. These three are the only samples that had flaming, and the peak heat release rates of the remaining samples were under 15 kW/m^2 and are therefore not included in this figure.

The final property which will be discussed is the mass loss of the samples. The mass loss over time for every encapsulation material is seen in Fig. 11.

Table 4. Post-heating images of each sample

Sample ID	Encapsulation Name	Post-Burn Photo	Char Depth (mm)	Flaming Observations
1A	Control	N/A[1]	N/A[1]	Immediate ignition, through to test completion
1B			11	
2A	Mahon Plater		0	No flaming, some smoke observed
2B			0	
3A	Holland Plaster		0	No flaming, some smoke observed
3B			0	
4A	Iron Plate		3	Flaming though screw holes
4B			2.5	

[1] Sample 1A was used to determine an appropriate exposure time and was heated for 15 minutes, at which point it had burned through. For that reason, char depth and post-burn photo are not provided.

5A	Copper Plate		0	No flaming or smoke observed
5B			0	
6A	Whitewash Paint		10	Ignition occurs 20 seconds after test begins, through to test end
6B			9.5	
7A	Gypsum Board		0	Flaming initially for 15 seconds, then no additional flaming or smoke

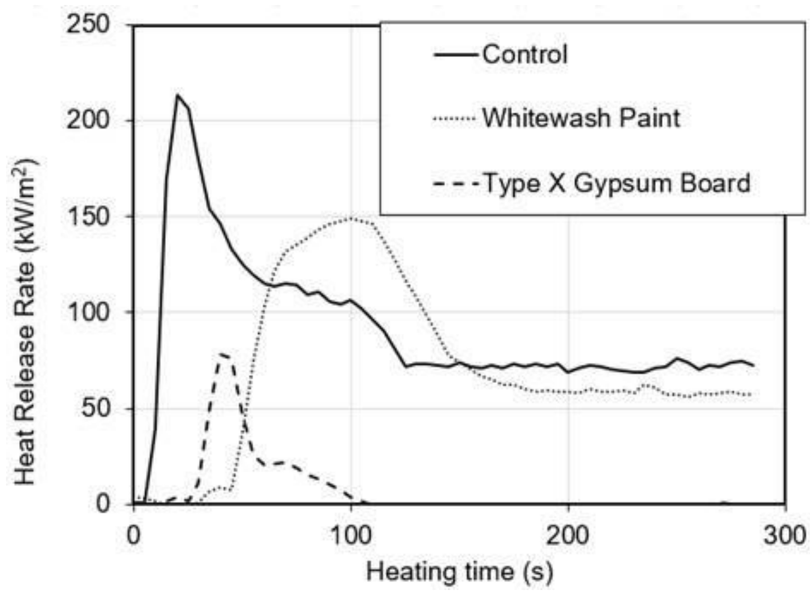


Fig. 10. Heat release rates over time for the control, whitewash, and gypsum board encapsulations (all heat release rates represent the average of two samples)

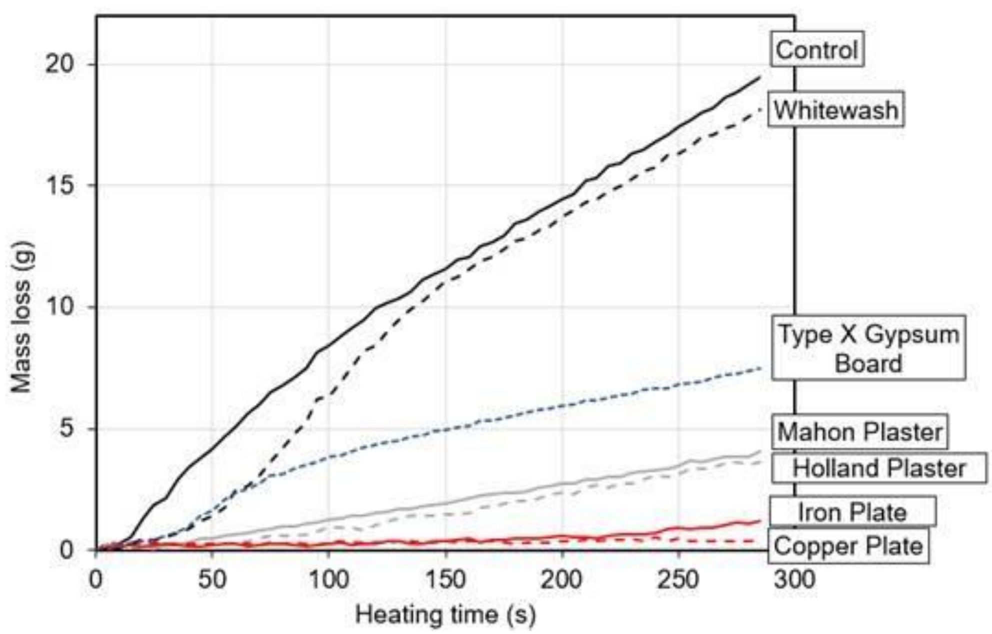


Fig. 11. Mass loss of the control sample, as well as the historic and contemporary encapsulations (all mass losses represent the average of two samples)

5. Discussion

The control sample (unprotected plywood) reported the highest amounts of char, mass loss, and heat release, as expected since it had no encapsulation. The plasters did appear, at first, to improve the fire performance of the timber. No charring occurred on any of the plaster samples, confirming historic fire tests performed by Mahon [10]. Some mass loss was recorded (Fig. 11), which is attributed to moisture evaporation in the plaster since no flaming or charring occurred on the timber. A major challenge facing the historic plasters was their cohesiveness. Since the plasters were applied to the plywood horizontally, they remained attached during testing, however afterwards they fell off when removed from the testing apparatus, which may be attributed to the dehydration of the plaster. This indicates that the plasters would not be suitable for vertical or upside-down applications, such as walls or ceilings (where they would be installed), as they would be likely to fall off of the surface they are applied to when exposed to fire. Since the plasters do not stay attached to the timber surfaces, they had little to offer with regard to improving fire performance.

The metal plates somewhat improved the fire performance of the timber. While the iron plates had some flaming through the screw hole, a char depth of only 2.5-3 mm was measured after testing (indicating a smouldering fire under the plate), which is still considerably (75%) less than the 11 mm on the control sample. Though the authors caution that the duration of heating was small, and longer duration testing may not show favourable performance. While away from the screw hole no flaming occurred, heat transfer into the timber still occurred, causing degradation to begin in the depth of the timber. This can be seen in Fig. 12. As heat transfer was noticeably occurring through the iron plate and into the timber, the effectiveness of the iron plate at protecting the timber was limited.

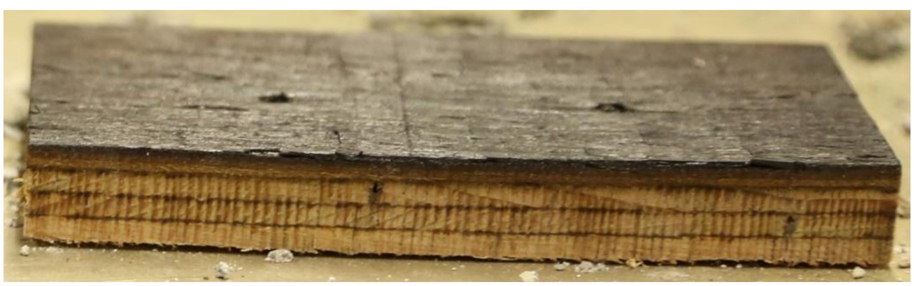


Fig. 12. Degradation process beginning on the timber, seen after removal of the iron plate

The copper plate did not have any flaming or charring, and for this reason, it could arguably be said that the copper plate performed superior to the iron plate. The performance of the copper however, is likely due to the reflective surface of the copper. The radiant heat emitted from the Cone Calorimeter would have been reflected by the surface of the copper, and therefore the timber underneath was unharmed. Oxidized copper plates were not tested, and these would be of interest to consider in future studies. Copper is known to oxidize, so while a new copper plate may be reflective, this reflective property will diminish once oxidation occurs [18]. It is likely that the fire performance of copper plates will therefore change throughout their life cycle depending on their reflectiveness at the time of the fire. As heritage building are often hundreds of years old, it is extremely likely that the reflective surface would no longer be present should these plates be found in a heritage building, and therefore their effectiveness at improving the fire performance of timber is likely to be reduced. Another consideration for both of the metal plates, is the possibility of a smouldering fire under the plates, especially as it may be difficult to avoid gaps in the continuity of the plates which would allow oxygen to promote a fire behind the plates. The possibility of metal plates fostering a smouldering fire would need to be considered should they be found in a structure.

Whitewash paint improved the fire performance of the timber only minimally. Ignition of the sample was delayed by about 20 seconds compared to the control sample, as seen in Fig. 10. The char depth was only slightly reduced, at 9.5-10 mm compared to the 11 mm measured on the control sample, a reduction of about 11%. This indicates that the whitewash paint method only marginally improved the fire performance of the timber, by very slightly delaying the time to ignition.

Finally, the contemporary gypsum board did improve the fire performance of the timber. The layer of paper on top of the gypsum board ignited approximately 35 seconds after beginning the test and flamed for approximately 15 seconds. This is reflected in the heat release rate seen in Fig. 11. Regardless of the small amount of flaming observed, the wood under the gypsum board was uncharred. Mass loss occurred in the gypsum board, which is attributed to moisture loss of the gypsum. The contemporary gypsum board was the only encapsulation method tested that improved the fire performance of the timber, whilst staying properly fastened.

6. Limitations and Future Research

Many of the encapsulations were assembled using assumptions (where missing information was not provided by the encapsulation inventor) and using materials available today. While the assumptions made in creating the encapsulations, as well as the materials used, may have altered the fire performance slightly, it is unlikely the results would be significantly different. There is no evidence to suggest that any of the alterations made to the plasters would have improved their cohesion, nor that any of the optional additives to the whitewash paint would remarkedly further delay time to ignition. The metal plates were taken arbitrarily as 3 mm, and in practical applications it is not likely that the plates would be found to be significantly thicker than this (to a point which would delay heat transfer into the wood at low heating durations).

The next limitation that will be discussed is the scale of the samples tested. The small scale of 100 x 100 mm is not representative of a room lined with a particular encapsulation. In addition, the heat exposure of 50 kW/m^2 for five minutes is not representative of a realistic fire. For these reasons it cannot be said that the tests performed represent a real fire that may occur in a heritage building. However, despite the small scale of the tests, this study was successful in showing that the historic encapsulations made no real contributions to the fire performance of the timber even at this low severity of exposure. Even the short tests described above were successful in determining that the plasters are limited in their capacity to stay attached to the timber, the whitewash paint only minimally delayed ignition, and the iron plate still allowed for flaming and heat transfer into the timber. A more severe heat exposure is likely to only amplify these effects.

Future research is needed on the fire performance more historic materials and assembly configurations, such as on the timber itself. In order to successfully conserve heritage buildings, architects and engineers need to have an understanding of how the original historic materials will perform in fire. As seen in previous sections, there are several differences between the historic materials used and manufacturing methods, and the materials and methods used today, all of which may alter the anticipated fire performance of these structures.

7. Conclusions

Heritage buildings often see immense public support for their conservation and keeping them safe from fire is an important part of this effort. This study was useful in examining the history of encapsulating timber to improve its fire performance, and in providing a preliminary indication of how much these encapsulations actually improve the fire performance. Plasters, metal plates, whitewash paints, and gypsum boards were all examined. Experimental testing through the use of a Cone Calorimeter apparatus gave insight to the charring, flaming, mass loss, and heat release rates of these historic and contemporary encapsulations, to understand how much these historic encapsulations improved the fire performance of the assembly.

The results of the experimental tests showed that the plasters performed relatively similar to the contemporary gypsum board, experiencing moisture loss but succeeding in protecting the timber from flaming and char. The improvement to the contemporary gypsum board is that it provides a smooth and flat surface for interior walls and remained attached to the timber better than the plasters (using screws). The plasters however, became detached from the timber quite easily after testing, making them impractical for the purpose of improving the fire performance of timber. Both the copper and iron plates significantly reducing the char on the surface of the timber, however, the iron plate still transferred enough heat into the timber to cause it to begin to degrade, and the performance of the copper plate is attributed to its reflective surface, which will have most likely been lost due to oxidation in most heritage structures. The whitewash paint delayed ignition of the timber by only about 20 seconds; otherwise, the performance of the whitewash was somewhat comparable to that of the unencapsulated control sample.

From these tests, it is seen that none of the historic encapsulations tested made significant contributions to the fire performance of the timber, with only the contemporary gypsum board successfully protecting the timber without any obvious disadvantages. To the authors' knowledge, this study is the only source of contemporary testing of these particular historic encapsulations, and the results of these tests suggest that should these encapsulations be found in a heritage building, they cannot be relied upon for fire. With regard to the conservation of the heritage building, it may be necessary to keep them in tact nevertheless (as they would almost certainly offer insight into the technologies of the time period), but even in this case they cannot be assumed to protect the timber against fire. Other strategies may be required in enhancing the fire performance of the heritage structure, which can be implemented without detracting from the heritage value of the building- for instance, there ways to respectfully integrate sprinklers into a heritage building, and regular building maintenance may also be beneficial.

This study provided a thorough analysis of the progression of historic encapsulations used for fire through time, as well as an evaluation of the fire performance of these encapsulations. By understanding the history and evolution of encapsulation materials as well as their fire performance, architects and engineers who encounter these encapsulations can better assess the most effective way to conserve a heritage structure. Through further research into the fire performance of historic structures and materials, the successful conservation of cultural heritage buildings becomes possible.

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References

[1] Australia ICOMOS, The Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance, Burwood, VIC, Australia, 2013. http://australia.icomos.org/.

[2] Canada's Historic Places, Standards and Guidelines for the Conservation of Historic Places in Canada, Her Majesty the Queen in the Right of Canada, 2010. doi:R62-343/2010E-PDF.

[3] CSA Group, CSA O86-14: Engineering Design in Wood, 2014.

[4] ASTM International, ASTM E1354 − 17 Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter, West Conshohocken, PA, 2017. doi:10.1520/E1354-17.

[5] Associated Architects, Resolutions of the Associated Architects with the Report of a Committee by them Appointed to Consider the Causes of the Frequent Fires and the Best Means of Preventing the Like in the Future., 1793.

[6] D. Hartley, Patent no. 1037, Securing buildings and ships from fire, 1773.

[7] D. Hartley, An Account of the Invention and Use of Fire-Plates for the Security of Buildings and Ships against Fire, 1785.

[8] D. Hartley, An Account of the Fire at Richmond House on the 21st of December 1791, and the Efficacy of the Fire-Plates on that Occasion, Stockdale, London, 1792. https://books.google.com (accessed May 27, 2019).

[9] B.L. Hurst, An iron lineage, Struct. Eng. 77 (1999) 17–25.

[10] C.L.V. Mahon, No. I description of a most effectual method of securing buildings against fire, Philos. Trans. 68 (1778).

[11] J. Gales, Structural Fire Testing in the 18th Century, Fire Saf. Sci. News. (2013) 32–33.

[12] R.W. Moss, Paint in America : the colors of historic buildings, John Wiley & Sons,

Washington, DC, 1994. https://books.google.ca/books?hl=en&lr=&id=LiK6MgYkNzEC&oi=fnd&pg=IA1&dq=thomas+child+whitewash+paint&ots=Y77JP1-uRf&sig=O07XnmTSwP64LpDfAWzw0aNrhHI#v=onepage&q=thomas child whitewash paint&f=false (accessed June 6, 2019).

[13] L. Paimboeuf, Improvement in the Mode of Preparing Paint for the Protection of Buildings against Fire, Patent No. 449, 1837. https://patentimages.storage.googleapis.com/79/5c/7a/51c986f2c47cae/US449.pdf (accessed May 28, 2019).

[14] A. Sackett, Inside Wall Covering, 520 123, 1894. https://patentimages.storage.googleapis.com/da/b1/d9/e909b90392f24a/US520123.pdf (accessed June 6, 2019).

[15] S. Kubba, LEED v4 Practices, Certification, and Accreditation Handbook, 2nd ed., Elsevier, 2016. doi:10.1016/B978-0-12-803830-7.00015-3.

[16] S. Inberg, H. Griffin, W. Robinson, R. Wilson, Technologic Paper of the Bureau of Standards No. 184: Fire Tests of Building Columns, Washington, DC, 1921.

[17] V. Babrauskas, Development of the cone calorimeter—A bench-scale heat release rate apparatus based on oxygen consumption, Fire Mater. 8 (1984) 81–95. doi:10.1002/fam.810080206.

[18] J. Li, J.W. Mayer, E.G. Colgan, Oxidation and protection in copper and copper alloy thin films, J. Appl. Phys. 70 (1991) 2820. doi:10.1063/1.349344.

Appendix A

Table A.1 Holland (1793) Experiments using Hartley Metallic Plates on Wood in Georgian Style Town House

Test Description	Material Description	Fire Description	Observations
Two timber compartments	One of the rooms was plated with of metal.	1 hour of fire exposure	Plated room's joists showed evidence of charring. Non plated room completely collapsed in 40 minutes.
Fire in the corner of a compartment in the building	Floor and walls were plated with metal.	1 hour of fire exposure	The fire burnt through floor boards, exposing metal plates. The base of the wall, although covered by plates, was charred over a height of a foot.
Fire on stairwell	The staircase was covered in metal. Floor boards were then applied on top of metal.	0.5 hour of fire exposure	Floor boards appeared charred. Timber under the plating was charred.
Fire in the corner of a compartment in the building	Metal applied to this and adjoining room.	1 hour 20 minutes of fire exposure	The flames burnt through the depth of floor assembly. The extent of the fire was limited to the room.
Attic fire test	Metal applied to joists and floor.	1 hour 40 minutes of fire exposure	The fire burnt through the bottom plate of the wall down to the top plate of the wall below. The grounds and linings were consumed. Entire height of attic damaged with char.
Compartment fire test	Walls were made of wood bricks and covered by metal plates, wooden panels and plaster (interior to exterior) on both sides. Metal plates were used on both sides of the door and on the interior side of the window.	2 hours of fire exposure	The flooring boards were burnt through where fire started, in other places only charred. The wall finishes and the ceilings were severely charred. Part of the wooden frame was charred. The wood bricks were also charred half an inch deep in general. No damage was found on the windows or the door, as well as in adjoining rooms.

Table A.2 Holland (1793) Experiments using Mahon plaster on Wood in Georgian Style Town House

Test Description	Material Description	Fire Description	Observations
Compartment fire test	The room was covered with plaster and finished. The ceiling was not covered.	1 hour of fire exposure	The skirting board was burned through where in contact with fire. The floor boards were charred nearly through, and the wall was lightly charred.
Compartment fire test	The room was covered with plaster and finished. The ceiling was not covered.	1 hour of fire exposure	The skirting board was burned through where in contact with fire. The flooring boards were charred nearly through, and the wall was lightly charred. In the seat of the fire the flooring boards were charred considerably. The plastering of the walls fell off, the wall was left exposed and was charred.
Fire on stairwell	Staircase covered with plaster along the steps and risers.	1 hour of fire exposure	The risers were considerably charred in the seat of the fire. The plaster was undamaged.
Compartment fire test	The room was covered with plaster and finished. The ceiling was not covered.	1 hour 45 minutes of fire exposure	The fire burnt through the floor and consumed part of the joists immediately under it. The plaster on the wall fell off. The wall was left exposed and was charred.
Compartment fire test	The room was covered with plaster and finished. The ceiling was covered as well.	3 hour 30 minutes of fire exposure [1]	In the seat of the original fire, the flooring boards were burnt through and two of the joists damaged two inches deep.
Compartment fire test	The floor, walls, and ceiling were secured with plaster. The door and window shutter with fire plates.	1 hour 45 minutes of fire exposure [2]	The flooring boards were charred. The ceiling plaster fell off. The joists and timbers which became exposed were charred. Fire remained contained to the room of origin.

1 – additional combustible material continuously added after 2 hours 15 minutes
2 – additional combustible material continuously added after 30 minutes