Functional Fires in Historic Buildings: Impact on environmental conditions and response of timber objects

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Summary

Open fires can enhance visitor experience by recreating authentic sights, sounds, smells and warmth but they also influence the environment that they heat. This thesis reports the environmental conditions inside a traditionally constructed, solid walled building at National Museum Wales, St Fagans when heated via open fires lit daily or banked in overnight. It evidences the environmental response of the building, the build-up and dissipation of heat in the chimney breast and offers a 3D understanding of relative humidity distribution. This data informed further laboratory study of the moisture uptake and loss of European Oak (*Quercus robur*) samples taken from historic furniture with original finishes.

The findings demonstrate the ability of the open fire to heat the fabric or the room and maintain a humidity under 60%RH over a period of time after the fire has gone out. They evidence that slow burning, banked in fires offer more heat output through the night than no fire, but also draw in more external air, causing a more uneven humidity distributions. A updated method for recording heat output of the chimney breast and calculating the open fire efficiency was devised utilising infrared imaging.

Response of oak samples to environmental changes was found to be slower than expected, yet offered understanding of smaller daily changes. It suggests that moisture response of the oak to daily fluctuations are limited to the outer layers of the wood. It was also found that coatings on timber samples influence the response of wood to environmental changes.

These findings have been used to advise management practices in running fires in historic properties at St Fagans.

Acknowledgements

This thesis would not have been possible without the joint partnership of the National Museum of Wales via the Arts and Humanities Research Council Collaborative Doctoral Award. Further to that, the help and guidance of Robert Pearce, Diane Gwilt, and Emyr Davies. It has also been brought to fruition thanks to the assistance and support given by Prof. David Watkinson, Dr. Nicola Emmerson, and Johanna Thunberg.

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1 Introduction

Overview

The overall aim of this study is to improve the understanding of the environment inside historic buildings when heated by open fires and the impact that has on historic furniture. This study is part of a Collaborative Doctoral Award, and is joint with Amgueddfa Cymru, National Museum of Wales St Fagans but does have wider impact. It is a timely study, the English government announced a ban of burning bituminous coal that comes into effect this year. The Welsh Government has consulted and will likely bring in similar measures, this will effectively end the 800 years of documented history of burning coal to heat houses in England and Wales (BBC 2021;Wright,1964,62). As such, it is an opportunity to understand how open coal fires heated buildings, and will allow for a more detail understanding of the environmental conditions within buildings historically. This is of interest to those researching how people lived, such as historians and archaeologists. It is also of benefit to architects and designers who may be working with old buildings, or who have an interest in the working properties of open-fires, energy conservation, natural ventilation and high-mass buildings. The study is primarily aimed at the field of conservation, in particular how objects respond to open-fire heating. Part of this study will look directly at historic timber and how it responds to environmental fluctuations. This is for the benefit of object conservation, but again has further applications in other fields, such as building conservation, timber research and engineering.

Energy Efficiency and Historic Buildings

As energy conservation and climate change have moved up the agenda there has been an increased interest in energy conservation and historic buildings. An argument put forward by Carl Elefante, former president of the American Institute of Architects, is that the greenest building is one that already exist (Adam,R.2019) and 21% of people in England live in pre-war dwellings likely with solid walls (English Housing Survey,2010,9).

In the overall approach to historic buildings there has been a gap in research which gives in situ results for environmental conditions inside buildings (Baker,P.2010,II) especially when traditional heating methods are utilised. This study demonstrates how a traditionally constructed dwelling-house responds to open-fire heating. It shows the patterns of heat and humidity within the building and how that related to fuel use and combustion patterns. It is a snapshot of how the internal environment in most buildings in Britain would have been before the widespread adoption of central heating. The fuel use, carbon output and comfort levels may be extrapolated from these results along with an appraisal of the efficiency of the appliance itself.

Social history

There are a limited number of resources for understanding the environmental conditions inside buildings historically. Problems arise with anecdotal statements which may be inaccurate or hyperbolic, few scientific studies exist before the Edwardian period which have reliable methodologies. As such, this study allows for a detailed understanding of living conditions experience by people in homes heated by open fires. This adds a more firm foundation to statements about the conditions inside British homes and gives a useful reference for historians and similar academics who may wish to back up an anecdote historical reference with more firm experimental results (Rudge,2012,6-7).

Living museums and historic houses

There is a clear benefit of this type of study to organisations who display historic buildings to the public in a museum setting. Organisations, such as National Museum of Wales St Fagans, The Black Country Living Museum and the National Trust all have historic houses which utilise open fires as a source of sensory interaction for visitors. This also feeds into the management of the environmental conditions within such buildings with regards the collection. As the joint partner in this Collaborative Doctoral Award, this study will focus on the National Museum of Wales, St Fagans.

1.1.1 National Museum of Wales, St Fagans

St Fagans National Museum of History was established in 1946 based on the Skansen model in Sweden of open-air museums (1976,National Museum of Wales,7). Historic buildings from around Wales have been reconstructed at the site, furnished, and decorated to display a certain period of history. There are a range of building types that represent not only different parts of Wales, but also different industries. For example, there are cottages, farmhouses, hall houses, a Prince's court as well as a tannery, woollen mill, corn mill, blacksmith, and pottery to name a few of the 46 historic buildings on site. St Fagans is a living museum, and crafts are manufactured and sold on site.

The collections housed in the buildings are used to create an atmosphere of the buildings at a point in time, and the use of fires as a method of heating helps to portray this accurately. This also feeds into the experience, with heat, light, smoke, and smells recreating authentic sensory aspects for visitors. Peat is used as a fuel in buildings from areas near bog lands, coal in areas near coal mines or after a certain time, and wood in buildings from more rural areas. The types of fireplace or appliance is also varied. For the school, a large cast iron stove burns coke, whereas peat is burned on the floor in the fireplace of Nantwallter. Some of the later interiors have cast iron grates, while other are iron and blacksmith made (Figure 1 - Figure 4).

Figure 1: Bryn Eryr Iron Age roundhouse as reconstructed at St Fagans showing the central fire with andirons/firedogs and suspended cooking pot (National Museum Wales).

Figure 2: Garreg Fawr Farmhouse originally constructed c.1544. The chimneys are likely to have been a status symbol. Cooking would have taken place on this open hearth in the hall (National Museum Wales).

Figure 3: Aberndowydd Farmhouse, a timber-framed thatched farmhouse built c.1678. Originally an open hall design with central fire open to the roof, the stone-backed fireplace and timber-framed chimney later additions c.1708 (National Museum Wales).

Figure 4: This Rhyd-y-Car terrace was built c.1795 and reconstructed at St Fagans to reflect different time periods, with the interior of No.2 showing a simple blacksmith made grate with brick 'hobs' for pots and pans (National Museum Wales).

1.1.2 Fire usage patterns at St Fagans

Running fires within the properties at the site requires planning and oversight. Over a typical day, several groups of people visit the buildings and attend to duties relating to the fires. First, at around 7:00 to 8:00 the cleaners will clean out the grates and lay new fires, often lighting them on colder days.

At 10:00 wardens are stationed at a particular set of buildings, and they are responsible for informing the public about the buildings and objects. The wardens also re-fuel and sometimes light fires in the buildings. During this period, the doors to the buildings are often left open so that visitors realise that they are open and may be entered. Fires are permitted to die down by the end of the afternoon.

At around 17:00 the buildings are locked and any remaining fires extinguished. A security team comes onto shift, they patrol the site throughout the night and into the next day.

1.1.3 The impact of fires on collections

Due to the nature of a normal working day, many of the objects on open display within the buildings at St Fagans are subjected to a highly fluctuating internal environment. The lighting of fires is somewhat subjective and based upon the individual preferences of cleaners or wardens on the day. The furniture and clock conservator notes that when fires are lit in buildings, the clocks run on time but if they are inconsistently lit, then they lose time. From this it had been determined that most buildings should have a fire in them at least every other day as the environment generated by the fires clearly has an impact on the materials in the room and the building fabric.

Figure 5 shows environmental data collected by the museum from the centre of the downstairs front room in Rhyd-y-Car No.6. A clear pattern of humidity can be seen:

- RH is most stable overnight when the door to the property is shut.
- RH increases by up to 10% when the property is opened in the morning.
- RH gradually decreases as the radiant heat warms the air in front of the fire.
- RH rises as the fire slowly dies down in the afternoon towards closure at 17:00.
- RH remains relatively stable following building closure until the following morning.

Throughout the day the temperature sits at around 10°C, and does not go above 15°C. On the 07/03/2014 11:01 the RH increases when the door is opened from 87.4% to 97.5%, the temperature is 10°C, which is at the dew point.

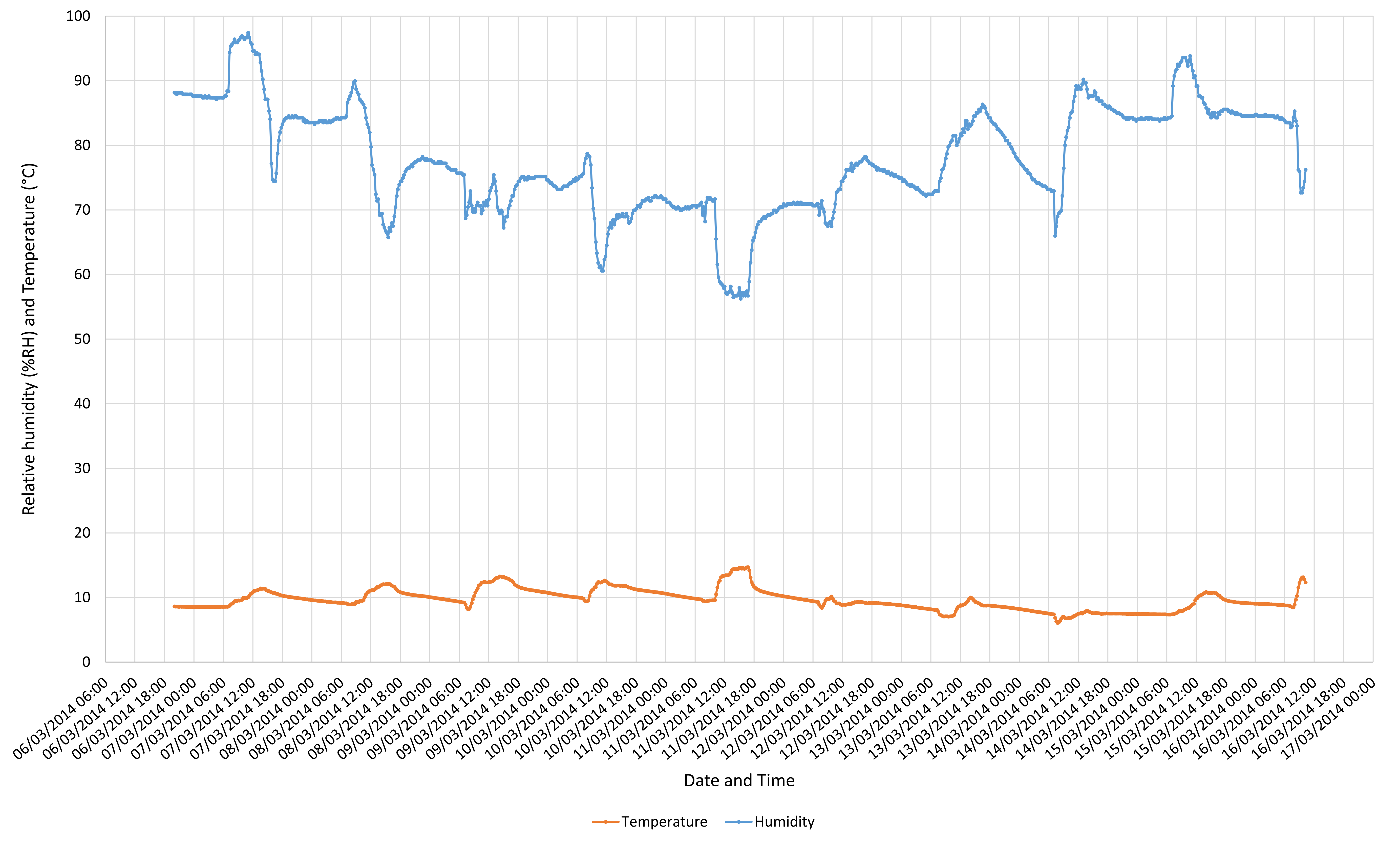


Figure 5: The environment in Rhyd-y-Car No.6, room centre, as presently managed.

Given the impact of environments in collections, an investigation was required to determine the influence of fire lighting patterns on internal humidities and temperatures and the possibility of optimising these. Of particular interest was the cyclic nature of lighting and fuelling fires on the environment and how this influenced the response of the historic furniture within the building to its environment.

This thesis reports a study that contributes to developing better understanding of the impact of open fires on the environment within the space they heat. It focuses on a wide range of questions regarding how effectively the fire is managed relative to its impact on the environment in the room it is heating. The nature, quantity, and quality of fuel and its impact on temperature, relative humidity and heat emission are central to understanding the impact of the fire on its environment. Can the fuelling procedure influence the impact of a fire on the room? Specifically, what is the impact of continuous fuelling relative to the 'stop start' process of letting the fire go out overnight? Principally, this centred on the concept of overnight burning, or 'banking in' of the fire so that it enters a slow combustion state and can be revived in the morning. In this way, it was thought a more even environment would be produced, as it regulates temperature extremes in the room. This concept originated from known practice in domestic open fire usage, though it is difficult to find much published literature relating to this, there is significant anecdotal evidence based around the application of small coal/ashes on top of the fire. Post war appliances were issues with certification if they could be banked in for a minimum number of 10 hours, as may be seen in the M.A.C. Catalogue of 1958. These principles were based on recommendations laid out by the Egerton Report on Heating and Ventilation (1945) and methods were largely achieved by limited the air rate through the fuel bed by the creations of an air-tight area under the grate.

To date there is no study that examines this concept. It was checked that the National Museum Wales was prepared to consider this overnight option before commencing the study. Beyond their compliance lies the concept that the general overview, if not the data set, can be extrapolated to management contexts in other historic structures, where all other factors such as risk have been taken into account.

Aim and objectives

The aim of this study is to determine how the pattern of lighting and fuelling fires in historic buildings impacts the relative humidity and temperature inside the building. This also extents to the response of historic timber samples to these fluctuations.

- Recording in three dimensions the impact of a fire on the humidity, temperature, and radiant heat within a historic building in St Fagans Museum.
- Utilising the data collected to determine the parameters for controlling the environment in a study that will assess the response of historic wood to the burning of a fire according to the patterns identified.
- Utilising the data from the experimental study to advise on the fire burning management regime that will produce the least damage for the applicable buildings and their contents.

Thesis structure

The thesis considers the history of the open fire, a heating method of long standing which has not been documented in one place before. It also highlights methods that have previously been employed to scientifically assess the fireplace. This history informs the building selected for the subsequent experimental study.

This is followed by a discussion of wood, its microstructure, and the manner in which it responds to changes in relative humidity and temperature once dried and used in objects such as furniture which might form collections in museums such as St Fagans.

The experimental collection of environmental data utilising an open fire in a traditionally constructed building follows. This is then extrapolated and discussed, which helps to inform the next stage of experimental study examining the reaction of wooden furniture to the environments recorded.

Historic wooden samples from furniture at St Fagans and their response to environmental fluctuations is the focus of the third major part of the thesis. Results of experiments investigating the reaction of wood to radiant heating, relative humidity and temperature fluctuations are discussed. This also leads onto a consideration of coatings and the impact they have on the reaction time of the timber samples to fluctuations.

From these experiments, recommendations are made for the best practice method for running the fires at St Fagans to produce the best results for their collection of wooden furniture on open display. Suggestions for the direction of further research are offered.

2 History of the open fire

Fire has been the tool of human kind for millennia, whether obtained from lightning, or created through learned techniques, it has served to heat, light, cook, and keep away predators (Forbes 1966, 2).

Earliest fires used by man were open in all senses of the word and would probably be recognised as a modern day camp fire (Forbes 1966,58). Stones were placed around the edge, and used in aid of support for the fire and cooking implements (Forbes 1966, 58). The fire was moved indoors in the Neolithic period, coinciding with early farming and stock rearing (Tringham 2013, 92). As the fire moved indoors, the obvious problem of smoke arose. This influenced the design of buildings, high roofs to collect smoke with vent holes allowing it to escape, eventually giving way to the chimney. The chimney allowed for division of space in buildings, creating more rooms, and more levels (Brunskill 1982, 191). In turn, this meant more chimneys to heat these spaces, and different types of fireplaces developed for different functions. Through time the kitchen fireplace developed into the complex cooking ranges of the late Victorian age (Wright 1964,121). Fireplaces in other rooms had grates solely for the purpose of heating, though often the living room grate could also be utilised for cooking, and even drawing room grates or bedroom grates sometimes had provision for heating a kettle (Eveleigh 1990, 4-6). This work will mainly look at the development of the fireplace as a heating apparatus, rather than expanding into the area of cooking fires and later ranges. The technology of the cooking range, and its development, is worthy of a separate study.

Fuel has an important impact on fireplace technology and will be discussed alongside the development of the fireplace. Wood was one of the most common fuels and burns best on a bed of ash(Wright 1964,10). The smoke from both peat and wood is much more fragrant and tolerable to an individual than coal (Wright 1964,63). Coal became the dominant fuel after the Jacobean period, and required different grates to burn, allowing air to pass under or through it with a draft (Galloway et al. 1996, 449).

The dimensions of the throat of the fireplace, and how close the throat is to the fire are important for controlling the amount of air that is drawn up the chimney and drawn through the fire. These dimensions reflect upon how complete combustion will be (McHugo 1955, 326). Some terminology for parts of the fireplace are given in Figure 6 and Figure 7.

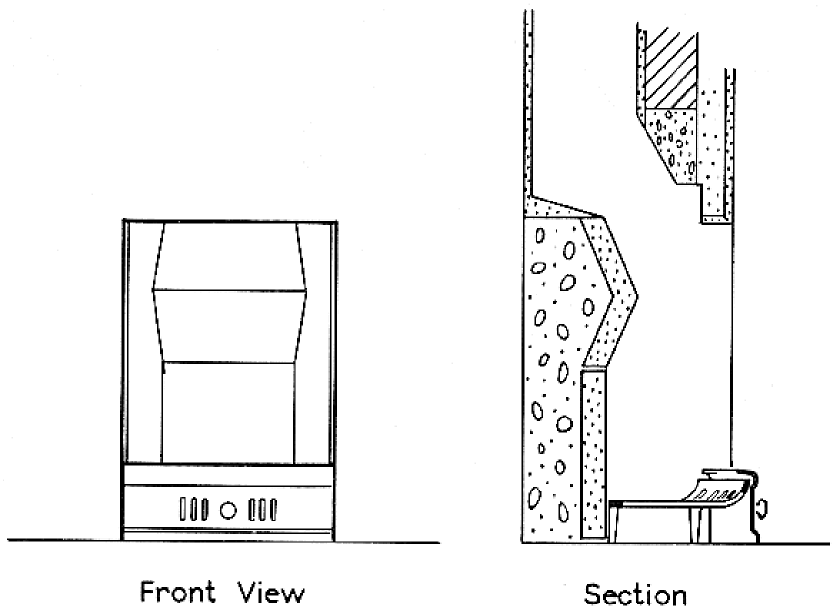


Figure 6: Cross section of open fire with stool bottom grate, showing the refractory clay fireback with rubble infill behind, throat opening, splayed sides, smoke chamber and flue, (Venables 1957b, 10).

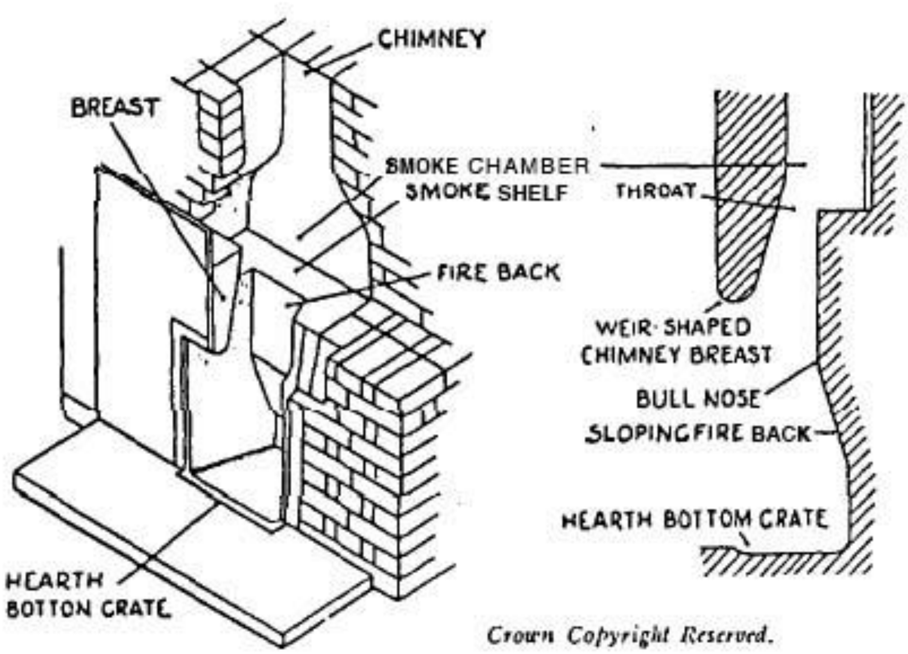


Figure 7: A detailed overview of the parts of the fireplace, however no grate is shown (Rosin et al. 1939,8).

Pre-Norman Britain

It could be argued that the Romans introduced to Britain the first form of 'chimney' in a domestic setting, (similar constructions existed in pottery kilns earlier) the terra-cotta box-flue tiles they used to take the products of combustion from under a hypocaust system and into the atmosphere bear remarkable resemblance to flue liners of the modern chimney. In the same way as a chimney, they create a heated room that is smokeless. However, the fire was entirely separate from the room, being fed from outside (Black 1985, 78). As such, the hypocaust system cannot be so readily compared to an open fire with chimney, and the Romans continued to use their braziers and central fires, rather than developing internal fireplaces with chimneys (Singer et al. 1954, 231).

The people of tribal Britain mostly dwelt in round houses, with earth, or wattle walls and thatched conical roofs . The open hearth was a central element providing heat equally throughout the building, unlike in a square or rectangular room. The benefit of having a large roof void filled with smoke was obvious for the preservation of meat, fish and other food-stuffs (Hagen,A. 1998,39;Lynch et al. 2000).

The Anglo-Saxons did not develop a chimney either, however the shape of buildings changed during this period. The rectangular hall imported from the continent was of timber construction, with thatch roofs, and utilised central hearths (Figure 8) (Denison 2012, 52).

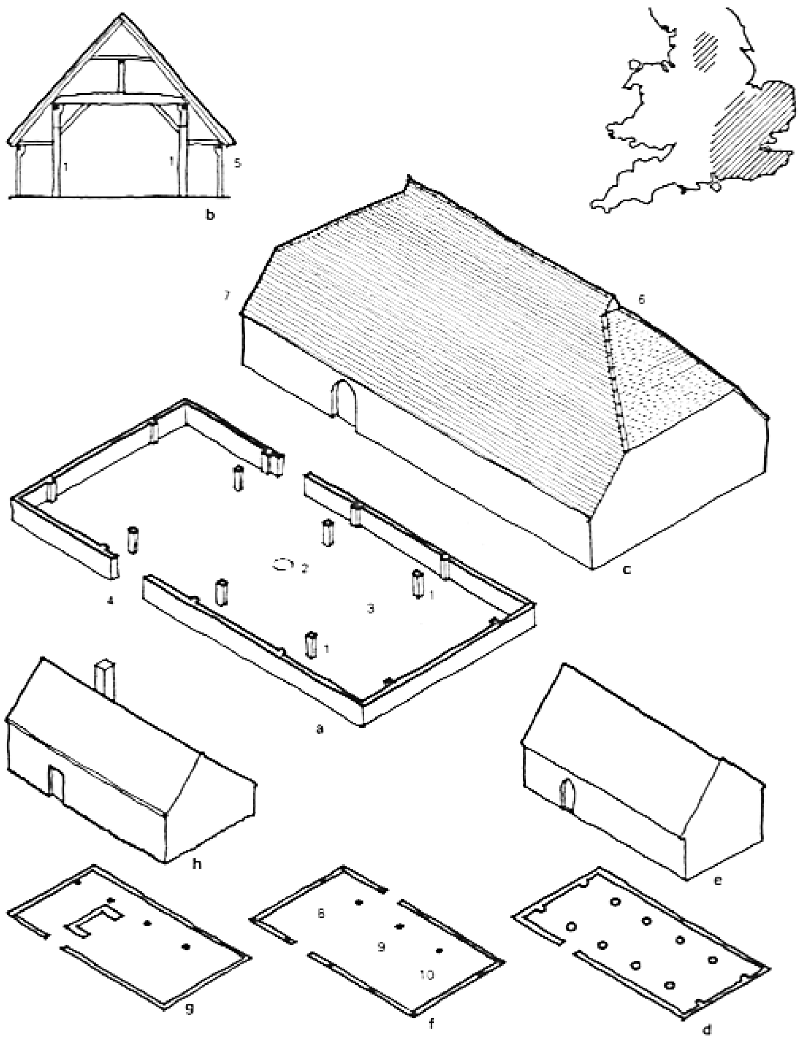


Figure 8: The aisled hall with central fireplace had its origins in Anglo Saxon halls, late 12th to early 15th Centuries (smoke hole at 6) (Brunskill 1982, 32).

In order to burn wood more easily, and to cook on the fire, andirons (or firedogs) had been in use since the Iron Age (Singer et al. 1954,2 32). A pair of andirons would normally be used, and wood could be lifted up and placed leaning against the andiron, so as to allow more air to access it and accelerate combustion. Loops or hooks of iron allowed food or pots to be suspended on a rod over the fire to be cooked or heated. Their use continued later in the chimney fireplace, well into the 16th Century and beyond. The basic design changed very little, but details and form did evolve over the centuries, such as rams-heads in the 12th Century (Figure 9 and Figure 10) (Shuffrey 1912, 128).

Figure 9: Celto-Romano firedog, one of the earliest found in Wales (National Museum of Wales).

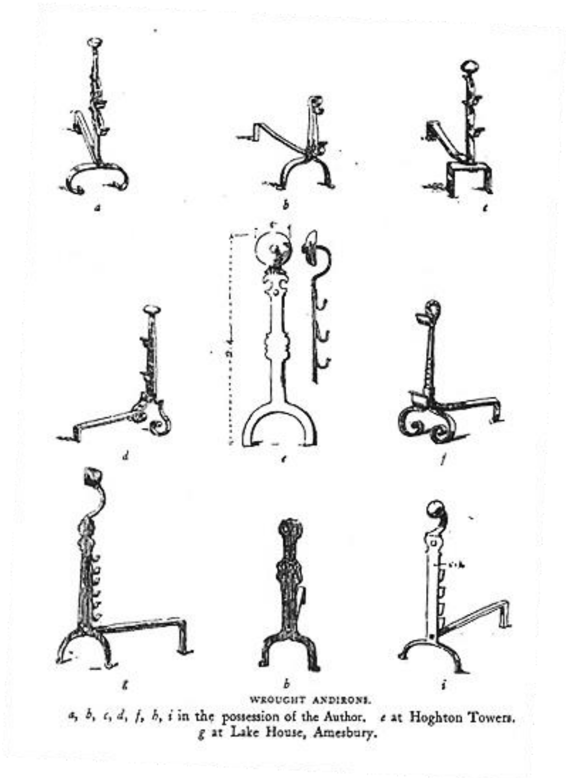


Figure 10: Various firedog/andiron designs (Shuffrey 1912, 131).

Post-Norman Conquest, Medieval Britain

After the Norman Conquest and the introduction of larger fortified buildings (Keeps) it was necessary to have habitable rooms on multiple levels within buildings. This led to the development of a ‘first floor hall’, which is a hall above a set of rooms created by a vaulted stone ceiling; upon this a fire could be safely lit. However, if rooms above this were to be used, and if the problem of smoke in rooms with lower ceilings was to be dealt with, then the chimney had to be devised (Brunskill 1982, 35). This led to the ‘fire recess’, which is not unlike a chimney, but only rose up to exit from the wall a few feet away, rather than to the top of the building. As such, it is unlikely they would have worked particularly well for directing smoke (Hills 1985, 24; Gotch 1985, 12).

The chimney as it is known today, extending above the roof, came soon after this. In the 12th and 13th Century chimneys were round in design (Figure 11), but later became octagonal (14th Century) such as the Abbots Kitchen at Glastonbury (Parker 1851, 90; Shuffrey 1912, 59). This development did not necessarily mean that chimney-less fires became redundant. Indeed, they existed simultaneously with their counterparts for some time, such as at the 13th and 14th Century Bishops Palace at St Davids, which utilises rooms with fireplaces and chimneys, and halls with central hearths (Evans et al. 2005). In higher-end buildings, the central hearths were more usually reserved for great halls, and it is thought the last such fireplace of this type in use was at Cambridge and was finally abandoned in 1866. However, more generally central hearths had given way to the chimney in other places much sooner (Shuffrey 1912, 13). One of the last grand buildings thought to have been built with an open, central hearth was Penshurst Place in 1341, the hearth being retained after extensive renovations in 1521 (Figure 12).

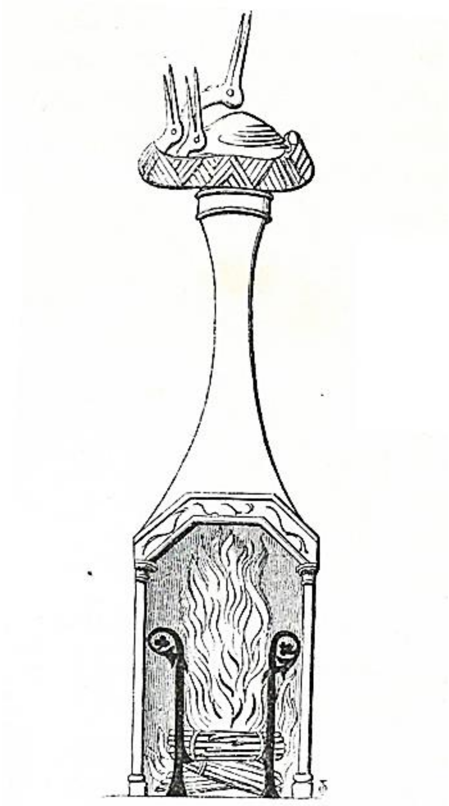


Figure 11: The earliest depiction of a chimney in Britain, complete with storks nest from 1344 (Parker 1851, 90).

Figure 12: Central fireplace in 14th Century Penhurst Place (Gotch 1985, 107).

Grander houses, such as those of the clergy or aristocracy, obtained chimneys much earlier than the buildings of ordinary people. One of the main purposes for the implementation of the chimney in houses of a lesser status was the dwindling supply of firewood, and the need for more rooms in a building (such as in towns)(Wright,1964,64). As access to reasonably priced firewood diminished, coal became the next best fuel to use (particularly in urban areas)(Wright,1964,64). The smoke from coal is less tolerable than that of wood, and thus it became essential for dwellings to have chimneys. A quote from Holinshed in 1577 (Book II Chapter 12) states:

"There are old men yet dwelling in the village where I remain which have noted three things to be marvellously altered in England within their sound remembrance, and other three things too much increased. One is the multitude of chimneys lately erected, whereas in their young days there were not above two or three, if so many, in most uplandish towns of the realm (the religious houses and manor places of their lords always excepted, and peradventure some great personages), but each one made his fire against a reredos in the hall, where he dined and dressed his meat." (Holinshed 1808).

The opposite of this trend may be seen in particularly remote areas, such as Shetland, where peat was used as a fuel. As peat smoke is rather tolerable, and perhaps due partly to remoteness or poverty, houses using a central hearth could still be found in the 1930's (Figure 13) (Fenton 1978, 198). The fireplace in the remote islands of Scotland were no less complex due to their lack of chimney, and often had a vent extending beyond the roof line which allowed the products of combustion to be drawn away. Often a long board on a pole would be utilised, extending beyond the top of the vent, the pole remaining in the room below (Figure 14).

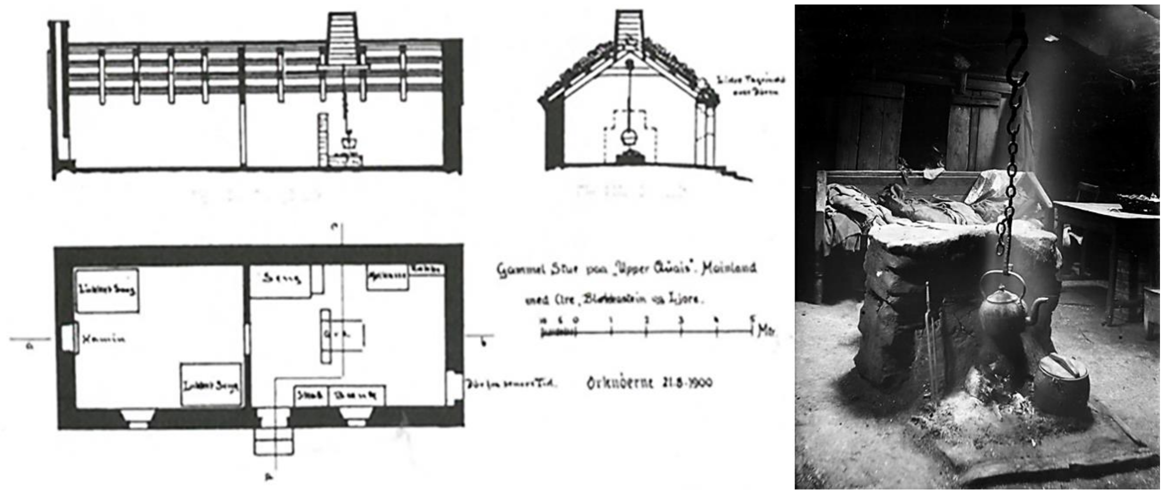


Figure 13: Orkney house with central fireplace 1906, showing clearly the roof vent (louvre) for the removal of smoke (Fenton 1978, 198; https://photos.orkneycommunities.co.uk/picture/number28451.asp).

Figure 14: The smoke louvre of an Orkney house central fireplace 1906 (Fenton 1978, 200).

This was to be moved to face the direction of the prevailing wind, and as it hit the board and passed around it, induced an up-draft from the roof vent, aiding the drawing of smoke from the building. This roof vent is remarkable in that it replicates the grander louvered vents of the halls of the middle-ages (Figure 15) (Parker 1851, 90; Shuffrey 1912, 7).

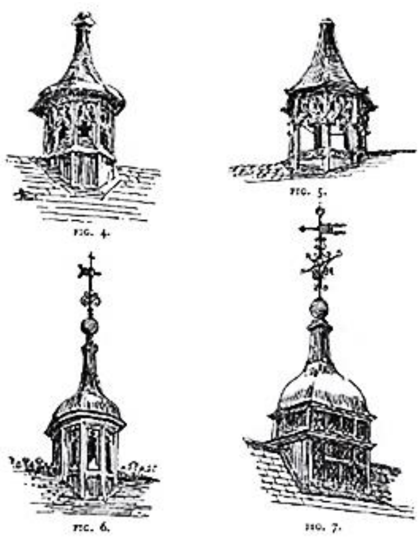
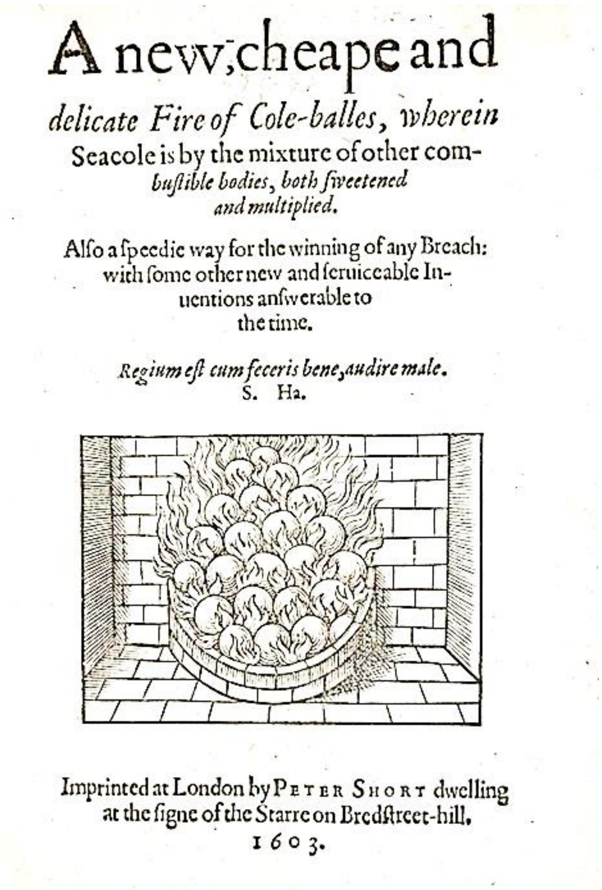


Figure 15: Various smoke louvres on Medieval Halls, showing the similarity in the design for the smoke apertures of chimneyless buildings (Shuffrey 1912, 7).

A change of fuels

More generally, by the Jacobean period, coal was on the way to becoming the fuel of choice for most people. Indeed, pamphlets were published giving recommendations on how grates should be constructed in order to be more conducive to the combustion of the fuel (Figure 16) (Plat 1603).



A new, cheape and *delicate Fire of Cole-balles, wherein* Seacole is by the mixture of other com-*bustible bodies, both sweetened and multiplied.*

Also a speedie way for the winning of any Breach: with some other new and seruiceable Inuentions answerable to the time.

Regium est cum feceris bene, audire male.
S. Ha.

Imprinted at London by PETER SHORT dwelling at the signe of the Starre on Bredstreet-hill, 1603.

Figure 16: Frontispiece showing coal grate design (Plat, 1603).

'*When Newcastle was held for King Charles, in 1644, the supply of coal to the capital was stopped, and they rose to four pounds a chaldron; parliament attempted to provide turf and peat to meet the exigency, but these being inadequate to the demand, great distress ensued among the inhabitants. One complaint ceased during the death of fuel. The brewhouses and dyehouses being either altogether idle, or using comparatively little fuel, the air of London became most salubrious, and "divers gardens and orchards planted," says Evelyn, "in the very heart of London, as in particular my lord marquesse of Hertford's in the Strand, my lord Bridgewater's, and some others about Barbican, were observed to bear such plentiful and infinite quantities of fruits," (Bernan 1845, 179)*

The extract displays how dependent London had become on coal, and how it was used so greatly it was considered to have impact upon the quality of the atmosphere considerably when the supply was suddenly removed (Bernan,1845,179). Further advancements were made in the design of grates in this period to burn coal as its use became more commonplace. Andirons were often utilised to support iron baskets to hold the coals (Figure 17 and Figure 18), and sometimes even disposed of altogether (Shuffrey 1912, 152). This led to a reduction in the size of fireplaces, as coal has a higher calorific content than wood, but also requires a draw of air to burn well.

Figure 17: Firedogs for burning logs, adapted for coal 17thC, in the hall of The Charterhouse, London (Shuffrey 1912, 154).

Figure 18: Firedogs adapted for burning coal at Penhurst Place, Kent (Shuffrey 1912, 152).

Introduction of the fireback

The mid to late 16th Century saw the introduction of cast iron firebacks, which became more popular in the 17Th Century (Figure 19) (Hodgkinson 2010, 39). This coincides with improvements to the manufacture process of cast iron products (Tylecote 1976, 81-105). The fireback served to protect the back wall of the fireplace from heat damage, and the casting of patterns and heraldic imagery into it suggest that it also afforded an aesthetic quality as well as a practical purpose. It is also suggested that the fireback reflected radiant heat back into the room more effectively than brick (Willis 2016,237). The fireback is the beginning of the mass production of a product for the fireplace, and many firebacks were imported from Holland (Shuffrey 1912, 135) as they had a more sophisticated method of manufacture involving sand moulds (Cox 1990, 129). The fireback may be seen as a transition to a more standardised fireplace, and developed into the production of whole grates which were cast of iron and fitted into an opening (Eveleigh 1990, 4).

Figure 19: A Cast iron fireback from Powis Castle, National Trust object number 1180886.

As manufacturing processes for cast iron developed, and coal became more common, other fireplaces started to be produced (Tylecote 1976, 84). Cast iron was an ideal material for the production of grates as it was resistant to heat, relatively cheap, and designs could easily be re-produced. By the 18th Century, new larger 'all in one' grates were being developed (Eveleigh 1990, 4).

The grate insert

Stove grates, hob grates, or duck-nest grates were very popular towards the end of the 18th

Century (Figure 20 and Figure 21) but were introduced around 1700, when house inventories start to list grates in other rooms in the house (parlour and upstairs rooms)(Eveleigh 1990,8). The design aided the combustion of coal with a smaller concentrated opening for air. Fundamentally, the hob grate raised the fire quite high up, nearer the opening of the chimney, lessening the chance of smoke entering the room. This further encouraged air to pass through the fire, rather than over it, accelerating the rate of combustion (Wright,1964,78,86). The increased amount of oxygen passing through the fuel bed heightened the rate of burning to a point of wastefulness, and led to some scientific thought about the fireplace and its design (Eveleigh 1990, 8).

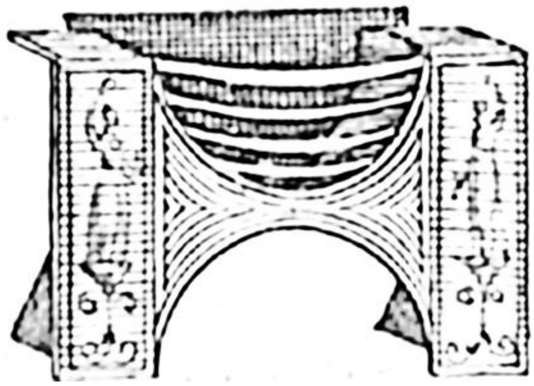


Figure 20: A hob grate, Thomas Upton Trade Card c.1800 (left); Georgian hob grate (right).

Figure 21: Tudor fireplace in the Renaissance style, reduced and a 19th C cast iron grate inserted for burning coal, at New Hardwick Hall.

Count Rumford is credited as the father of the modern fireplace, producing dimensions and rules which would produce more efficient fireplace (Rumford 1796, 336). By lowering the fire from the throat, any air going up the chimney did not have to pass through the fire, accelerating the rate of combustion. This improved controllability of the fire, but to combat the problem of smoke entering the room Rumford narrowed the area of the throat, and angled the sides of the fireplace, getting narrower towards the back (Figure 22). This improved the aerodynamics of the fireplace, so that no smoke would enter the room. The whole fireplace was to be built of brick, and iron kept to an absolute minimum. Brick is a more insulating material, and was chosen to reflect the heat from the fire into the room, unlike iron which would absorb heat into the structure of the building (Rumford 1796, 348).

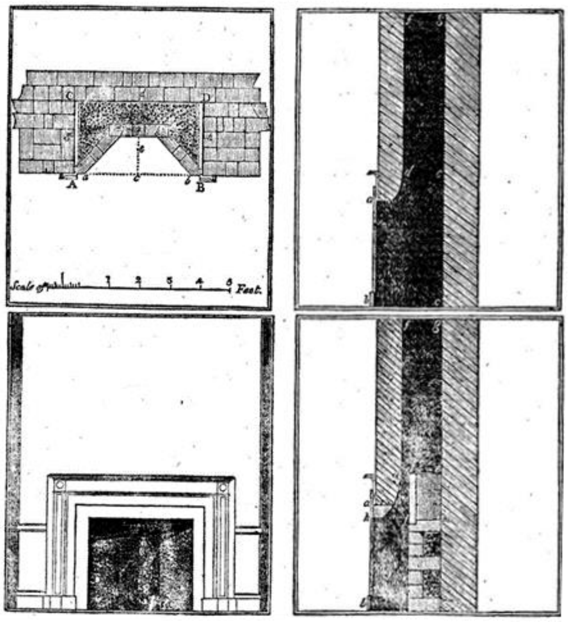


Figure 22: Rumford's fireplace, top right showing before alterations (Rumford 1796).

However, the industrial revolution with its proliferation of cast iron goods, saw grate development following completely different designs to those laid out by Rumford (Figure 23) (Muthesius 1982, 52). Mass production of cast iron goods made fireplaces cheaper, and easier to fit. A relatively unskilled builder could install a cheap grate that was guaranteed to not smoke, and not require complex brickwork or formula to follow. Thus the vast majority of fireplaces sold in the 19th Century do not conform to the principles of the Rumford fireplace, as they are made of iron and not brick. This is clearly seen in the Ironmongers trade card which advertises a stove grate on Rumford's principles, but the illustration shows a fireplace which does not conform to any of Rumford's design ideals, as it is made wholly from cast iron, and it is doubtful the angles or throat dimensions are correct, though an attempt has been made to replicate them (Figure 23).

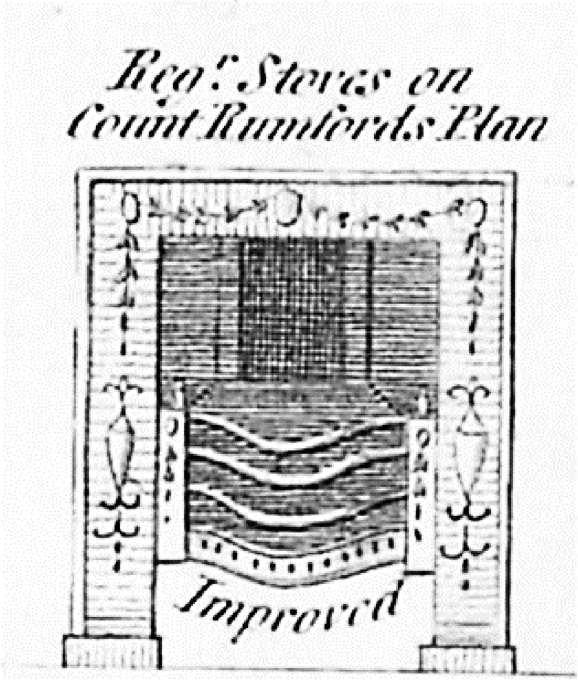


Figure 23: Thomas Upton Trade Card c.1820 showing cast iron grate made on 'count Rumford's Plan'.

The later 19th Century

By the 1880s, work by Teale had set a new standard for the design of fireplaces and introduced formulas by which fireplaces should be constructed to be more efficient (Figure 24).

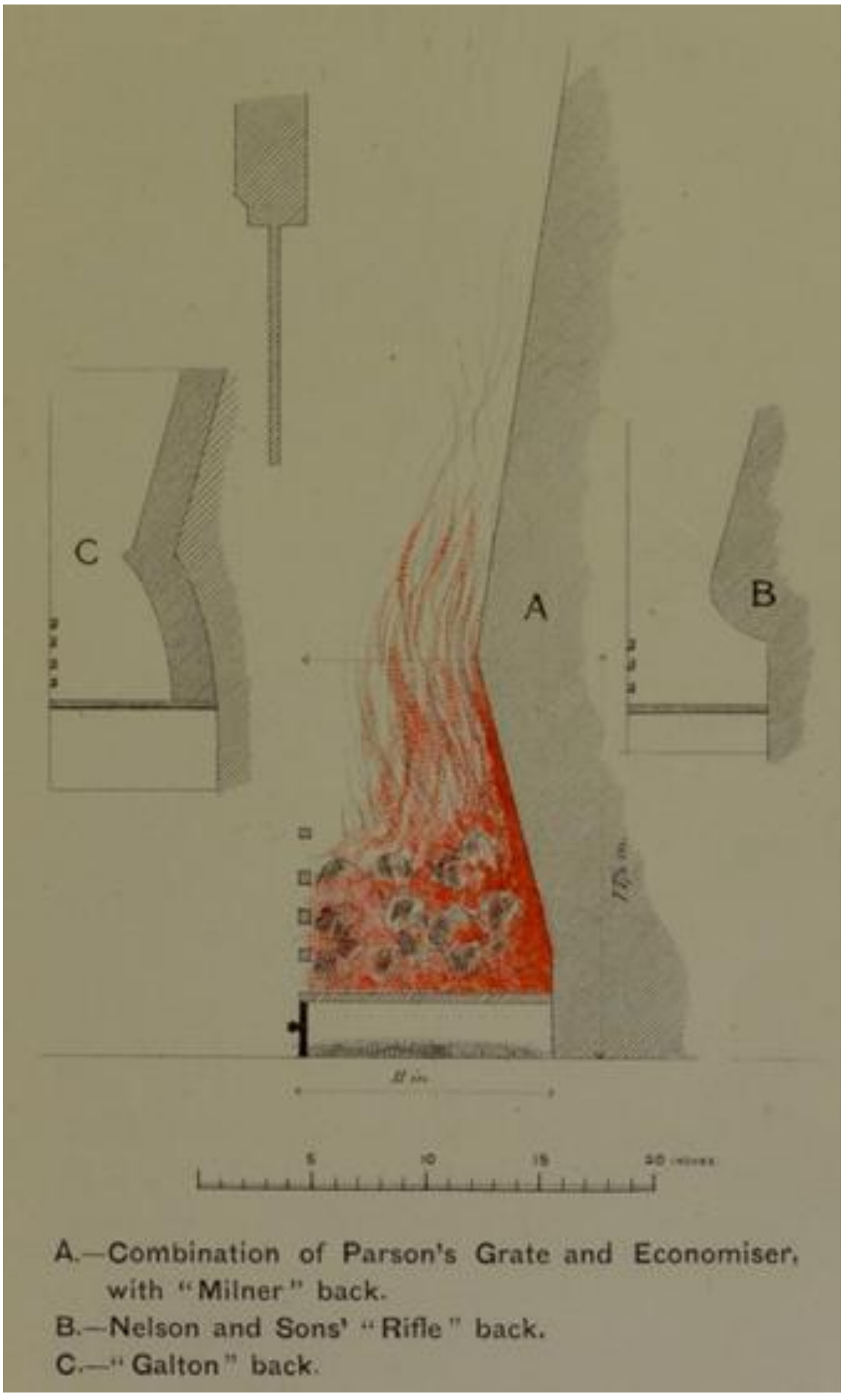


Figure 24: Cross sections of Teale's improved grates, showing the minimal use of iron and use of fireback angles to minimise heat loss up the flue (Teale 1883, 37).

Manufacturers did take up the new principles of grate design by Teale, but also contiued to manufacture other fireplaces which did not (Teale 1883, 12; Sutcliffe 1898, 124; Middleton 1906, 137). The manufacturers' catalogues of the period, advertising side by side the more old fashioned grates, and the ‘improved whole fire brick back’ based upon Teale’s principles (Figure 25) (Smith 1990). Teale had also recommended the removal of ‘firebars’, so as to not block the path of the radiant heat into the room. Teale’s principles are basically an extension of those already laid out by Count Rumford but adapted and modernised for the industrial age. Teale extends this to a fireclay back to reflect heat into the room, and sides that are angled inwards along the same lines as Rumford. However, the sloping forward of the fireclay back is original to Teale, the idea being that it will be heated by the fire more readily if the fireclay is above it, and that this heat will be radiated into the room. The other recommendation on the limitation of the size of the throat of the fireplace is merely another of Rumford’s principles which was largely ignored (Teale 1883, 12; Sutcliffe 1898, 125).

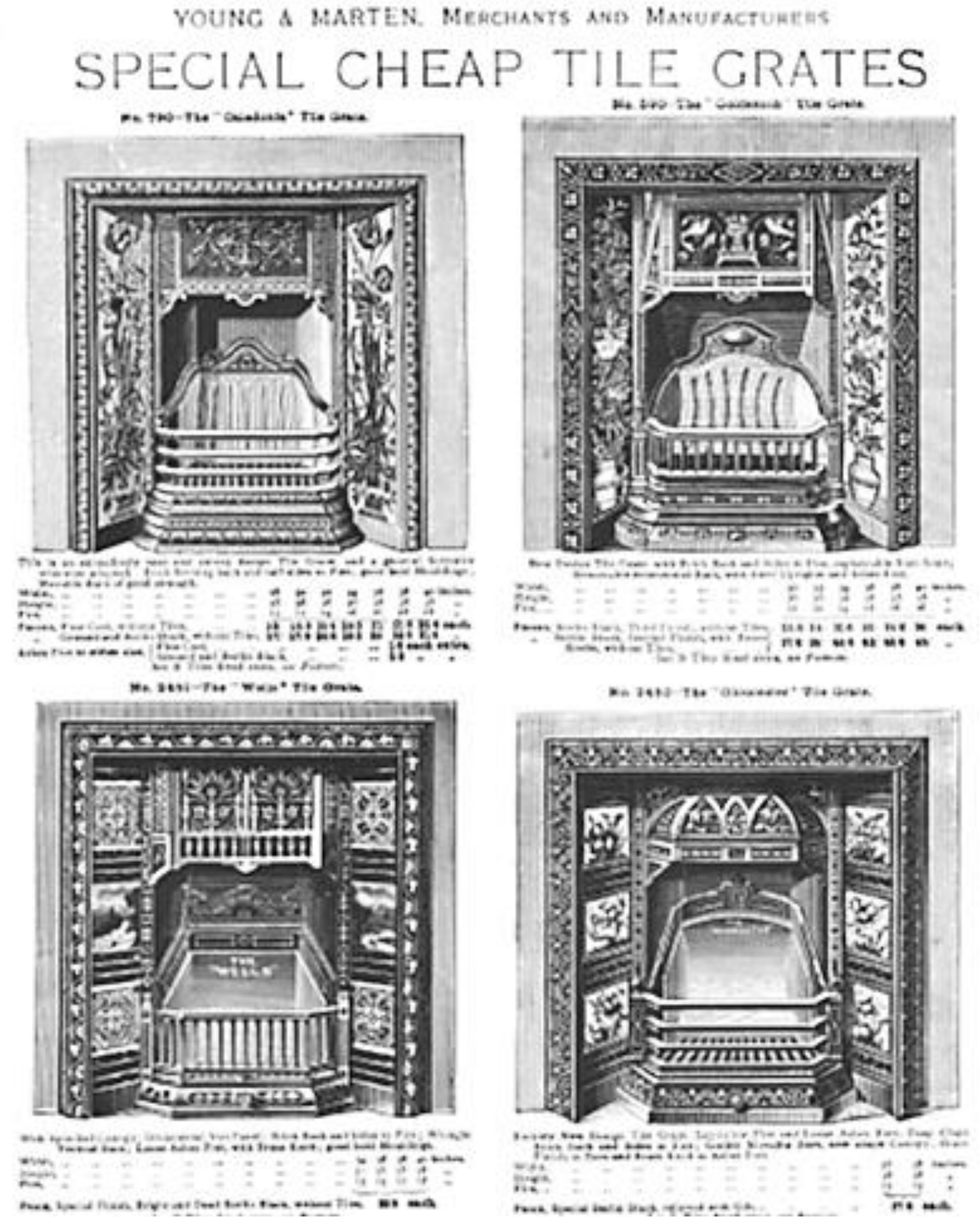


Figure 25: Mass produced fireplaces from an 1897 trade catalogue (Smith 1990).

Towards the end of the 19th Century, technological advancement had meant that other forms of heating, such as central heating via pipes, hot air, or radiators, were now attainable by most of the more well-off members of society. Indeed, certain mansions do possess heating systems, such as the Large Neo-Tudor Stradey Castle in Carmarthenshire (Built in the 1850s and extended in the 1870s) (Palmer 2016, 95-97; Wilson 2016, 91).

The central heating system at Stradey Castle, for example, which is Victorian, does not extend to the bedrooms. Nor does it provide much more than background heating to the rest of the house. Indeed, many similar properties of this period, possessed by wealthy individuals, have no central heating system. This is because in Britain there was a strong prejudice in favour of the open fire, and also staff to keep fires burning (Palmer 2016, 95-97;Wilson 2016,85,91). This became grounded in Science in the Victorian period, ventilation was considered essential for human health, and radiant heat was also considered preferable (Muthesius 1982, 52). Furthermore, the fairly mild climate of Britain meant that the limitations of open fire heating were rarely felt as often as in the colder climes of certain American states and continental countries (Fishenden 1920, 73). This is not to forget the general cheapness of coal too, which made up for the inefficiency of the open fire heating as stated in 1920 *'with coal at 45s per ton, gas at 4s 6d per thousand cubic feet, and electric power at 1d per unit, the cost of a coal fire for continuous heating is … one-third that of a good gas fire, and one fifth that of an electric fire of equal heating capacity.'* (Fishenden 1920, 73).

The Smoke Abatement Society sought to reduce smoke output from domestic fires, publishing the results of tests on certain appliances in 1904 and 1906 (Figure 26) (S.A.S 1906, 182; Fishenden 1920, 99).

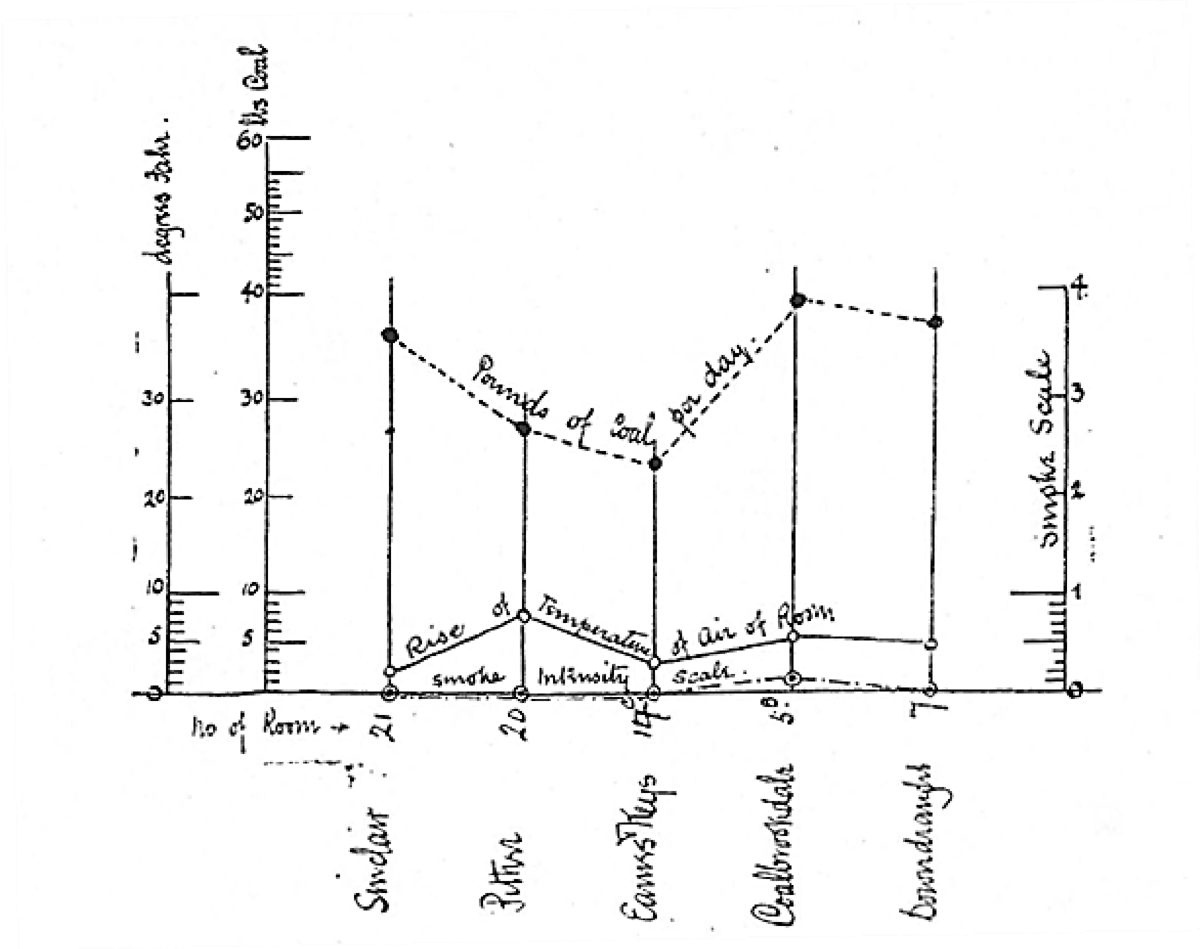


Figure 26: Results from testing of fireplaces showing rise of air temp, smoke intensity, and pounds of coal burnt (Smoke Abatement Society 1906, 182).

Whilst stoves could easily attain results, it was clear that they had a limited purpose, and more generally are advertised for heating hallways, servants' quarters, and occasionally dining rooms (such as the Pither stove at Batemans) (Sutcliffe 1898, 125; Phillips 1920, 24). The Pither stove (Figure 27) is an interestingly British product of a society that desired always to have an open fire. It is a stove lacking in a door, so that the fire is always exposed. This appeals to those who wanted the efficiency of a stove, but also the benefit of direct radiant heat from the combustion of the fuel, as seen in the naming of the device 'Pither

Radiant Stove'. An efficiency of above 80% is achievable with a Pither Stove, however, when tested by the Smoke Abatement Society they concluded that it 'couldn't be accepted as an open grate as the sense intended or as suitable as where an open fire is required' despite achieving better results than all other grates tested (S.A.S 1906, 1414).

Figure 27: A Pither Radiant Stove, Lattice Model (author's own).

The Chimney and Flue

As houses gained more apartments, fireplaces became more numerous, and more chimneys were utilised. Flues became smaller, and broadly general principles or rules for construction were followed, after the Great Fire of London it was stipulated in the 1666 Act for Rebuilding the City that timber be excluded from the flues, and in the Building Acts of 1707 and 1709 flues were to be parged (plastered) internally. It was not until the Building of Chimneys Act 1834 that a flue size was set in law. The main limiting factor to flue size was the ability of them to be cleaned by a boy climbing up them. The development of mechanical methods of sweeping meant that dimensions could be reduced, to the standard brick by brick (9" square, or 9" x 14" for large cooking ranges). The Builder Magazine (Godwin1860, 303) suggest socketed clay pipes had been invented and utilised for drains and chimneys in 1842. The lining of flues provided a smoother conduit for the products of combustion, reduced friction, and reduced the availability of ledges and crevices for soot to collect and resultantly reduced the likelihood of chimney-fires. It has been the law when constructing chimneys to utilised liners since Building Regulations 1965.

The scientific theory behind the construction of chimney flues and the relationship between fuel, draw, length and internal diameter was known by the Edwardian period. Barker (1912,423) provides formula which allow for the correct sizing of chimney flues, this was of particular importance at the time beyond the use of chimneys but also for ventilation where mechanical methods could not be utilised and thus natural ventilation through flues was utilised (Barker 1912,192).

Research into fire efficiency

2.1.1 Early scientific research

Scientific advancement throughout the 19th Century had led to the development of the thermopile, an instrument which could provide a voltage output relative to its exposure to radiant heat (Figure 28). A further instrument, the galvanometer, was capable of measuring very small electrical currents to a high degree of accuracy. Used together, the instruments could measure the radiant heat outputs of open fires, thus allowing for a more detailed study of the efficiency and heat output of open fires (Seebeck 1825, 253; Peltier 1834, 278; Thomson 1852, 99; Fishenden 1920, 2). The 1890s saw the use of the instrument widen, and even used to measure the radiant energy from the moon during an eclipse in 1895 (Abel 1896), and by this period it had been used to measure radiant energy from solid fuel as well as gas fires (Des Vœux 1907, 155).

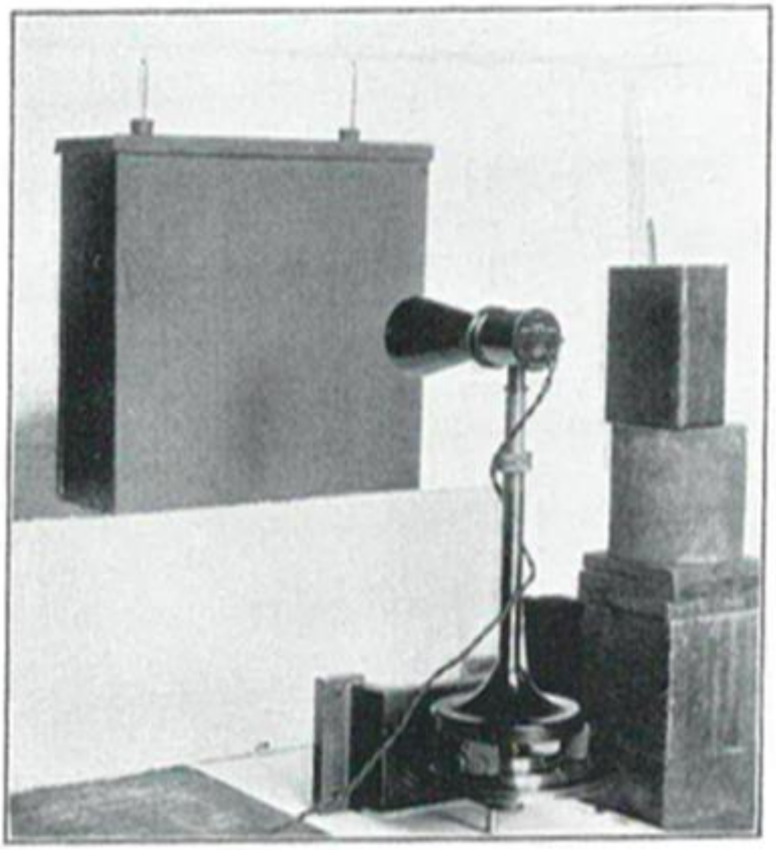


Figure 28: A thermopile being calibrated against a known emitter (copper box coated in lampblack, filled with water of known temperature).

Dr Margaret Fishenden in 1916 as part of Manchester Corporations Air Pollution Board advisory team, tested several grates using a thermopile. Under laboratory conditions several types of open fire grate were tested. The results of the tests gave data for heat output and efficiency, and also set a standard method for measuring radiant heat output of open fires (**Figure 29**) (Fishenden 1920, 18).

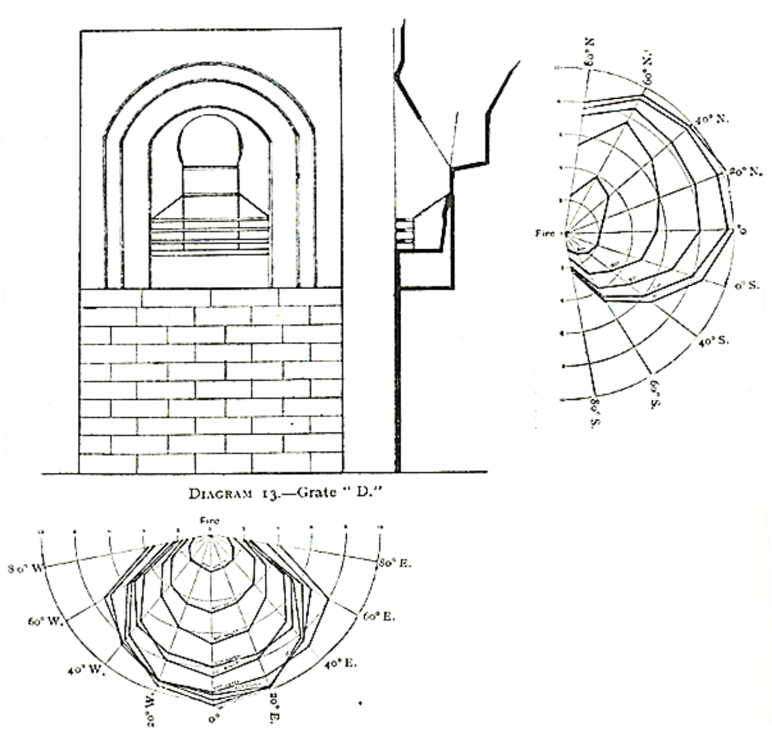


Figure 29: Results from testing of fireplace showing radiant heat distribution (Fishenden 1920, 18)

Dr Fishenden tied into this another study which looked into the heating capacity of the open fire and human comfort (Figure 30). This concluded that the cheapness of coal, and mildness of climate had meant that the open fire was generally an acceptable heating method within the United Kingdom (Fishenden 1925b, 263).

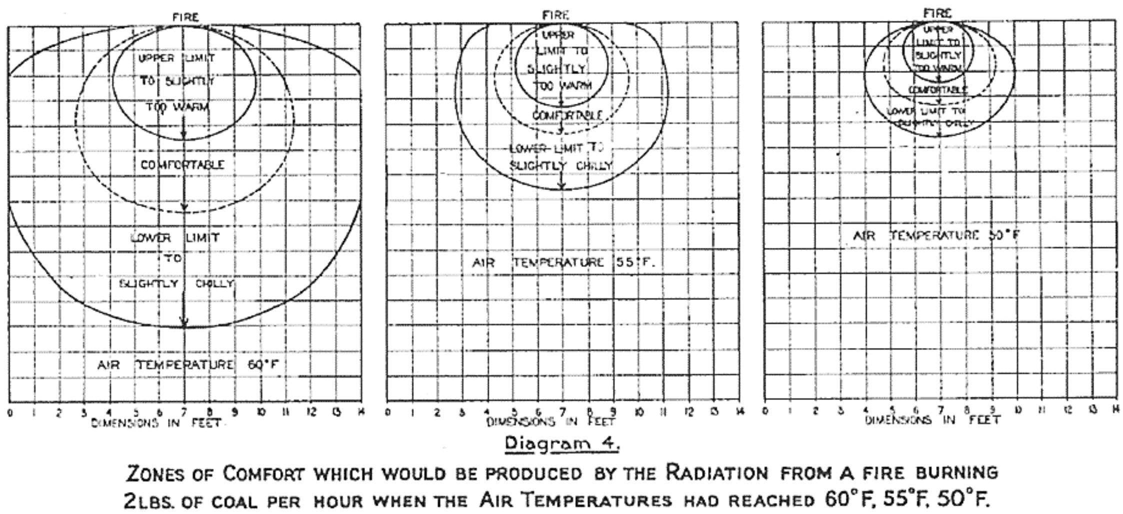


Figure 30: Comfort zones from open fire in relation to air temperature (Fishenden 1925b).

A further work was published by Fishenden in an attempt to find the best practical design of fireback and grate for efficiency of the open fire. The experimental method employed for measuring fireplace efficiency was the same as that utilised in her previous work, The Coal Fire, but the dimensions and proportions of a fireplace were altered until the best results were obtained (Fishenden 1925a, 5).

2.1.2 Inter-war scientific research

The inter-war period saw the extension of the science of aerodynamics to the fireplace. A study was undertaken utilising scale models of fireplaces to determine the flow of air and gasses and the rate of combustion based upon aerodynamics (Figure 31) (Rosin 1939, 16). This was done by using dye-streams in a water tank. Certain ideal designs were drawn from this for the manufacture of cast refractory fire-backs (Senf 1995, 4).

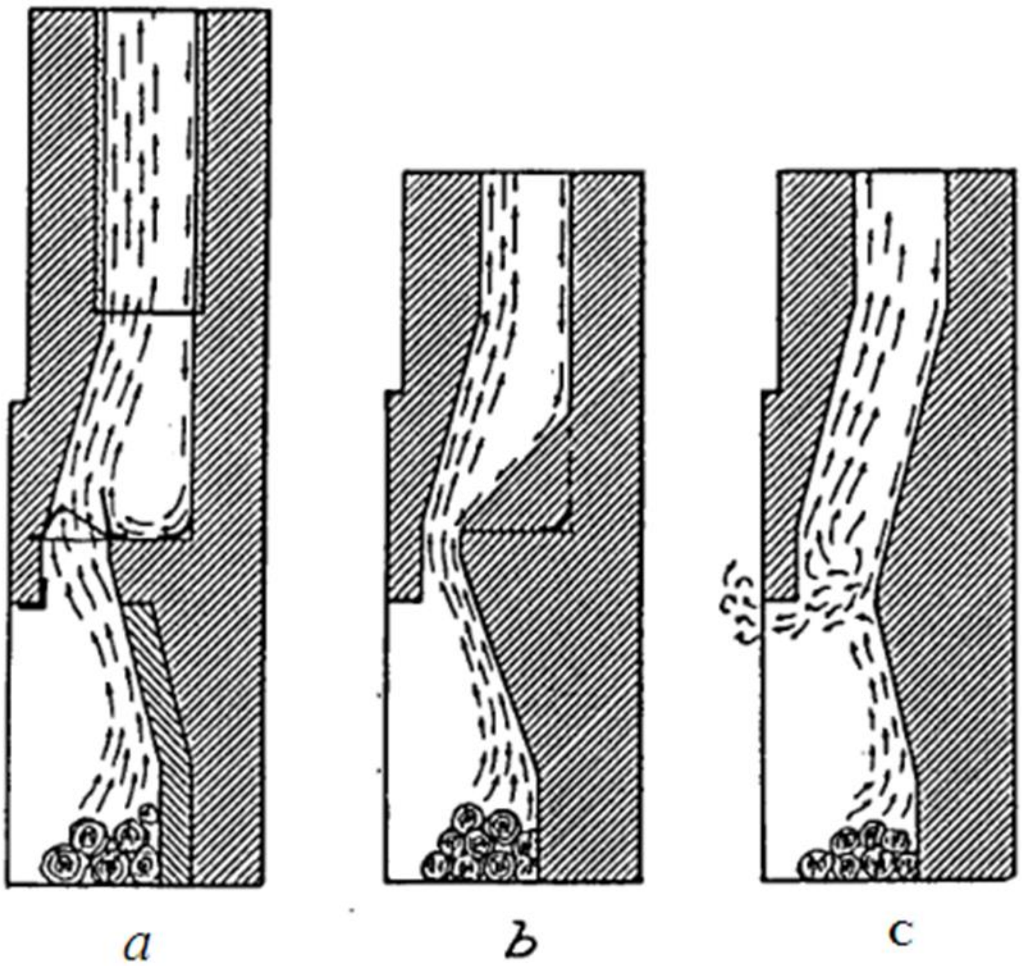


Figure 31: Cross section of fireplaces and different throat openings (Rosin 1939, 16).

A greater desire for scientific understanding of the thermal performance of buildings and their heating requirements in the 1930s was motivated by increasing cost of fuels and reduction in the availability of labour (for example, servants to make up fires) (Blackie 1938, 20).

Blackie (1938, 21) developed a similar instrument to Harcourt's Radiometer, it being utilised for measuring the radiant heat output from an open fire burning coke. The equipment was part of an experiment which was attempting to optically determine smoke concentration levels (Figure 32). A radiometer was made of copper with a honed finish, painted with lamp black. Water passed through the radiometer block, and its temperature was measured as it entered and as it left, the water was supplied at a constant temperature. Through this, it was possible to determine the heat output at a given time by measuring the increase in temperature to the water.

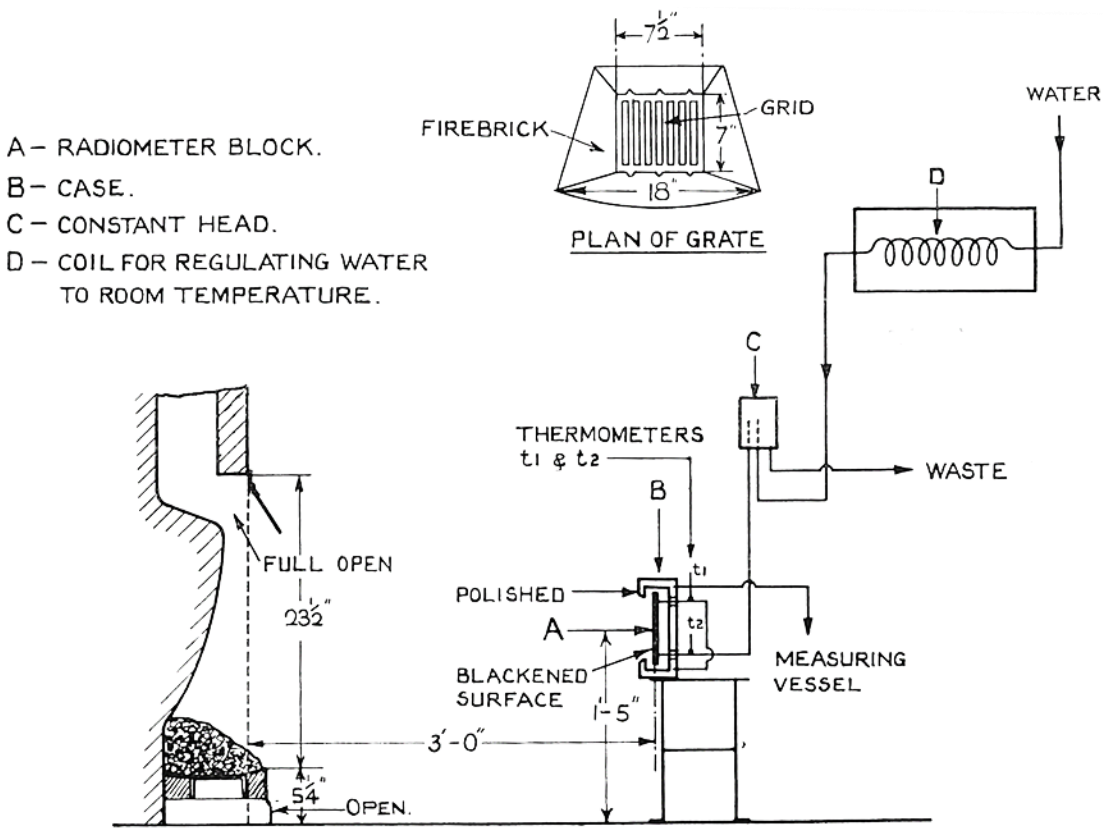
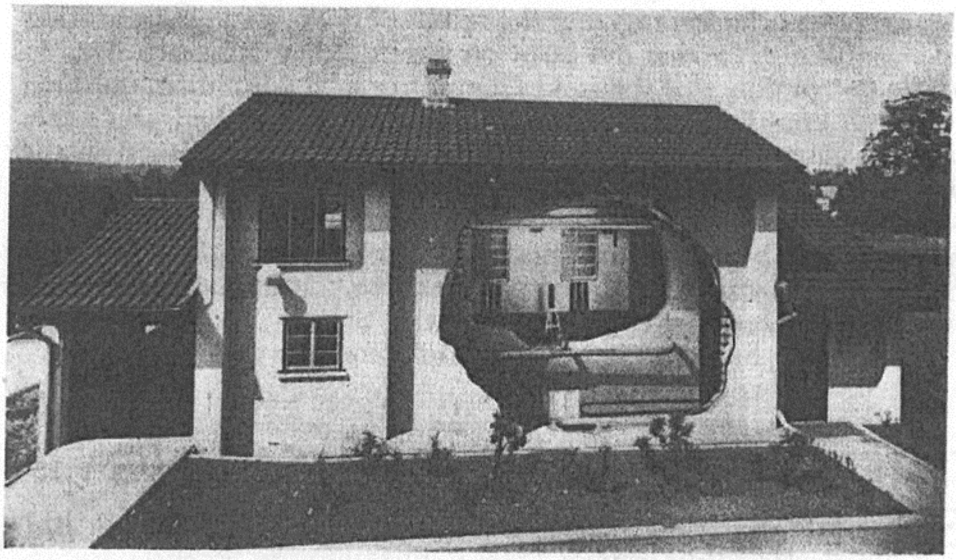


Figure 32: Fireplace and apparatus for measuring radiant heat output (Blackie 1938, 21).

Government funding in the inter-war period from the Department of Scientific and Industrial Research helped to build a 'Heating Laboratory'. This comprised of a test room built to the constructional standards of the time, within a larger building. The temperature of the environment the test room was kept in could be maintained perfectly via heating ventilation and air conditioning (HVAC) equipment, so that the variable of weather had no impact of the experiments within the test room (Figure 33). This was one of the most comprehensive studies in heating that had been undertaken at the time, and the first time such a major variable as the weather could be removed from test results for the heating of rooms (Dufton 1942, 17).



THE HEATING LABORATORY.

Figure 33: Cut-away model of heating laboratory showing test room within the controllable environment of the building, (Dufton 1942, 17).

Wartime shortages and more extensive state control led a new drive for improved efficiency in house heating, after the war the Egerton Report on Post War Buildings was published, dealing especially with heating and ventilation (Egerton 1945, 1). This major publication sought to give a detailed picture of the nation's heating and make recommendations upon it for the future. It was an extremely comprehensive study, based upon survey and technical data, and sought to provide the most satisfactory solution for the heating of dwellings for the majority of people. Recommendations were made for the development, installation and operation of heating appliances, as well as testing and standardisation (Egerton 1945, 94). Results from the survey colour the development of domestic heating systems and are useful for gaining an insight into the opinions of the population at the time. For example, one question 'would you still like central heating if there were no coal fireplace' gave a response of 60% saying 'no', and in some areas as many as 79% of housewives rejected the idea (Egerton 1945, 172). Later on it can be seen that products, such as the high-output back boiler, allow people to have central heating and hot water, all from their living room fireplace (Eaton 1956, 9).

2.1.3 Holistic research into building heating

The Building Research Station experiments at Abbots Langley in 1949 required 20 houses to be built and was the largest study that had taken place looking at house design and heating (Figure 34) (Weston, 1949,237).

Figure 34: BRS Test Houses (Weston 1949, 237).

Efforts were made to compare 'existing' or 'pre-war' type heating systems with more modern types, such as central heating and all-electric. It was the study which evaluated the efficiency of the appliances as part of a whole building, rather than solely on a 'test bench', for example the chimneys were found to give out as much as 25% of the heat from the fuel burned in an open fire. As such, it was found that an open fire gave an overall efficiency of over 52% in one of the test houses (Weston 1949, 254). Cost was taken into consideration, as well as the time taken to keep a system running, overall it was found that the open fire performed better than expected in efficiency, it was not the most expensive system of heating, but it was one of the worst performers for heating by measuring air temperature throughout the house (Figure 35) (Weston 1949, 243; Weston 1951, 47).

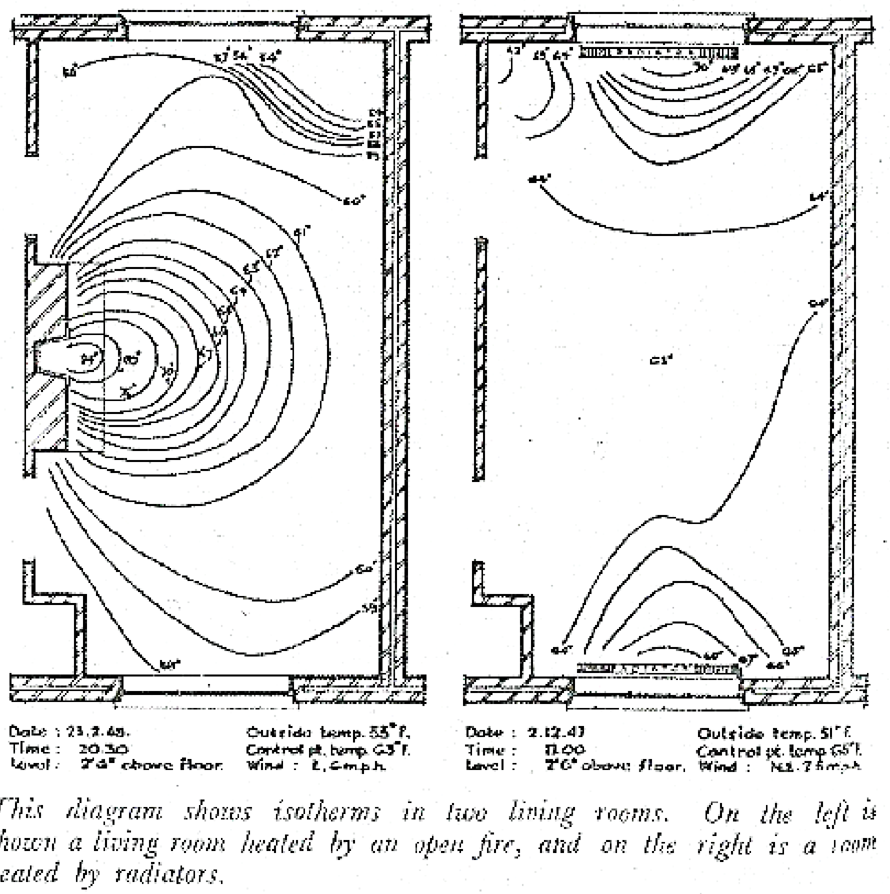


Figure 35: Some results on the BRS heating trials, comparing heat distribution throughout a room heated by open fire, and by radiators (Goddard 1950, 132).

The British Coal Utilisation Research Association was established in 1938 and researched and developed further applications for coal . The organisation developed and tested various open fires, refining the instruments used to measure the radiant heat output of open fires, for which most publications are from the 1950s (Copson 1957, 3; Venables 1957b, 1). BCURA utilised a method for measuring radiant heat that was developed by Brearley in 1907 for the testing of gas fires using a thermopile, and later drawn on by Fishenden in her study The Coal Fire (Fishenden 1920, 77). BCURA took this method and refined it to produce the BCURA Radiometer (Figure 36), this standardised the instrument and it is included in BS 3376: 1991 as the approved method for measuring the radiant heat output from solid fuel appliances (Venables 1957a,1; BSI 1991). A number of experiments were conducted by BCURA into measuring various aspects of solid fuel appliances, and this is perhaps the last real technical development for open fires.

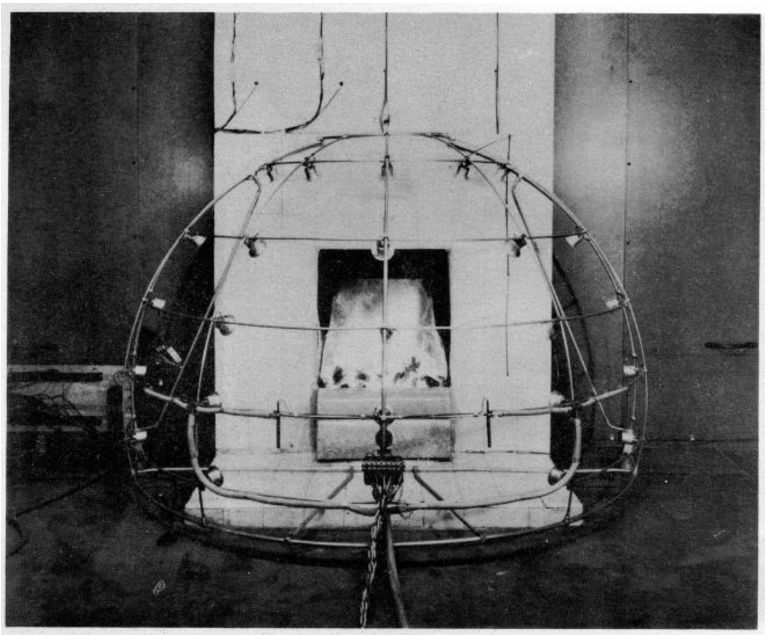


Figure 36: A BCURA cage radiometer in use (Venables 1957a, 8).

Whilst other open-fire appliances are manufactured, the advent of heatproof glass allowing people to have a stove and see the flames, gave people the best of both worlds; the ability to see the flames without having the high air exchange rate (Figure 37) (Trianco 1981). Also, post-war there was a steady increase in the uptake of central heating, which took off after the introduction of natural gas in the 1970s (Palmer 2013, 13,46). As such, the practical heating demands of the open fire have not seen much development since the 1960s.

Figure 37: A Trianco stove/'roomheater' with a door containing heat-proof glass (Trianco 1981).

There is perhaps one last product that is of importance when discussing the post-war open fire. The back boiler and the high-output back boiler, the later becoming popular in the 1950s as more people wished to run central heating but maintain a fire. The simple back boiler was developed in the later years of the 19th Century to heat domestic hot water from a kitchen range (Shaw 1954, 273) (Figure 38).

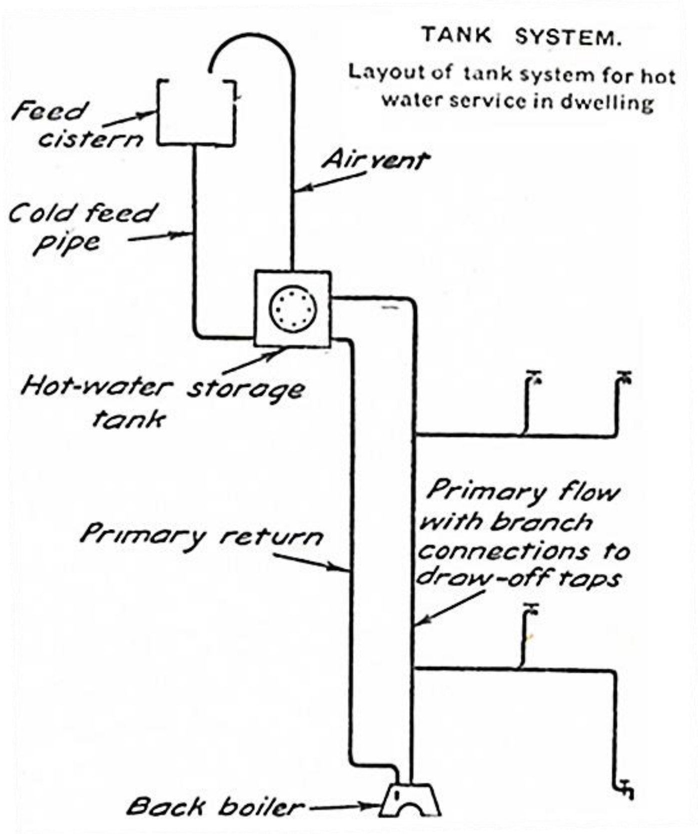


Figure 38: How a back boiler heats domestic hot water (Stubbs 1949, 1039).

This was usually a copper, steel, or cast-iron box which sat behind the fire. As gas became more popular for cooking, the boiler moved to behind a normal fireplace, and this method was commonly employed for heating domestic water from the 1920s to the 1950s. By the 1950s this developed into a more sophisticated 'high output' boiler, which could heat radiators as well as the domestic hot water (Figure 39) (Eaton 1956, 9).

DUNSLEY BAXI BOILERS

A full range of central heating boilers are available to suit any of the Burnall underfloor draught fires from 16" to 18". The complete unit is over 70% efficient and is amongst the top select few providing this high level of efficiency.

400mm 16"	Direct Radiation	Damper 1.5 kW open 5,100 BTU/hr	Damper 2.0 kW closed 6,800 BTU/hr
	Water	Damper 5.7 kW open 19,450 BTU/hr	Damper 3.8 kW closed 12,950 BTU/hr
450mm 18"	Direct Radiation	Damper 1.9 kW open 6,500 BTU/hr	Damper 2.3 kW closed 7,850 BTU/hr
	Water	Damper 6.8 kW open 23,200 BTU/hr	Damper 5.2 kW closed 17,750 BTU/hr

Figure 39: A Dunsley high output back boiler with underfloor draft and sunken grate (Dunsley Heat 2009).

Dunsley Heat were a market leader in this field, and introduced their first high output model in 1952 with an efficiency of 55% (Broadbent 2017). Consistent development of this product has now delivered an efficiency of over 70%, which is akin to many closed stoves (Dunsley Heat 2009). This is due to the water-jacket type boiler, rather than a simple box, which has its own flue-ways. This absorbs much of the heat that would otherwise be lost to the brickwork of the chimney or the atmosphere by the flue gasses. This water is then used to heat radiators. In conjunction with a valved external air feed, draughts are kept to a minimum and the rate of burning can easily be controlled. It is close to the best an open fire can ever be in terms of efficiency and controllability, without becoming a stove, and is still manufactured today (Dunsley Heat 2009).

2.1.4 Research going forward

It has taken a global pandemic to re-instil a viewpoint that ventilation is beneficial to health, with Professor Catherine Noakes advising the SAGE committee on improving ventilation to reduce the spread of airborne diseases (The Life Scientific 2021; BBC Radio4). From a modern perspective it has until the last year (2020) been difficult to fully appreciate the historic obsession with ventilation, and the wilful desire to utilise an inefficient heating method so readily. The Fishenden study (1920) for the Manchester Corporations Air Pollution Board advisory team cites a key benefit of the open fire being ventilation. Looking forward towards lowering carbon footprints and improving energy standards, this has been the only time that there has been an overlapping of these historic motives for higher ventilation rates with current scientific thought.

Whilst scientific research into open fires has largely diminished over the last half a century, the focus within that time has been on improved energy efficiency of buildings. Previous scientific research focused on improving the efficiency whilst maintaining the open fire and excusing this lack of efficiency for the benefits of ventilation. Furthermore, technological development has meant that it is much easier to take measurements, such as with a thermal imaging camera. Computers and small data loggers also mean three dimensional models of the environment within the room can be created with relative ease.

In following on from the previous studies into the open fire, an overall larger picture that encompasses not only heat, but also humidity, can be built upon the foundation of this earlier work. Whist the outcome of this study is different to those previously, there are crossovers. Museums and historic houses will have a clearer idea about environments in rooms and buildings that utilise open fires, but also a better understanding about the environments that existed previously.

3 Wood use and environmental response

Overview

As the technology for heating has evolved over time, so to have the environmental conditions inside buildings changed. This impacts the way that the timber responds, which is based upon the chemistry and structure of wood.

The cellular structure of timber and its relationship with moisture is discussed in relation to the development of standards and guidance for displaying wood in museums and within historic houses. The impact on timber of gradual seasonal fluctuations in unheated contexts has been researched widely. This is of particular relevance to the National Trust, as many of their properties have limited heating throughout the year and they have produced strategies for winter control of environments within their properties (Blades et al., 2010). The use of fires in historic properties for visitor comfort is often associated with income-oriented events or, as occurs at St Fagans, for visitor experience and heating. This produces a greater diurnal temperature range and a consequent variation in relative humidity. Understanding the relationships involved between the environmental variables and timber can be used to consider its responses in the conditions that will be recorded during the fire burning experiments at St Fagans, where there is no control of the environment, other than by lighting fires.

Timber

As a material, timber is used in construction of buildings as well as furniture. A great deal of research has been carried out into the strength, rigidity, buffering qualities, thermal qualities and structure of timber (Ozden et al., 2017; Bratasz et al., 2008; Hameury, 2004; Padfield et al. 2011; Hon 2001).

Trees in their natural habitat must be both strong and flexible to support themselves but also not fracture or break when subjected to external forces (wind or weight of rain on foliage, for example) (Ozden et al., 2017). The hygroscopic nature of timber relates to the transportation and storage of water within the living tree. Once it is cut, wood is susceptible to dimensional changes based upon atmospheric changes to RH and temperature (Sjöström 1993, 11).

Cellular structure of wood

Trees are broadly categorised as being either softwood or hardwoods. The hardwood *Querqus robur* (European Oak) will be used in the experimental part of this thesis for examining the pattern of fire lighting on the uptake of water by wood. It is an Angiospermae (flowering), deciduous tree that has broad leaves and a denser structure containing more cells than softwood (Hon 2001,1). There are several intrinsic differences between the cellular structure of different species of timber (Figure 40). Hardwoods may be described as heterogeneous, they contain four types of cells: parenchyma, tracheids, fibres, and vessels (Domone 2010,408). Parenchyma cells are actively involved in photosynthesis and food storage, while tracheids are elongated cells that transport water and mineral salts vertically within a tree which is a function also performed by the larger vessels. In contrast, fibres are elongated cells that offer support to the tree and chemically differ to other cells in that they have a high lignin content to provide strength. Softwoods only contain tracheids and parenchyma cells and are defined as gymnospermae (cone bearing), such as pines and firs (Barnett et al. 2009,30). The terms are occasionally misleading, as hardwoods can be low density, and softwoods high density. As this study focuses on oak (*Q. robur*) then the structure of hardwoods will be discussed, and occasionally softwoods mentioned for illustrative and comparative purposes.

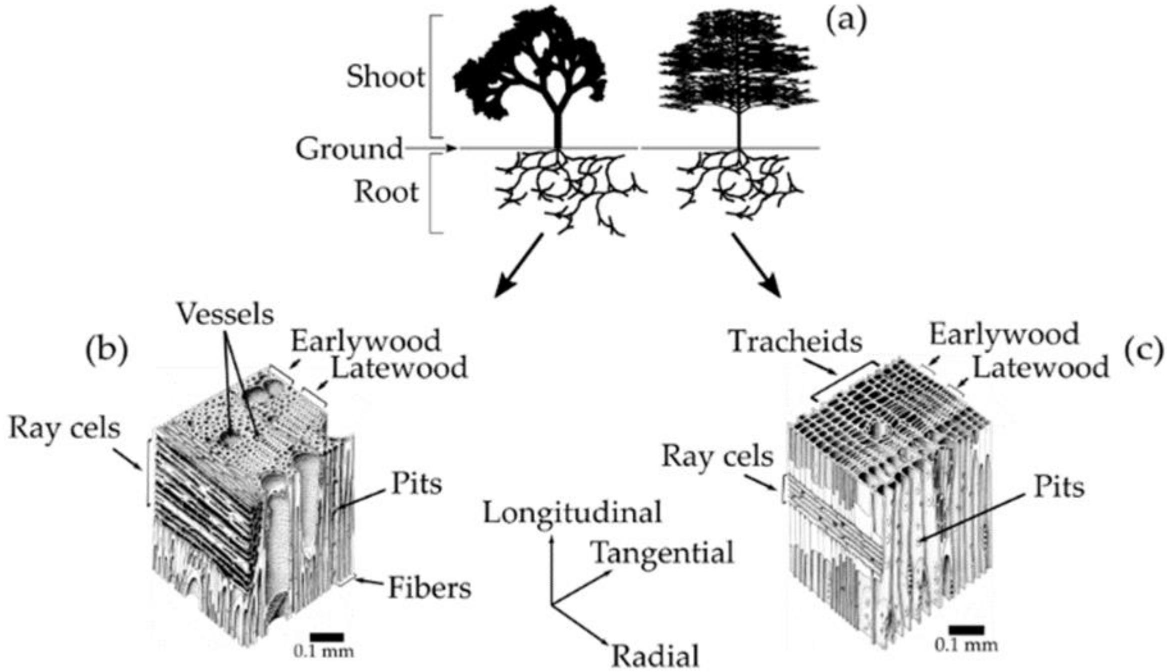


Figure 40: Representation of structure of hardwood (b) and softwood (c), giving an overview of cellular structure in all three directions with various elements, such as the earlywood and latewood forming rings, the pits between vessels, vessels, and ray cells (Arzola-Villegas et al. 2019, 3).

Fibres provide mechanical support and are about 1-2mm in length, they are long, thin and tapered at the ends, their cell walls are thick, with small cavities containing pits (Domone et al. 2010, 408). The term ‘fibre’ can refer to any type of cell, but more specifically relates to the supporting tissue that may be called libriform. They make up the larger proportion of the structure of hardwoods and are not intrinsic for water movement, as they are in softwood tracheids(Barnett 2009,31; Domone et al. 2010, 408). This, in part, is why their cell walls are thicker than in softwoods. The elongation of the fibre tips is considered an important and necessary for interlacing of fibres (Desch et al. 1996, 74; Domone et al. 2010, 408).

Vessel elements or pores are shorter, (0.2-1.2mm) and up to 0.5mm wide, If stacked they form a conducting tube and their cell walls are either partly or totally dissolved (Barnett et al. 2009, 47-49, Domone et al. 2010, 409-410). They form channels of moisture transport and may be several meters long, and their size in oak varies with the season, being wider in Spring. The ends of the vessel cells are formed in such a way as to best facilitate the movement of water, being perforated and not containing a membrane. It is believed that microfibril angle is a result of water tension within the vessels, as a result being near 90 degrees. Inter-vessel pits are essential in the movement of water (Barnett et al. 2009, 47-49, Domone et al. 2010, 409-410. As vessels do not stretch the whole length of the tree, inter-vessel pit pairs are necessary for water to move laterally between vessels and form an anastomosing network. Pit membranes are reduced to extremely thin microfibrils by a hydrolysing enzyme. In some hardwoods, tyloses form in vessels in the shape of a hot-air balloon, they are from the parenchyma and block the lumen. This blocks the passage of water and is why oak may be used for barrels. The concentration of tyloses is higher closer to the heartwood (Barnett et al. 2009, 47-49, Domone et al. 2010, 409-410).

Rays are made up entirely of parenchyma cells, forming tangentially. Medullary rays characteristic of oak are formed of parenchyma transporting water perpendicular to the growth rings, thus when the trunk is quarter sawn they are dissected and visible in the finished timber, as seen in Figure 41 (Desch, et al. 1996, 74; Eames 1910, 161; Domone et al. 2010, 408; Özden et al. 2017, 60; Barnett et al. 2009, 43-47).

Figure 41: Quarter sawn oak showing medullary rays as lighter patterned highlights on the door of an early 17th Century English long-case clock (author's own collection).

Considering the function of the parts of the tree, the roots take up moisture and nutrient salts, the leaves photosynthesise light energy (Wadsö 1993, 2). In-between the two, the trunk (protected by a bark layer), transports moisture up to the leaves and branches, and the compounds from photosynthesis down to the trunk and roots for use or storage (Wadsö 1993, 2).

Cell growth by division is formed at the cambium layer. It is living, though dormant in winter consisting of a single circumferential layer, in spring subdivision rapidly creates a layer some ten cells in width (Figure 42) (hardwood cambial cells rarely exceeding 2mm, in comparison to the 10mm of softwoods) (Desch 1996, 27). The primary wall is created within the cell, and as the growing season progresses, these cells subdivide into daughter cells which, depending on their location, will become either bark or wood. The increase of the circumference of the tree is accommodated by occasioned division of the cambial cells tangentially, which can lead to the development of spiral grain in timber (Domone et al. 2010, 407; Woodhead 2015, 7).

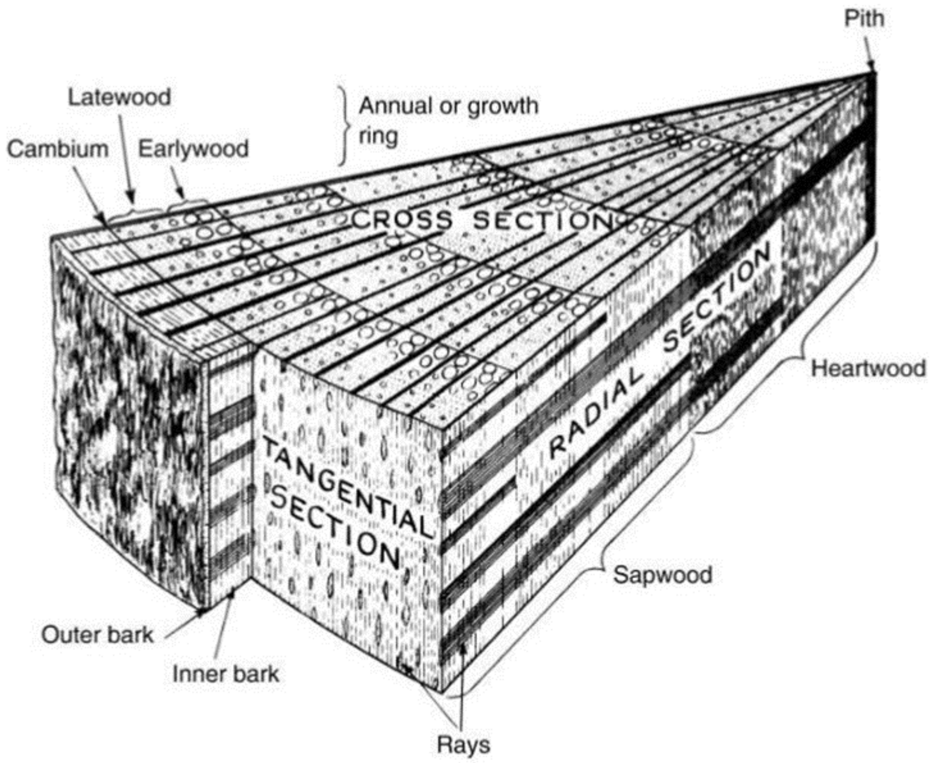


Figure 42: Five year old wedge of timber showing makeup of the wood (Desch et al. 1996, 11).

After the cell has stopped growing, its nucleus dies as it is effectively a vessel of water transport or storage. Water moves through these cells from root to leaves via negative pressure created by evaporation of moisture at the leaves. The heartwood of a tree can become cut off from moisture transport, which is focused on the sapwood. The early wood from spring has larger lumens for moisture movement, whilst the latewood from summer is made up of a higher percentage of cell wall and fibres. Water in hardwood moves via the vessel elements. These distinctions may be clearly seen in the microscope picture taken from one of the samples, and this phenomena in oak is known as ring-porous (Figure 43) (Sjöström 1993, 2-4; Desch et al. 1996, 23; Wadsö 1992, 2).

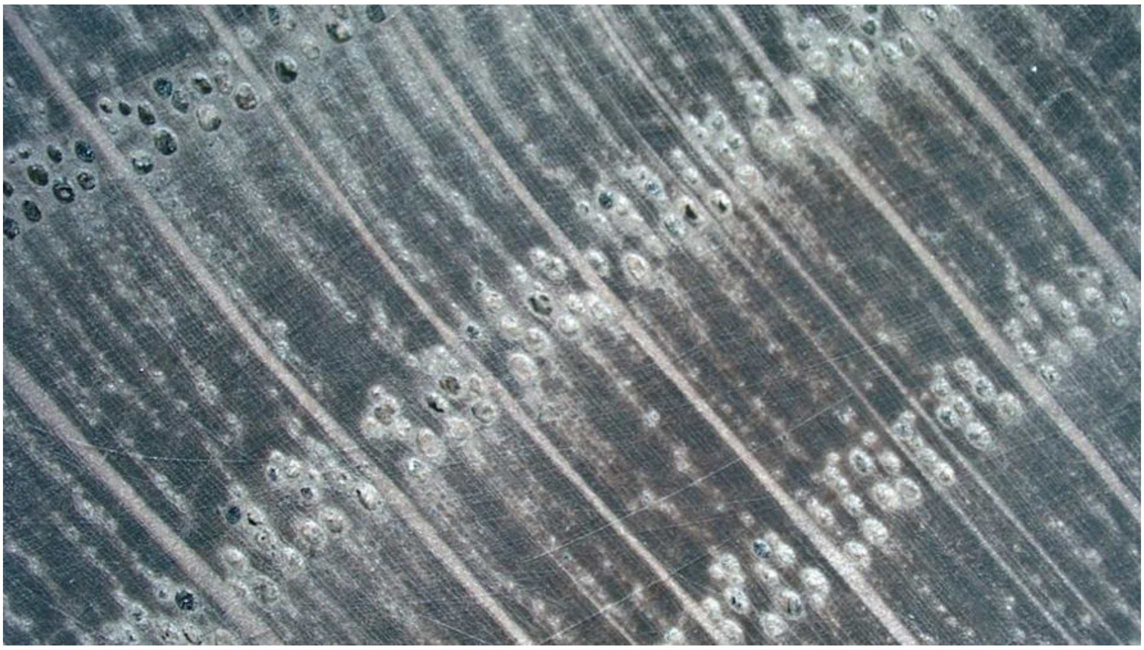


Figure 43: Cross section of oak sample from St Fagans, showing how lumen size changes seasonally. Also showing medullary rays at near ninety degrees to growth rings.

Wood chemistry

The chemical makeup of wood varies, but may be broadly described as 45-50% cellulose, 20-30% hemicelluloses, 20-35% lignin, and 0-10% extractives. Glucose ($C_6H_{12}O_6$) is formed as a product of photosynthesis and, in the cambial zone, these units bond forming long monosaccharaide chains; two glucose molecules bind, eliminating a molecule of water. This forms repeating anhydroglucose unit, glycosidically linked in the 1,4 positions, the first and fourth carbon atom clockwise after the oxygen atom, which necessitates them being flipped vertically (Barnett et al. 2009, 55; Desch 1996, 37).

The cellulose molecule is at least 5000nm long, and 1nm wide for a plane cross section of the pyranose ring. The polymerisation in wood of cellulose ($C_6H_{10}O_5$) is about 10,000 glucose units, 36 parallel cellulose molecules, held together by hydrogen bonds between adjacent monomeric units. Secondary bonding of hydrogen bonds and van der Waals forces link sheets; hydrogen links exist within the cellulose and also between separate cellulose to form a sheet of a single pane. The weaker van der Waals forces link the sheets and thus form a fibril, which is crystalline and known as cellulose I.

The nature of the structure of the fibril changes along its length, some areas are crystalline, some semi-crystalline, others amorphous based upon looser association between molecules. It is estimated that 70% of the cellulose is crystalline, 48 molecular chains of cellulose form the crystalline core of the fibril which is encased in an area of low crystallinity formed of hemicelluloses and non-crystalline cellulose (Figure 44).

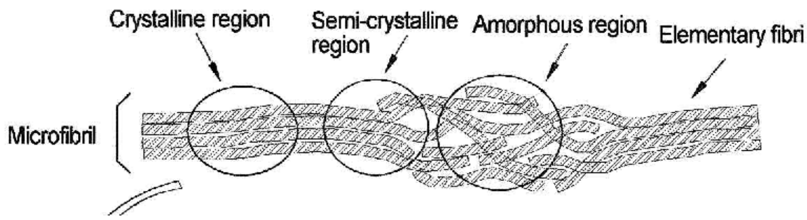


Figure 44: Structure of microfibril proposed in (Stokke et al. 2006, 134).

The outer regions of this layer are comprised of lignin which is amorphous and non-crystalline. The -OH groups of cellulose molecules allow the hydrogen bonding but are also attractive to water (Figure 45) (Barnett et al. 2009, 55; Sjostrom 1993, 12; Gardener et al.

1974).

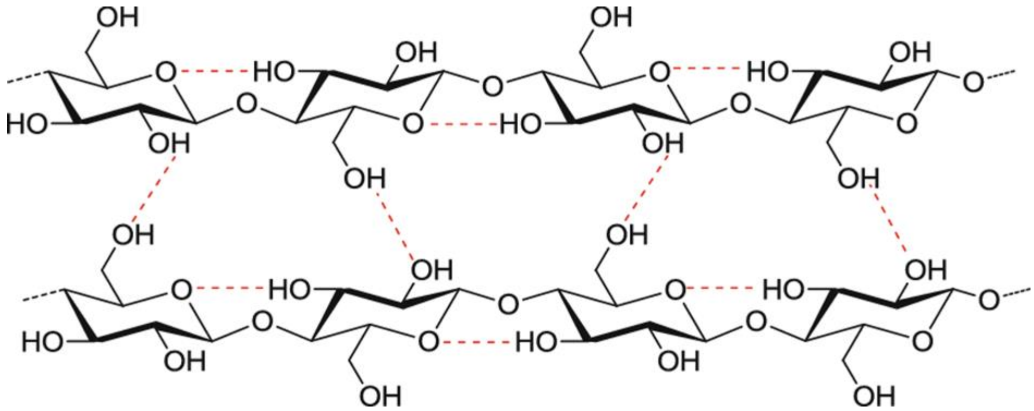


Figure 45: Intramolecular and intermolecular H-bonding in cellulose (Pingping et al. 2015, 212).

Hemicelluloses are non-cellulosic polysaccharides formed of basic sugars such as mannose, galactose and xylose, and like cellulose are carbohydrates. They are low in density of crystallinity, comprising of 150-200 sugars per molecule, therefore their degree of polymerisation is much lower than that of cellulose. Their composition is not molecularly uniform and varies from species and wood type. Hardwoods contain a great portion of hemicelluloses than softwoods and are largely made up of xylans (O-acetyl-4-O-methylglucuronoxylans) and in smaller numbers glucomannans, both of which make up cell walls (Barnett et al. 2009, 60; Desch 1996, 40).

Lignin is a highly complex, non-crystalline, aromatic polymer. As a molecule it is 20-30% of the cells wall material in wood generally, and 25-30% of the weight of dry oak heartwood. Their hydrophobicity contributes to resistive qualities to moisture permeability in oak. Its structure and composition depends on wood type, but because of their size and complexity they are not fully understood and are the subject of continuing research. It is known to be a macromolecule from the polymerization of three phenylpropane monomers. Oak lignin is largely formed from phenylpropenoic alcohols; hydroxy-4-methoxy-3-cinnamic alcohol, hydroxy-4-dimenthoxy-3.5. cinnamic alcohol. The final structure is space-filling and generally isotropic, it is three dimensional consisting of phenylpropanoids linked by covalent bonds (C-O and C-C) (Figure 46). It is amorphous without an organised supramolecular structure. It is rigid, and the last part of the cell wall to form attaching to the hemicelluloses, adding strength and hydrophobicity to the structure of tree cells. It becomes a component of the cell after the cellulosic structure is finished (Desch 1996, 40; Barnett et al. 2009, 64; Vivas et al. 2006; Domone 2011, 414).

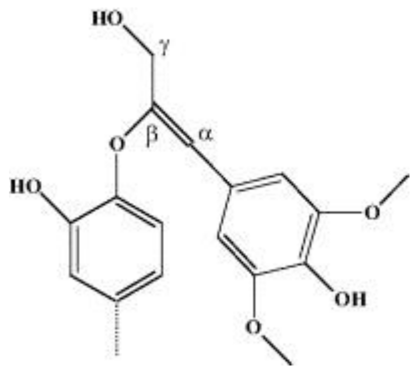


Figure 46: Hypothetical structure of lignan's linkage from oak put forward by Vivas et al. (2006)

The cell wall

The walls of the cell are divided into layers, all of which are made up of microfibrils. Cambial division produces the primary wall, which can increase its surface area. It is very thin and made up of random microfibril patterns. In a mature cell it can be difficult to distinguish between it and layer 1 and the adjacent cells between the two (the middle lamella). As such it can be referred to as a compound lamella.

After cell division the secondary wall is formed and it is made up of three layers, the outermost S1, middle layer S2, and innermost S3. S1 is thin, making up less than 10% of the cell wall thickness. It is formed of microlamella at an angle of about 40 to 50 degrees of the vertical axis. This there is then a shift of orientation and the lamella of the fibrils form at the opposite angle forming a cross-hatch pattern known as 'crossed fibular texture'. S2 is 85% of the cell wall thickness and contains a high degree of parallelism in its microfibril makeup. They are organised in a helical pattern at 10 to 30 degrees from the horizontal. About 75% of the total bulk of lignin is found within the secondary cell wall, and the properties of the wood and linked mostly to the properties of this layer. S3 make up 1% of the cell wall thickness, the shift in microfibril angle from S2 to S3 is sudden, S3 being made up of a similar microlamella patten to S1. It is, however, loosely textured, and less developed than S1 (Figure 47) (Hon et al. 2001, 12-16; Desch 1996, 41; Domone 2011, 414).

Highly complex organic extractives make up the remaining compounds found within trees. They often lend themselves to the odour of wood, such as sandalwood or in this case oak, which is useful for the barrel making and flavouring of whiskey and wine (Desch 1996, 42; Domone et al. 2010, 414; Vivas et al. 2006).

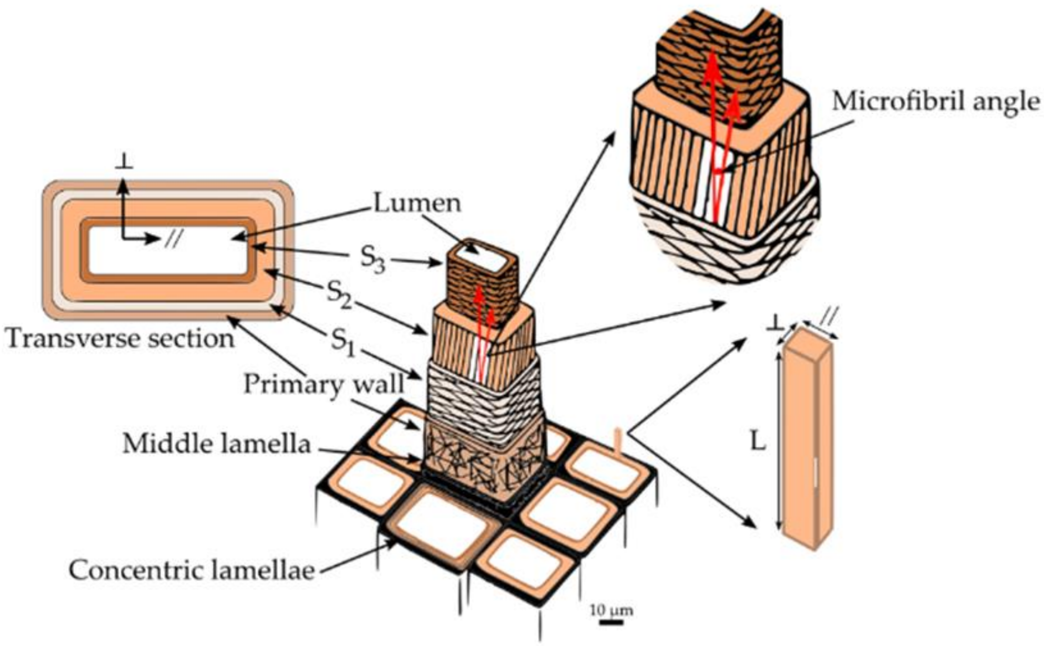


Figure 47: Diagram showing makeup of cell walls and patterns of primary, S1, S2 and S3 show microfibril orientation. Directions in cell wall are shown in the parallel (k) and perpendicular (⊥) and defined in the transverse plane in relation to the lumen surface (Arzola-Villegas et al. 2019, 4).

Moisture in wood

When timber is absorbing moisture from a figure below the fibre saturation point, it first enters the cell wall, hydrogen bonds onto the cellulose fibrils and moves them further apart until the cell wall is saturated and no further bonding can occur. It is the removal of the bound moisture that creates shrinkage of the swollen cells, due to the impact of its loss on the distances between the cellulose fibrils and eventual inter fibril bonding of cellulose, reducing the size of the swollen cell wall (Desch 1996, 89; Skaar 1988, 128).

When timber is absorbing moisture from a figure below the fibre saturation point, it first enters the cell wall until it is saturated, then the areas of free water begin to saturate. It is the removal of the bound moisture that creates shrinkage (Desch 1996, 89) (**Figure 48**).

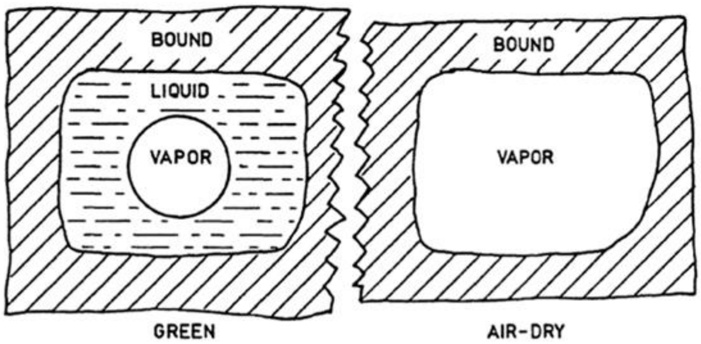


Figure 48: Diagram showing three kinds of moisture in green wood, and two types in air-dry wood (Skaar 1988, 22).

As timber is hygroscopic, it responds to the external vapour pressure (relative humidity). It these are equal to that of the timber there is no enthalpy and thus no transfer of moisture (Skaar 1988, 1). The moisture content of timber is dependent on temperature, as may be seen in Figure 49 and Figure 50.

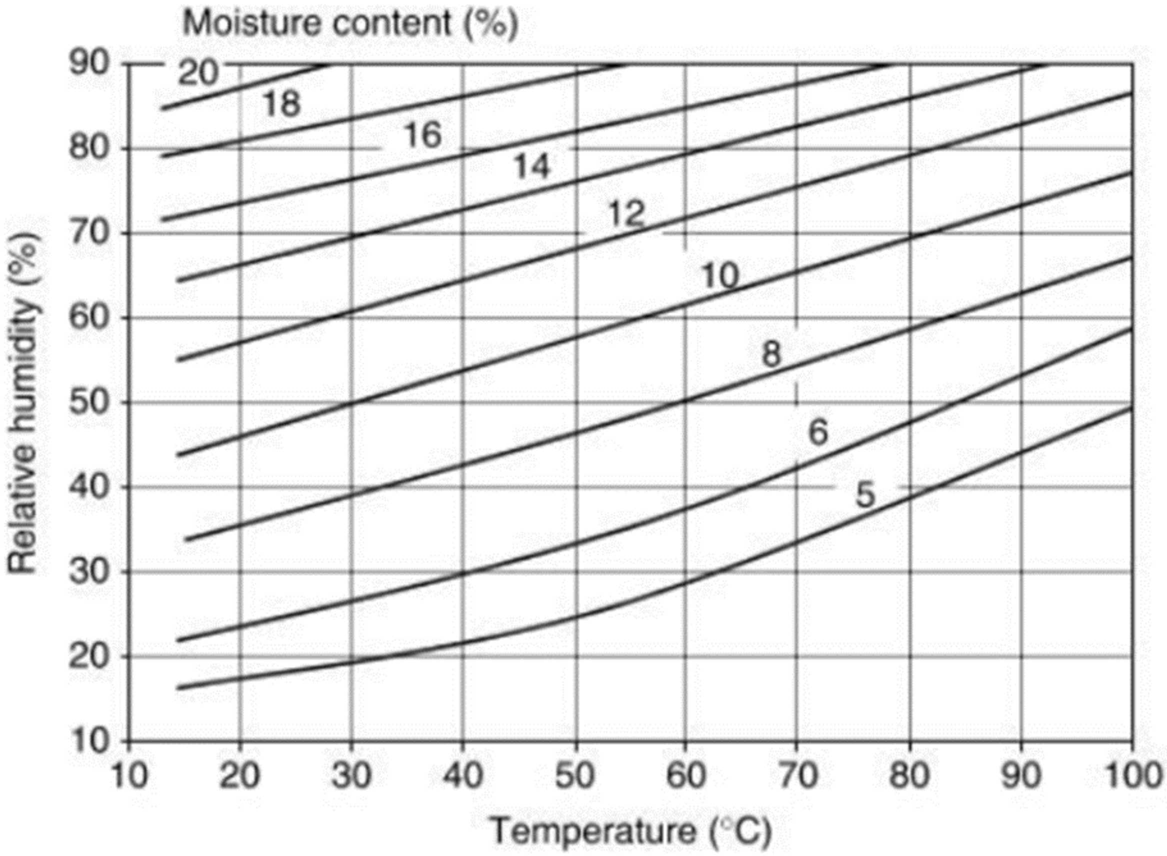


Figure 49: Relationship between moisture content and temperature and humidity in timber (Domone et al. 2010, 423).

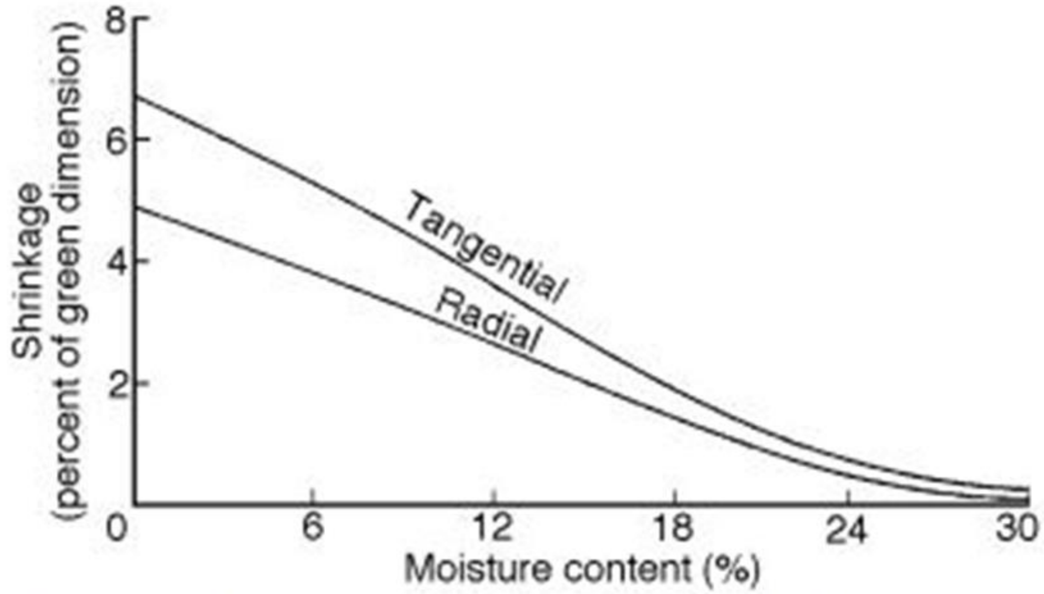


Figure 50: Typical moisture content shrinkage curves (Simpson 2001, 13).

The moisture content of the wood relates to radial and tangential dimensional change of the timber. A moisture content change from fibre saturation point to nearly complete dry can lead to as much as 6.8% tangential shrinkage in some timbers (Simpson 2001, 13).

Figure 51 shows the moisture content of *Quercus robur*, the wood that is used in this study, as a function of relative humidity, illustrating the importance of ambient relative humidity on wood. When this changes, it influences the EMC of wood and a hardwood with denser cell structure like oak, undergoes significant dimensional change to moisture content. The 10°C to 30°C temperature range found in buildings offers a comparatively small moisture content change in timber if the relative humidity does not change (Figure 52).

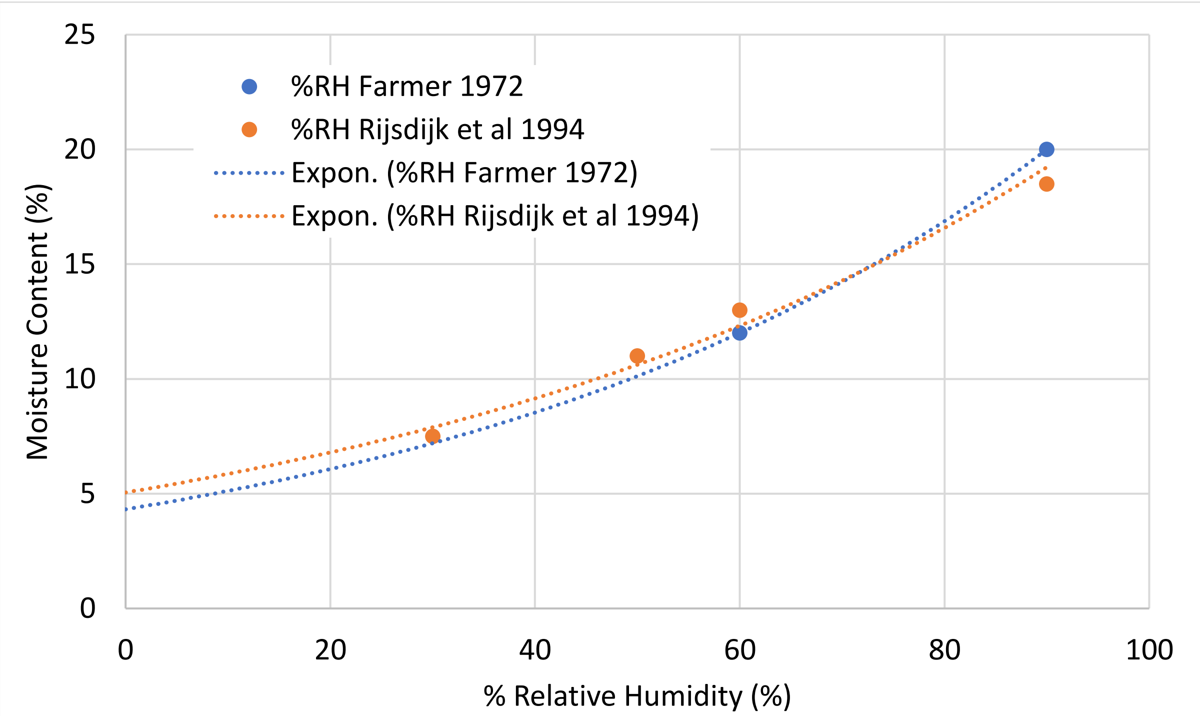


Figure 51: Moisture content of Quercus Robur at different RH levels (Farmer 1972; Rijsdijk et al. 1994).

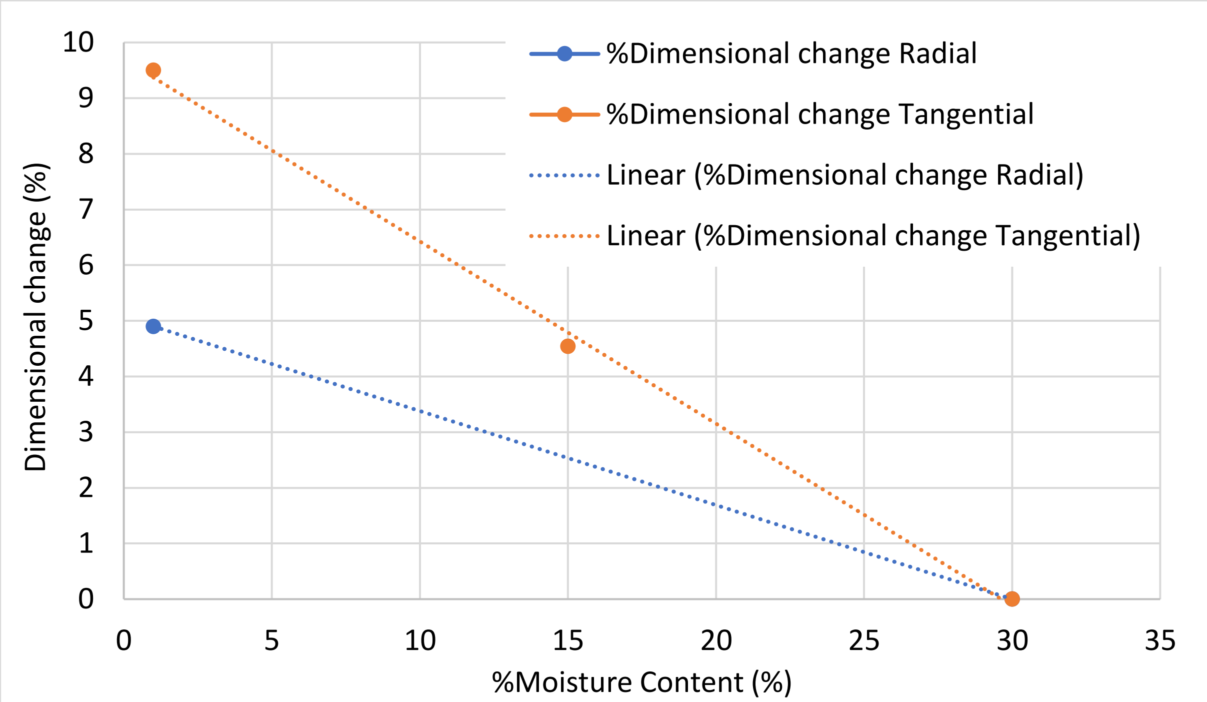


Figure 52: Shrinkage of European oak, 30% to 12% Moisture Content tangential-7.5% radial-4%. 20% MC at 90%RH, to 12% 60% RH is tangential-2.5% radial-1.5% (Farmer 1972, 147).

As water lost above 30% is ‘free’ and sitting within the cell cavity its loss has no impact on the strength or dimension of the timber. The loss of ‘bonded’ water below the saturation point of 30%, does have an impact as it is chemically bonded via hydrogen bonds to the cellulose molecules in the non-crystalline structure of the cell wall. This is taken up in either the amorphous regions of the cellulose, or the hemicellulose. The lignin is hydrophobic so takes up a very small percentage of the water. The crystalline regions of the cellulose cannot take up moisture as the bonds in the hygroscopic hydroxyl groups are satisfied. Therefore, the change is limited to the non-crystalline material within the cell, where it is a monomolecular layer between one and six layers. With the loss of moisture comes increased strength but also shrinkage, both the result of the microfibrils coming closer together. Moisture below the fibre saturation point moves by diffusion, either in the form of intergas diffusion through the air in the lumens, or bound water diffusion within the cell wall. This loss of water beneath the saturation point involves bond breaking and thus uses up energy (Desch 1996, 39; Skaar 1988, 47).

The sorption and desorption of moisture to timber is not a mirror of the same isotherm, and therefore is a hysteresis loop, as seen in Figure 53. The EMC to ratio absorption to desorption is skewed 0.85 towards desorption, thus timber in a dry state absorbing moisture to EMC will always give a lower EMC than timber in a higher moisture content state losing water.

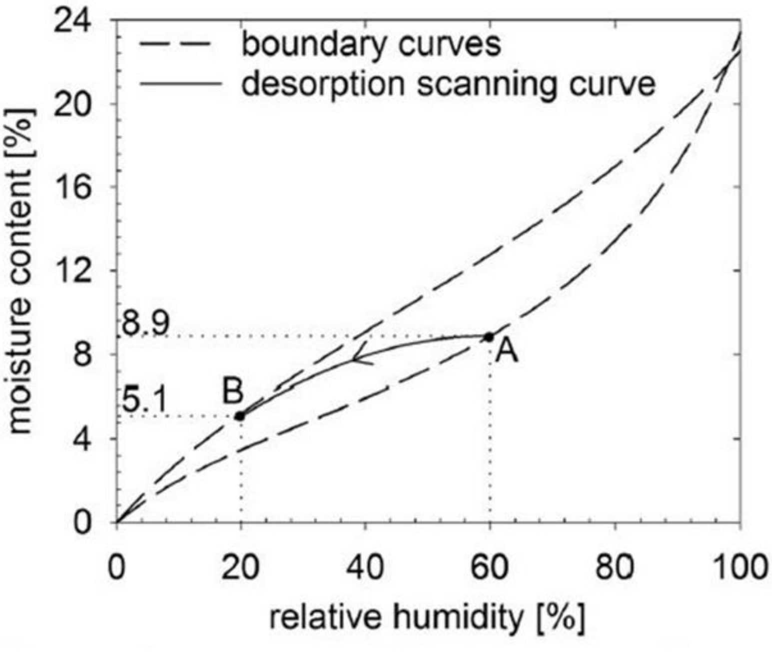


Figure 53: Moisture hysteresis of oak (*Quercus robur*) oak panels paper (Lumies 2018).

The dimensional change of timber is anisotropic, a result of the makeup of the cells, their distribution and density. Change happens on three planes differently. These are tangential, radial and longitudinal. Longitudinal shrinkage is very low, from green to 12% often less than 0.1%, whereas tangential and radial are more significant, as may be seen by Figure 54. The difference in shrinkage on the longitudinal and horizontal plane is based upon the microfibril angle, which shrink as they lose moisture from the non-crystalline structure and are drawn together more on a horizontal plane.

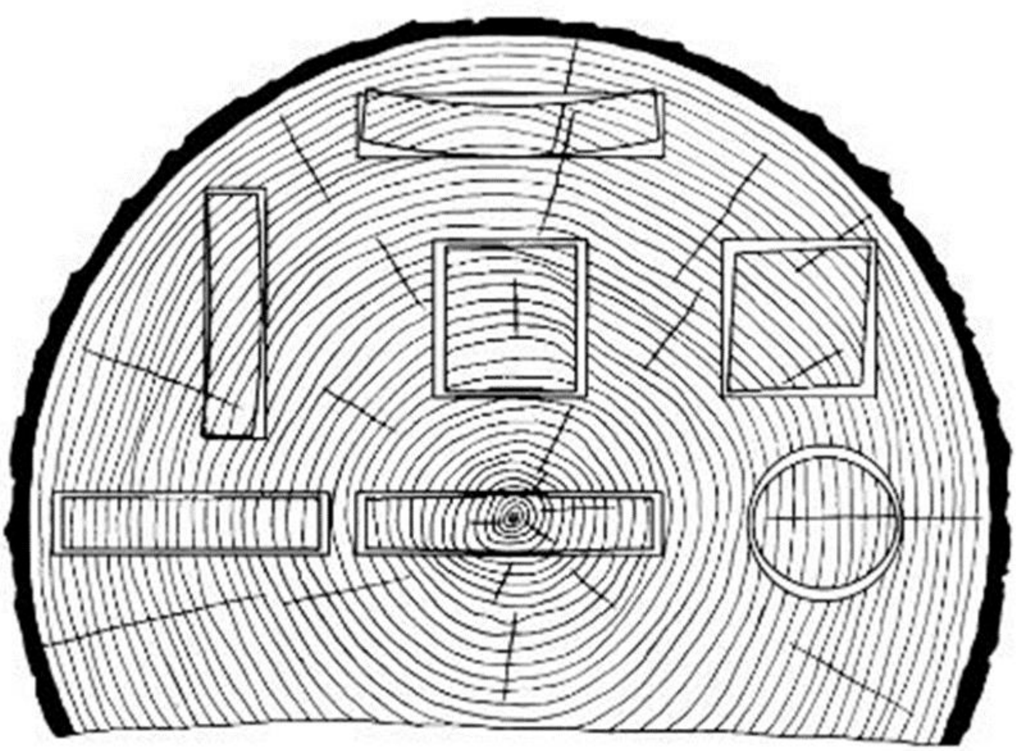


Figure 54: Results caused by differences in tangential and radial shrinkage (Simpson 2001).

The impact of the micro-structure of the wood on the distortion of a piece of timber caused by moisture loss or gain follows the grain pattern, producing dimensional changes in timber which may malform or damage the objects they make up (Figure 54) (Domone 2010, 423-427; Desch et al. 1996, 89; Hoadley 1980; Skaar 1988; Simpson, 2001; Farmer 1972, 147).

4 Internal environment and objects

Early publications regarding objects and environmental conditions are centred around limits that were achievable by the technology at that time rather than any empirical research into the deterioration of objects (Brown et all, 1996,12-13). As a result of WWII and the need for the British Museum and Victoria and Albert Museum to store pictures somewhere safe from aerial bombing they were moved to a disused underground quarry in North Wales, where it was found that an environment with small RH and temperature fluctuations produced a large reduction in the type of damage to pictures that occurred in the museums (Brown et al. 1996, 13-14). When they were returned to London at the end of the war, the damage ensued once more. The damage was largely that of cellulose based materials wood absorbing/desorbing moisture to produce dimensional changes. In pictures, this produced cracking, warping and blistering (Brown et al. 1996, 13-14). This is perhaps one of the key events in the 20th Century which led to more research into environmental conditions and the response of objects within them.

Ideas about ‘correct values’ proliferated the post-war period until the 1990s when broader thought was put into how some objects had clearly been exposed (often repeatedly) to ‘incorrect’ values and not suffered noticeable damage. In 1993 Michalski published an appraisal of relative humidity in museums, whereby assessment of the reaction of various materials to RH and temperature led to specifying a broad range of values for mixed collections (Michalski,1993). The ‘U’ curve (Figure 55) was produced which he described as ‘a wide forgiving region with a sudden steep climb to danger’ based upon the number of fluctuations. The production of this graph is not fully explained in the publication, and the references for the data make it unclear exactly how they are linked to the graph. Statements go unreferenced and overall the publication is somewhat unsubstantiated, such as those about polychrome sculpture (Michalski 1993b, 626). In the study references 21-30 are used for the paragraphs relating to the modelling of RH fluctuations and deterioration, three specifically relate to timber. One of these is Madsen (1975, 48-53) takes 180 specimens of Douglas fir and subjects them to load pressure to determine their failure point over a certain amount of time. Michalski (1991) is referenced for cracks in gilded material. This publication has a method which utilises 'two small pieces of gilded wood' that are exposed to different temperature and RH points, the type of wood in question or the method for the attainment of these RH points is never discussed. The Wood Handbook (1987) is referenced for data on timber, it is not specified which timber or which pages are used. How any of the data from these references is utilised to produce Figure 55 is not disseminated in any detail.

However, the basis of many of the ideas is interesting and worth further evaluation, and the idea of proofed fluctuation is of particular interest. Past environmental conditions having proofed an object based upon the idea that if an object has been exposed to an extreme RH value and it has caused a crack, this crack will act as a stress relief joint in the future when that value occurs again. The damage has already happened, and it cannot happen again. The alternative is that if the timber did not crack, then it is able to withstand that value.

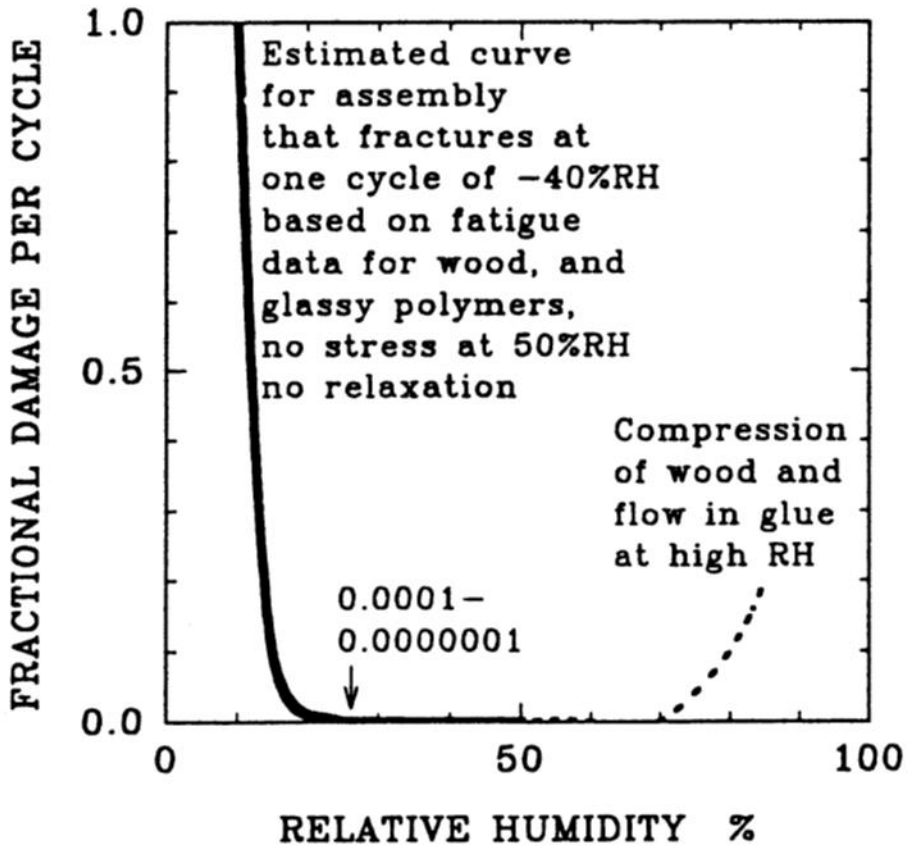


Figure 55: Estimated shape of a curve for mechanical damage function of RH fluctuation from some middle value. The solid line for shrinkage fracture assumes a linear rise in tension from 50% RH to some critical value at 10% RH. (Michalski 1993a, 626).

Furthermore, Michalski (1993b) discusses the benefits of coatings for the reduction of moisture transfer during fluctuations, and the impact that a buffer (i.e. linen in a chest of drawers) has on the response of an object to a fluctuation. This is a key link between thinking practically about an object as more than 'timber' but rather the whole package of finish and form. Furthermore, the key element is the discussion of the exposure of objects to known extremes in the past and how that may allow for a created flexibility in the future.

'Relative Humidity Re-examined' by Erhardt and Mecklenburg (1993) suggests more relaxed values for the storage and display of collections, with no ideal point able to serve all materials. There was also some discussion on the idea of fluctuations and their impact on materials, such as pine. This is shown as stress (MPascals) against change in length (percentage), safe limits for RH changes being defined by the elastic region. However, though RH changes are plotted there is no definition of the length of time these fluctuations take. As the title suggests, this ties in with a general thought about more realistic parameters for materials and objects. However, the overall usefulness of the paper, in relation to timber, is somewhat limited as it mostly discusses the yield points of pine to stresses caused by fluctuation, but with no relation to a time limit. Without this information it is difficult to think practically about the way an object might respond to a fluctuation.

Timber dimensional change and quantifying damage

Predicting or calculating the damage that wood will sustain from the impact of gain or loss of moisture is difficult to accurately achieve. Basic common-sense concepts can be identified in terms of risk of damage due to moisture uptake and loss in wood, larger dimensional changes likely resulting in higher degrees of perceived damage (Luimes et al 2018,22-23). The definition of damage and the parameters surrounding that relate to object stakeholders (Ashley Smith,1999,111). Due to the anisotropy of wood, factors such as the cut, whether it is restrained and loading on it will influence damage due to moisture loss and gain, as these factors govern stresses and strains that determine whether physical damage such as compression will occur(simpson,2001,13). Additionally, construction factors that include jointing, thickness surface finishes and the use of adhesives and veneers will influence adsorption and desorption of moisture and the nature of the resulting stresses and strains (Luimes et al 2021, 253). Therefore, calculating allowable change in moisture content, relative to the damage it will cause in wood as a function of relative humidity and time, remains a contextual issue that is a function of the object and not just the environment. With regards to the dimension change of the timber components, a large study would be required to determine how resilient different timber joints and finishes are to different changes (Hunt 2012, 12). It is also likely that further studies would be required to determine what may be thought of as 'damage'. Calculating and verifying what this might translate into as damage is beyond the scope of the study. It is also entirely contextual according to a large number of variables associated with the wood. For this dissertation, on the impact of humidity on wood, the goal was to determine what moisture response occurred as a function of environment and time.

Internal environment and historic buildings

Michalski discussed the concept of proofed fluctuations in 1993(a) and provided a more detailed account in 2007. The premise of extreme RH is that if a fracture is caused then it can act as an expansion joint. If it did not fracture, then the object can withstand that value. This relies on certain factors, such as knowing the history of the environmental conditions of an object. This can prove difficult without accurate data to call upon. Others have looked at various methods to ascertain past values (Michalski 2007, 11).

Taylor et al. (2005, 5) attempted to use computer simulation to understand the past environments inside the library of a historic house, Brodsworth Hall. In this study he broke down the environment inside the library into three separate periods, one was heated by open fire, one by central heating, the last a mixture of both. The study illustrates the problems of reliably understanding the usage and heat output of an open fire, and how to quantify that into a known value. Their estimate that the open fire delivers 507 watts an hour was based on historic coal delivery figures, the number of fireplaces in the house, and the efficiency of the appliance at 20%. No references are given for fireplace efficiency in the paper, but most open fire grates were found by Fishenden (1920) to be between 20 and 30% efficient, with further research (as seen in Chapter 7) confirming this is accurate for radiant heat (HETAS 2016). Based on the figures in the Taylor et al. paper, they estimate the fireplace to be consuming 2535 watts of coal per hour, translating into 320 grams an hour, or two medium lumps of coal.

Published figures for coal consumption in ordinary domestic grates can be found in Fishenden (1925, 68) who reports 1.13kg coal/hour was found to be an average rate of coal consumption in an ordinary domestic grate, this figure is similar to that found in the experiments reported here at St Fagans in later chapters. Using the Taylor et al. 7.9kw/kg for coal and 20% efficiency figure, the heat output of the open fire would be 1.7kw/h. Over 6 hours would give 10.44kwh, rather than the 3.043kwh in Taylor’s published paper. Based on this rate of consumption, rather than the published figures, the grate would use 210kg coal a month. This is over three times the published figure of 66kg.

Brodsworth Hall has 19 ground floor fireplaces and three ranges based on the floorplan, and clearly a similar number upstairs if 47 is the total. If 20 of the grates were in use, at 200kg/month each that would be 4 tonnes a month in winter at 6 hours a day use each, and 2.8 tonnes a month in spring and autumn at 4 hours a day. This would be 9.6 tonnes a year, and does not include the ranges, which Fishenden (1924, 133) suggest use at least 400kg of coal a month. A house such as Brodsworth Hall contains three ranges, if one was in use all year then that is a consumption of 4.8 tonnes. Collectively this illustrates how difficult it is to know the past environments inside buildings, as bringing only one more range into use changes the figure given in the publication of 8.2 tonnes a year to a monthly statistic for a full house in winter. How coal was allocated, which rooms were heated and to what regime they were burned is very difficult to tell. Indeed, the impact of the kitchen ranges being in use may have had a minimal effect to the conditions in the library, but they have a large impact on the calculations for coal consumption and how modern-day calculation using this figure might be carried out. What can be done, however, is modelling of existing functioning systems within historic properties to ascertain the impact of a fire on internal environment according to the structure of the building, burn pattern of the fire, and the time of year.

Recording environment inside historic buildings and objects

In situ monitoring of the dimensional changes of objects have been measured utilising lasers. For example, Bratasz et al. (2005) recorded the dimensional responses of various parts of a polychrome wooden sculpture in a church in Italy. Similarly, Knight et al. (2007) measured the dimensions of a crack in a gilded wooden table at Chiswick House. These studies linked the previous research of response of historic timber samples in laboratories to in-situ response of objects in their display environments. However, how useful such data collection is when considering other scenarios is difficult to quantify and a balance between real-world scenarios and lab-based experimentation does need to be struck. With these experiments an improvement would have been to also measure alongside the objects some base samples of similar materials, to show more generic response of components. One step better than this would be to record the environment and model it in a climatic chamber so that it may be repeated indefinitely on a variety of samples.

Vara-Muriel et al. (2014) published a paper where, via in situ monitoring, the hygro-thermal conditions within a church could be accurately modelled, giving a three dimensional overview of the environment which was displayed in cross sections. Here, a warm air system was analysed, as well as the church being in use with congregations. This in-depth analysis demonstrated how the heat and moisture were spread within the building, and in ways which people at ground level would not be about to detect. Not only was the impact of the heating system evaluated, but also areas of high moisture build-up in the building fabric were discovered. This identified variation within a room as a function of an action such as a heating system or a congregation, as well as trends according to time and activity, which can be equated to the intermittent use of a fire. Furthermore, the predictions introduce a concept of extending computer modelling to dynamic recording in-situ to understand the environmental conditions within the building. This allows for the interlinking of real events with the clearer visual imaging that modelling provides.

Local conditions related to events could impact on objects within a space. Huijbregts et al. (2015) modelled the temperature and moisture strain of a historic cabinet to various environmental conditions. In order to understand the response of a 1690/1700 veneered cabinet inside a 17th Century Dutch castle historic weather data was fed into building environment software (HAMbase). This provided an overview of selected RH and temperature patterns that may have been experienced inside the castle historically, which were then fed into a computer model to predict the strain tangentially experienced by the cabinet front. Further to this, a physical model of the cabinet door was made. This incorporated the many veneers and a hollow centre, inside which a logger was placed. It was then exposed to a sudden change in RH, the internal environment between the layers was measured and compared against a predicted one. This demonstrated the buffering ability of the wood.

This study produced some interesting results, in particular the way the environment inside an object responds to external changes. It creates a link between computer modelling to derive an understanding of the internal environment and physical experimentation to gain data on furniture response, which has the potential to provide synergistic data to better understand environment/object relationships. The reproduction of historic environmental conditions, whether modelled or actually recorded, in a laboratory is a way to obtain control, repeatability and accuracy for an experiment involving an object or material, potentially producing data that can be extrapolated back to better understand risk experienced in the past or that may occur in the future. For the experiments in this thesis, this focuses on development of management patterns for offering visitor experience by the use of fires, while understanding the risk this poses for furniture in the room being heated.

Environmental standards: development and flexibility

Since Thomson's (1978) initial work on setting parameters for environmental control there has been the logical concept of the smaller the change in RH, the safer the environment is for organic materials, which adsorb and desorb moisture or are subject to biodeterioration (Thomson 2005, 210). Some authors argue that his work has been interpreted wrongly as being very rigid in parameter setting and he was exploring the National Gallery context for its HVAC plant (Boersma et al. 2014, 6-7; Casanovas 2014, 49; Atkinson 2014, 205) and never meant to offer what are often realistically unattainable standards, without massive capital investment and ongoing energy costs. Other work has sought to identify whether materials can accept less stringent change without damage, according to range and number of fluctuations (Bratasz 2011). Nevertheless, high energy solutions are becoming more unacceptable morally and research into the properties of materials can provide understanding for designing preservation systems with reduced energy consumptions and cost benefit. This is best served by building data sets linking the performance of materials to the variables that drive their change and to the environments in which they are housed.

Since the new millennium there has been an increased interest in the reduced running and environmental costs of HVAC equipment in museums, historic houses and cultural institutions. Bratasz (2011) appraised the standards set for collections and discussions around energy consumption. This appraisal has been across the board, and this is reflected in the ASHRAE standards introduced in 2003 which set five classes of environmental parameters for Museum Archives and Libraries standards. It was important to note that instead of listing the standards A, B, C, D, E, standards were set AA, A, B, C, D, E. This was designed so that institutions could attain ‘level A’ whilst not conforming to extremely rigid set points of ‘level AA’. It was assumed if institutions were at ‘Level B’ they would strive to move up to ‘level A’. These adjustments of standards allow for an increased conservation of energy that is balanced against the impact of this on collections. It also highlights a change of direction from large, energy consuming HVAC plant rooms, to ideas about passive or lower energy solutions. This change in directing may be seen in organisations like the National Trust who have appraised the energy consumption of their conservation heating (Michalski 2007, 5; Blades et al. 2010, 127). Similarly, there are examples of passive structures which require little energy input. The Archives at St Hellier, Jersey were opened in 2000, and are designed to utilise passive systems, thermal inertia, solar gain and natural ventilation (Williams 2001, 129-132). There is no large HVAC system, and the building demonstrates how modern insulative materials coupled with intelligent design and thermal mass, can create a building which requires limited energy input (Williams 2001, 129-132). In contrast:

"However, it has also been found that similar objects, kept under apparently less than ideal and fluctuating conditions, to which they have acclimatised, do not seem to have suffered. Many factors contribute to the discussion of whether a collection, or an individual art work, should be kept under more or less strict climatic conditions, or whether it will suffer as a result of change in these conditions if it travels for temporary exhibition elsewhere. The reduction of unsustainably high-energy costs and a museum's carbon footprint is to be encouraged, and relaxing the control of the values for RH and temperature may contribute to this if it can be done without damage to the collection. Much has been learnt from the study of buildings and their behaviour and the materials comprising the artifacts; what is lacking is further observation of the behaviour of the objects themselves. As cultural heritage objects are usually complex, composite structures and each one is individual in its

construction and history, this research may be challenging, but is also necessary" (Atkinson 2014, 210).

The dimensional change of timber and its relationship to damage is difficult to quantify. Different objects are constructed in different ways, and as such some are more resilient to change that others. Damage is usually concentrated around fixed points, such as joints, through veneers or layers and though warping. For example, a loose panel in wainscoting or a piece of furniture will likely be more resilient to potential damage from dimensional change than a fixed panel, which will likely crack around the restraints. What may be considered damage is somewhat subjective and relates to the object stakeholders. There is no quantified figure for what is considered damage and what point damage may be said to have happened. There is potential in this area for further studies to put a figure to the perception of damage.

This statement focuses on the need for better understanding of the materials science of objects to specific conditions, ranging from the chemistry of reactions to measurement and recording of physical change considered detrimental to the aesthetic. Overall, there is a clear gap between studies which link environmental data from historic contexts to the laboratory, where real time controlled and reproducible testing of their impact on materials can be carried out, producing evidence based prediction of how those environments will affect materials. This linkage of real time data to controlled experimental conditions, where the variables can be readily set and quantitatively recorded, is a goal of the study in this PhD.

5 Heating experiments: method

Experimental rationale

This first experiment collected data on the environmental conditions within a historic building that is heated by an open fire, both as the fire is presently managed (lit daily) and as it could be managed (banked in overnight). This data was then utilised in a second set of experiments in the laboratory to programme conditions within climatic chambers containing historic wood to determine its reaction to relative humidity. The resulting data can then be used to identify how differing management patterns for the fire impact on the wood. This linkage of fire management to environment and its impact on wood, will inform management decisions seeking to balance the ambiance of place and the comfort of staff and the public, with the potential damage to furniture within the room, as well as the use and expenditure of fuel. Overall, it can help identify the price of visitor experience in relation to potential damage to historic objects in the room.

It was therefore necessary to utilise one of the buildings at St Fagans for experiments, providing data sets for use in the laboratory tests. Variables considered when choosing the building were building fabric, layout of the room, fuel type and usage, external climatic conditions and the design of the fireplace. Choosing and understanding the design of the fireplace and its flue was an important part of the experimental design, as it may offer greater scope for extrapolating performance and data to contexts other than the room in which the experiment was carried out.

Central to the experimental design was the spatial collection of data to reflect the impact of the fire on all parts of the room and to consider the broader context of the building acting as an absorber and emitter of heat. These goals were addressed by using temperature and humidity loggers in a three dimension grid pattern throughout the room and by recording wall and chimney temperatures with an infrared camera. This combination would provide spatially distinct relative humidity and temperature values and offer information on thermal mass, heat gain from the flue, and heat loss from the wall. External temperature and humidity was recorded to determine how it might have influenced the data collected, while information on the fire burn involved choice of fuel, time weighted mass of fuel burned and the speed of the flue gasses.

The loggers used are matt black and in these experiments record the radiant temperature rather than the air temperature, though in locations with limited radiant heat (such as upstairs) they are likely recording close to or at air temperature.

Variables: overview

The external envelope of buildings are sometimes thought of as thermal control devices (Rapoport 1969, 84) but this must be linked to the performance of the fire and the weather, which may be seen as a balance of inputs and outputs. The weather impacts the parameters of the air entering the building and the rate at which the heat leaves the building, while the fire influences air parameters within the building and the rate at which the heat is obtained (Barker 1912,411; ; Weston 1949, 254). Other weather factors such as solar gain and wind velocity also determine heat gain and loss, as does the use of a room and the people within it. External humidity, precipitation and temperature will influence moisture levels and heat loss Rapoport 1969,84. Factors to consider include a damper building more readily conducting heat and the impact of wind on heat loss, draughts, air exchange rate and draw of air into the fireplace Barker 1912,195). Feeding oxygen into the fire will influence its burn rate, which in turn affects heat output and fuel expenditure (Weston 1949, 254).

The design and construction of a fireplace, rate of combustion, application of fuel and the calorific quality of fuel are all variables affecting heat gain (Fishenden 1920). Fuel application method is the only variable that will change, except for the external climate, other factors will remain fixed except for opening and closing the front door to fuel the fire. Burn patterns in this study were either overnight banking of the fire or re-lighting it daily. Opening and closing the door to re-fuel fire allows external air into room, previous studies have noted how the air exchange rate rapidly increased when the door to a room with an open fire was open (Weston 1949, 254). The door was therefore closed throughout the experiments other than for refuelling. The air exchange rate of the room was required to accurately calculate the heating requirements of the building, which with other figures from the heat output of the fire and chimney breast, allow for a detailed understanding of heat loss and gain.

Infrared photography was used to capture a visual image of heat transfer throughout the building. Images of the walls and chimneys recorded during the experiment were used to visualise and measure the heat output of the chimney. The thermal imaging was also used to determine the thermal storage of the bricks. The data gathered from the loggers in conjunction with the imagery from the thermal camera was used to correlate heat patterns within the chimney to relative humidity in the room. Furniture within the house and its distribution will also affect how the radiant heat moves through the room, the volume, positioning, and composition of materials forming the furniture may have a buffering impact on RH.

The weather is both a main and an uncontrollable variable, as it is impossible to ensure the same precipitation, humidity, temperature, and wind conditions for the entirety of a study. Some studies into heating have involved the construction of rooms within large scale climatic chambers. These tests, whilst highly accurate, are not within the budgetary limits of this study (Dufton,1942). As such, the external conditions have been closely monitored, and all recorded data from the experiments related to it, so as to remove/explain any related unexpected occurrences. The impact of sunshine and daylight hours was minimised by straddling the winter solstice. In this way it was possible to attempt to keep the number of daylight hours equal across the experiments, though cloud cover will impact this as well. This also provided similar diurnal time cycles for the experiments.

Climate Consultant 6 was utilised to give the average weather data for Cardiff, showing hours of daylight, monthly diurnal averages, temperature ranges, wind speed averages, dry bulb temperature and relative humidity, and also dewpoint. Whilst the weather cannot be controlled, it can be planned for and compensated for. By utilising these graphs (Figure 56 to Figure 61), the weather can be limited as a variable against past data. Past weather conditions which best match each other were selected for the experiments, so that temperature, hours of daylight and wind and dew point might be expected to be closest during the various phases of the experiment. December and January were selected, but due to the Christmas functions Experiment 1 had to start in late November. Past data suggested November to be a slightly warmer month than December, but this would be the last week of

November rather than towards the start of the month. Furthermore, external conditions were recorded and could be considered. What was more essential was that the external temperature remained lower than the internal temperature, and the solar gain could be kept low across all experiments. The average monthly data suggested that the experimental period selected would pose no difficulty in reaching these goals. Ideally, it was necessary for the external RH and dew points to be similar across all experiments, it may be seen that December and January have the most similar monthly averages for these figures. As such it could be ensured that there would be a heat gradient from the building to the external atmosphere, whilst also a continuous stream of higher RH air entering the building.

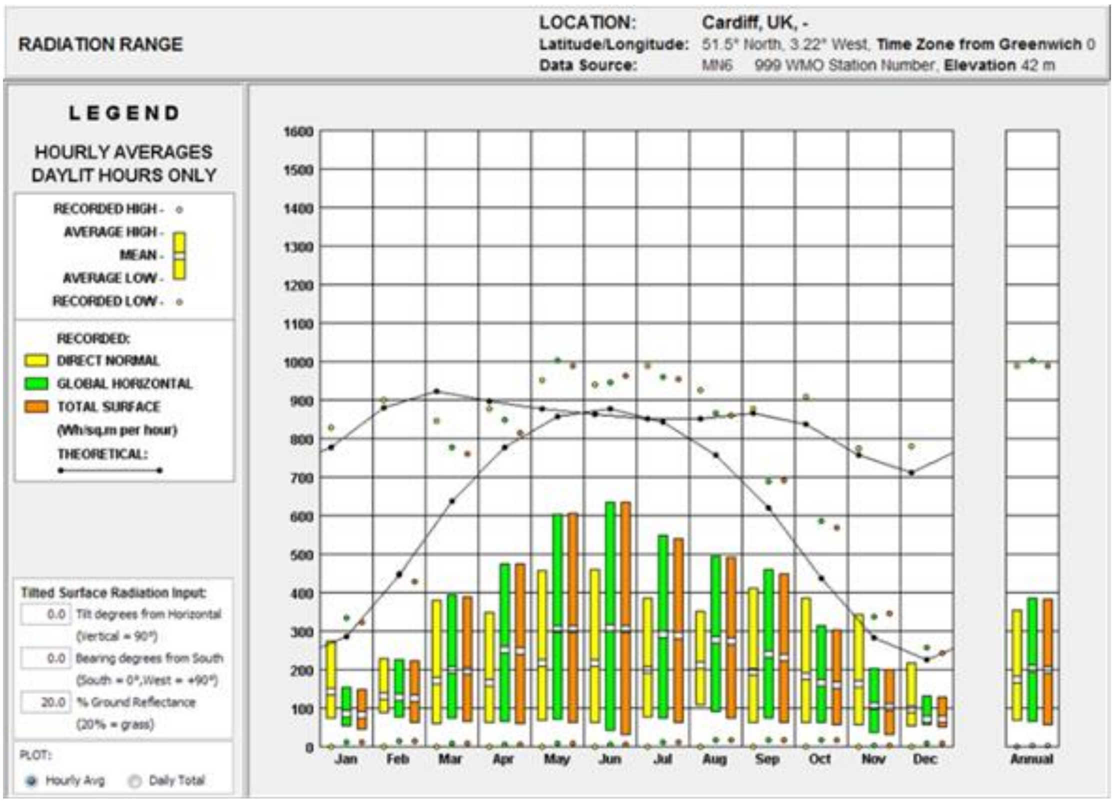


Figure 56: Average hours of daylight, Cardiff (Climate Consultant 6).

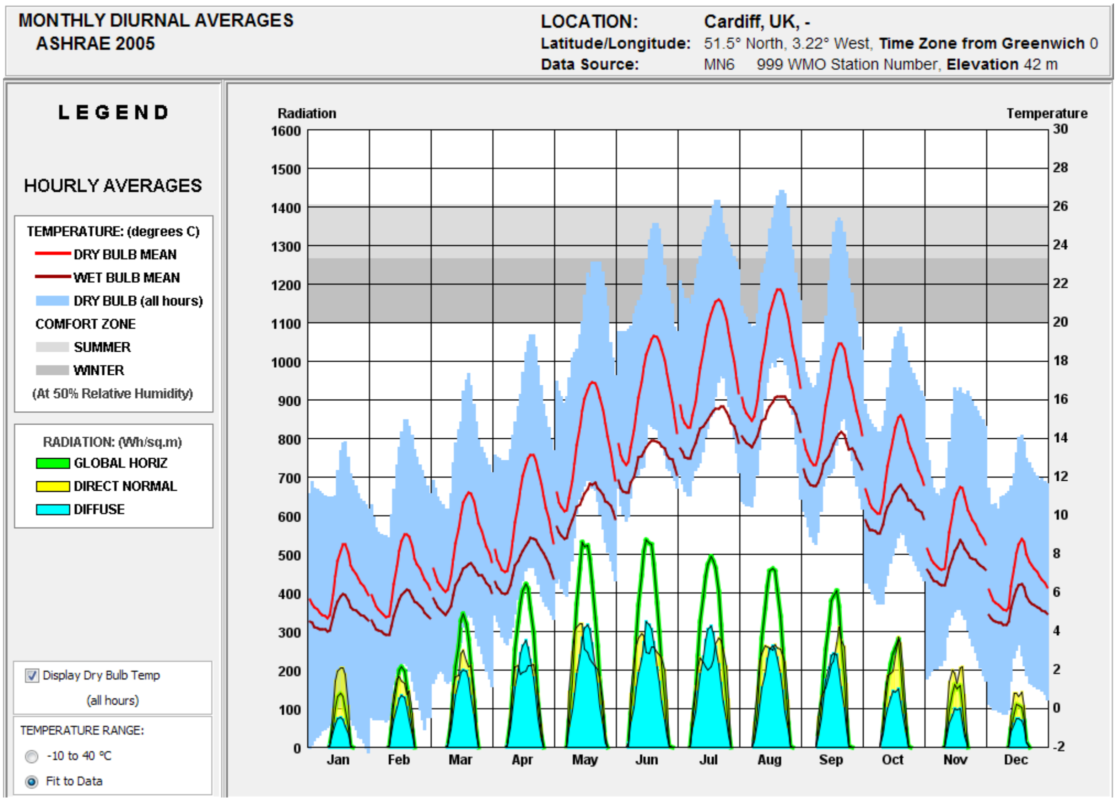


Figure 57: Monthly diurnal temperature average, Cardiff (Climate Consultant 6).

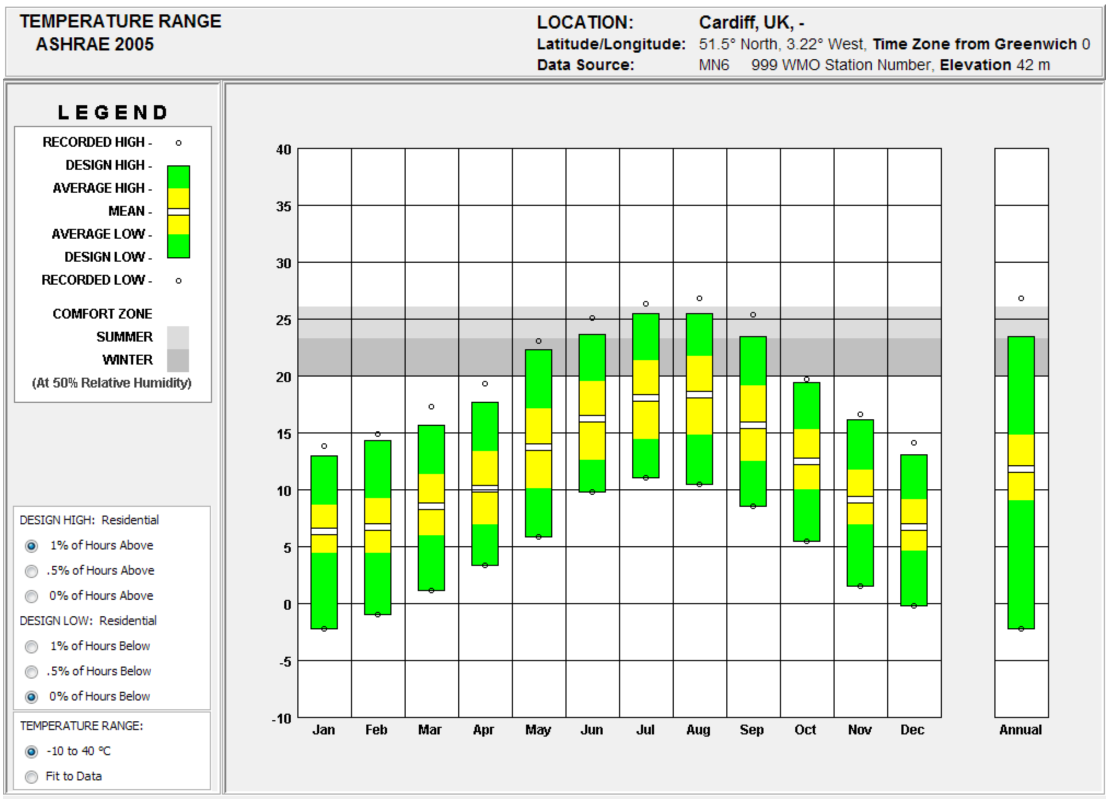


Figure 58: Monthly average temperatures, Cardiff (Climate Consultant 6).

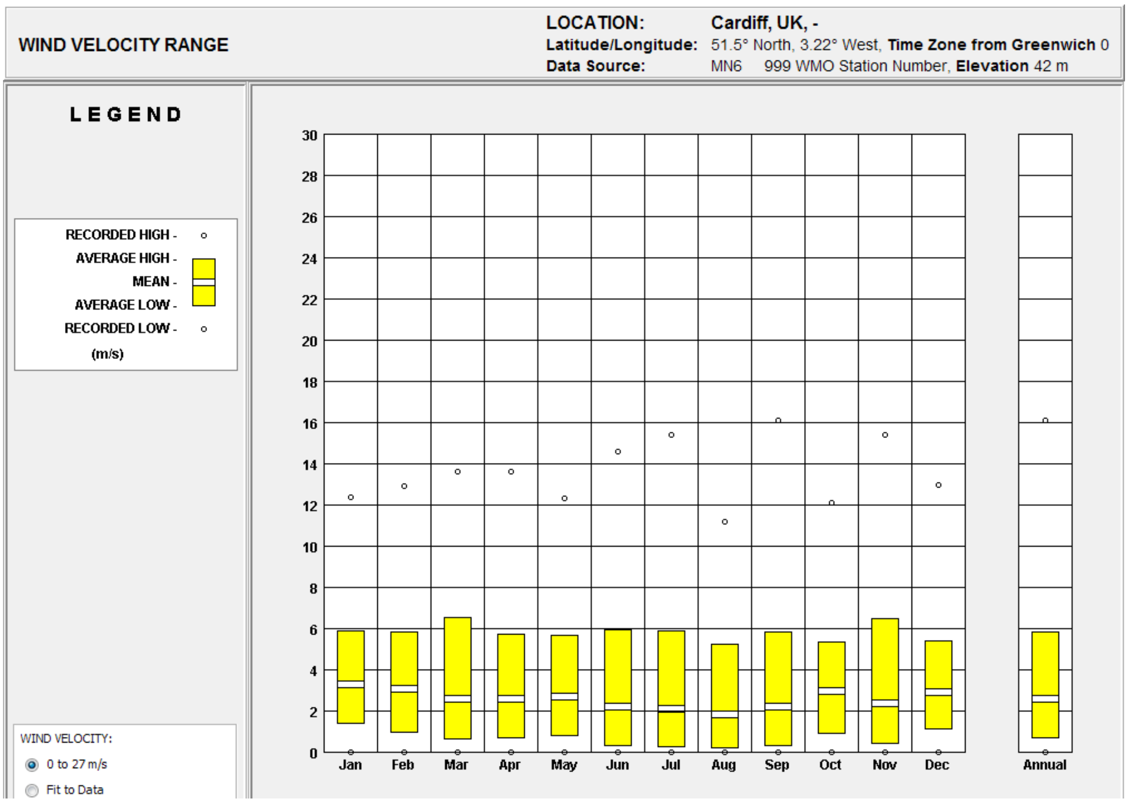


Figure 59: Monthly wind velocity, Cardiff (Climate Consultant 6).

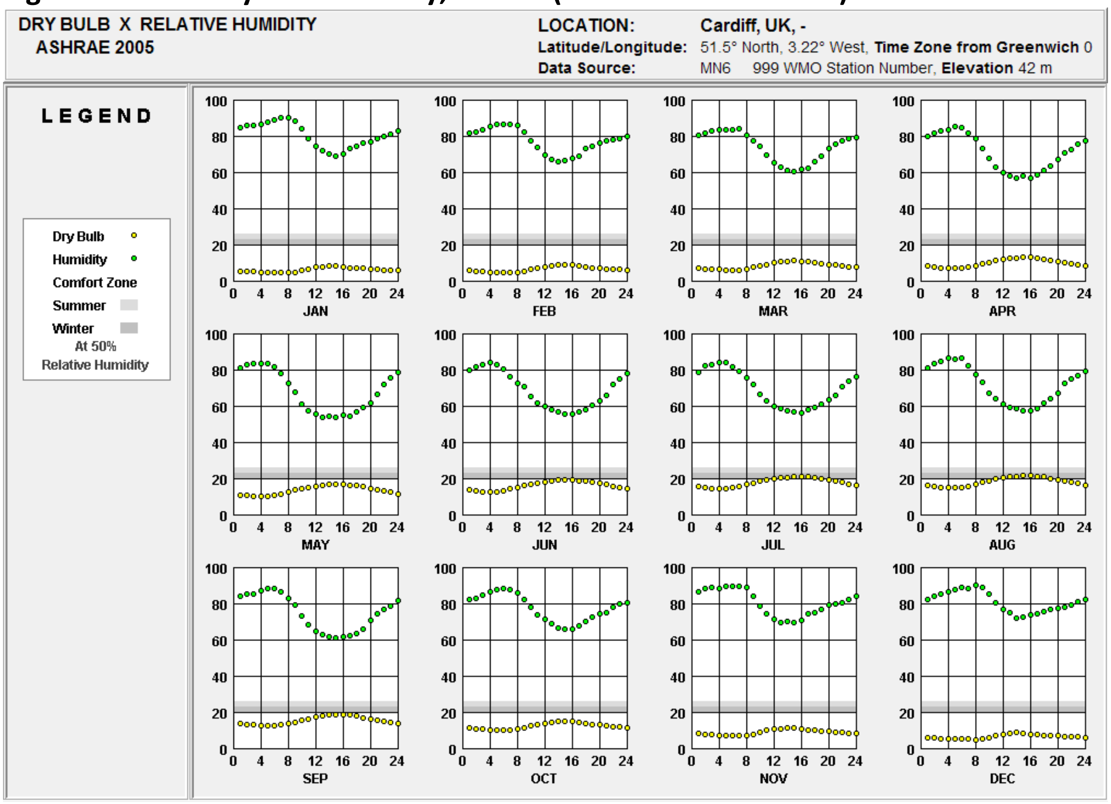


Figure 60: Average daily dry bulb temperature and relative humidity, Cardiff (Climate Consultant 6).

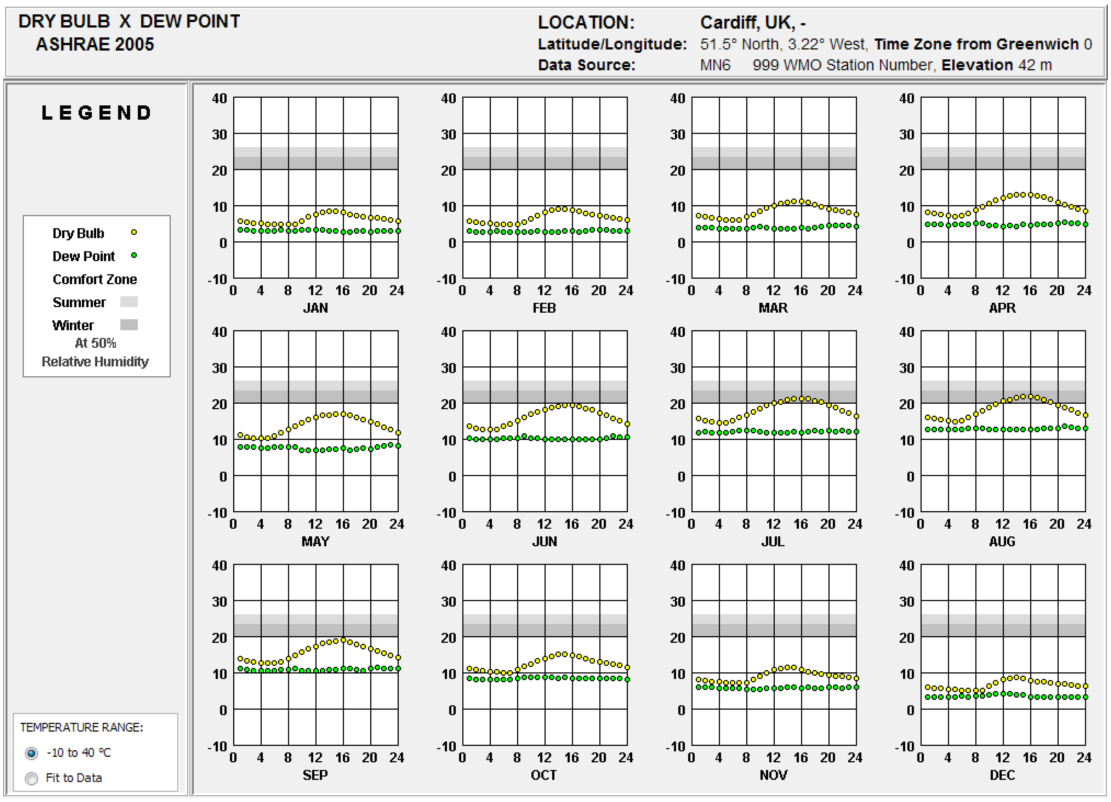


Figure 61: Average daily temperature and dew point, Cardiff (Climate Consultant 6).

Selection of test building

The National Museum of Wales made a row of cottages (Figure 62) at St Fagans National History Museum accessible for the main environmental data collection. The cottages are of traditional, solid, random stone wall construction. They are built to reflect various periods in history, starting with 1805 and moving forward to 1855, 1895, 1925, 1955 and 1985. The size and layout of each cottage is nearly identical, but certain aspects change as the timescale progresses; for example, thicker, rougher stone roofing tiles are replaced with thin, Welsh slate, and then concrete tiles.

Figure 62: Rhyd-Y-Car Cottages as re-erected at St Fagans National History Museum.

One of the main developments is the change of the fireplaces from less efficient, basic designs to modern engineered firebrick. The last cottage (No.6, far right in Figure 62 and Figure 63) set in the 1980s, was used in the experiment. It contains the only fireplace designed for heating and does not serve any other purpose (i.e. cooking, heating of ovens). The cottage has a common fireplace design and conforms to British Standards BS4834;1990, which is beneficial as all post-war open-fireplaces are built to this standard and therefore the data will be relatable to earlier research and calculation (which is expanded on in the next section). The layout of the furniture in the cottage was advantageous for the experiment as it did not impede radiant heat from the fireplace, such as a large settle might, or a kitchen table (see Chapter 5.7).

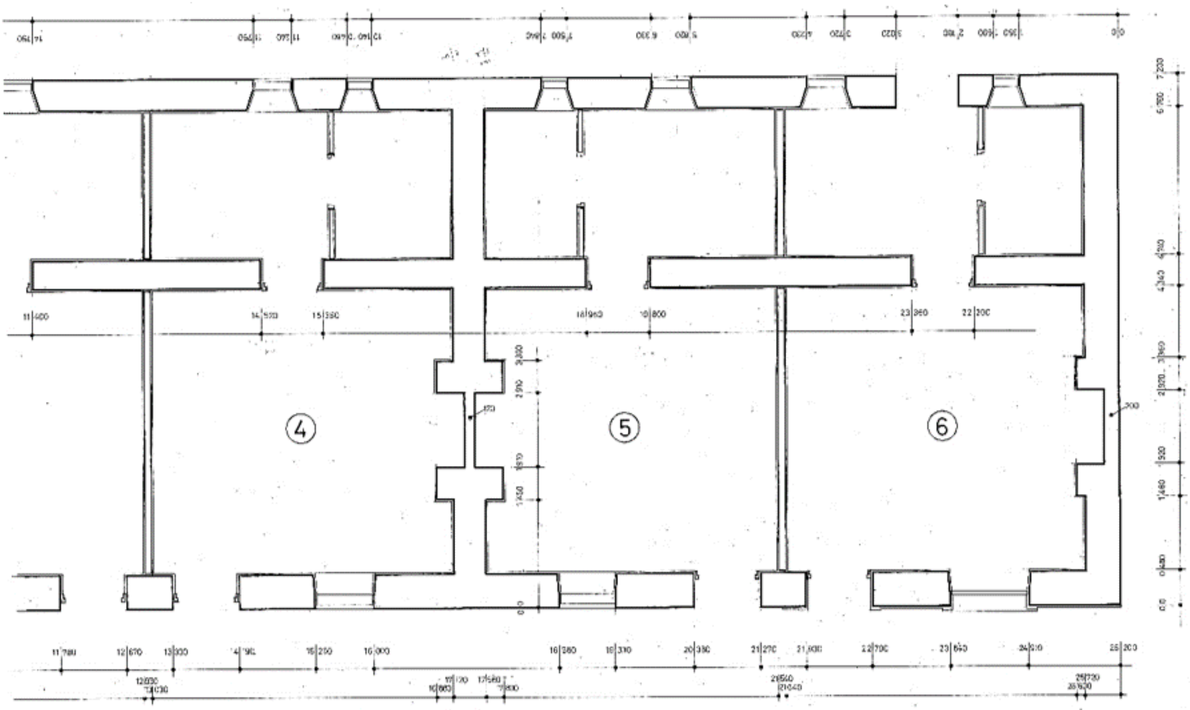


Figure 63: Downstairs plan of Rhyd-Y-Car cottages 4, 5, and 6, plans provided by NMW.

Although more historic fireplaces could be related to the data to specific designs, the reality is that each scenario will differ according to the room and the building design and materials. In this instance other fireplaces in the Rhyd-y-Car cottages were found to be inappropriate for the experiment due to their lack of controllability, or poor functionality due to over-use. However, some similarity in the design of the modern fireplace in the cottage used, with aspects of the design in earlier fireplaces, did offer some relevance to other designs. The initial test in Rhyd-y-Car 4 demonstrated the fireplace caused considerable smoke siphonage into the bedroom (Figure 64). This only became apparent when the front door to the cottage was shut (creating a negative internal pressure). This was a problem caused in part by the fire design requiring more air to go up the chimney than is readily available through the gaps around windows and doors. As such, the fire creates a negative internal pressure which draws in external air through other available openings, such as the bedroom fireplace. This fireplace sharing a chimney cowl (two slates cemented on top of both chimney in an upside-down V shape, covering both flues) meant smoke-filled air was being drawn back into the building.

Figure 64: Upstairs in Rhyd-Y-Car No.4 Following insertion of the fire hood downstairs, it was discovered smoke was syphoning down the bedroom fireplace chimney.

Fireplace and chimney

The fireplace in Rhyd-Y-Car No.6 has a 1980s varnished stone surround, the design of the fireback and the grate conform to British Standard (BS4834;1990) and have their origins in the principles of fireplace construction first published in 1796 (Rumford 1796, 25). The fireclay back slopes forward, and has a grate with no front bars, according to the Teale's principles (see Chapter 2 for more details) (Teale 1883, 12). Thus, whilst the fireplace outwardly is from the latter half of the 20th Century, the functioning parts (grate, fire back, throat size, gather size, and chimney) are of a considerably earlier design. This is of significance, as the fireplace relates to all post-war British Standards designed fireplaces, it also related to many fireplaces built in the 19th and first half of the 20th Century. As such, any results from the fireplace relating to heat output, fuel consumption, rate of draught, will have a degree of comparability to a great many other fireplaces of similar construction from the 19th Century to the present day.

This is also applicable to the chimney, which is constructed of unlined brick, being 9" square internally. This type of chimney was commonly used from the introduction of mechanical sweeping from at least the 1830s, but more definitely after the sweeping of chimneys with boys was firmly banned by the 1875 Chimney Sweeps Acts (Strange 1982, 35). Chimneys were constructed out of brick, often with an internal 'parging' coating until the 1965 Building Regulations stipulated a lining of refractory clay or other heatproof material must be used (pp71). As such it is a chimney that may be considered to have an overlap with a great number of similarly aged structures. The flue gasses will provide heat to the brickwork in a way that is proportional to the size of the flue, and as such having a flue that is of a standard applicable to many others gives the results the widest possible interpretation for other historic structures. This does not negate the aspects which will not be comparable with other structures, of which there are many, such as chimney height and exposure, it reduces them to best within the scope of the project.

Choice of fuel

Fuel is a key factor in the experiment with its energy content, ash content, application protocol, rate of combustion and size being influential variables (Fishenden 1920,vi). Energy content is important but can mean a denser fuel which requires more air to burn, it can also mean a higher ash content which block grates easily and influence how long the fire can be left unattended and continue to burn successfully (Fishenden 1925,120-121). The use of a fuel impacts how it will combust, as will the size of the fuel impact the amount of surface area of fuel exposed to air (Bedford 1948,255;Fishenden 1925,103,120-121). Collectively these factors impact the heat output, and thus the environmental conditions.

It was suggested by staff at St Fagans that Rhyd-y-Car cottages utilised Welsh Steam Coal. Welsh Steam Coal is a denser, higher quality fuel with cleaner emissions and higher energy content than bituminous coal (Table 1) (Solid Fuel Advisory Committee, 1980). It was thought that a utilising this fuel would have offered a closer approximation of how the houses were lived in. However, trial burning of ½ tonne of Welsh Steam Coal in an ordinary BS4834;1990 open grate over a month long period established that it was particularly difficult to keep this fuel alight. It produces a large amount of ash and if left unattended for a short time (1-2 hours) in an open grate it readily ceases to burn. Due to its high ash content, for this fuel, a higher grate with wider gaps between firebars would be of importance to avoid clogging, as in the coke grate seen in Figure 65 (Bedford 1948, 256). Welsh Steam Coal is more suited to closed stoves, such as steam raising boilers, where a high air flow can be provided which ensures a higher amount of oxygen reaches the fuel and higher temperatures are achieved for ease of combustion (Barker,1912,372). It was therefore decided that high quality Columbian bituminous house coal should be used; it is also the fuel utilised by most of the buildings at the museum and mirrors their usage. It is also of note that bituminous house coal is the standard fuel for open fires, and therefore of more relevance to a wider context.

Fuel	**Properties**
Housecoal (bituminous coal)	Ignites and burns with a bright yellow flame, cannot be used in smoke control areas. Will burn with normal air flow in open grate, has a moderate ash content.
Welsh dry steam coal	Smokeless fuel, slow burning, requires high air flow to burn, similar to anthracite but with higher ash content.
Welsh anthracite	Smokeless fuel, high density, slow burning requiring high air flow to burn, low ash content.
Coke	Coke is derived from bituminous coal via a process which removes the gasses and impurities leaving a purer form of carbon. It is a smokeless fuel, requires high air flow to burn. It has a low ash content.

Table 1: Types of solid fuel, guidance from Solid Fuel Advisory Committee (1980).

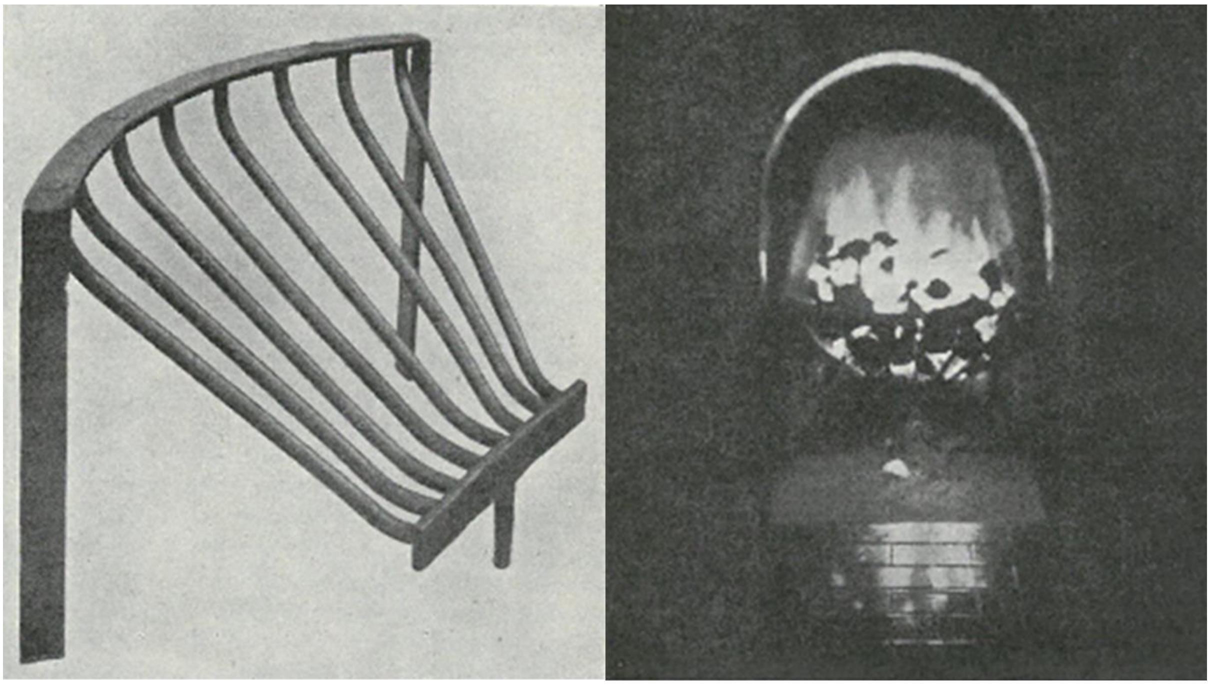


Figure 65: A grate for burning anthracite in an open fire; note the deep fuel bed and wide firebars ensuring little ash build up and a higher surface area of fuel to air (Bedford 1948, 256-257).

For continuous fire burning, day and night or ‘banking in’, the slow combustion state of the fire depends upon reducing the air flow through the fuel bed. This is achieved by covering the fire with ‘slack’ or ‘small coal’, which is made up of tiny parts of coal found at the bottom of coal bunkers or bags. The sizes of the pieces small coal vary, but generally are around the size of oatmeal with the occasional larger lump around the size of a conker. A layer of this on a fire reduces the airflow considerably, but to aid this further a layer of ash was utilised on top on the small coal. Welsh Steam Coal slack was utilised for its high ash content and higher combustion temperature, which aided a reduction in air supply to the bituminous coal.

Method

The set up for the experiment was developed from the method used by the author previously (Johnson 2015). To record the impact of traditional heating on the internal environment the fire in Rhyd-y-Car 6 was lit for six five-day periods using a series of burn patterns (Table 2). Three of these were before Christmas (Nov 20th-24th, Nov 26th-Dec 1st, Dec 11th-15th 2017), and three after (Jan 8th-12th, 15th-19th, 22nd-27th 2018). The initial three weeks (Experiment 1-3) were the continuous fire experiments where the fire was not allowed to go out. The fire was lit on Monday at 9:00 and once the fire had taken hold was refuelled about every four hours, according to the combustion rate of the fuel for the full period of the experiment. The fireguard was used continually to mitigate against it being a variable.

Heating Experiment	Date	Fire type	Experiment length (Monday to Friday)
1	November 20th 8:00 -24th 17:00 2017	Continuous (banked in overnight)	109 hours
2	November 26th 8:00- 1st December 17:00 2017	Continuous (banked in overnight)	109 hours
3	December 11th 8:00 to 15th December 17:00 2017	Continuous (banked in overnight)	109 hours
4	January 8th 8:00 to January 12th 17:00 2018	Daily fire (no overnight burn)	109 hours
5	January 15th 8:00 to January 19th 17:00 2018	Daily fire (no overnight burn)	109 hours
6	January 22nd 8:00 to January 27th 17:00 2018	No fire	109 hours

Table 2: Fire cycles used in the heating experiment.

Furniture and layout

Various pieces of furniture were present in the living room of Rhyd-y-Car No.6 presenting an interior of the 1980s to the public. One piece of furniture in particular, a large upholstered sofa, was placed in such a way that it obscured a significant amount of radiant heat reaching the greater proportion of the room (Figure 66). This original placement facilitated the museum visitors access to the kitchen of the property.

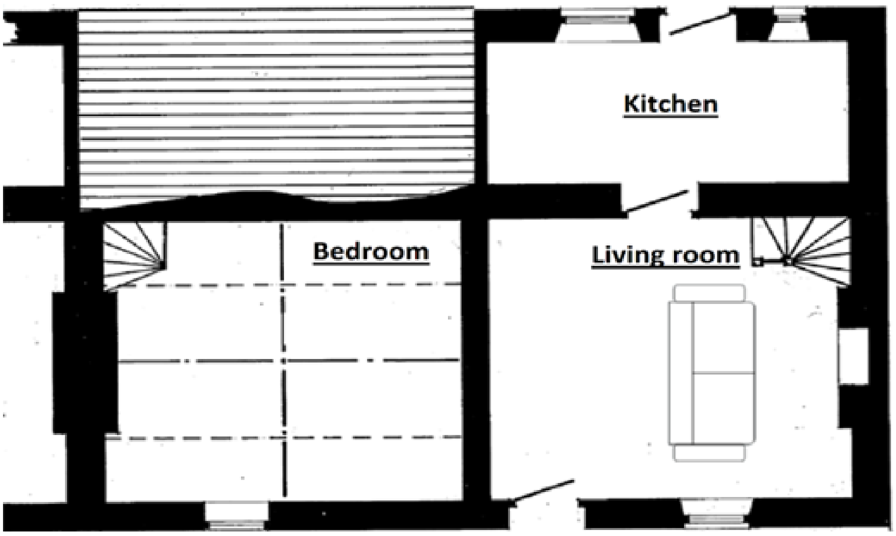


Figure 66: Inside of Rhyd-Y-Car No.5 & 6, showing layout of sofa in No.6 prior to re-positioning. Bedroom (shown to the left) is above the living room (shown to the right).

By moving the sofa against the rear wall logging could proceed without obstruction (Figure 67) allowing a more accurate picture of the environmental conditions to be recorded whilst still keeping a furnished room allowed for any buffering furniture would normally supply.

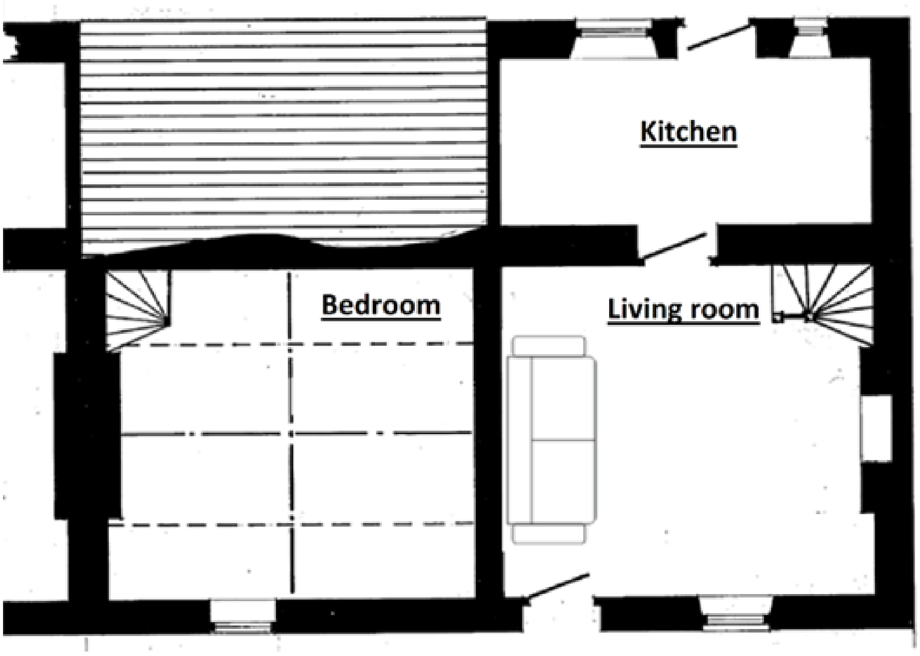


Figure 67: Inside of Rhyd-Y-Car No.5 & 6, showing layout of sofa in No.6 post re-positioning. Bedroom (shown to the left) is above the living room (shown to the right).

Fire management

For the lighting of the fire a standard practice of sticks and newspaper was utilised. This commenced at 8:00 on experiment day 1 for the banked in experiments and on days 1, 2, 3, and 4 for the daily fire experiments. Refuelling was carried out throughout the day

(Appendix 1 contains times and quantity of fuel applied). For overnight burning (or banked in), small coal (or slack) of Welsh Steam Coal was used on top of the bituminous house coal, with a layer of ashes placed on top.

The mass of all fuel added was measured on a Salter Compact (433 SVDR) mechanical bathroom balance which was tared before each use. All refuelling times were recorded. Columbian bituminous coal has an average energy content of 7.3kw/kg (World Coal Quality Inventory: Colombia). The measured radiant efficiency of the British Standard fireplace, such as in Rhyd-Y-Car, has been shown to be between 24% and 36% though the overall efficiency of the whole structure (including chimney) may be different (Barker 1920; Fishenden 1920; Weston 1949; Shaw 1953; HETAS 2016). The rate of consumption of the fuel has a large bearing on the heat output, and the design of the grate in the cottage gives very little control over that (Copson 1957). Welsh steam coal has an energy content of 9.2kw/kg and a ratio of 2kg of small Welsh steam coal to 3kg of Columbian house coal on average was used banking the fire in (Web reference 3). As much ash as required to cover the fire was then put on top. See Fire Log in Appendix 1.

The fire was usually banked it at 22:00 but this could fluctuate to accommodate the combustion rate of the fire. Between 8:00 and 8:30 the fire was poked, and re-built. On the final day of the experiment, the fire was left to go out after the initial re-building with coal; this was to record the cooling of the building.

After Christmas, the first two sets of experiment followed a pattern similar to that currently used by the museum. The fire was lit every day at about 8:00 and re-fuelled every four hours, twice. The last re-fuelling of the fire was at about 16:00, and the fire was allowed to go out naturally. Lighting the fire at exactly the same time every day was not practicable but was possible within a narrow window. For example, if the fire failed to light first time, or was sluggish to start, it was difficult to determine when it was fully alight. On Friday the fire was not lit so as to record the cooling of the previous fire (see Table 1).

Recording room environment

MadgeTech 101A (±3% RH ±0.5°C) humidity and temperature loggers were used to record the room environment. These were calibrated with Binder 720 climate chambers using two RH and temperature points of reference. MadgeTech 4 software was used to calibrate, set up the loggers, and download the data. The method for this is laid out in Thunberg et al. (2020, 9) and normally reduces error to ±1%RH and ±0.2°C. Being matt black, the loggers record radiant temperature in the room, a shielded logger recorded air temperature to the side of the fireplace.

To allow three dimensional recording, loggers were set at three positions on a length of plain cotton string; ten centimetres above the floor, ten centimetres from the ceiling, and exactly halfway at 101cm. The full ceiling height was 202cm. The positions of the data loggers within Rhyd-Y-Car No.6 are given in section Figure 68 and plan Figure 69 views and are seen in Figure 70.

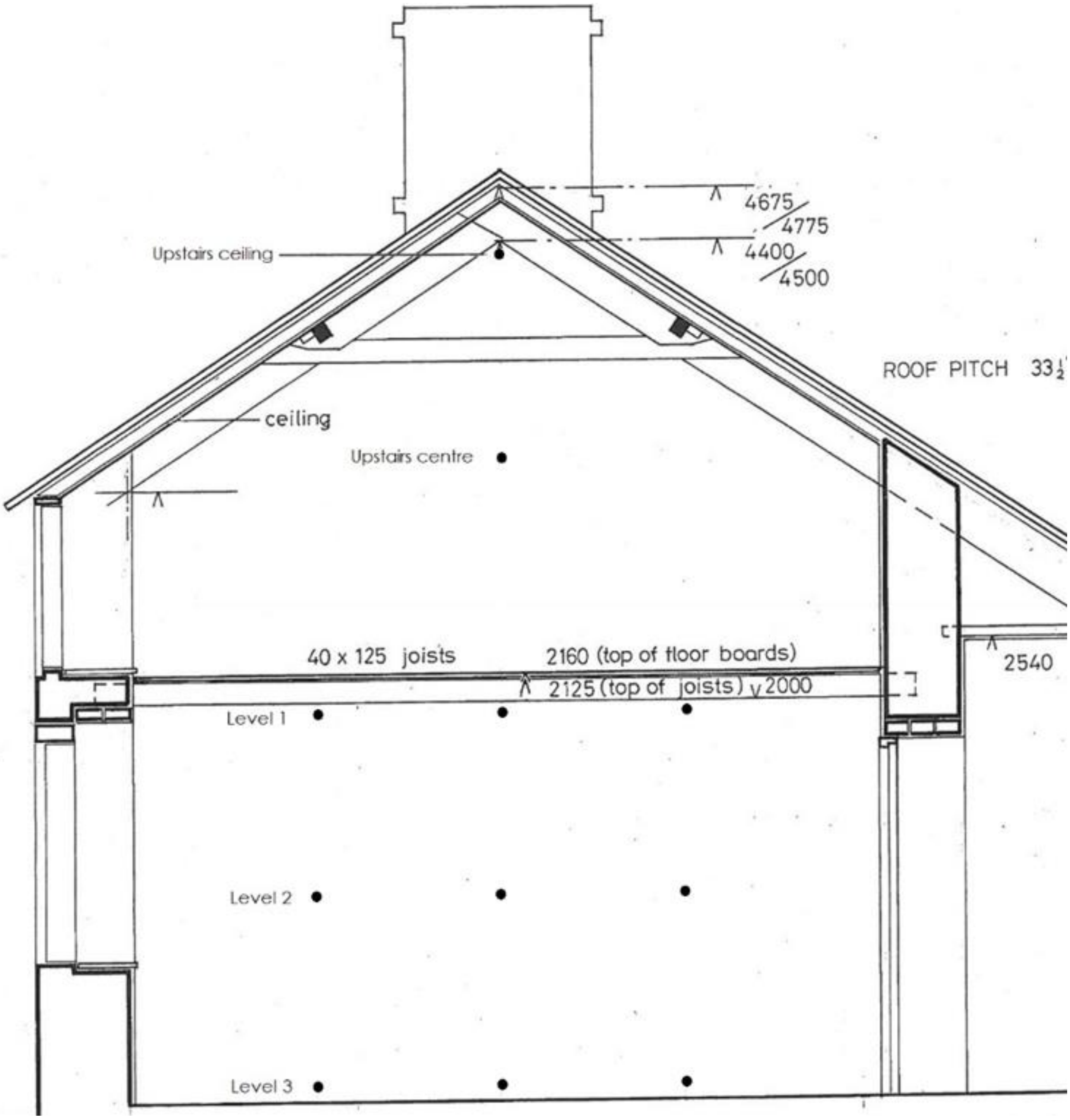


Figure 68: Data logger locations in elevation view.

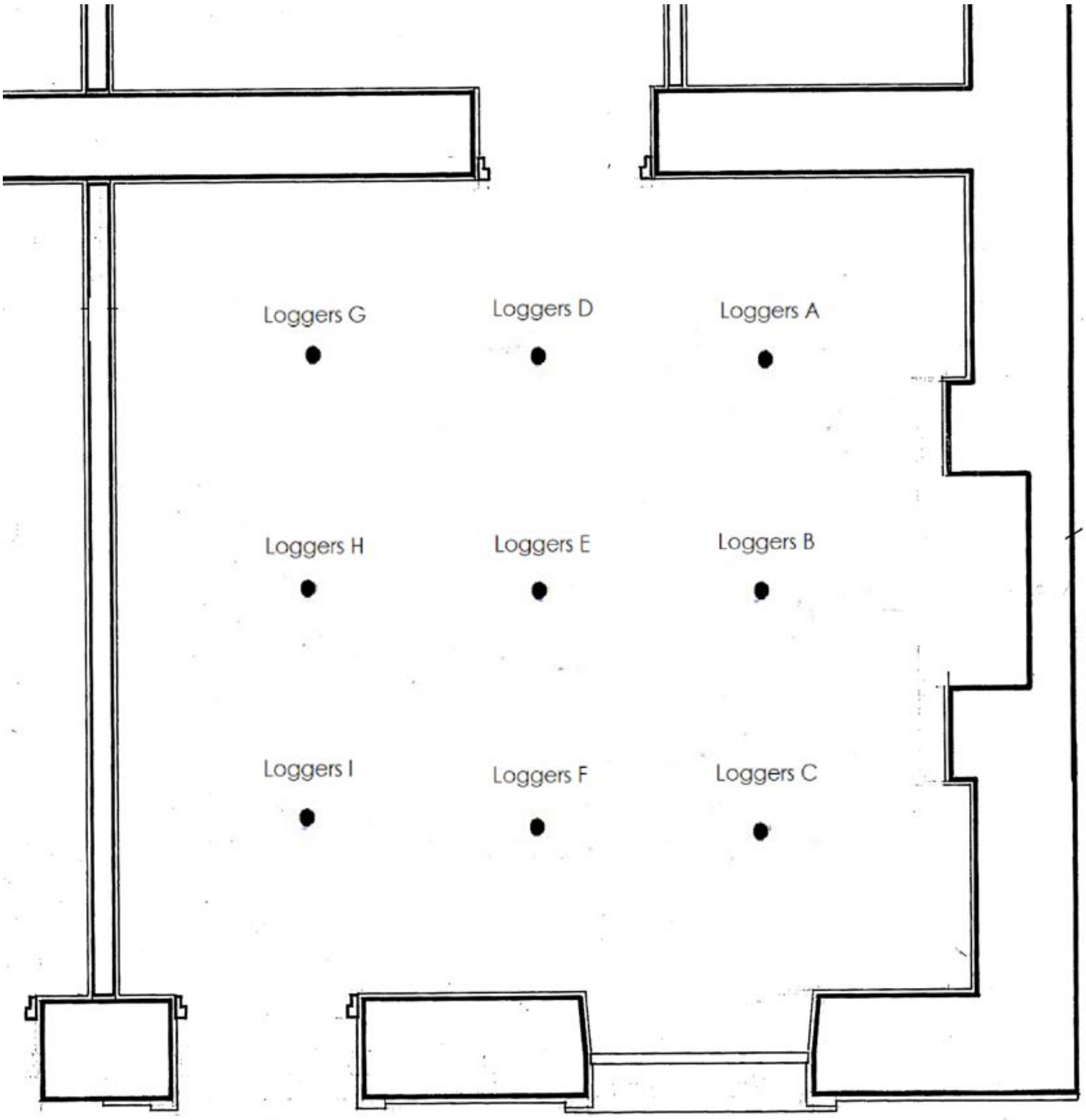


Figure 69: Data logger locations in plan view.

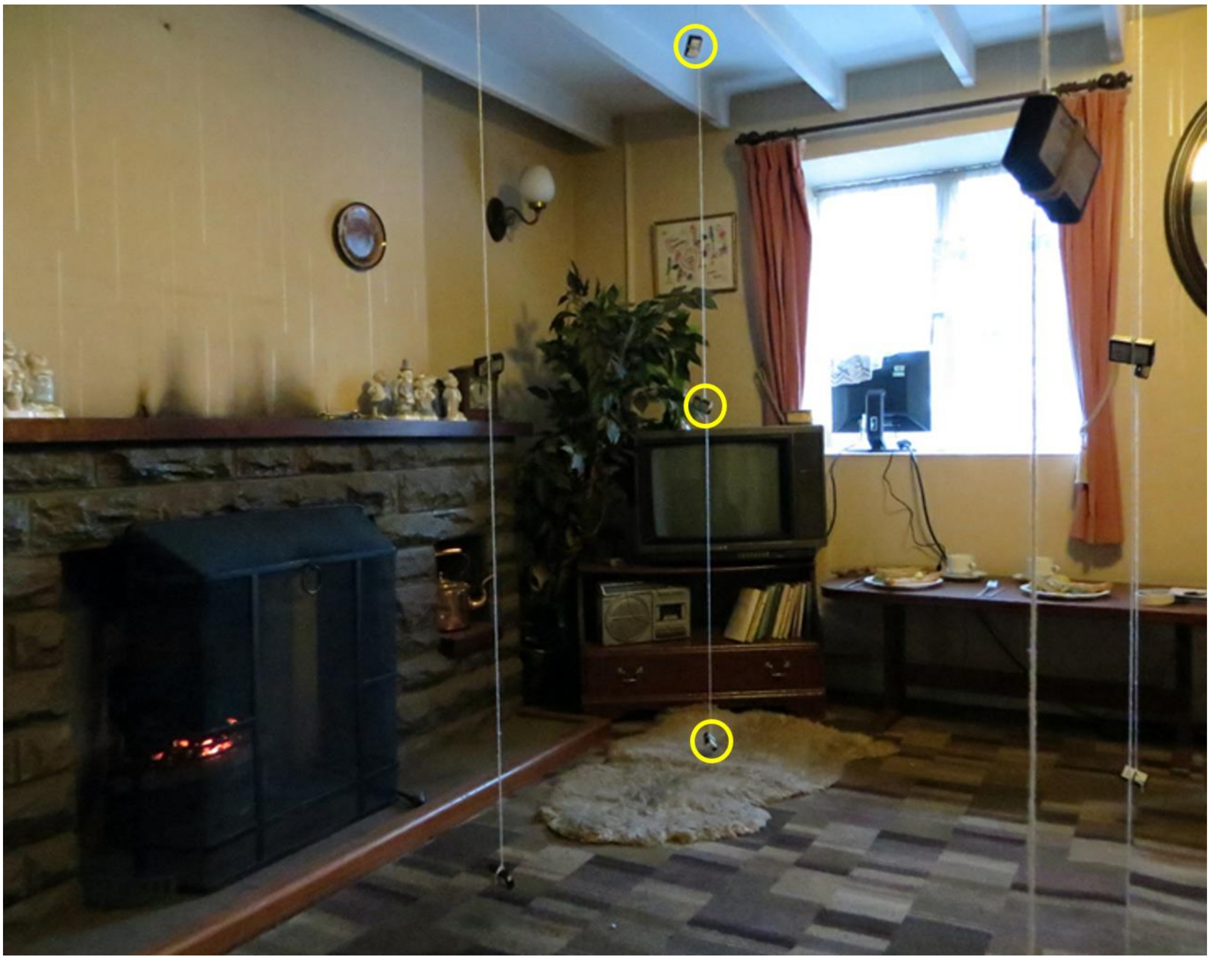


Figure 70: Loggers on string, fireplace and chimney breast. Yellow circles indicate the locations of three loggers on one string from ceiling to floor.

The placement of ceiling loggers was chosen as loggers positioned too closely to the ceiling may be impacted by stagnant air pockets in a room with exposed joists as warm air rises and sits in the spaces between joists (O'Connor 2011). The loggers were 10cm from the floor to avoid measuring the temperature of the surface of the floor. Upstairs (Figure 71), three loggers were deployed: one on the chimney breast, and two in the centre of the room to gain an idea of the impact to the room which shares a chimney breast (Figure 72). Of the upstairs centrally positioned loggers, one was ten centimetres from the ceiling, the other halfway between ceiling and floor. The external environment was recorded from a slightly sheltered position on the top of the external wall of the coal shed. This was located less than three meters east from the front wall of the house. The upstairs loggers provide a continuous view of the environmental conditions, at weekends the doors of the cottage were open to allow visitors entry and loggers removed.

Figure 71: The bedroom upstairs in Rhyd-y-Car No.6.

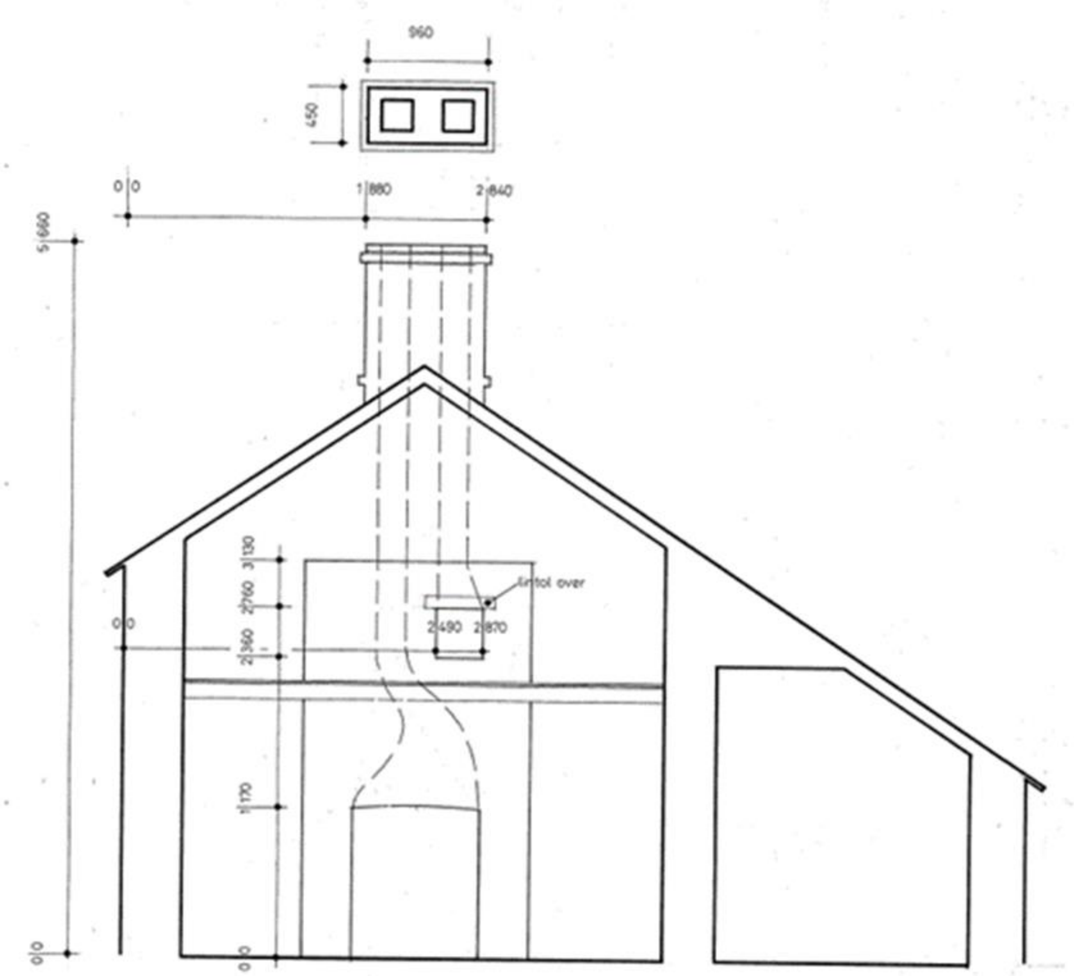


Figure 72: Cross section of fireplaces and chimneys, Rhyd-y-Car Cottages

Photography and infrared photography

A Fluke TI200 infrared camera was utilised on a tripod with a wide angled lens (42.5° x 32.5°). The camera was aimed at the wall just above the fireplace, not including the fire itself, in order to keep the temperature and colour scale within a narrow limit and provide better resolution. The Fluke TI200 has a ± 2°C error at 25°C. A mains power pack ensured continuous power supply, and the infrared camera took an image every ten minutes on a time lapse setting.

The infrared camera was also utilised to calculate the heat output of the chimney breast in watts throughout the experiment utilising method detailed in Chapter 7.3 (Figure 73). This, together with the SAP rating calculated from the air exchange rate (Chapter 5.11), allows for a detailed picture of heat gain and loss in the cottage.

A digital SLR camera Pentax Coolpix P600 was employed to record the state of the fire throughout the experiments. Set on a tripod, to take time lapse photographs of the fire every 10 minutes, it was positioned to take a photo level with the fire, but not impede the radiant heat to the loggers. The photographs highlighted the different stages of combustion at different points. When an outliner, or unusual pattern occurred it was possible to check the time lapse pictures and to investigate the condition of the fire.

Figure 73: Loggers on string, infrared camera and fireplace.

Air exchange rate

These tests were conducted with the help of the Welsh School of Architecture. The air exchange rate of the building was calculated by the use of a dg-700 pressure and flow gauge manufactured by The Energy Conservatory, and the corresponding Minneapolis Blower Doors $_{TM}$. Its use followed the guideline laid out in BS EN ISO 9972:2015. The door kit and blower were installed in the front door (Figure 74). To improve overall accuracy large air gaps (such as the chimney) were blocked and the air loss via the aperture calculated separately and added to the final figure. The blower was started and initially was set to create positive pressure, and then negative pressure, the results for pressure difference being shown on the display in pascals and the air flow rate in m/s (Figure 75). This was repeated three time to produce an average for both. Cross ventilation was measure between the two adjoining cottages by utilised two blower kits, one for each house. The results for the air exchange rate, air permeability index and effective leakage is then calculated utilising the formula in BS EN 9972:2015

The air exchange rate was used to calculate heat loss figures for the buildings, feeding into the discussion around the heat output of the fire, the thermal mass, and the response of the RH. It allows for a more accurate understanding of the response of the building to the heating scenarios.

SAP Calculation and U-values for solid walls

Figure 74: Blowers inserted into doorways for Rhyd-y-Car No.5 and 6.

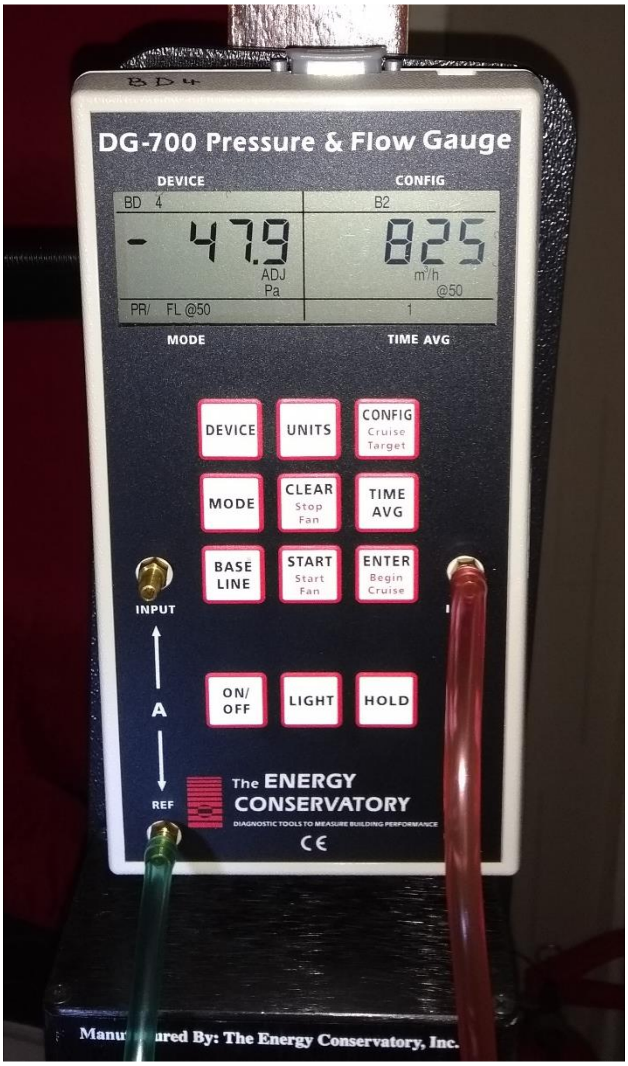


Figure 75: Pressure flow gauge from air exchange test.

The U-value of solid walls in traditionally constructed buildings has come under scrutiny and in-situ measurements have found it to be better than calculated equivalents (Baker,2011,II). SAP was updated in 2019 (RdSAP 2012 version 9.941) to reflect this, and as such U values for solid walls utilised in this thesis may be higher than reality. It may be of some benefit for future researchers of similar experiments to take in-situ readings themselves to improve accuracy and add to this body of knowledge for traditional construction performance.

Control, repetition and reproducibility

Repetition of the fire experiments produced three sets of data for the banked in fire. The daily fire experiment had two sets of data, and the week with no heating provided a control for comparison to no heat input. The weather was a variable for each of these tests and, as such, they are not exact repetitions of each other. Overall, the reproducibility of the experiments is limited unless the external environmental conditions can be repeated, i.e. through having a room constructed inside a large climatic chamber. The equipment employed for the fire lighting experiments is listed in Table 3.

Equipment
Madgetech 101A RH and Temp logger
Fluke TI200 infrared camera, wide angled lens (42.5 ° x 32.5 °) and tripod
Pentax Coolpix P600 and tripod
Omega-flo HHF710 Digital hygro-thermometer anemometer
The Energy Conservatory DG-700 pressure and flow gauge with Minneapolis blower door
Salter Compact (433 SVDR) mechanical bathroom balance
Galvanised bucket
Poker
Fire guard
Small coal shovel
Heatproof glove

Table 3: List of equipment used for heating experiments.

6 Heating experiments: results

Experimental data outcomes

The experimental data gave both recorded and calculated outcomes.

The recorded outcomes show:

- The environmental conditions in the house when heated and unheated.
- The temperature of the wall which includes the fireplace.
- The temperature and humidity in a three-dimensional pattern within the room.
- The times the building fabric took to reach an equilibrium when heated by the fire.

This fed into the calculated outcomes:

- The difference between the impact of banked in fires and fires re-lit daily on temperature and humidity.
- The heat stored and emitted by the chimney breast within the room.

For ease of reporting and to avoid repetition, a standardised nomenclature is used throughout the results and discussion (Table 4).

Abbreviation	Property
T_{ex}	External temperature
T_{dc}	Downstairs internal room centre temperature
T_{uc}	Upstairs room centre temperature
T_{cha}	Downstairs chimney breast average temperature (from thermal image)
T_{uch}	Upstairs chimney breast temperature (from logger)

RH_{ex}	External relative humidity
RH_{dc}	Downstairs internal room centre relative humidity
RH_{uc}	Upstairs internal room centre relative humidity
RH_{uch}	Upstairs chimney breast relative humidity
K	Difference between indoor and outdoor temperature
W	Watts

Table 4: Standardised nomenclature for results and discussion.

Environmental conditions outside the building

The external conditions (T_{ex} RH_{ex}) for the entire period of Experiments 1-6 (20/11/2017-26/1/2018) were relatively stable (Figure 76). The average RH was 98.6% and the average temperature was 5.2°C. The frequency of specific RH values are displayed in (Figure 77), demonstrating that RH_{ex} was predominantly above 90%. T_{ex} was predominantly below 10°C (Figure 78). BS 5250 suggests a 60-day UK winter: outdoors 5°C, 95%RH; indoors (dry-moists) 15°C, 65%RH; indoors (moist-wet) 15°C, 85%RH.

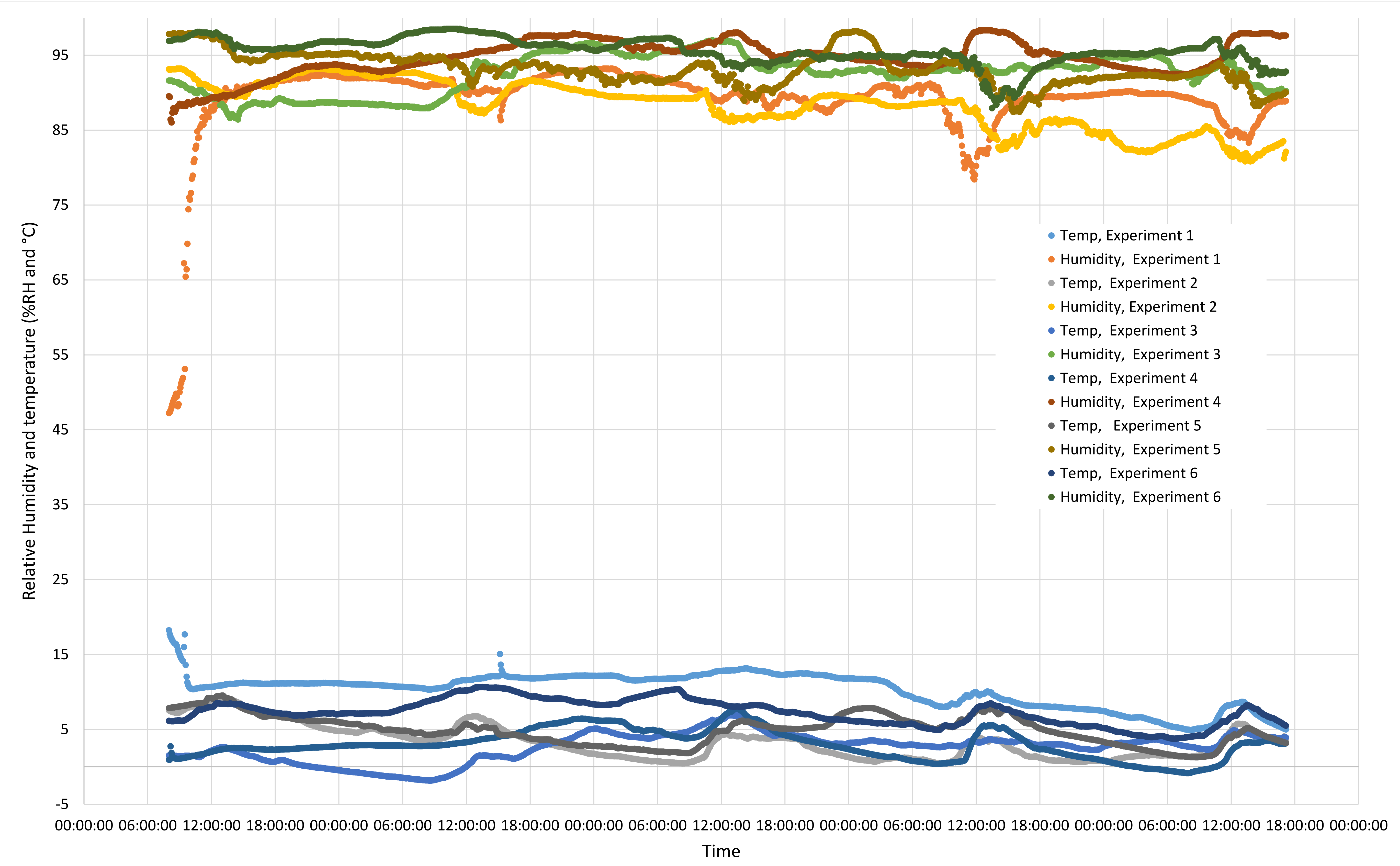


Figure 76: External RH and temperature data for Experiments 1-6.

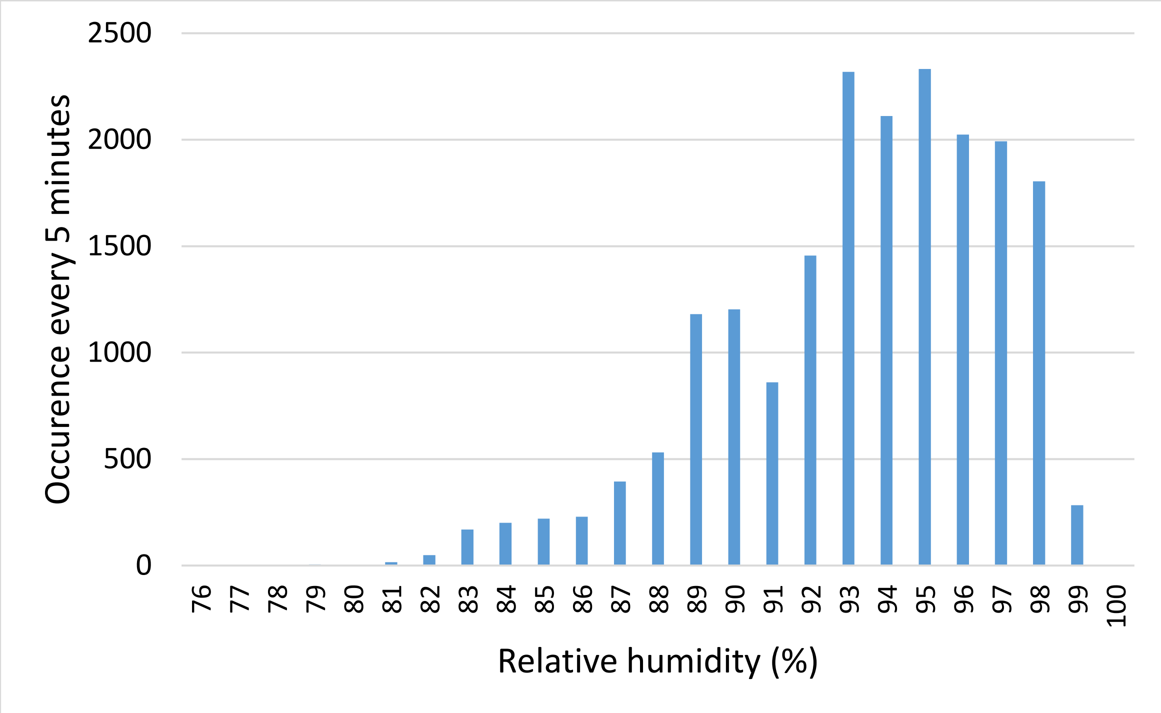


Figure 77: External RH frequency calculated to whole numbers for Experiments 1-6.

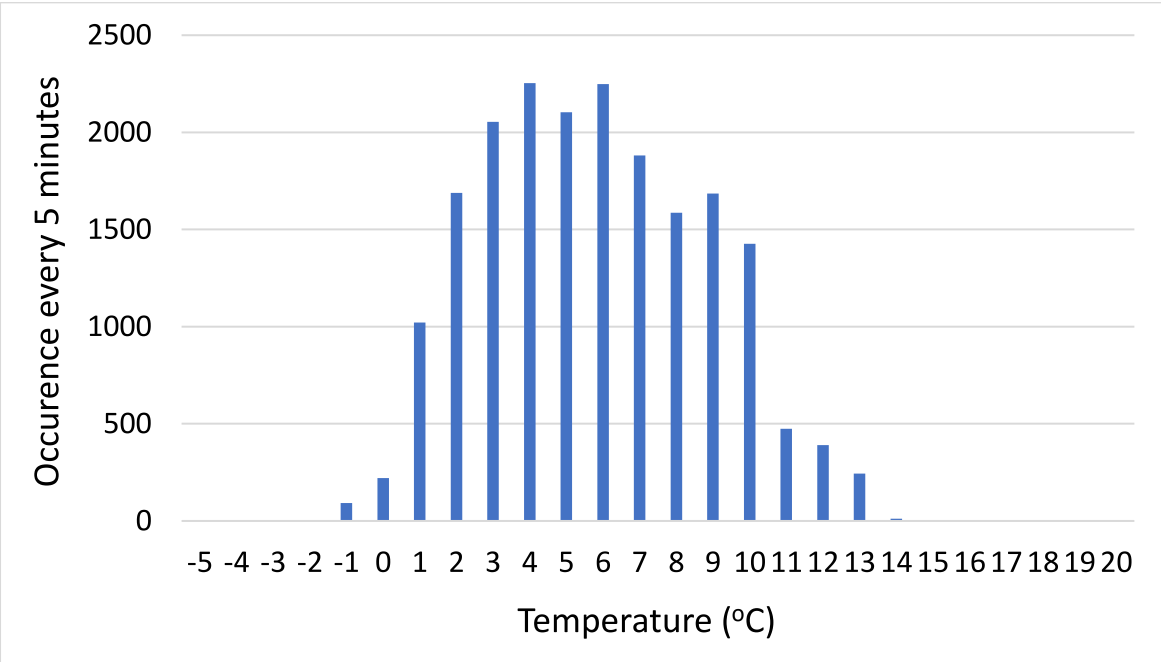


Figure 78: External temperature frequency calculated as whole numbers for Experiments 1-6.

Overview of environmental conditions inside unheated building

Before lighting the fire on the first day of experiment 2 banked up fire cycle, an infrared image of the chimney breast downstairs was recorded, showed the wall temperature to be 7°C, with the coldest area recording 5°C (Figure 79). Downstairs loggers provide information on typical conditions within the unheated living room during Experiment 6, Figure 80 and Figure 81. The T_{dc} was either at 9°C or 10°C. The RH_{dc} ranged between 69% and 79%, but the most common RH was 71%, with a higher cluster of frequency from 70-72% RH. Figure 82 shows the unheated period prior to the Experiment 1, the internal environment was fairly stable at 11°C, and the humidity rises overnight from 63%RH to 78% RH. The loggers upstairs give the $T_{uc,}$ RH_{uc} , T_{uch} and RH_{uch} and remained in position over the entire experimental period, whilst the downstairs loggers were removed at weekends.

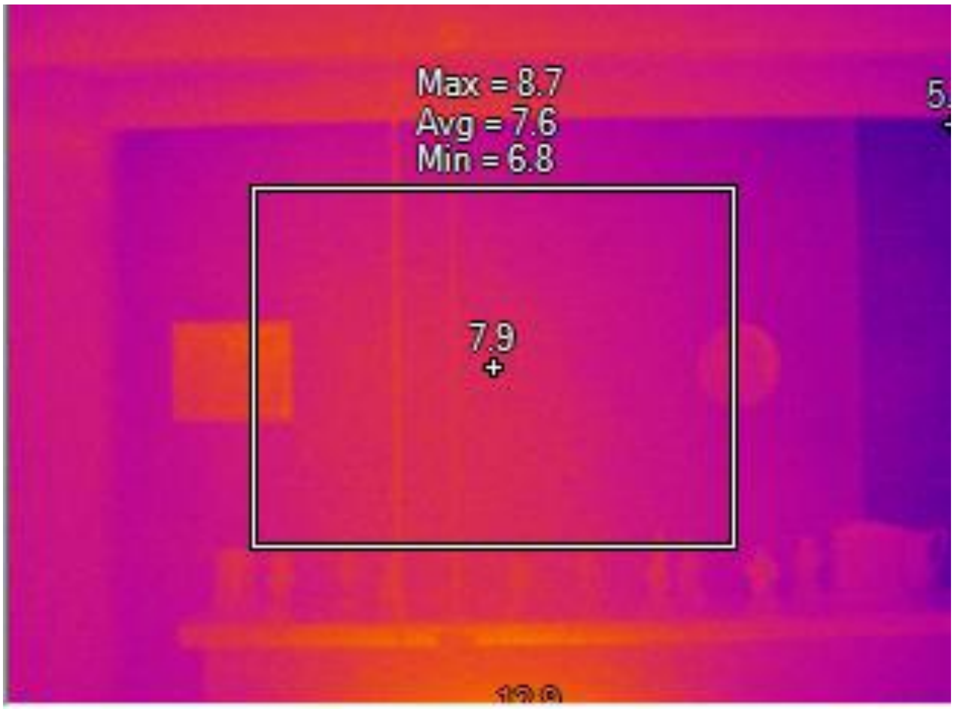


Figure 79: Infrared image of chimney breast 8:39 1st day of Experiment 2 with the white box showing an average surface temperature of 7.6°C.

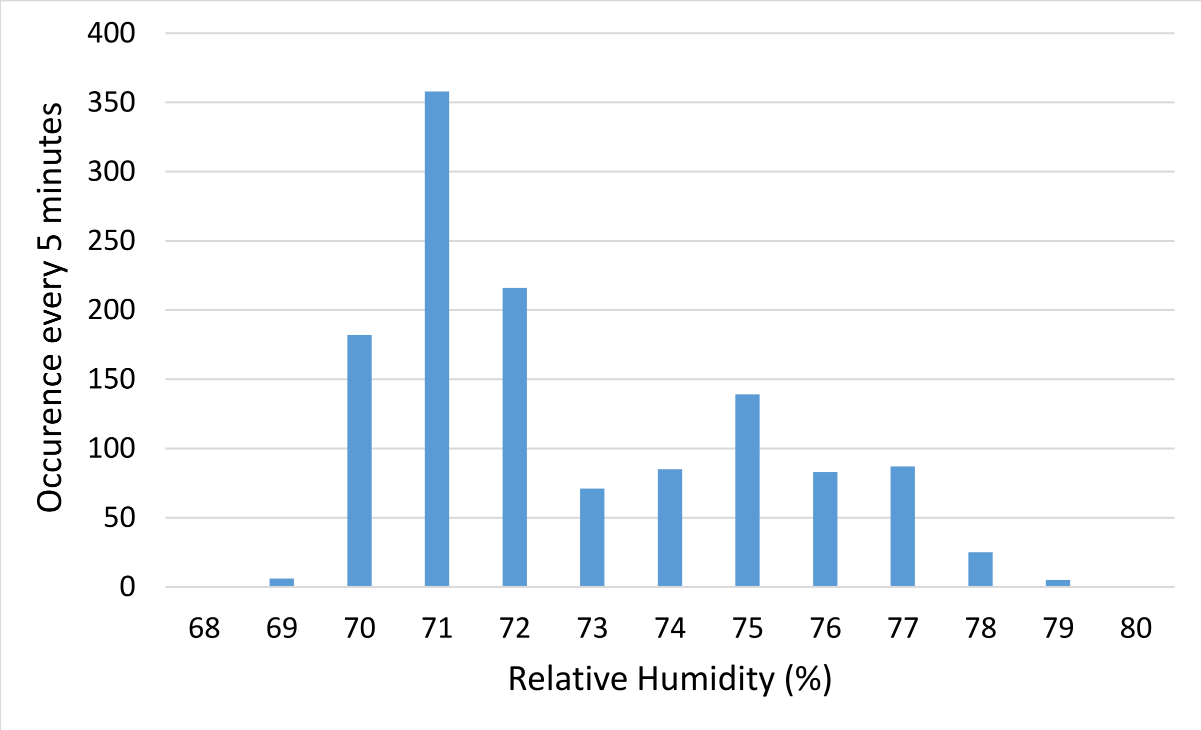


Figure 80: RH frequency for room centre during Experiment 6, 22-26 Jan 2018 unheated room.

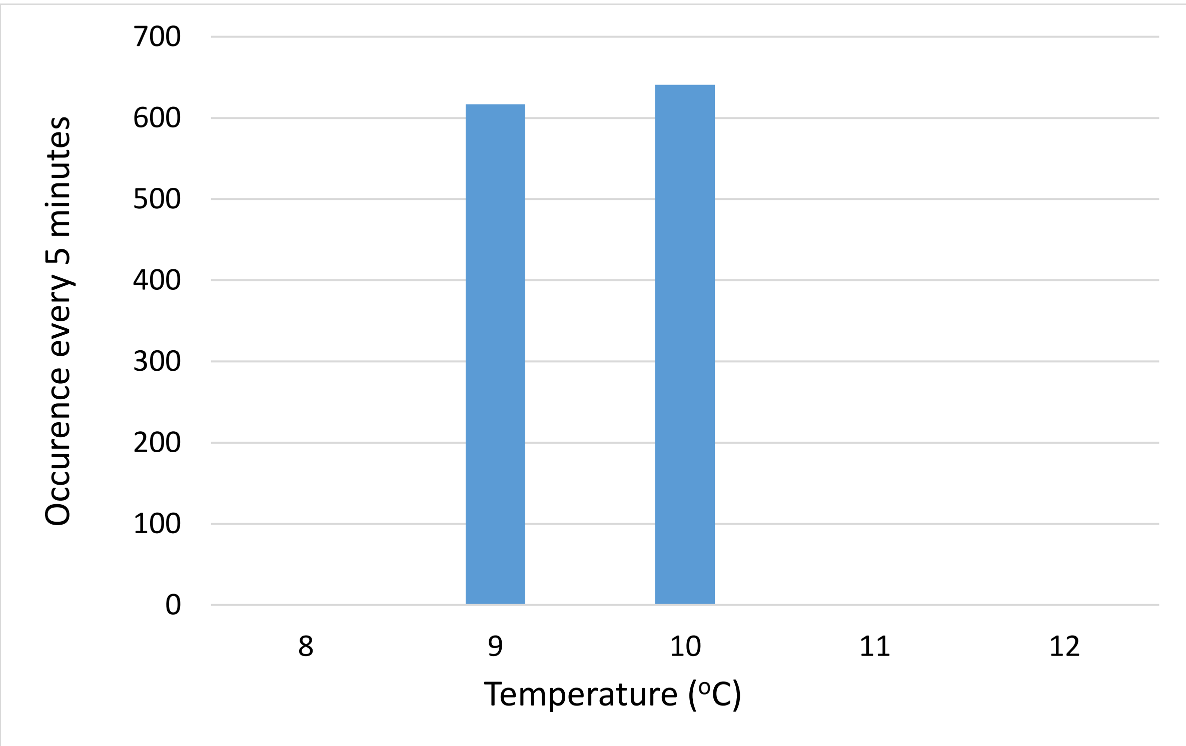


Figure 81: Temperature frequency for room centre during Experiment 6, 22-26 Jan 2018 unheated room.

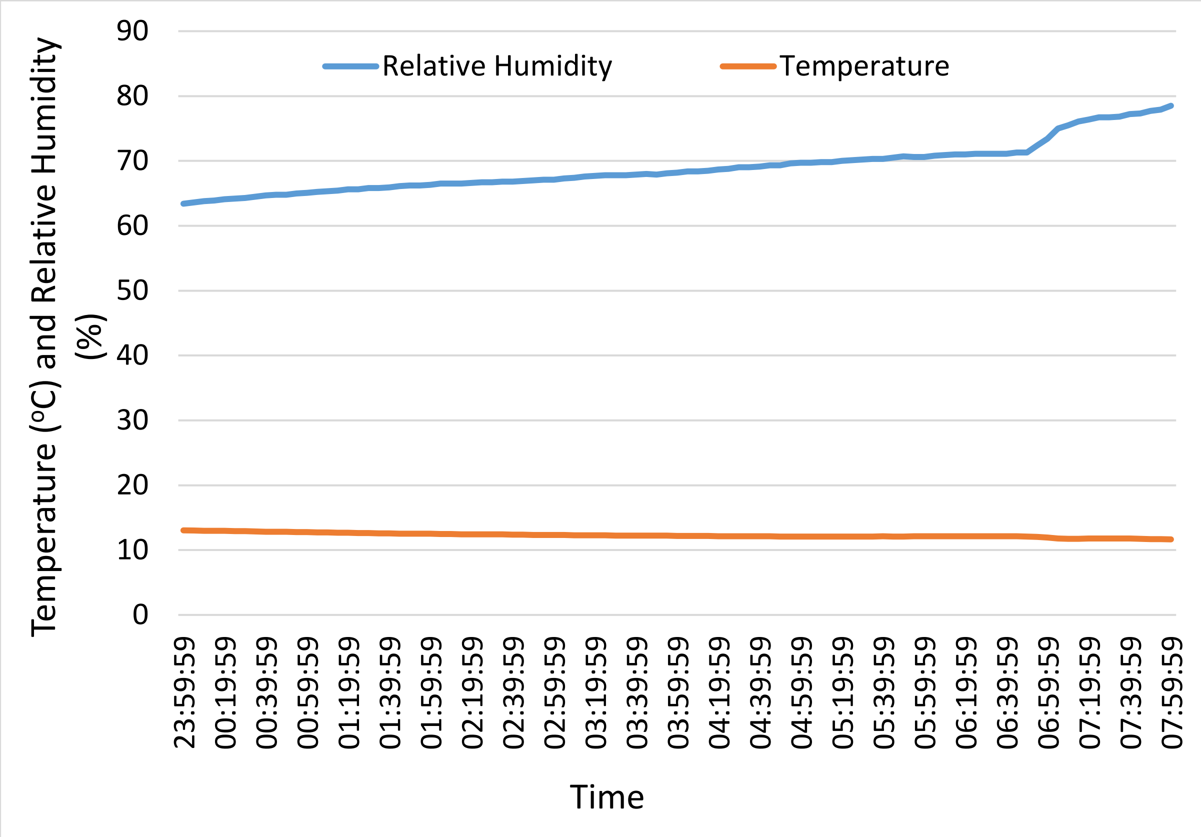


Figure 82: Internal environmental conditions on 19-20th November prior to Experiment 1 as recorded in the centre of the downstairs room.

The following section utilises climate evaluation charts (a development of psychrometric charts) to display the recorded data from the central logger in the downstairs room. They were compiled using the online application 'http://www.monumenten.bwk.tue.nl/', initially produced by van Schijndel et al. (2011). The chart records the temperature and relative humidity, with the set temperature and humidity goals for the room delineated by a field outlined with blue lines (30%RH-70%RH, 15°C to 25°C). This range (blue box) was defined as 30%RH to 70%RH and 15°C-25°C by considering acceptable temperatures for the comfort of visitors, and for collections using BS-EN16893:2018 which identified mould growth starting above 70%. Recorded points are shown plotted inside and outside of the defined field, and the percentage of these falling in any particular field is shown in total distribution figure.

Figure 83 shows environmental conditions within the room when unheated during Week 6 (22-26 Jan 2018). Temperature was entirely below the 15°C target and 15% of the RH values were within the RH range, with the remaining 85% all above 70%. The average temperature was 9°C and RH was 72%.

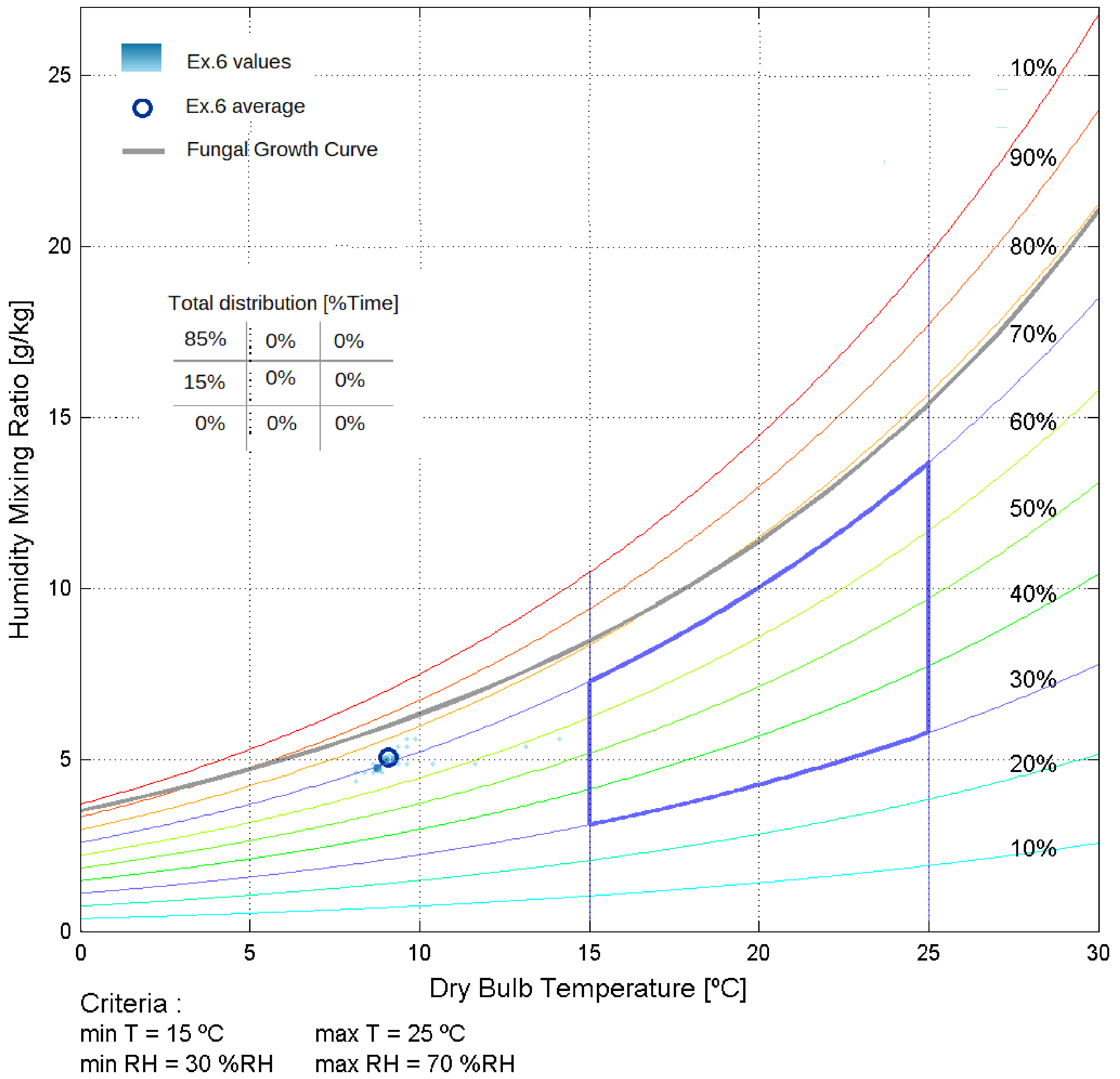


Figure 83: Climate Evaluation Chart showing that RH and temperature measured during Week 6 (circled in pale blue) fall outside the defined RH and temperature goal values (darker blue outlined region).

Overview of environmental conditions: fires overnight (banked in) and daily (relit)

6.1.1 Banked in fires (Experiments 1, 2 and 3)

The environment in the room with banked in fires sits within the preferred RH and temperature limits which are shown with Figure 83 and

Figure **84** shows the recorded values for the banked in fires, with the unheated period (Experiment 6) of the experiment, and the fire lighting period removed. This is done so that the graph only depicts results from the heating period, rather than showing results from before the fire is properly alight. It provides a clearer picture of the results from a continuously heated building, sometimes described as a 'flying start' method (Eaton 1956, 125). Therefore, the graph has data for Monday 12:00 to Friday 12:00. The 'total distribution' of the graph shows the percentage of recorded values outside the set parameters. These parameters were selected at 30%RH to 70%RH and 15ºC-25ºC, as mould growth starts above 70% RH, based on BS-EN16893:2018 and temperatures for comfort for visitors.

The total distribution shows only 1% over the 70% RH mark, and none under 10% RH. However, 28% of readings were under the minimum temperature of 15°C whilst the remaining 10% of readings were over the 25°C threshold. The weekly average figure is shown by the brown cross, RH values are 52%, 38%, and 37%. Temperature weekly averages are 22°C, 21°C, and 15°C respectively for Experiments 1, 2 and 3.

6.1.2 Daily fires (Experiments 4 and 5)

Fires lit daily show slightly different results (

Figure **85**). When assessing the 'total distribution' within the preferred parameters (20%RH-70%RH 15◦C-25◦C) the majority (53%) of recordings fall outside of the delineated region. All recorded RH data falls within the humidity range, but 49% of the recordings are under 15◦C, which would be uncomfortable for attendants and visitors, and 4% are over 25◦C which would be cosy. 34% fewer recordings are within the parameters than the banked in fires and 6% fewer readings were over the 25◦C mark, showing that high temperatures were recorded more often with banked in fires.

6.1.3 Overview of all environmental experiments

Figure 86 shows the environmental conditions recorded for all experiments as a function of time, and Appendix 3 gives a plot of the environmental conditions of the whole experimental period upstairs in the cottage.

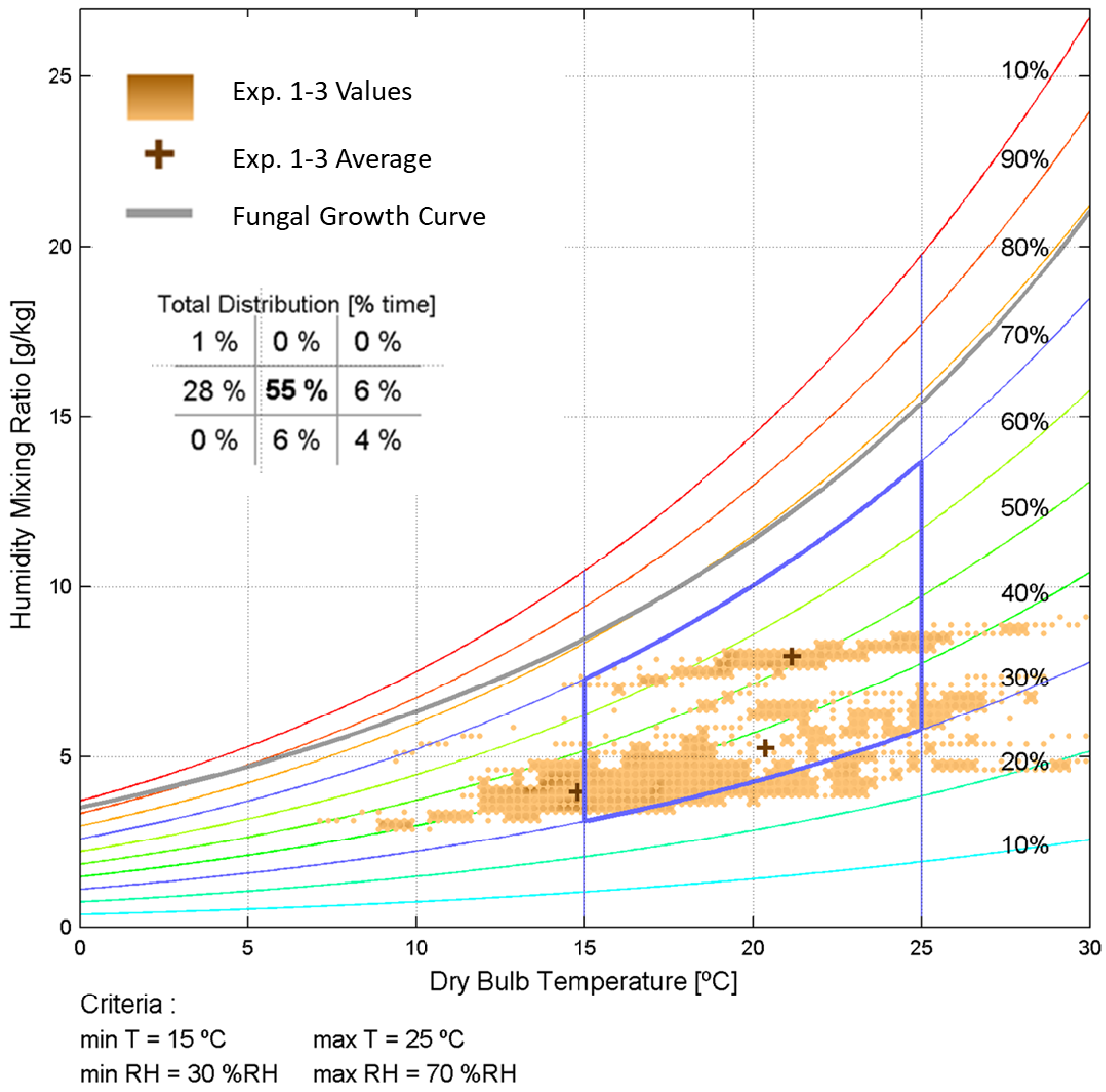


Figure 84: Climate Evaluation Chart showing RH and temp data for experiment 1, 2, & 3 (Monday before 12:00 and Friday after 12:00 removed) .

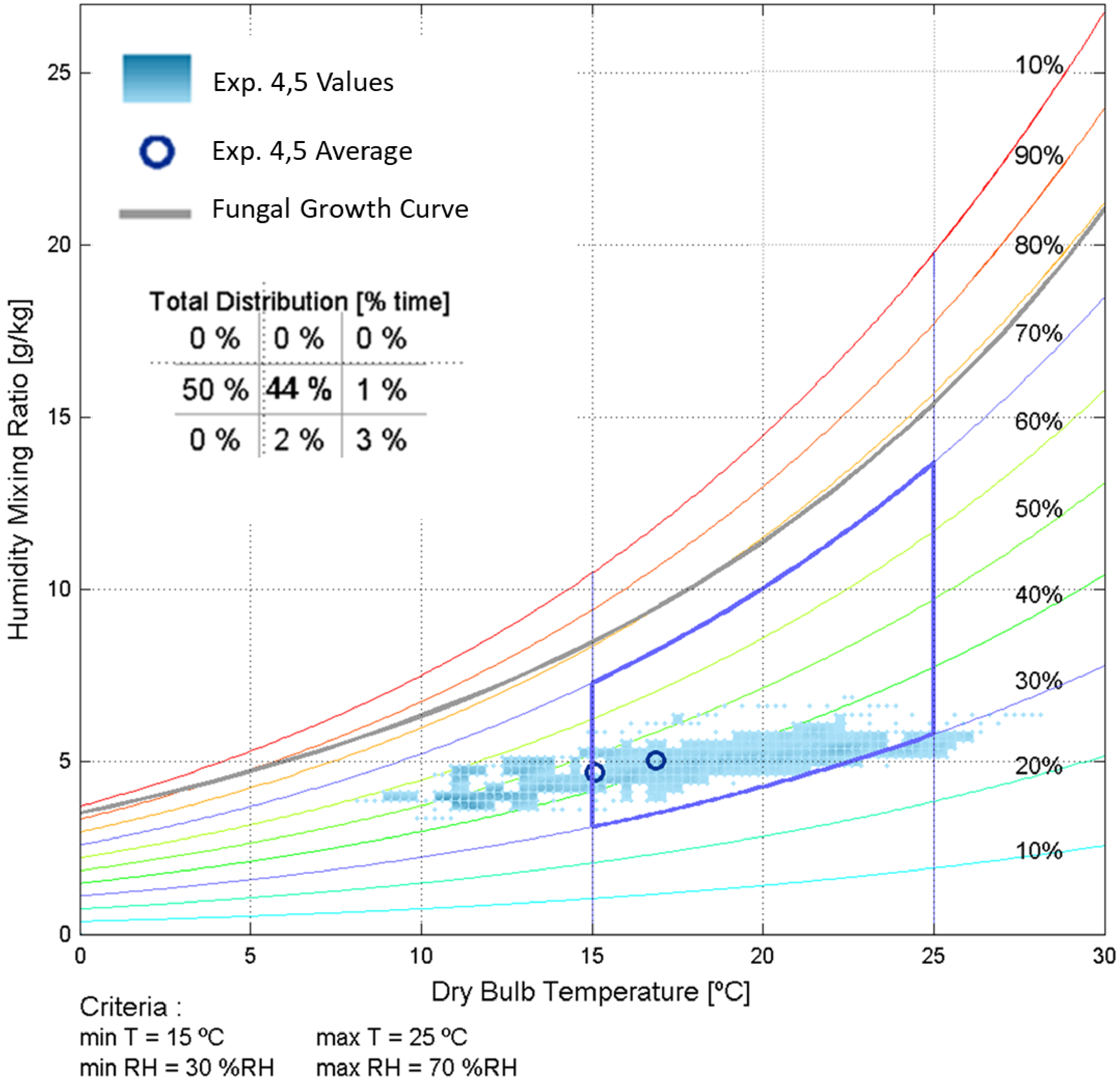


Figure 85: Climate Evaluation Chart showing RH and temp data for Experiments 4 & 5 (Monday before 12:00 and Friday after 12:00 removed).

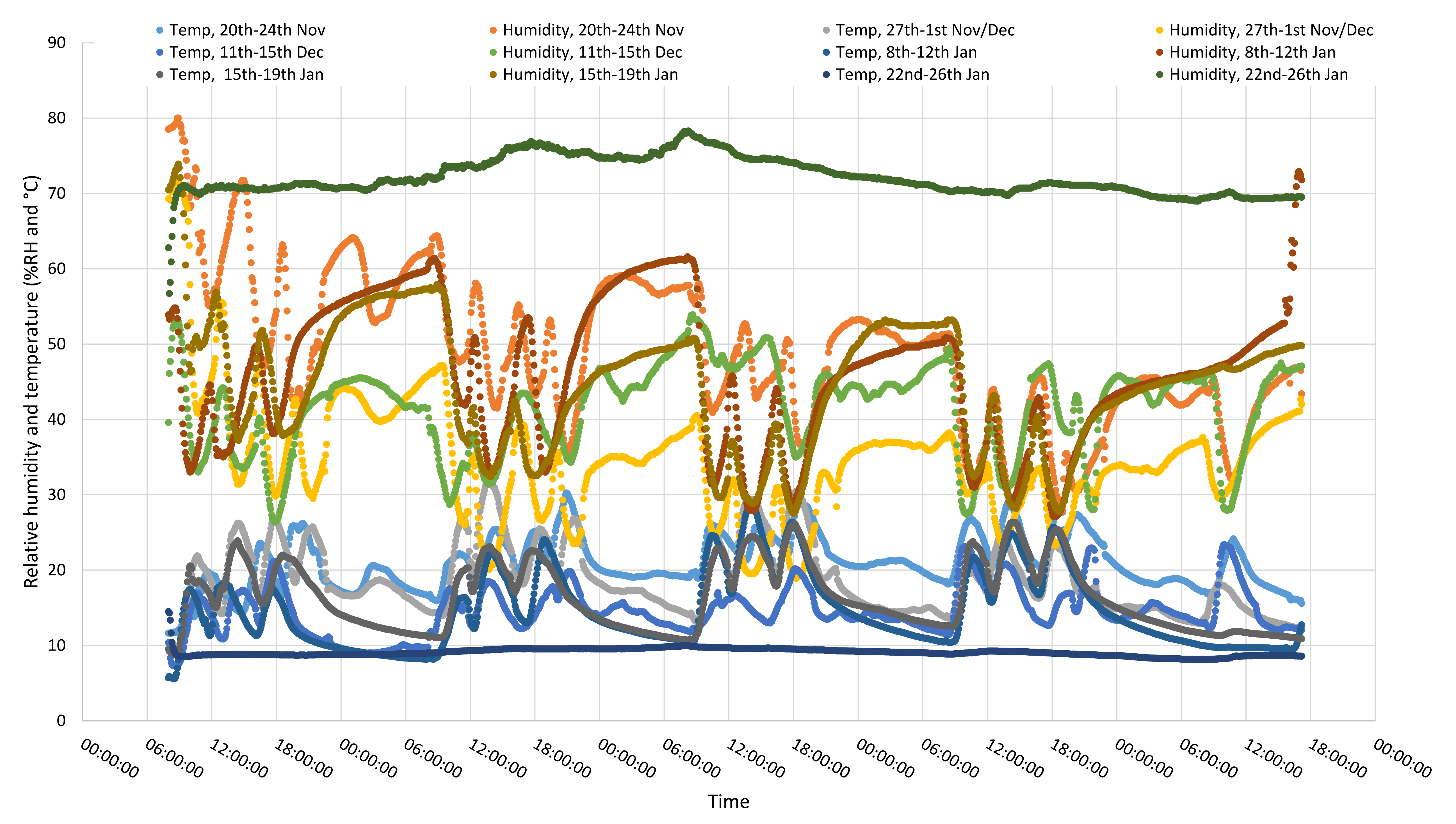


Figure 86, Environmental conditions recorded from room centre during all experiments

Visualising humidity

As a means of visualising the relative humidity within the room, three dimensional graphs that use a colour scale have been devised utilising MATlab to plot and calculate infill values between recorded datapoints (Figure 87). To make two dimensional viewing simpler several cross sections have been produced: frontal, lateral, and aerial (Figure 88-Figure 111). These create an 'isotherm' style layout, but with a higher degree of visual clarity.

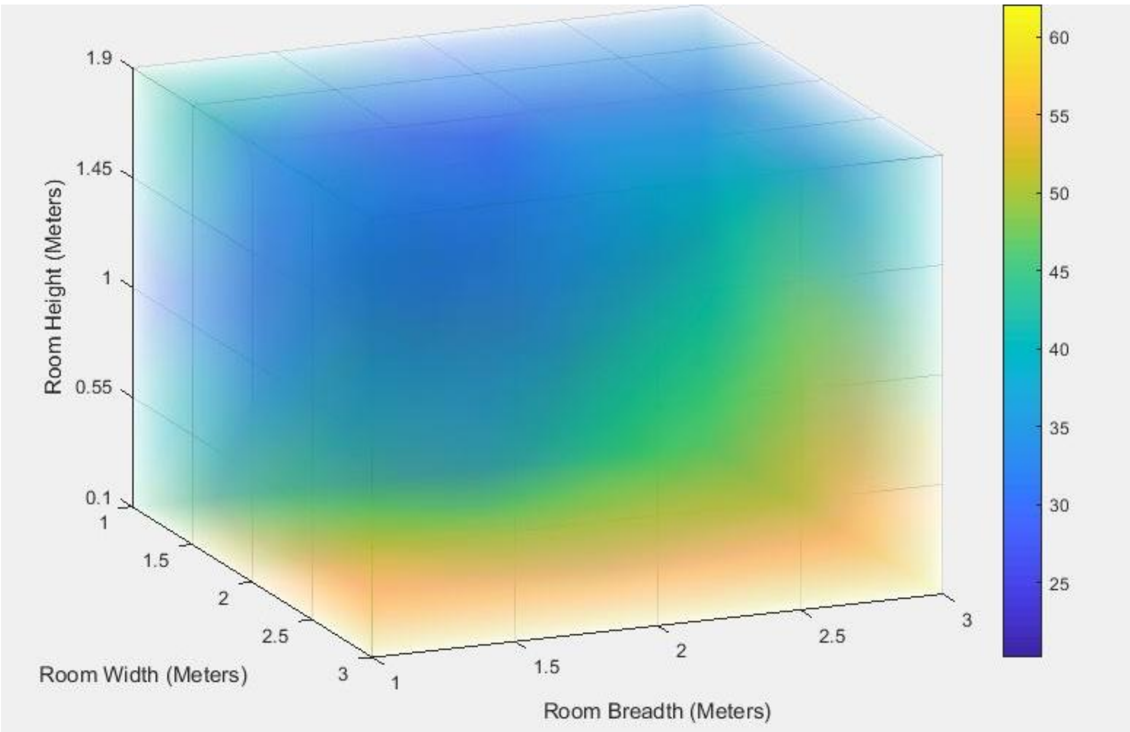


Figure 87: 3D interpretation of RH in Rhyd-y-Car No.6 at 22:00 21/11/2017, Experiment 1 (scale is different to later graphs)

The days used in the following graphs come from results typifying the fire performance and where no unforeseen events occurred whereby the fire was sluggish, nearly ceased to burn or did not bank in properly.

6.1.4 Banked in fires: relative humidity distribution cross sections

Figure 88 shows the distribution of RH within the room at the point where the fire is lit. The minimum RH in the room is 73%, and the majority of the area is above 75% into 80%. After the fire has been alight for half an hour, a pattern of heat directed upwards to the ceiling and outwards in a semi sphere 2.4 meters from it is visible, but not pronounced. Ingress of humid air from under the front door may also be seen in the lateral cross section (middle).

By 10am Figure 89 shows that a 2.4m hemi-sphere from the fireplace has attained a 50-60% RH range, the frontal cross section (right) showing the higher RH towards the back of the room, related to gaps around the front door. Re-fuelling of the fire has caused a dip in radiant intensity, as the new coal blocks the radiant heat. The walls at lower than air temperature, the radiant heat sphere from the fire is very noticeably concentrated centrally in the room and that later on when the building has acclimatised and the fabric reached a higher temperature, the lower RH air stratifies to the top of the room, partly due to warmer air rising, and partly to the radiant heat hitting the ceiling from the fire.

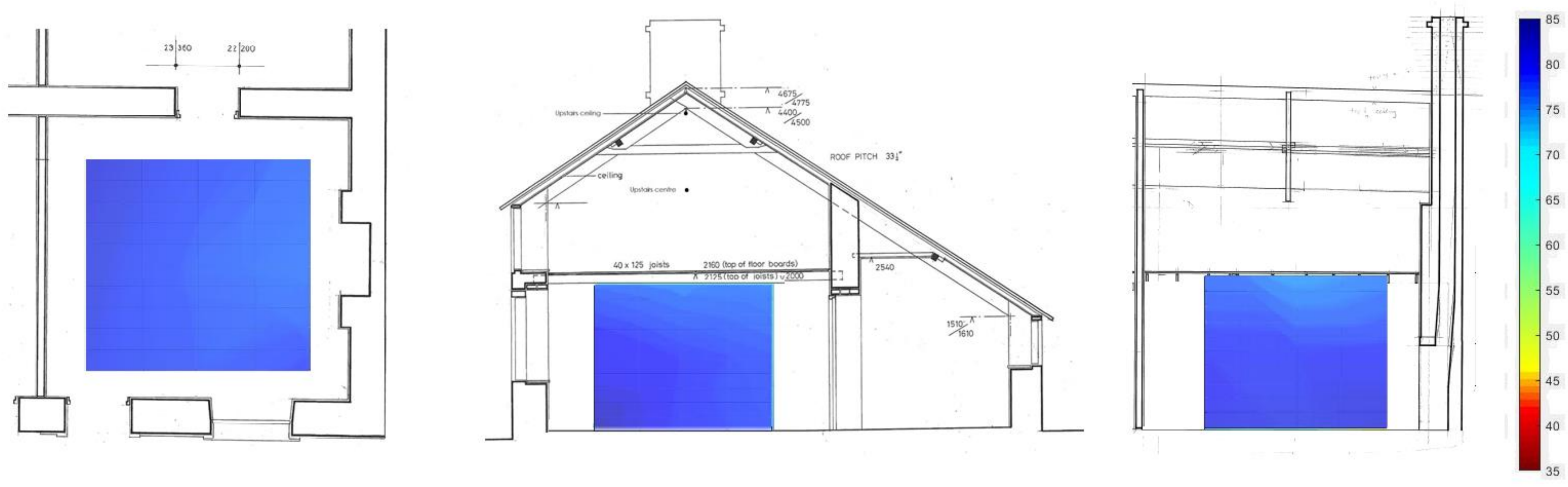


Figure 88: Cross-sectional image of RH distribution at 8AM 20/11/17 Experiment 1 Banked fire.

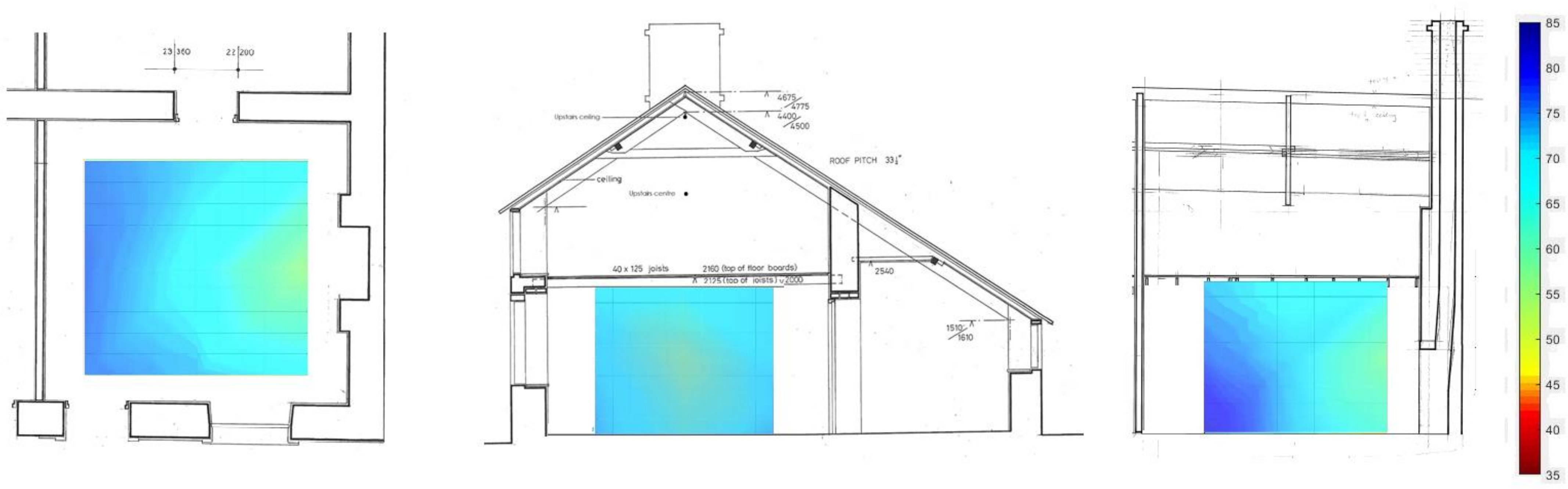


Figure 89: Cross-sectional image of RH distribution at 10AM 20/11/17, Experiment 1 Banked fire.

There is a lower RH on the ceiling area, which by mid-day (Figure 90) has re-emerged. Mid-day represents a trough for RH with a low around 40%RH +/-10 within 1.5m of the fire, and the ceiling sits at 50%RH +/-10. This time stamp is shortly after the peak for fire output, as may be seen by logger data of B3 (in front of the fire) reaching 30 °C at 11:00. At 14:00 (Figure 91) shortly after re-fuelling has caused the radiant heat output from the fire to dip, the overall RH of the room has increased. This is a good indication that the fabric of the building takes many hours to reach a level temperature, and a related length of time for any water vapour present in the materials to be reduced by that increase in temperature. Other lower RH areas are clearly due to air ingress, and this appears to travel across the bottom of the floor towards the fireplace.

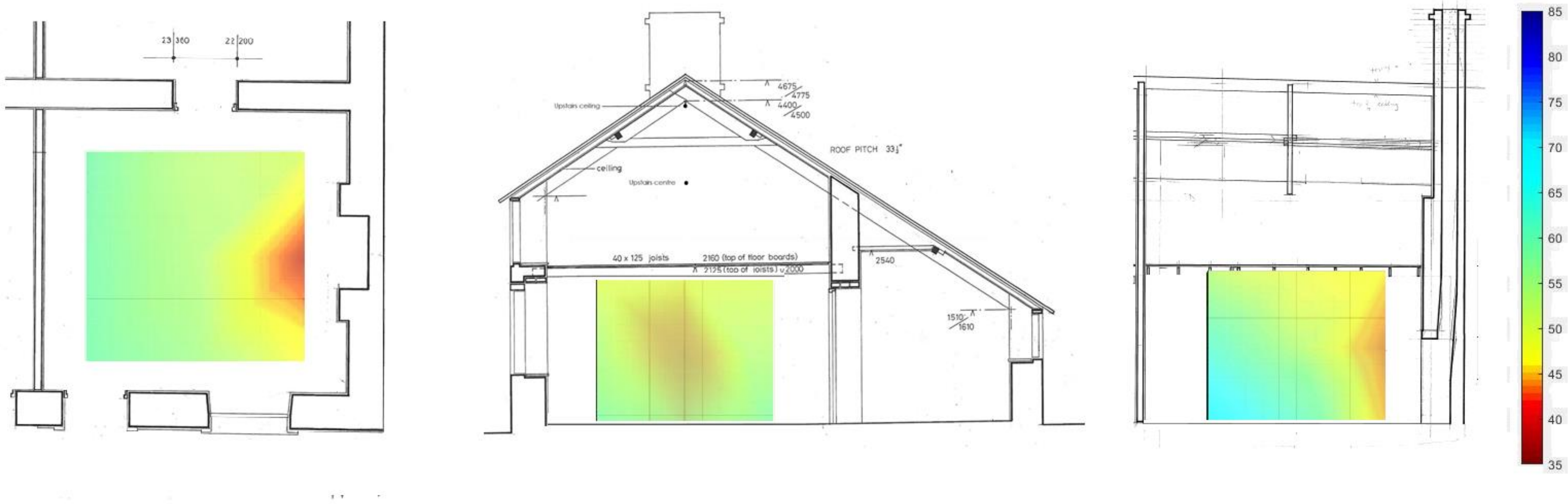


Figure 90: Cross-sectional image of RH distribution at 12:00 20/11/17 Experiment 1 Banked fire.

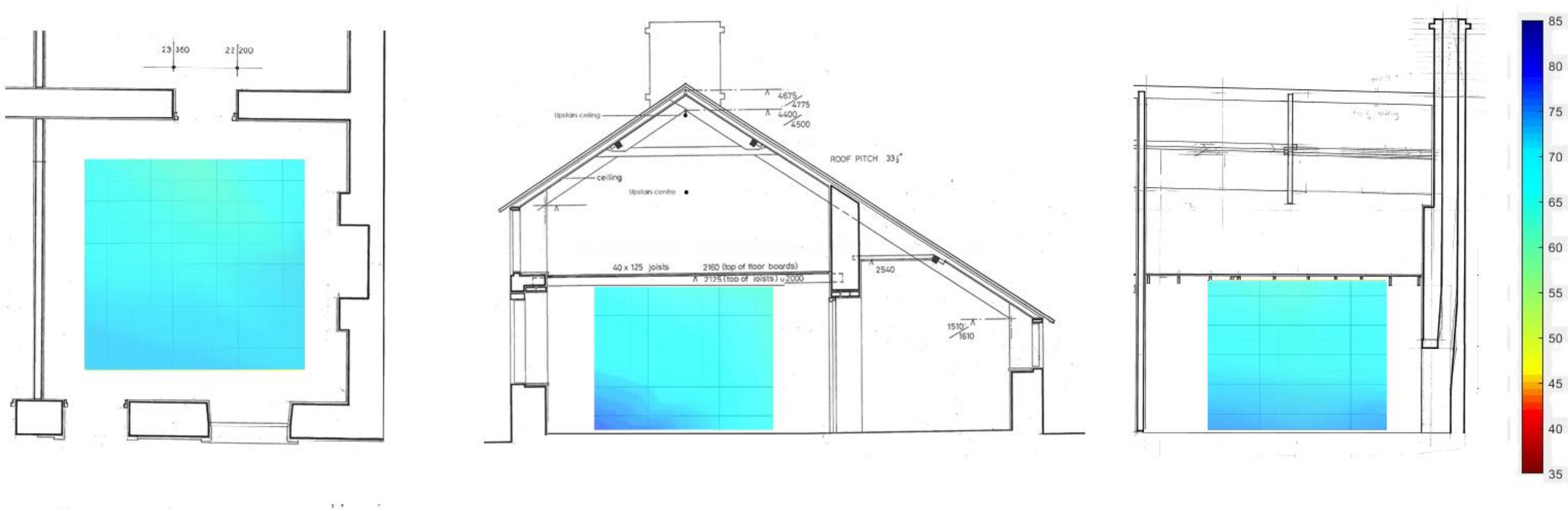


Figure 91: Cross-sectional image of RH distribution at 14:00 20/11/17 Experiment 1 Banked fire.

At 16:00 (Figure 92), after the fuel has been burning at a steady rate, the building fabric temperature is likely to still be low and possibly retains a high water vapour content. This is shown by the quick return of blue areas two hours later at 18.00 (Figure 93). An area of more humid air between the ceiling and a hemi-sphere of lower RH immediately before the fire are also visible.

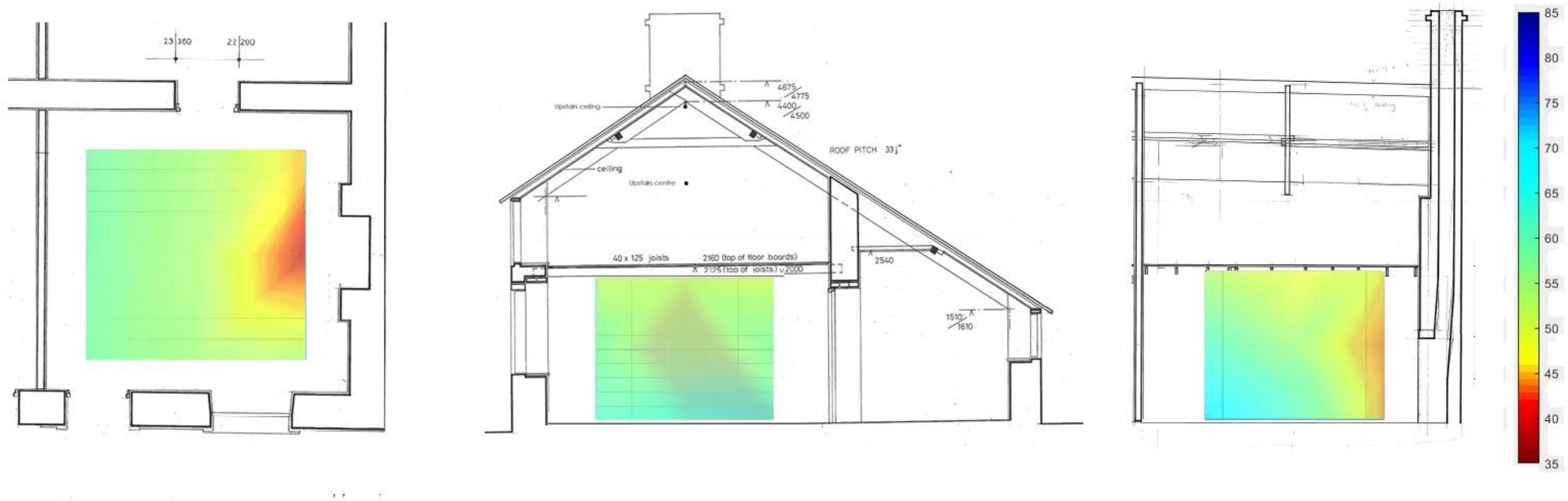


Figure 92: Cross-sectional image of RH distribution at 16:00 20/11/17 Experiment 1 Banked fire.

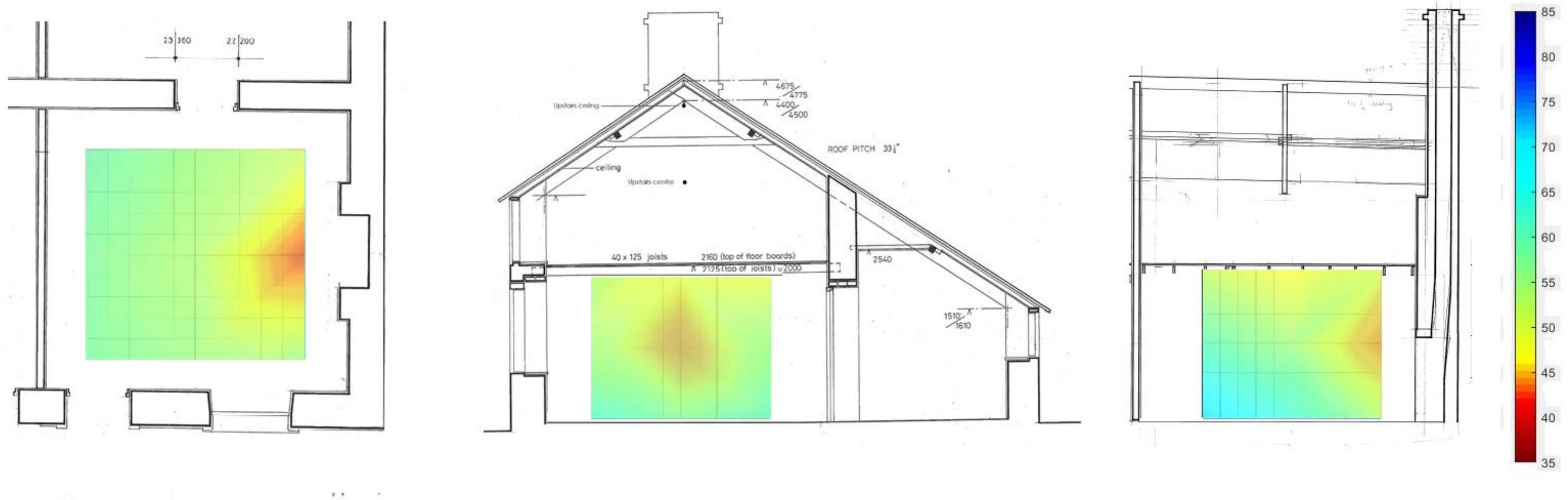


Figure 93: Cross-sectional image of RH distribution at 18:00 20/11/17 Experiment 1 Banked fire.

Figure 94 shows a peak in fire output for the day at 20:00, with the temperature and RH at logger B3 (Figure 68 and Figure 69) being 32°C and RH 30%. Red low RH areas (35-45%) are clearly visible directly in front of the fire and across the ceiling. Whilst earlier, the low RH areas seemed to come out of the fireplace in hemi-sphere, now the lower RH seems to be more of a half-hourglass shape (split down the middle), slightly narrower at the bottom. There are a wide range of RH values in the room, with some areas down to 35%RH whilst others over 65%.

Figure 95 shows the RH in the room at 22:00 which is the time the fire was banked in. Overall, the area encompassing lower RH extremes has reduced, and a higher portion of the area of the room is at a lower RH, the values being more evenly spread, the majority of the room being between 55%RH and 65%RH. The floor has returned to being the higher RH area, whereas at the peak output in Figure 94, it was the central sides of the room that offered the higher RH.

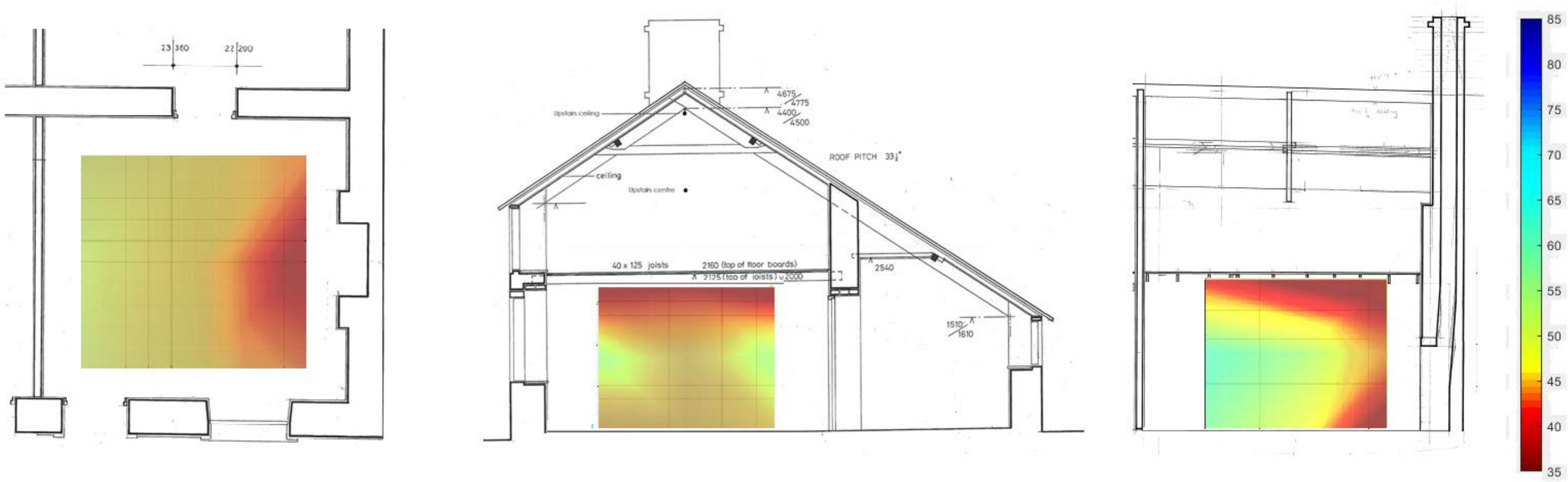


Figure 94: Cross-sectional image of RH distribution at 20:00 20/11/17 Experiment 1 Banked fire.

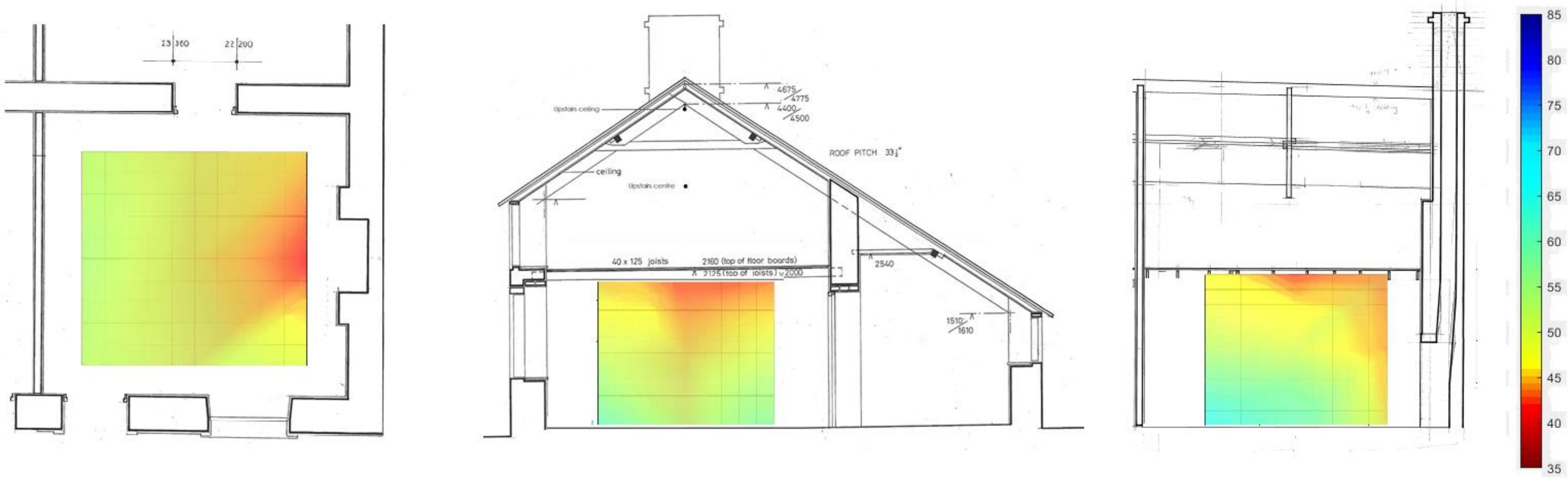


Figure 95: Cross-sectional image of RH distribution at 22:00 20/11/17 Experiment 1 Banked fire.

Figure 96 perhaps illustrates more clearly than the other three dimensional diagrams how the radiant heat has created low RH areas directly, whilst not wholly drying out the fabric of the building. It shows the environment 4 hours after the highest daily peak, revealing the lowest RH at mid-night is 47% RH near the ceiling, and 74%RH at its highest near the floor.

Figure 97 shows the environment at 02:00 has a lower RH zone around the fireplace and ceiling. The combustion of the fire is higher than at midnight and results in this lower RH, but that RH is higher around the floor as external air is drawn into the room.

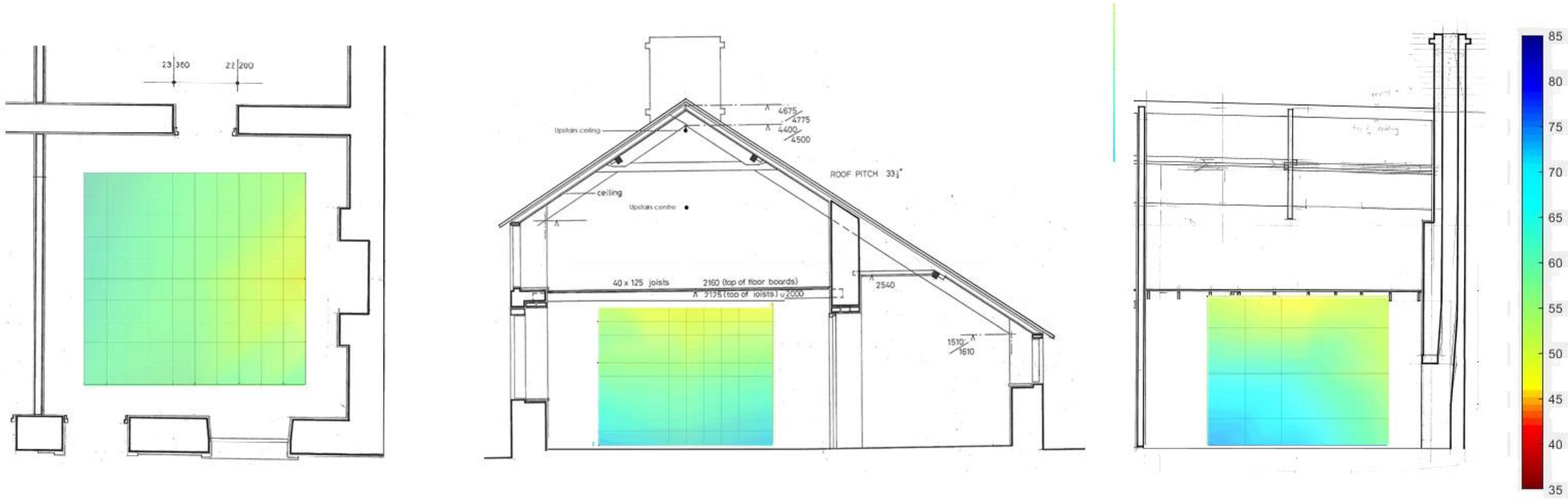


Figure 96: Cross-sectional image of RH distribution at 24:00 20/11/17 Experiment 1 Banked fire.

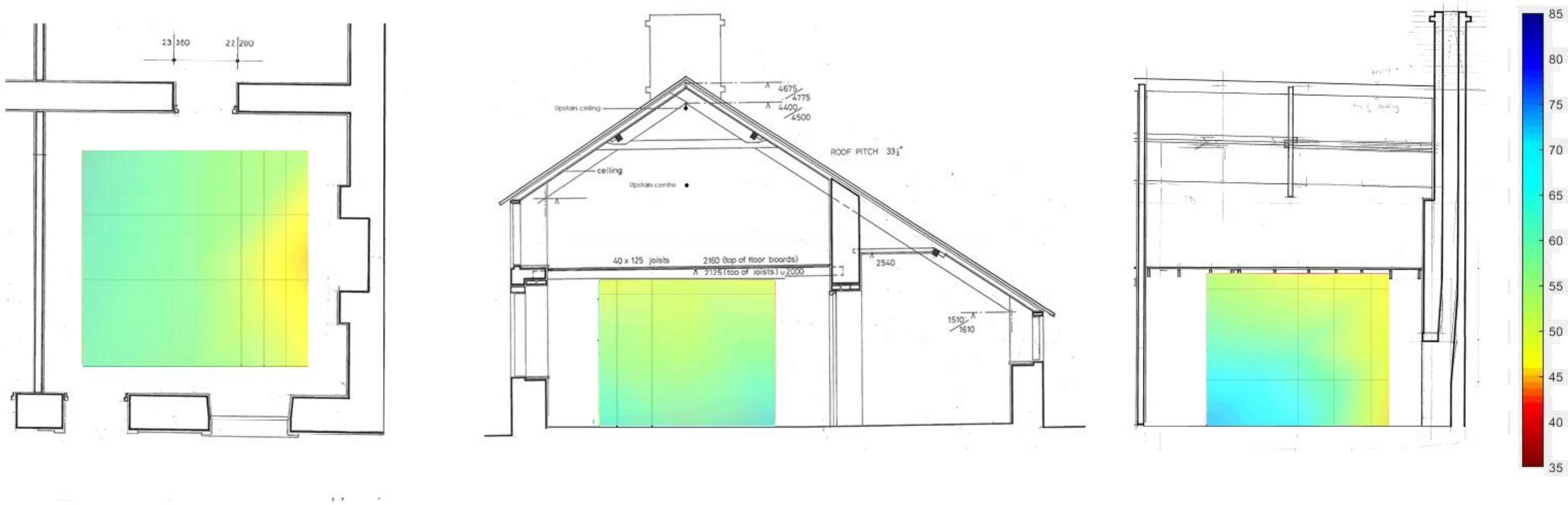


Figure 97: Cross-sectional image of RH distribution at 02:00 21/11/17 Experiment 1 Banked fire.

Figure 98 shows the RH at 04.00 on day 2 (21/11/17) when the banked in fire has started to combust at a higher rate and the room is now at a lower RH. Across the whole room RH is between 45% and 55%. The lower RH areas are near the ceiling and fireplace, the highest RH area is around the floor on the far wall opposite the fire, where the air is likely to be coolest.

Figure 99 at 6:00 shows a room sitting at 55%RH to 65%RH. The fire is very low at this point and cannot compensate for the ingress of higher RH air it induces under the front door to the same extent as it was earlier. This is the state of the environment in the room an hour before the cleaners might arrive in a working scenario to replenish it. It is a fairly dry environment, however the low level of fire combustion has drawn in external air. This low level of combustion cannot compensate for the intake of new air, and the overall RH does rise over the night, rather than stay constant or reduce.

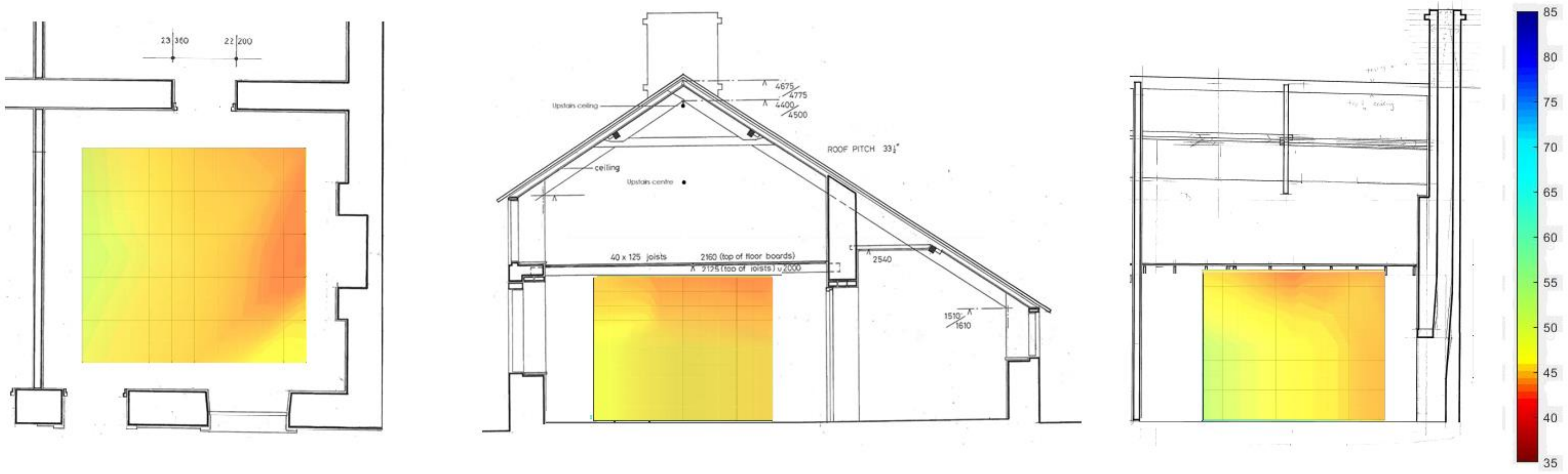


Figure 98: Cross-sectional image of RH distribution at 04:00 21/11/17 Experiment 1 Banked fire.

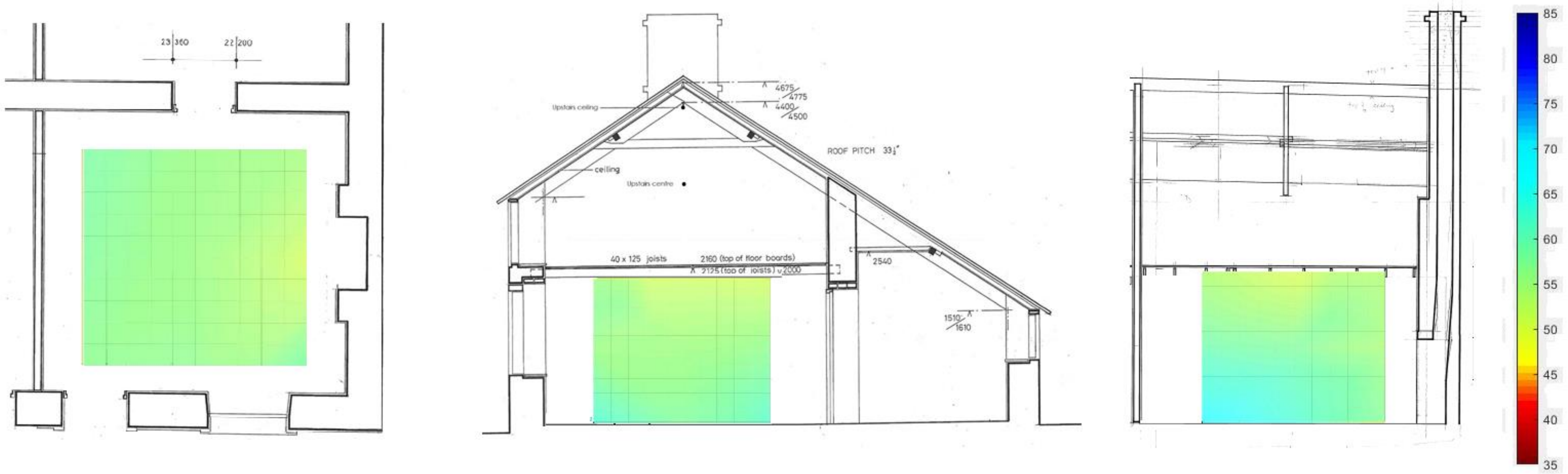


Figure 99: Cross-sectional image of RH distribution at 06:00 21/11/17 Experiment 1 Banked fire.

6.1.5 Daily fires: Experiments 4 and 5

Figure 100 shows the RH distribution in the room as the fire is lit. A lowest RH zone is apparent at the ceiling and near the floor, centrally to the room (60-50%RH). The highest RH area is toward to front door, opening onto the street. The general RH appears to sit around 70%.

Figure 101 showing the fire as it is starting to build up to a peak, but the thermal mass of the building is still cold, as is the air. There is a much lower RH zone within a radius of 2.5m from the fireplace. The radiant heat is concentrated centrally from the fire. Low RH areas and again concentrated around the front door. Zones are apparent in the middle of the room with higher RH levels.

Figure 100: Cross-sectional image of RH distribution at 08:00 15/01/18 Experiment 5 Daily fire.

Figure 101: Cross-sectional image of RH distribution at 10:00 15/01/18 Experiment 5 Daily fire.

At mid-day Figure 102 repeats this pattern, yet with more extreme low RH levels. Most of the room is under 45% RH, much of it is under 35%. Around the front door RH is under 50%RH and a small slither of higher RH 60-65%RH occurs at the very bottom. Figure 103 is six hours into a burn cycle and shows how a well burning fire can produce very low RH levels which encompass anywhere its radiant heat can reach. A small amount of higher RH air is still apparent at floor level, this is likely the external air from under the door being drawn in by the fire to feed its burn.

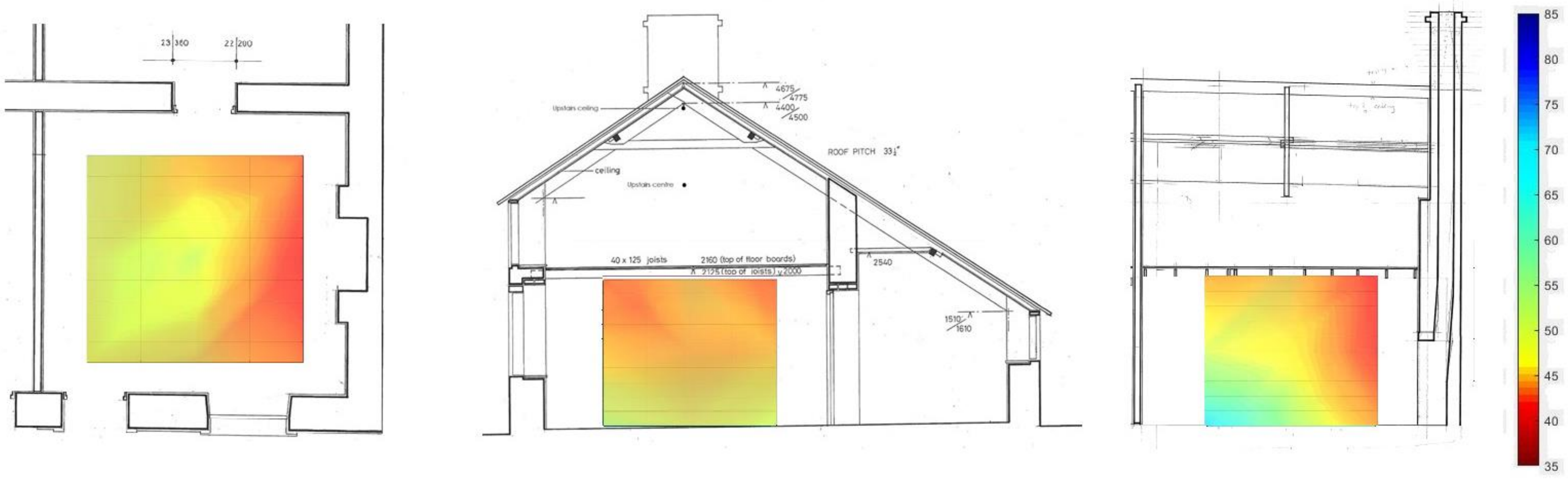


Figure 102: Cross-sectional image of RH distribution at 12:00 15/1/18 Experiment 5 Daily fire.

Figure 103: Cross-sectional image of RH distribution at 14:00 15/1/18 Experiment 5 Daily fire.

Figure 104 and Figure 105 show the fire after eight and ten hours of burning. The fire is refuelled at 16:00 causing a peak at 18:00. This therefore should be seen in an RH rise in Figure 104 and a dip in Figure 105. However, this is not obvious, and the room appears to continue with the low RH levels seen previously. This could be seen as a result of the heat being built up in the building fabric from the high burn point at mid-day contributing to heat output that influences RH values through to the evening. The majority of the room is under 40%RH, with some higher RH levels visible near the door.

Figure 104: Cross-sectional image of RH distribution at 16:00 15/1/18 Experiment 5 Daily fire.

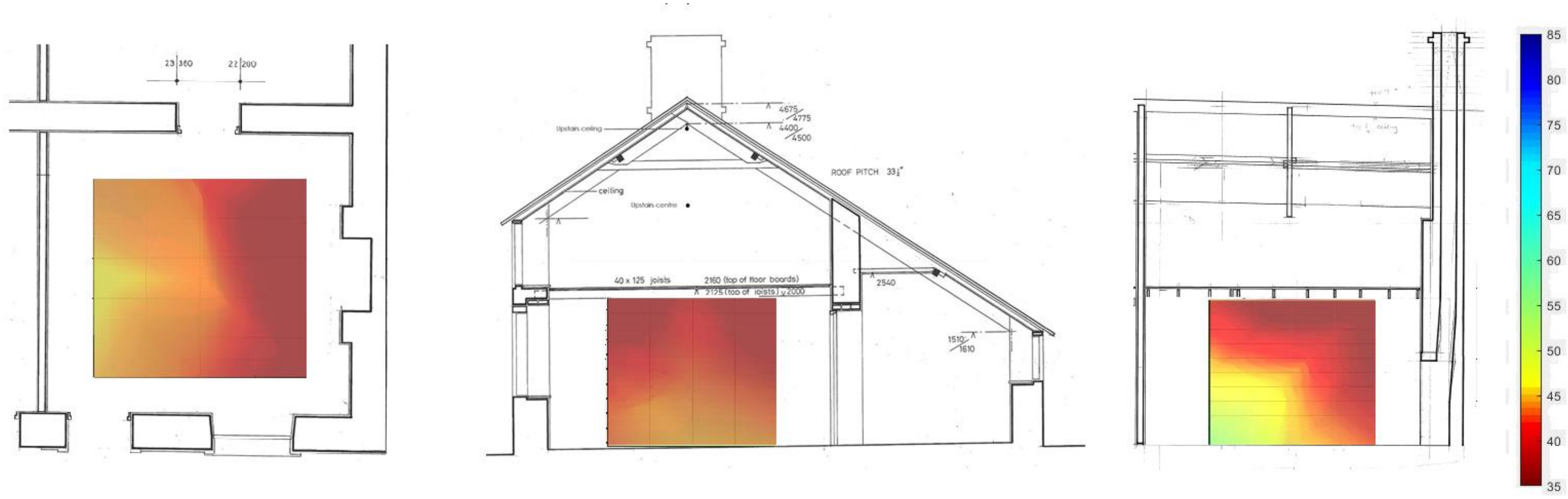


Figure 105: Cross-sectional image of RH distribution at 18:00 15/1/18 Experiment 5 Daily fire.

Figure 106 shows the room with the fire still burning, but after its last refuelling. The pattern is much the same as in Figure 104 and Figure 105, with the only slightly higher RH area being towards the front door.

Figure 107 shows the room as the fire begins to die down. The room is predominantly under 50%RH, and only a small potion sits around 55%RH. The top of the room shows the lowest RH areas, at under 45%RH. The usual sphere of lower RH in front of the fire is not so obviously present and is skewed to one side, which may be an impact from uneven burning of fuel in the grate.

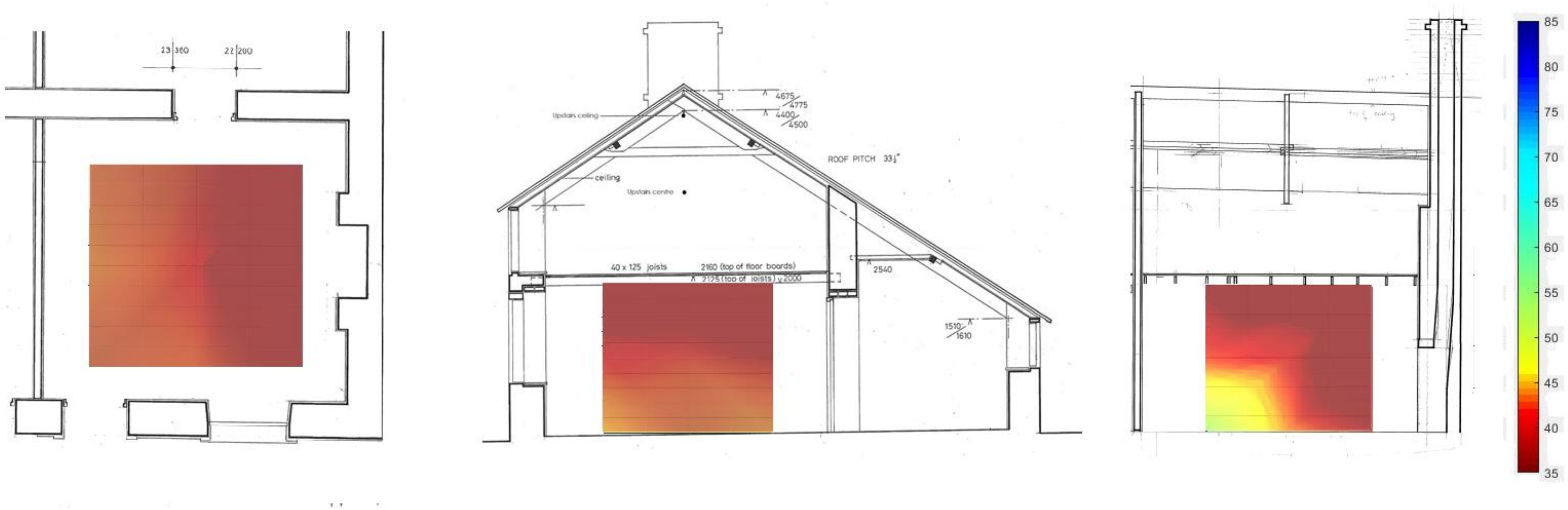


Figure 106: Cross-sectional image of RH distribution at 20:00 15/1/18 Experiment 5 Daily fire.

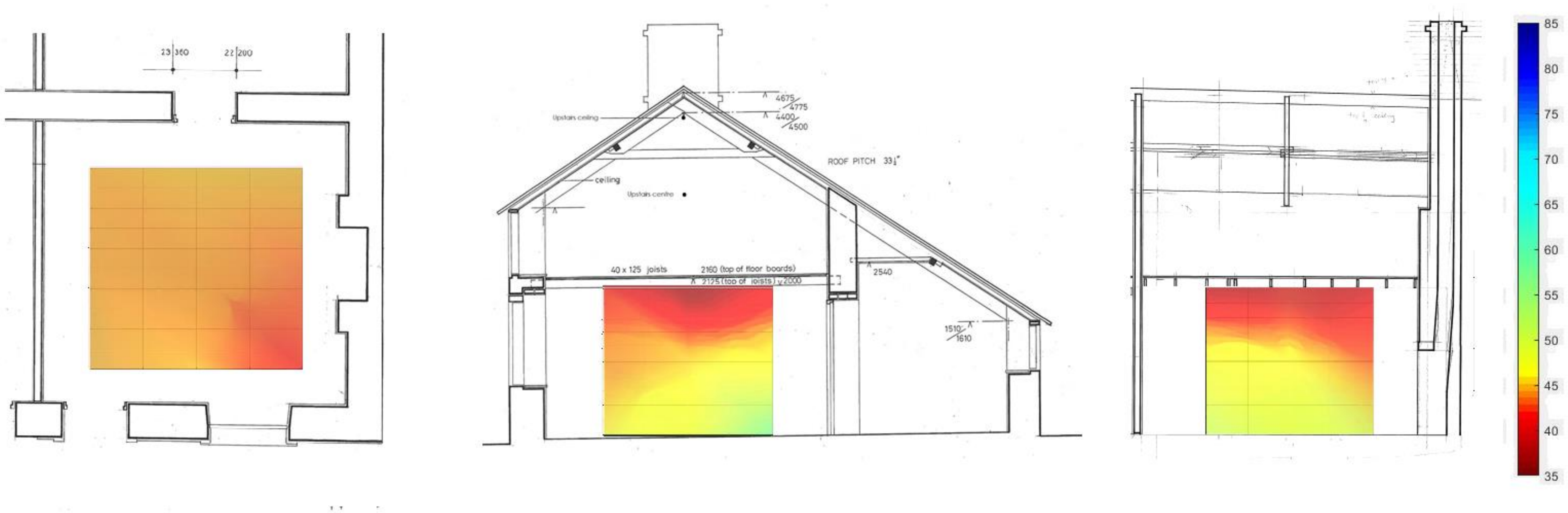


Figure 107: Cross-sectional image of RH distribution at 22:00 15/1/18 Experiment 5 Daily fire.

Figure 108 shows the RH in the room as the fire is at its last dying embers. Low RH zone concentrates at the ceiling centre. The majority of the room sits under 55% RH, the rear of the room has higher RH levels at 65% to 70%.

At 02:00 (Figure 109) the room shows a more even RH distribution, the ceiling is no longer showing a under 45% RH zone at its centre, almost all of the room is between 45%RH and 55%RH. Compared to Figure 108 the lower part of the room now is at a lower RH than earlier, despite the fire going out.

Figure 108 and Figure 109 show little to no change in the environmental conditions between midnight and 02:00 in regard to RH. This is likely related to the fire being out and not drawing external air to the same extent.

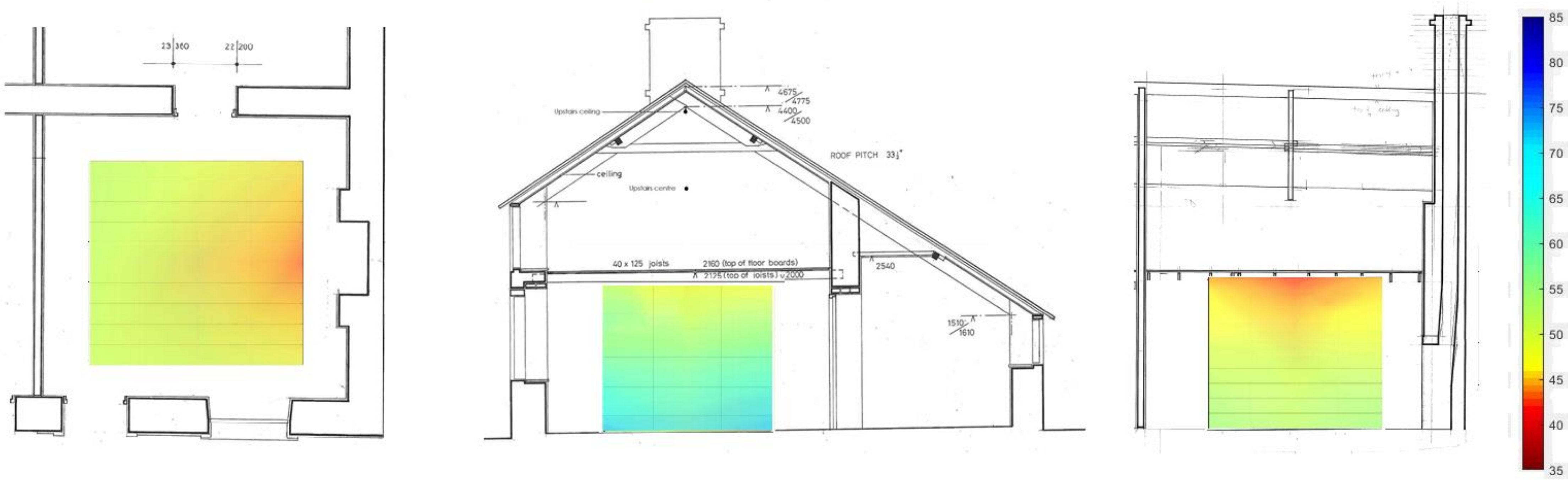


Figure 108: Cross-sectional image of RH distribution at 24:00 15/1/18 Experiment 5 Daily fire.

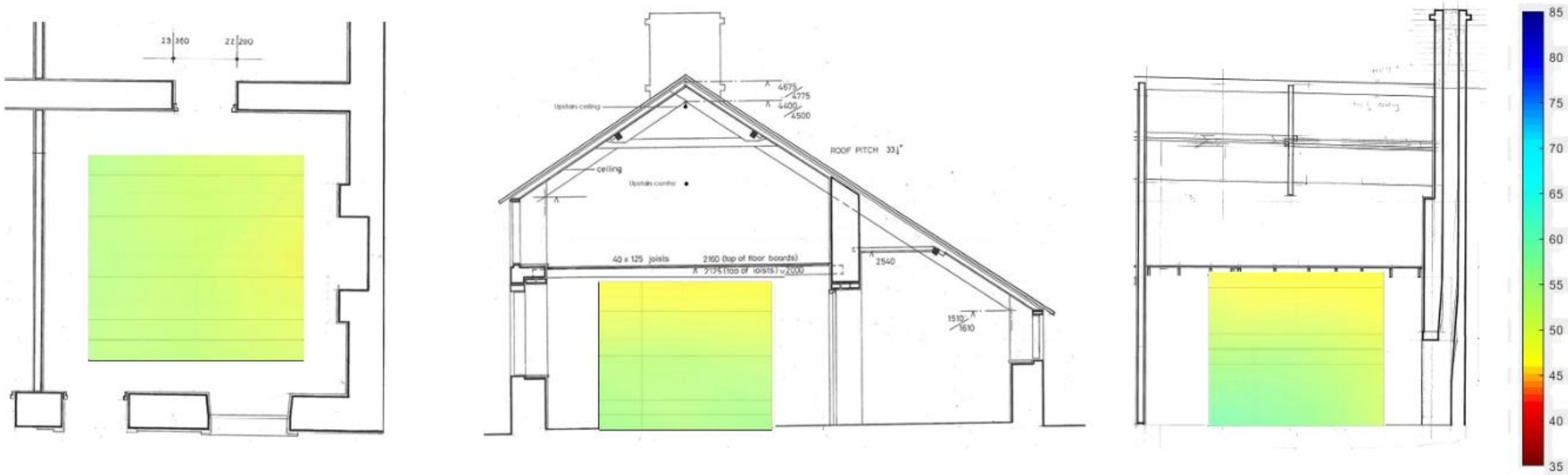


Figure 109: Cross-sectional image of RH distribution at 02:00 16/1/18 Experiment 5 Daily fire .

Figure 110 and Figure 111 show the environment in the room at 04.00 and 06.00. There is very little difference between the two, and the fire has been out for around four to six hours. The residual heat in the thermal mass of the room has maintaiend an even and dry atmosphere of between 50%RH and 60%RH. It is likely that with the fire out, less air is drawn into the room and high levels of residual heat in the thermal mass maintain an even atmosphere.

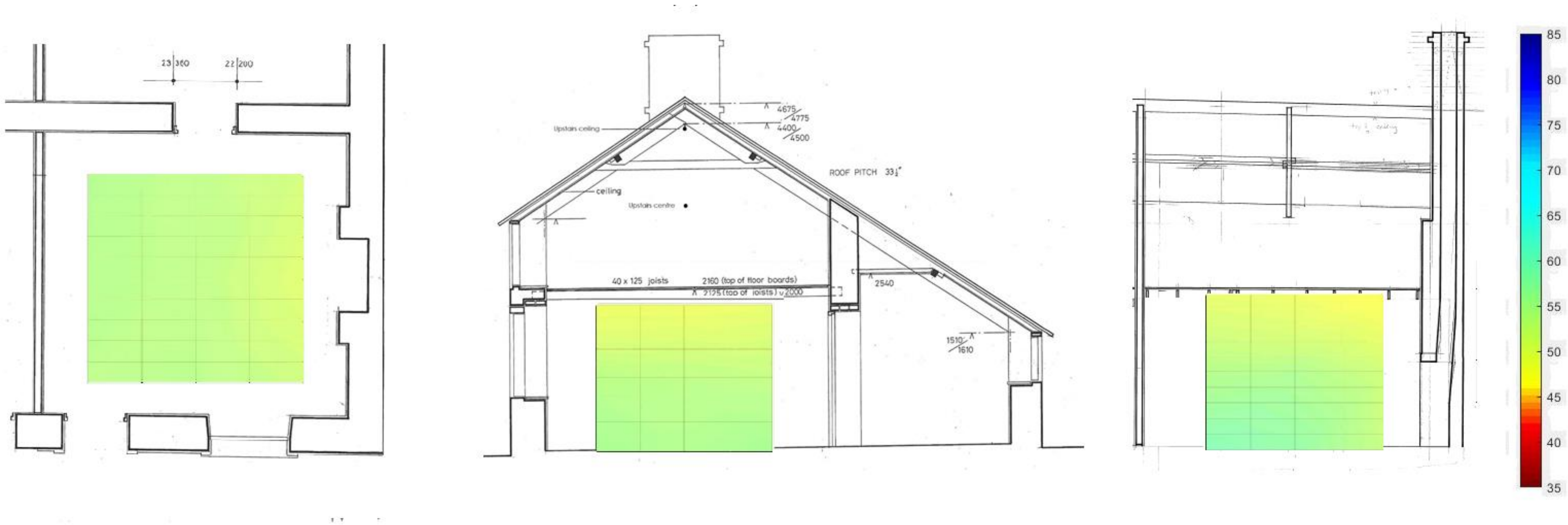


Figure 110: Cross-sectional image of RH distribution at 04:00 16/1/18 Experiment 5 Daily fire.

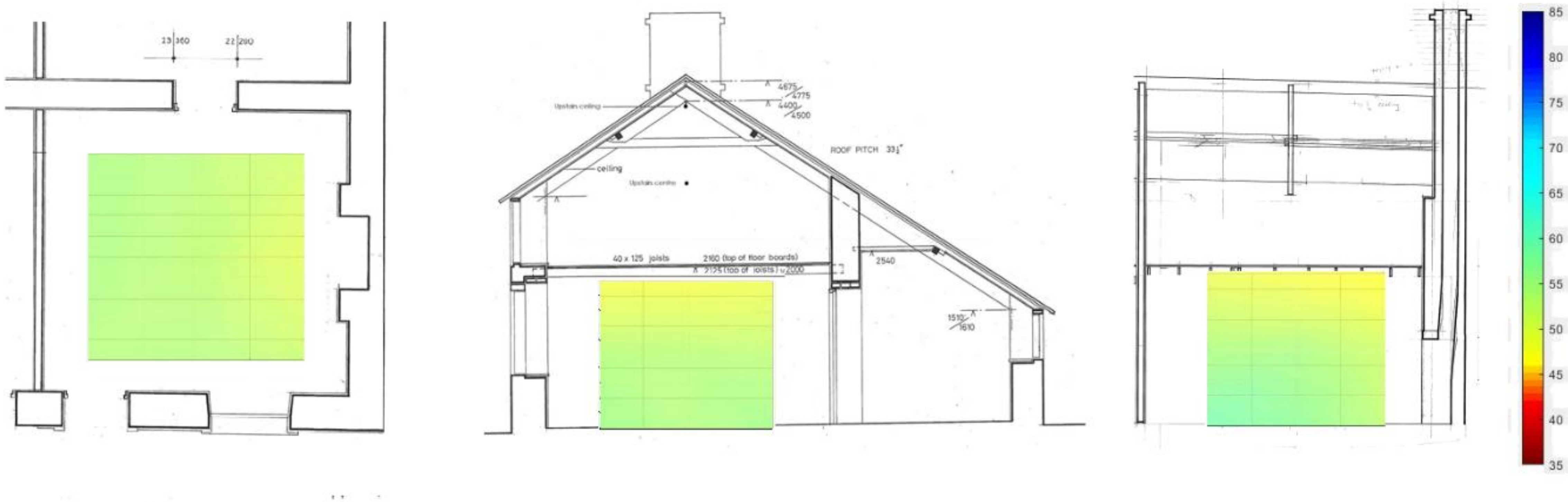


Figure 111: Cross-sectional image of RH distribution at 06:00 16/1/18 Experiment 5 Daily fire.

Refuelling impact on heat output, temperature and humidity

6.1.6 Time lapse photography, banked in fire

Time-lapse photography recorded the condition of the fire during experiments (e.g. Figure 112 to Figure 125) and can be related to the environmental data (Figure 126 to Figure 130), including heat output of the chimney breast and room temperature.

Figure 112: 22:40 The fire before being poked and riddled.

Figure 113: 22:50 The fire ready for refuelling.

Figure 114: 23:00 Fire being banked in, ashes being applied.

Figure 115: 23:10 Fire banked and guard in place.

Figure 116: 24:00 Banked fire in slow combustion.

Figure 117: 01:00 Banked fire in slow combustion.

Figure 118: 02:00 Banked fire in slow combustion.

Figure 119: 03:00 Visible combustion through firebars.

Figure 120: 04:00 More visible combustion and flames from combustion of volatile gasses to left.

Figure 121: 05:00 Ashes are falling away as fire moves, combustion visible.

Figure 122: 06:00 Higher combustion levels, more volatile gasses being produced and burning.

Figure 123: 07:00 Most gasses burnt off, glowing coals.

Figure 124: 08:00 Due to lack of oxygen from clogged grate fire has reduced in size. The burning off of volatile gasses has meant that a higher oxygen ration is required for the purer form of carbon remaining.

Figure 125: 08:20 Ashes pocked through and air induced through fuel bed by newspaper over opening.

6.1.7 Experiment 1: continuous fire burning energy output

The energy output from the fire is examined in this section, relative to the burn cycles of the fire and both internal and external temperature. The calculations for Wattage are provided in Chapter 7 Section 5 and relate to the building fabric and its capacity to absorb and emit heat. This data is included here to complete the understanding of how the fire and its outcomes influence the environment in the room.

Figure 126 shows Experiment 1, a banked in experiment. The initial external temperature before lighting the fire is the air temperature in the house and a daily pattern quickly emerges. The temperature of the chimney breast and heat output from the chimney breast increase with every fuelling of the fire. An initial dip as new fuel is added is later offset by a large peak in heat output, reflected in the delay in heat output from the chimney influencing the heat output into the room measured as internal air temperature. The thermal mass of the chimney and its 14.8 KW/h (see calculations in Chapter 7.5.2) heat capacity does not mitigate a great deal against its response to the heat output of the fireplace. It is also clear that outside temperature has a significant impact of the internal environment. The high thermal mass of the structure is not effective at compensating for the poor U-value of the building fabric, as is clear from the strong mirroring of the inside temperature to the outside temperature before the fire is lit.

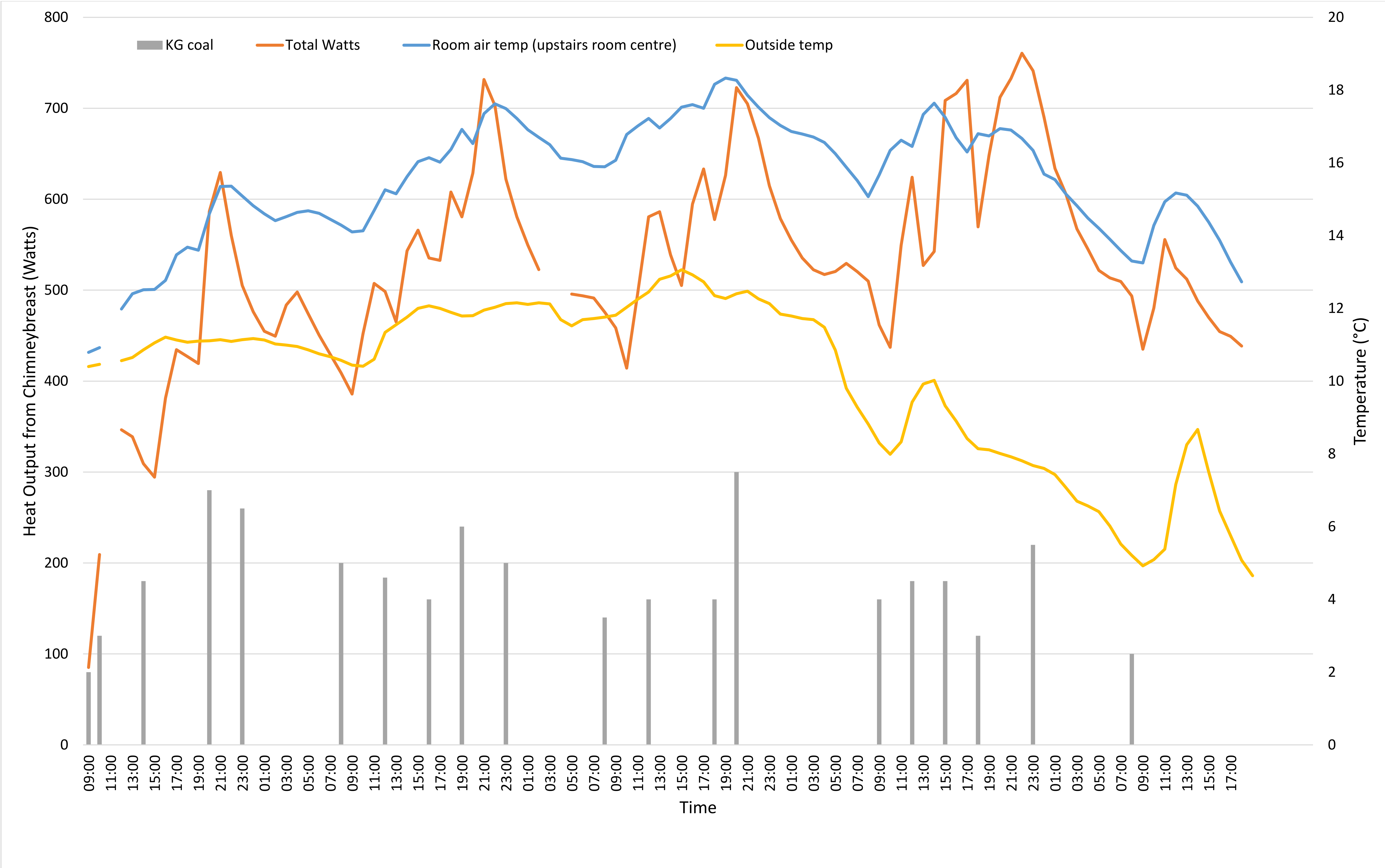


Figure 126: Watts output from chimney breast against room air temperature, outside temperature and coal consumption for Experiment 1, banked in fire.

6.1.8 Experiment 2: banked in fire

Figure 127 shows Experiment 2 overall displays the same patterns and trends as Experiment 1, the external temperature is much lower than the previous week. The internal air temperature is correspondingly lower, which increases the heat transfer rate from the chimney breast into the room, which provides a higher chimney breast heat output than the previous week. The external RH is broadly similar to Experiment 1 (85-90%RH for both), but slightly lower than internal RH. It is possible that this decrease in internal RH is due to the lower external temperature, which when heated leads to a larger drop in RH than Week 1, which had the same RH but a higher temperature (and therefore held more moisture). It could also be that residual parts of the building fabric are losing stored water vapour slowly over a longer period of time due to the continual heating.

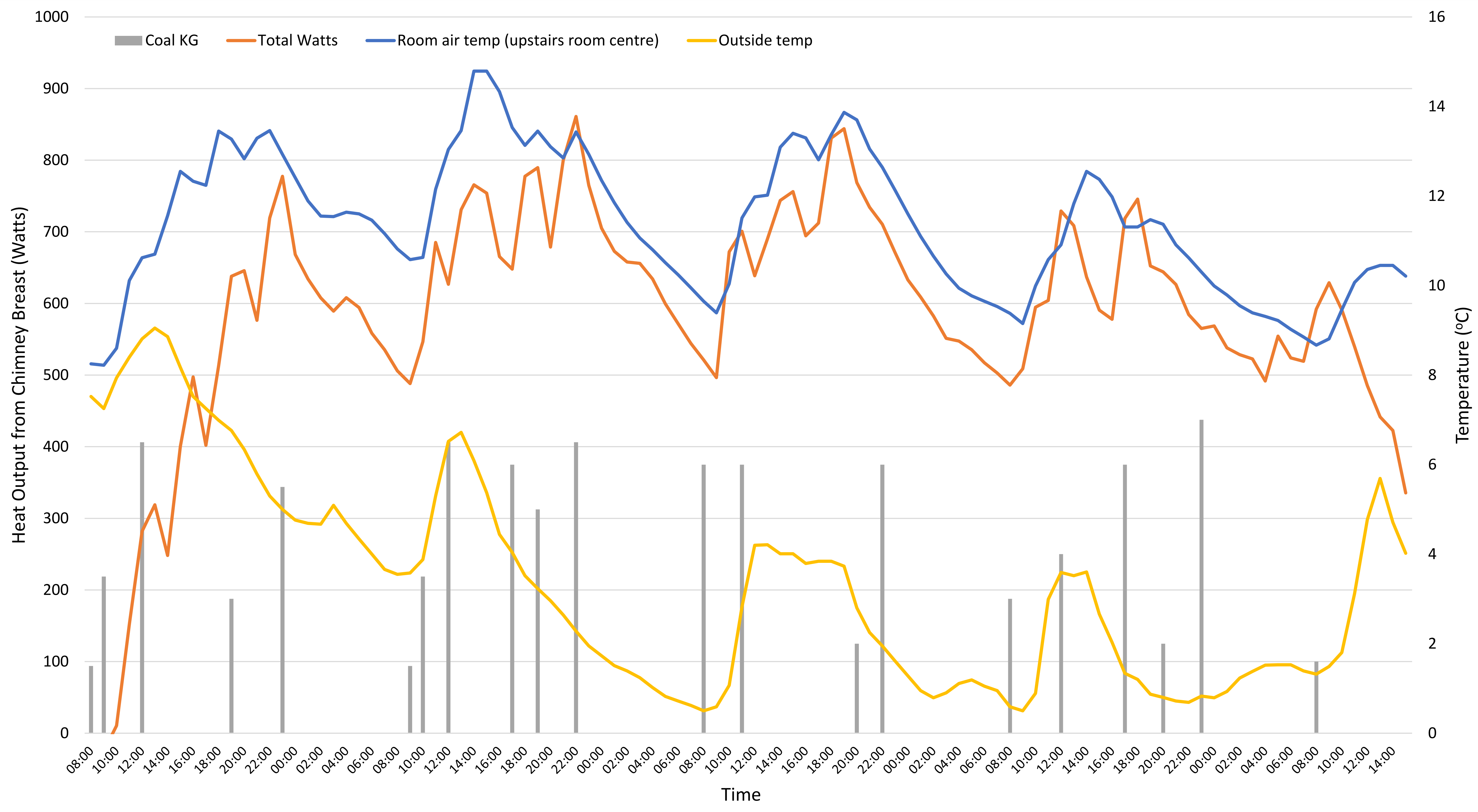


Figure 127: Watts output from chimney breast against room air temperature, outside temperature and coal consumption. Experiment 2, banked in fire.

6.1.9 Experiment 3: banked in fire

An initial start to the week sees in Figure 128 a repetition of trends and patterns in Figure 126 and Figure 127, however, the second overnight fire is not a success and the fire fails to recover to the same degree as the previous weeks. Fuel consumption is lower, and smaller more frequent fuelling patterns result in a lower overall heat output. This reveals the unpredictability of fires. Following the same procedure may not result in the same burn pattern.

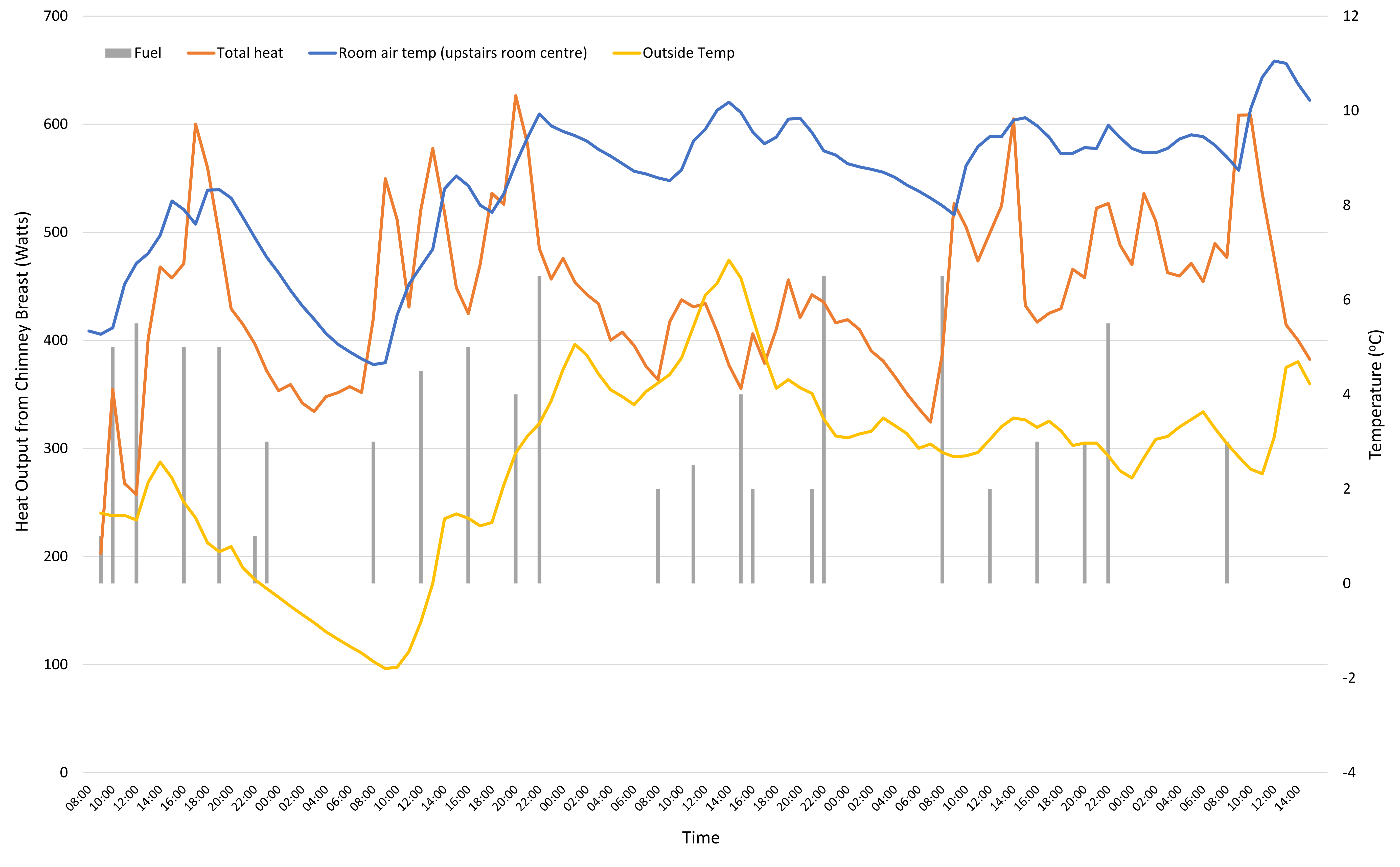


Figure 128: Watts output from chimney breast against room air temperature, outside temperature and coal consumption. Experiment 3, banked in fire.

6.1.10 Summary of banked in heating results

Whilst the chimney breast introduces a significant amount of heat to the building, its ability to store this for any prolonged length of time is limited. The chimney breast can remain warmer than the internal air temperature for 20 hours, but it responds very quickly to the heat output of the fire (a delay of less than 1 hour) (Figure 126 - Figure 128). It is difficult to quantify the impact of the banked in fire on the chimney breast temperature. Room air temperature is warmer with banked in fires, and heat output is correspondingly higher with lower indoor temperatures. Therefore on colder days, the stored heat output appears higher. The chimney temperature is likely to be warmer for longer due to the heat input continuing until later in the evening than a non-banked fire, but it seems to delay the cooling effect rather than mitigating it. There is some heat input and a spike in chimney temperature in the early hours of the morning, when sometimes the fire falls in on itself (Figure 121) and combusts more quickly, but the overall state of slow combustion does not provide enough warm air to heat the chimney. It does provide radiant heat to the room well into the early morning (Figure 122 - Figure 123).

6.1.11 Experiment 4: daily fires

Experiment 4 (Figure 129), shows the external temperature started at around 1^{o}C but reached a mid-week high of 7.34°C on the third day of the experiment, before dipping down to a low -0.8°C Friday morning. This dip in outside temperature corresponded with a period where no fire was running, as it was left to die out the previous evening and was not re-lit on Friday morning. It is interesting that there is an increase of internal temperature at 09.00 on Friday morning, as at this point the only heat source for the room is the thermal mass of the building, there is some potential for solar gain. The chimney breast temperature is high enough above internal air temperature to mean that the chimney breast is emitting 380 watts to the room at this point. From 19:00 the internal temperature has been going down, as the thermal mass of the chimney breast along with the heat from the dying fire have not been enough to mitigate against the heat loss of the building. However, when the external temperature starts to increase after sunrise at around 08:15, there is enough thermal capacity to raise the temperature of the room by 0.5°C. Whilst perhaps insignificant in relation to heating for comfort, this is demonstrably beneficial to the maintenance of the RH levels within the room and the moisture content levels of materials within the building envelope.

The possible overall effect of cumulative impact of running fires on consecutive days may be seen in the internal air temperature, which has a higher daily peak for three days in a row. The chimney breast temperature starts each day slightly higher but on the evening of the third day, external temperature dips down to around zero, this impacts the internal temperature, lowering the starting temperature of the chimney breast as more heat is lost to the external atmosphere.

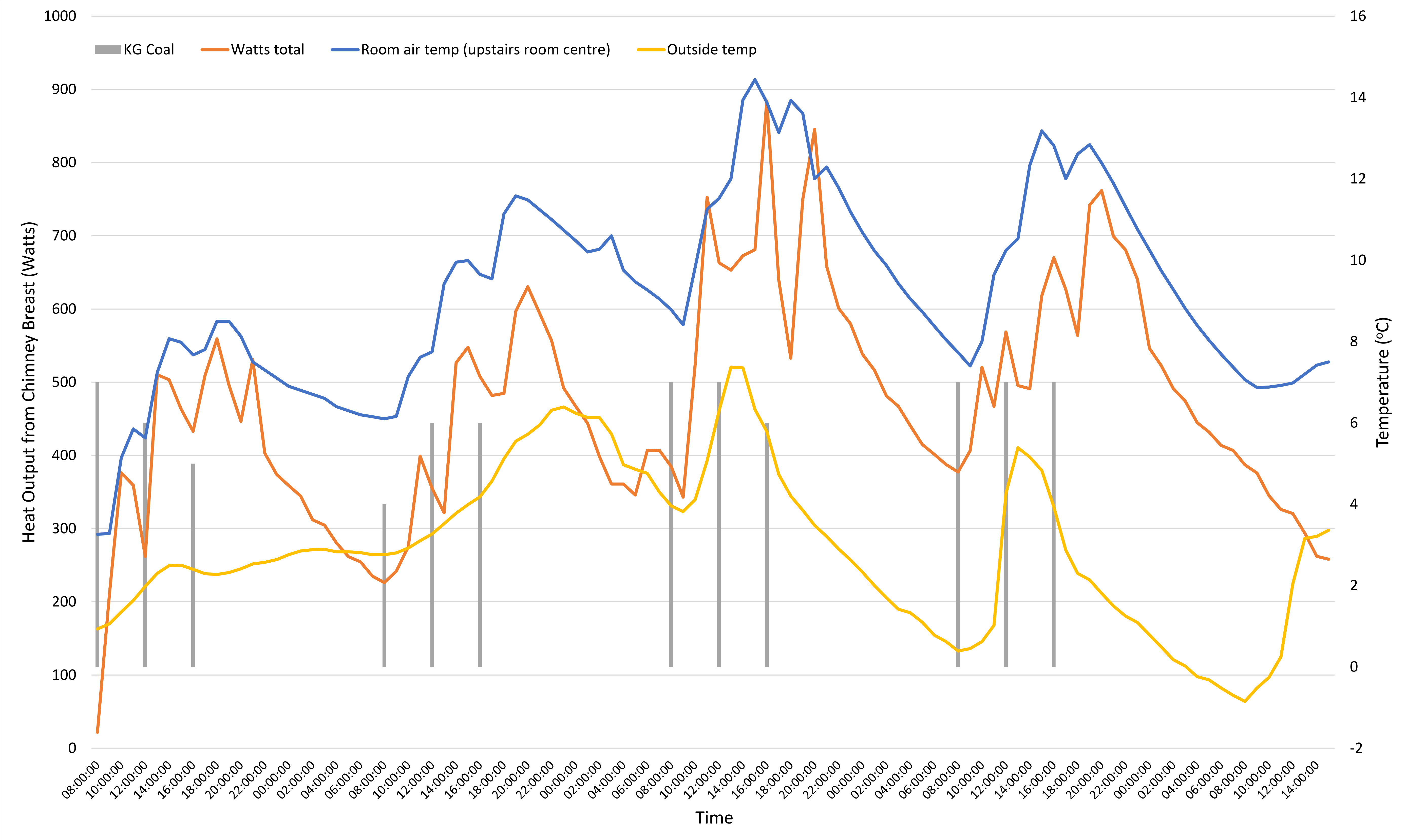


Figure 129: Watts output from chimney breast against room air temperature, outside temperature and coal consumption. Experiment 4, daily fires.

6.1.12 Experiment 5: daily fires

The cumulative impact of daily fires on temperature is evident in the internal air temperature in Experiment 5 (Figure 130). It is possible that the external temperature has stopped any further chimney breast temperature increase on the fourth day. However, there is clearly a limit to which the thermal capacity of the thermal mass can be reached. These graphs suggest that this is occurs after three days, as this correlates with the previous experimental weeks. At 15:00 on the fifth day and with no fire running the chimney breast is emitting 183 watts, which is 20 hours after the chimney breast temperature peaked. It is not a significant figure in heating terms but is clearly of benefit to the structure of the building and the maintenance of a more stable RH.

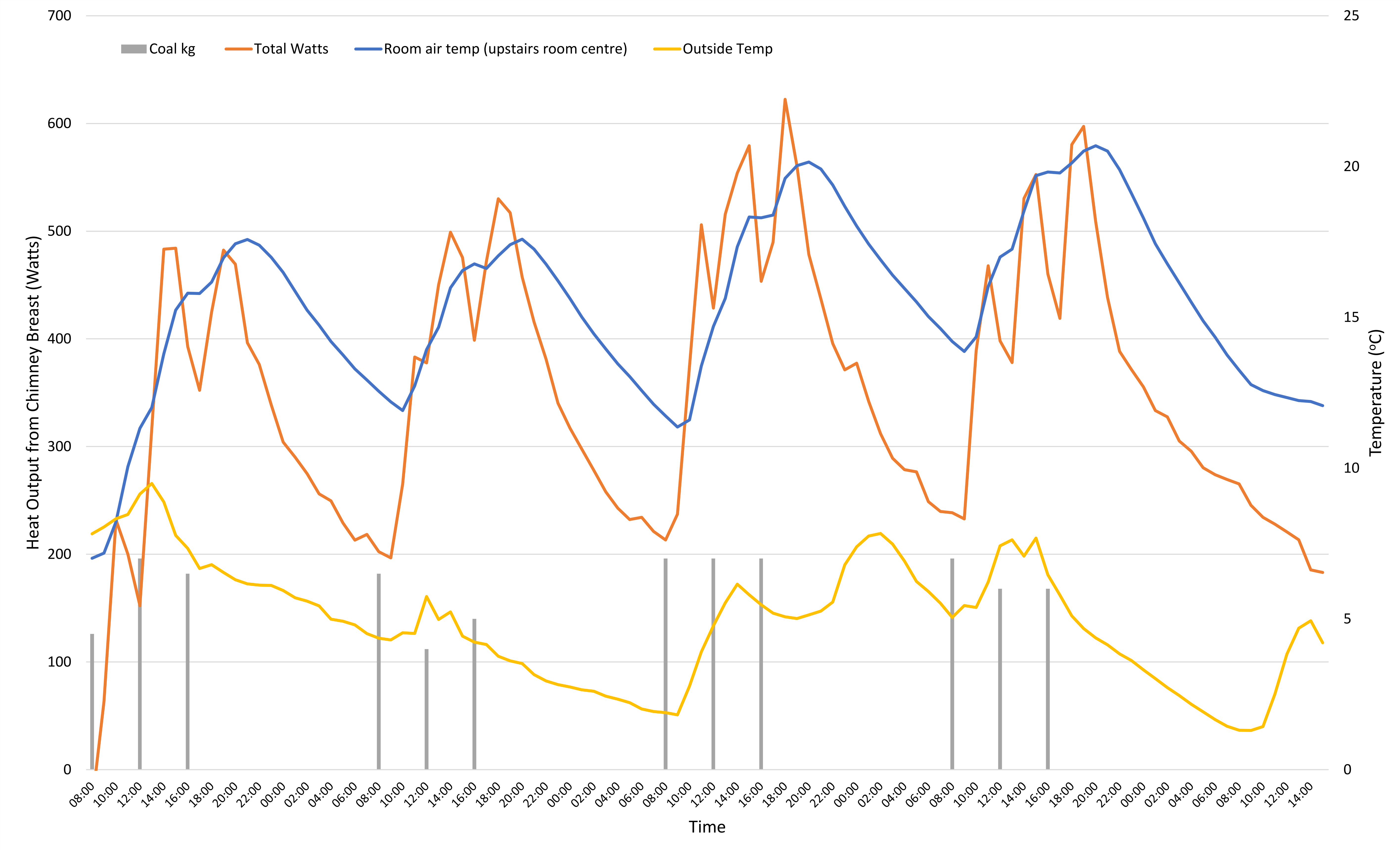


Figure 130: Watts output from chimney breast against room air temperature, outside temperature and coal consumption. Experiment 5, daily fires.

7 Heating experiments: thermal aspects

Heating characteristics of the open fire

In order to understand how effective the fire is in heating the cottage, the characteristics of the heating patterns are discussed. These are compared to similar published experiments conducted on open fires. Whilst a focus of this study is relative humidity and the impact it has on timber, heat influences this. No previous studies interrelate the impact of the heat from an open fire with relative humidity, only its effect on temperature.

First temperature effects are discussed before relating these to relative humidity. Figure 131 shows the heating pattern throughout the building after the fire has been alight for 11 hours, identifying heat output as a hemi-sphere of high intensity radiation from the source. It is also evident that a large part of the radiation is directed at mid-height forwards and upwards.

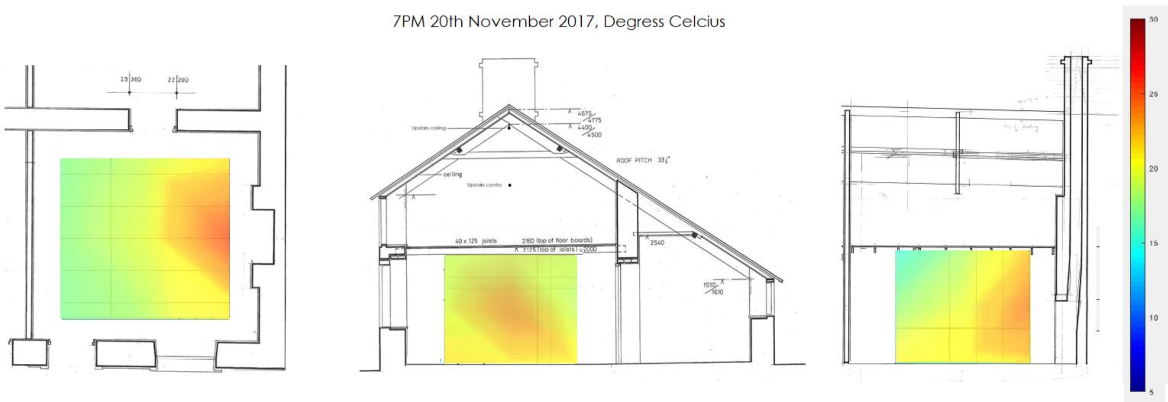


Figure 131: Cross-sectional image of temperature, 19.00 20/11/17 Experiment 1.

Venables conducted experiments on an identical grate to the one in the cottage used in this study (1957b) but within a purpose-built test room within another building. The results from this may be seen in Figure 132. Venables utilised a cage radiometer (see Chapter 2) to measure the direction of the radiant heat output, showing it as a percentage of the total output. These are shown on the figure as horseshoe lines with a percentage figure, the fire being in the centre. The higher proportion of directional radiation is aimed upwards, evidenced by the 6%, 5%, and 4% horseshoe lines. At each intersection of the hemisphere a measurement is taken, 6% crosses three lines, giving 18% of the total fire heat being aimed at 150 degrees (180 being dead upright). 5% intersects 5 lines between 120 degrees and 150 degrees. This is 25% of the total radiation, and 4% also intersection 5 lines, adding another 20% of the radiation being directed between 100 degrees and 150 degrees. In total, the study shows 63% of the total fire radiation is directed upwards and forwards. Venables hemi-sphere shows symmetrical radiation being emitted, which is due to the laboratory conditions his experiment took place in. Taken out of the laboratory environment, windows and doors offer a reduction in radiant heat output, which helps explain lower temperature values and higher RH values near windows and doors, as seen in the cottage experiments.

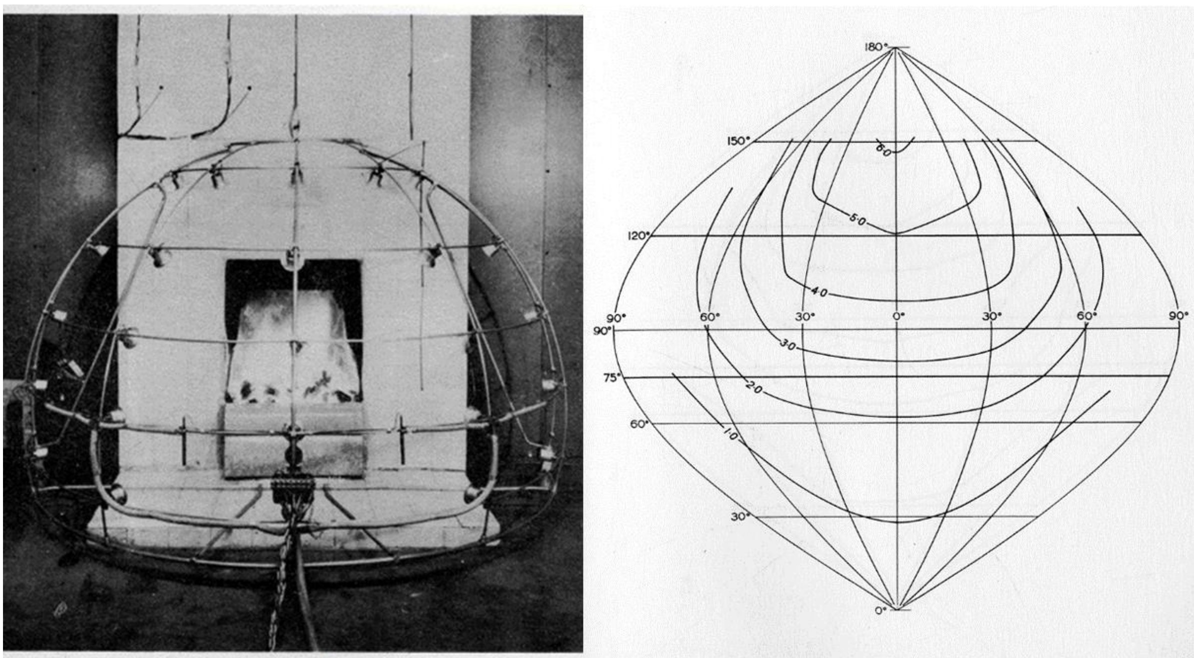


Figure 132: Distribution of radiation from inset open-fire (Venables 1957a; Venables 1957b).

Mary Davidson (1955) reported open fire heating tests within an ordinary house rather than a laboratory. Her results (Figure 133) show how a window may impact the temperature experienced in the room when heated by open fires or convection heating. Two isotherms of a room are given, one heated by a slightly improved open fire of the post-war period, the other a convector heater. The former is comparable to an ordinary open fire, but due to a special adjustable cast iron plate at the throat of the fireplace (a throat-restrictor) air exchange rate has been reduced, whilst improving the controllability of air through the fuel-bed. These points assessed, the inset grate is still largely comparable to the open fire at St Fagans in other respects, such as grate size, fireback, and opening dimensions. Comparing the histogram from the inset-grate and the 3D graph from the heating experiments in this study (Fig. 90), the heat is primarily aimed forward and upwards; there is also a clear reduction in temperature due to the windows (Figure 133).

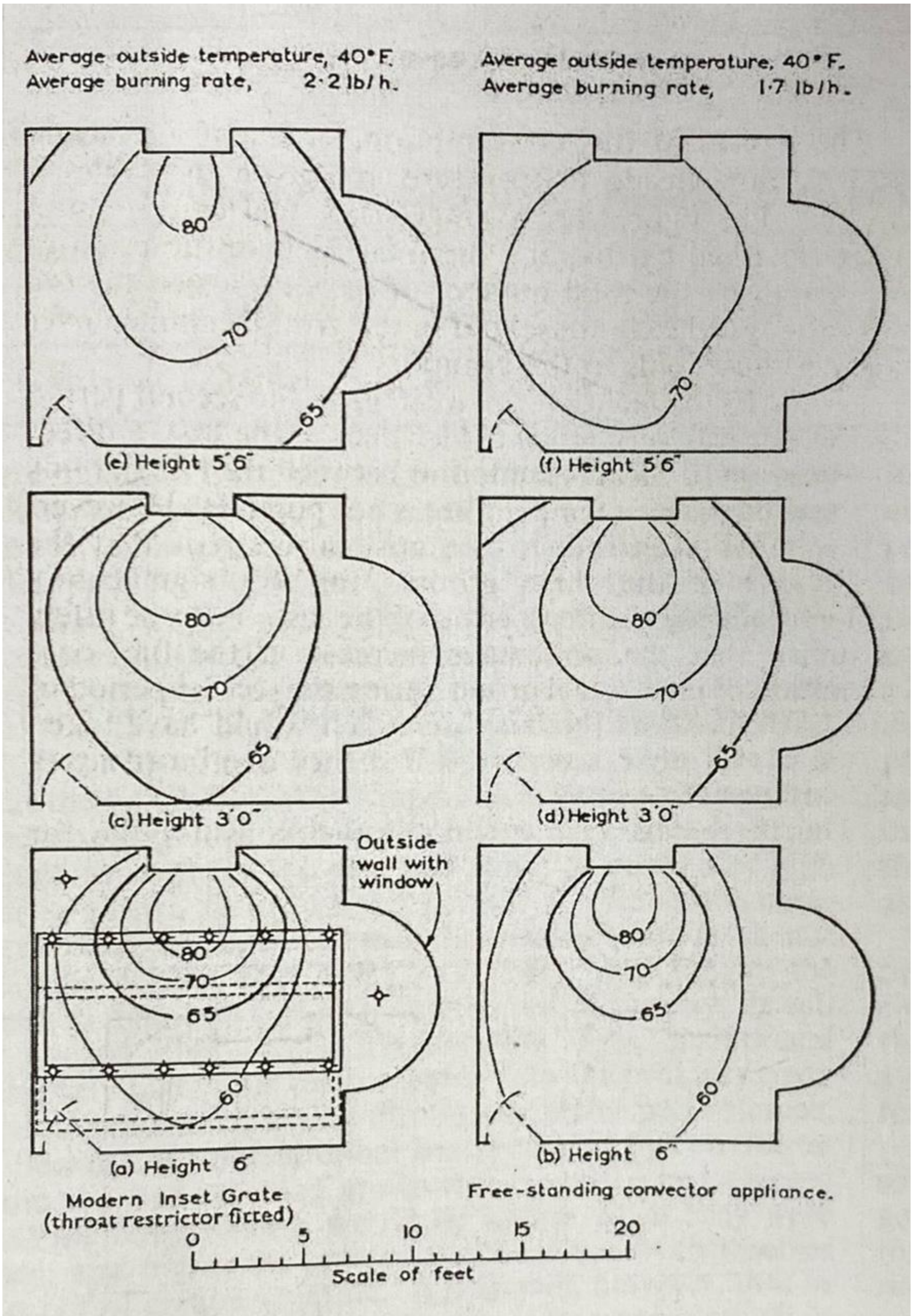


Figure 133: Isotherms of room heated for 10 hours by open fire (left) and convector heater (right) showing patterns of low temperature caused by windows are more stark with radiant heating. (Davidson 1955, 128).

Fishenden (1920, 6) experimented on a very similar fireplace to the one utilised at St Fagans (Figure 134) and did so in a normal room with ordinary windows and doors, rather than a specific test room. Fishenden also uses a hemisphere to show the direction of the heat output from the fireplace, showing that most intense radiation was at between 40 and 80 degrees. Unlike Venables, Fishenden starts her hemisphere at 90 degrees, rather 180. To gain parity with Venables histogram, Fishenden's figure (Figure 135) has to be increased by 90 degrees, showing the highest degree of radiation to be at between 130 degrees and 170 degrees, the mid point being 150 degrees. This is very similar to the results of the Venables experiment.

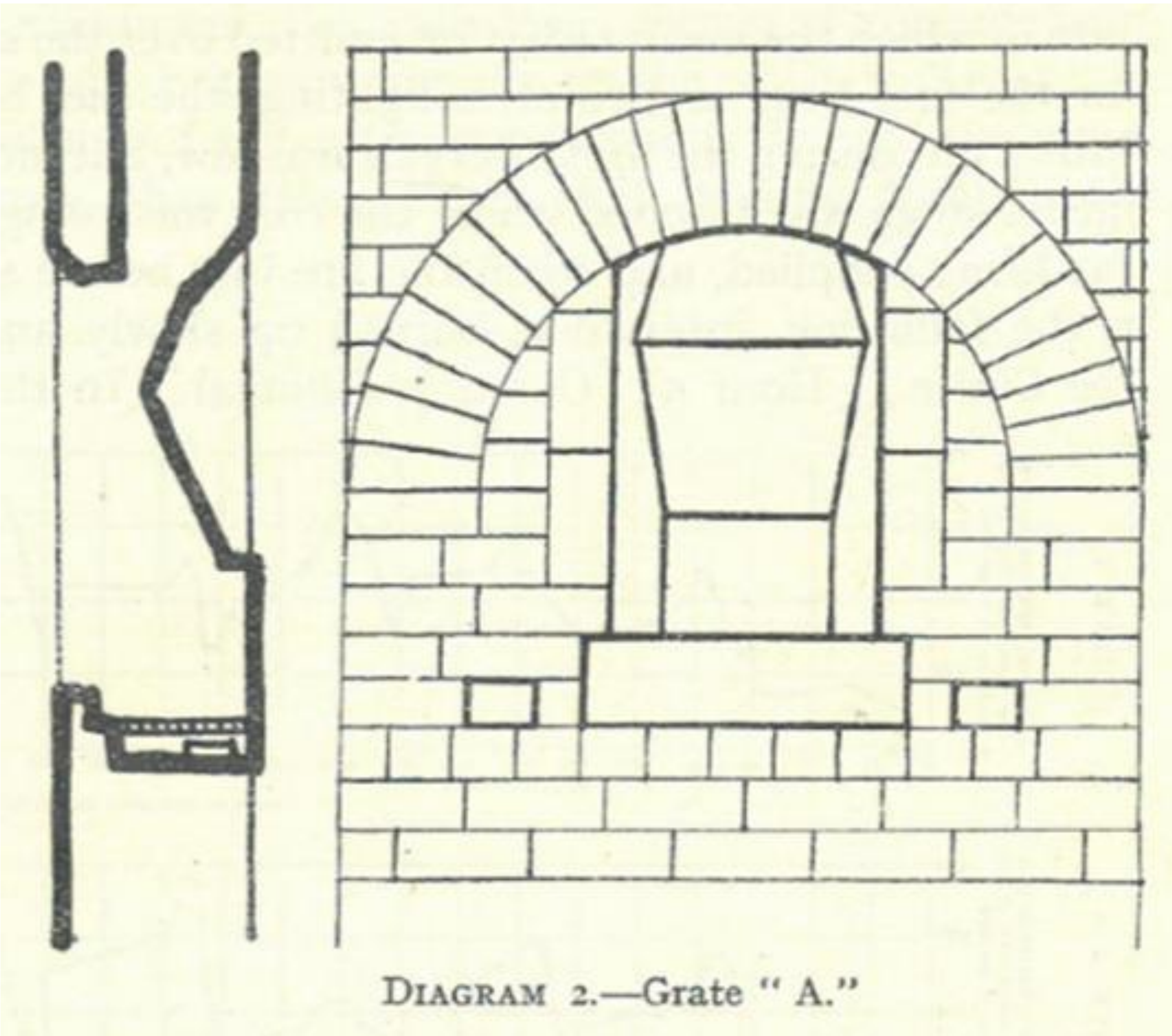


Figure 134: Fireback and grate design for Fishenden (1920, 6) experiment in Coal Fires.

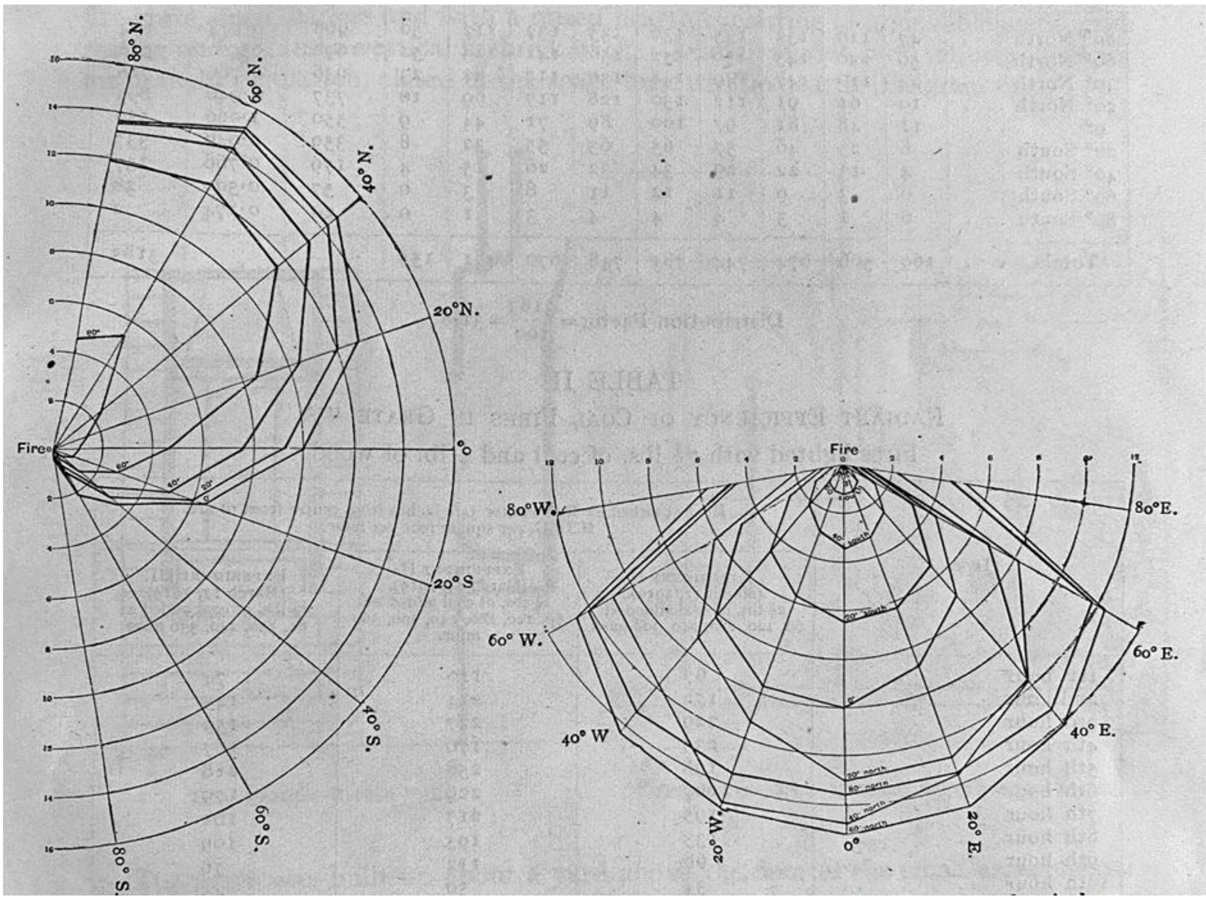


Figure 135: Intensity of radiation from open fire recorded by thermopile (Fishenden 1920, 7).

There is a clear overlap in all studies listed above showing the cool air zone on the floor caused by draughts of air. Davidson (1955) points out that an ordinary stool bottom grate (as utilised in experiments at St Fagans) has an air exchange rate of 6.5 times an hour, and that this flow is encouraged under the bottom of doors and through windows (Figure 136). This aligns with the results for the experiments at St Fagans, which offer a much higher degree of detail for the environmental conditions and their development over time than previous studies. The RH 3D plots show clearly a higher-RH zone (c.65-70% RH) around the bottom of the doors into the room, especially the front door (Figure 95 and Figure 101). Lower temperature in this region can be seen in the infrared image from the experiment (Figure 137). This higher-RH region is present during banked in experiments overnight, but is not present when the fire is not banked in. This is partly why there is a more even environment in the room when the fire is not banked in, as the small fire that is present cannot overcome the intake of higher RH, low-level external air, whereas with no fire drawing in air the thermal mass of the room keeps a more even RH. During the Experiment 1 (banked in) Figure 96 shows that at midnight the air around the base of the door and room is at 65-75%RH, whilst the rest of the room is between 46-54%RH. The external RH at this point is 93% (Figure 76), showing that the banked fire is reducing the RH of the air ingress around the door by 18-28%RH. The daily fires for experiment 5 show an area of higher RH at low level and around the door, this is between 55-65%RH, whilst the rest of the room is at 43-50%RH (Figure 108). The external RH is 95% at midnight, showing that the thermal mass is reducing the RH of the incoming air by 45-52%RH.

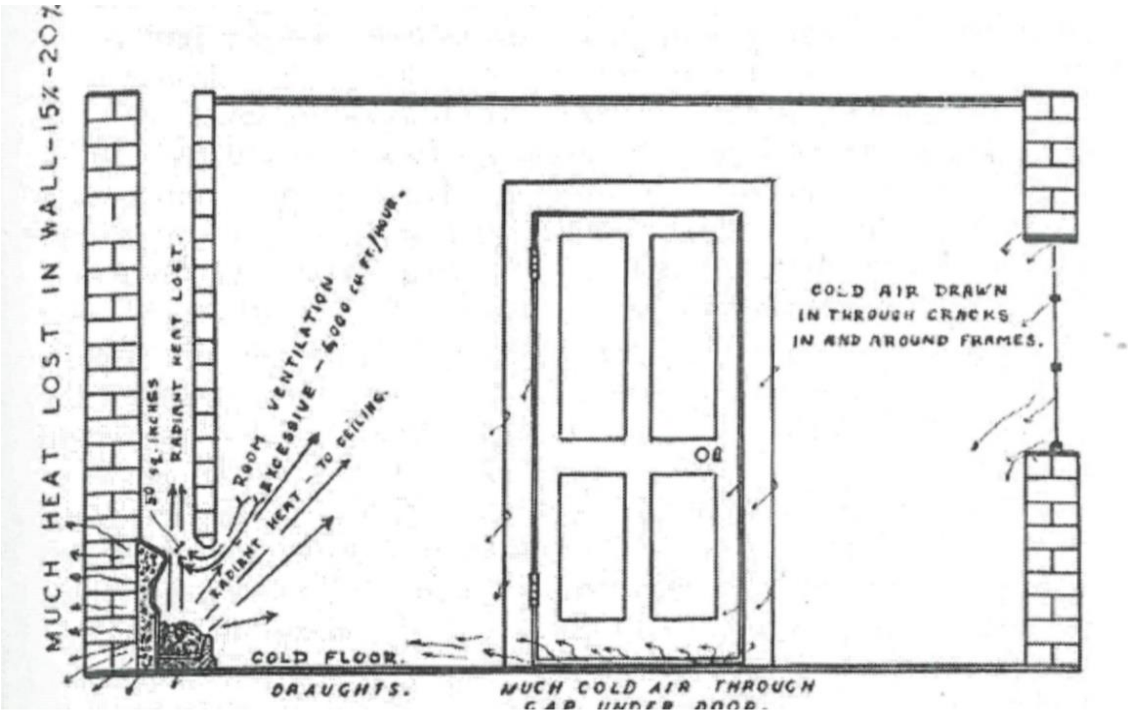


Figure 136: Warming and ventilation from open fire (Angus 1956, 135).

Figure 137: Infrared image showing low temperature external air ingress into the room.

Fishenden (1920) also discusses the ventilation qualities of the open fire, and it has been shown in this experiment that they are considerable. The 3D graphs (Figure 87) from RH display the nature of radiant heat and high thermal mass buildings also result in lower RH areas in the middle of rooms, as the IR energy travels through the air and hits the wall opposite its source. This wall then increases its temperature and creates a zone of drier air around the edge of the room, depending on the thermal qualities of the wall. For example, if the wall is an external wall, or has large windows, this phenomenon is less pronounced. It is possible for the walls of the room to be warmer and at a lower RH than the air in the room. This is dependent on how long the walls have been exposed to the radiant heat, and how many air changes there are.

Heat output cycles

'When a coal fire is left overnight it serves a useful purpose in maintaining the temperature of the house' (Journal of Royal Society of Arts, 1927, 581).

Figure 138 shows the irregularity of the heat output from an open fire with the peaks and troughs mirroring the combustion stages of bituminous coal. There is a clear relationship between the stages of combustion for coal and the heat output for the room. The initial volatile gasses burning produce a high yellow/orange flame. These having been burned, along with other compounds such as bitumen, the remaining fuel is coke (mostly carbon) which burns cleanly and with a blue flame, or no visible flame. This coke burns with an intense red glow (see Figure 113), slowly cooling until more coal is added to the fire, blocking the heat entirely until the process repeats.

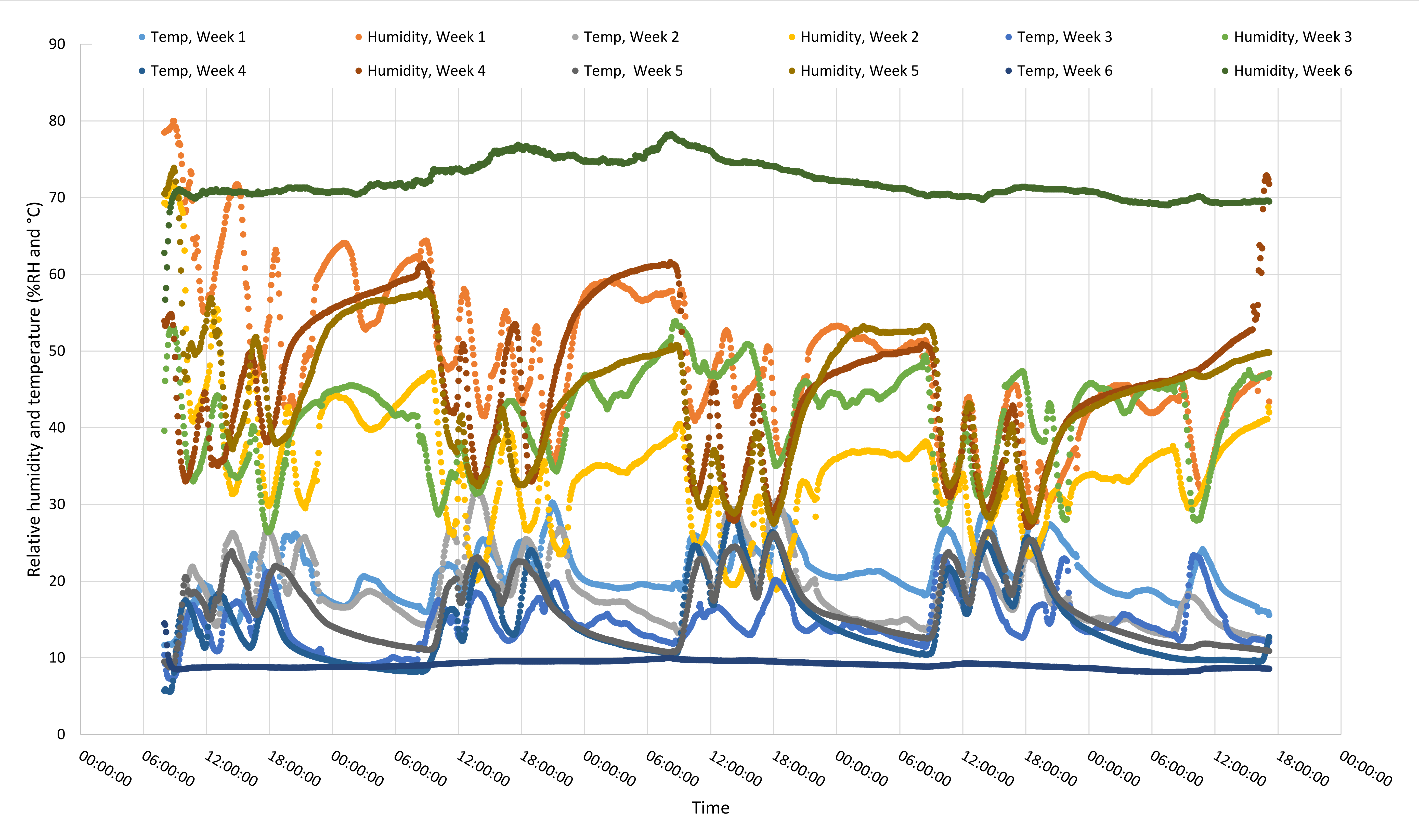


Figure 138: Data from logger E2 (room centre) for heating experiments. Week 1-3 banked in, week 4-5 daily fires, Experiment 6 unheated.

Blackie (1938) and Fishenden (1920) show in Figure 139 and Figure 140 how the heat output curve is very similar to that of Figure 138, with a clear peak for the combustion of volatile gases, a low slope for the burning coke, and a sudden dip followed by a spike when fuel is added, and then combusts.

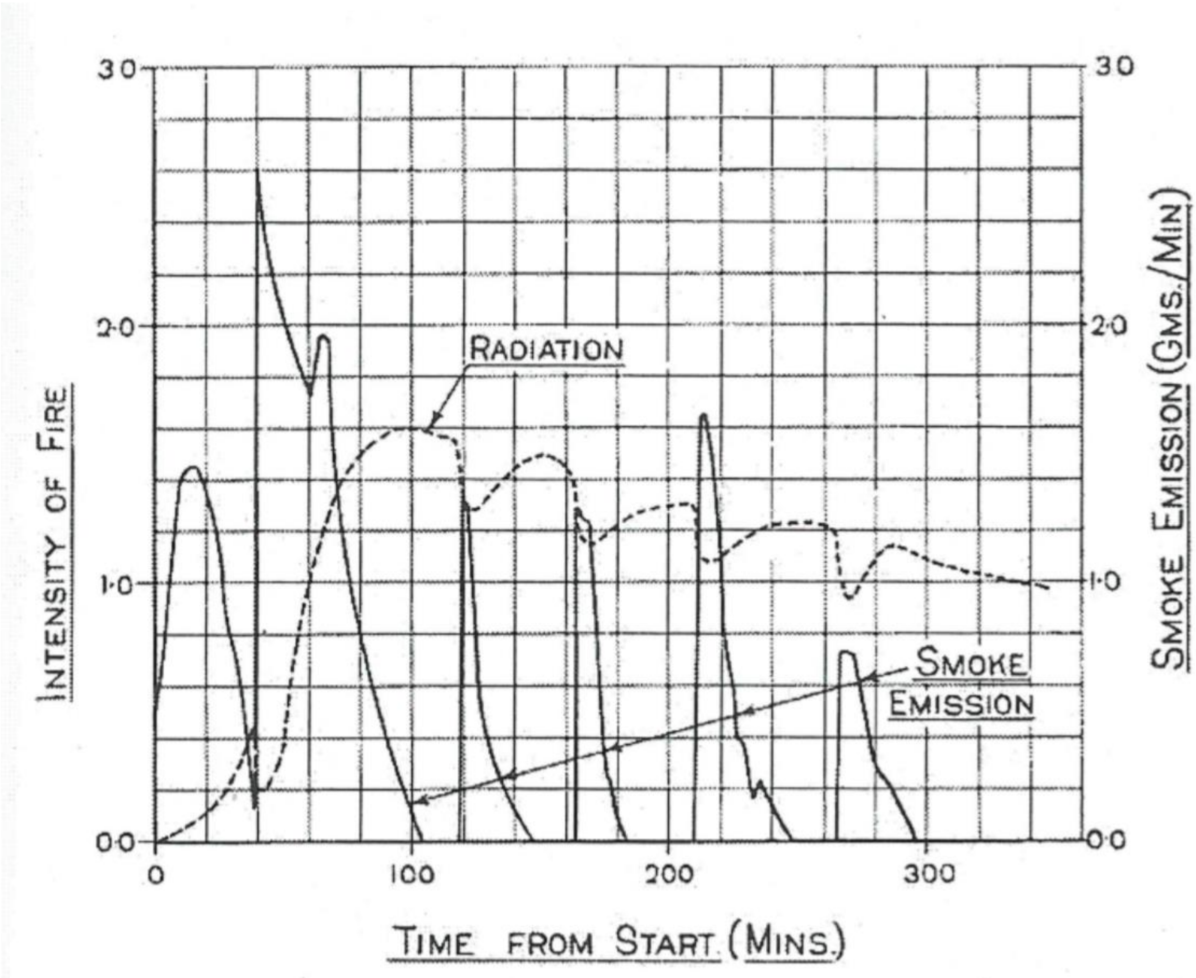


Figure 139: Radiant intensity from open fire against smoke emission (Blackie 1938, 24).

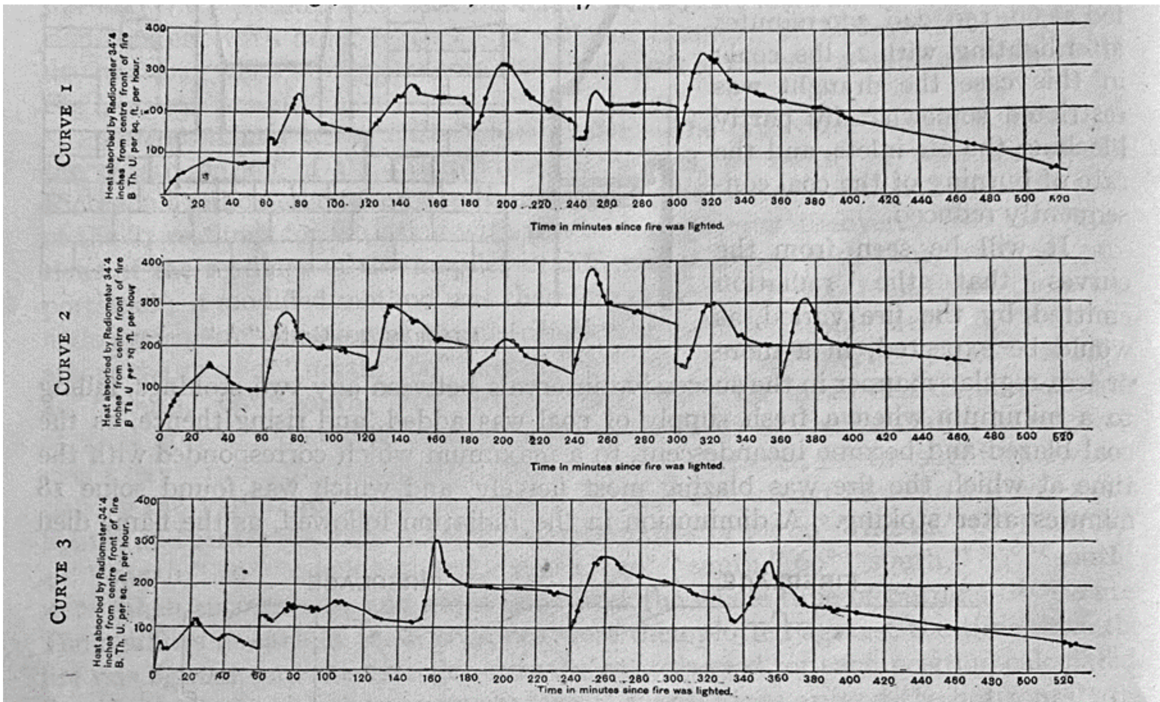


Diagram 4.—Variation with time of the heat absorbed by the radiometer 34·4″ from the centre front of coal fires in grate "A."

Curve 1.—Fire lighted with 7½ lbs. coal and fed with 2½ lbs. coal 60, 120, 180, 240, and 300 minutes after lighting.

Curve 2.—Fire lighted with 7½ lbs. coal and fed with 2½ lbs. coal 60, 120, 180, 240, 300, and 360 minutes after lighting.

Curve 3.—Fire lighted with 7½ lbs. coal and fed with 2½ lbs. coal 60, 150, 240, and 330 minutes after lighting. Slight draught restriction.

Figure 140: BTU per square feet per hour, 34.4inches from fireplace (Fishenden 1920, 7).

It was thought that the thermal mass of aspects of the building, like the chimney breast, would iron out some of these peaks and troughs as the brickwork takes such a long time to gain and release heat. However, this is not as pronounced or obvious as assumed. Similarly, within the room, the RH is directly related to the radiant temperature, so varies throughout these troughs and peaks. This can mean that objects in the room centre, two meters from the fire, are reaching RH values as low as 19%, as seen in Fig. 137, 14:27 on the 29 November 2017. Fig 137 shows that by the morning the temperature in the room centre is little higher that when the experiment starts at around 11-13^{o}C.

Overnight the RH range is 45% to 61% with daily fires, which is less than the unheated RH range of 70 to 75 %. This is caused by the thermal mass providing low-level background heat throughout the night. Overall, there appears to be a cumulative impact on RH which is greater than impact on temperature. Figure 138 shows this clearly, with day 5 of 5 for the experiment showing RH around 35-45%RH, 10%RH lower than on the Monday. This is likely due to moisture buffering that may be related to the timber components of the building rather than the brick or stone of the walls (Hameury 2005, 1411). The impact of the external RH at this point cannot be related to the 10% RH change as it is consistently between 82-95%RH (Figure 76).

Heat output chimney breast

One of the aims of this study was to fully understand the impact open-fire heating had on the internal environment, and the chimney is an integral part of this. It is a large part of the building, and it is warmed by the flue gasses. It is made of brick and offers considerable thermal mass. As such, results from thermal imaging and loggers are extrapolated and discussed below to provide a detailed picture of the impact the chimney breast has on the internal environment.

7.1.1 Calculation based on recorded figures

Relative to surface temperature and air temperature, radiant heat output increases on a low exponential curve, whereas convected heat output increases in a linear fashion. The two reach a parallel at around 100^{o}C, after which radiant heat output increases above the rate of convection (Figure 141 and Figure 142) (with a background temp of 20^{o}C and a convective heat transfer coefficient 7.5 and an emissivity coefficient 0.9 (CIBSE 2001). This is important when understanding the chimney breast temperature relative to the heat output, which delivers the majority of its heat via convection, unlike the fire itself, which delivers almost all of its heat via radiation (Fishenden,1920).

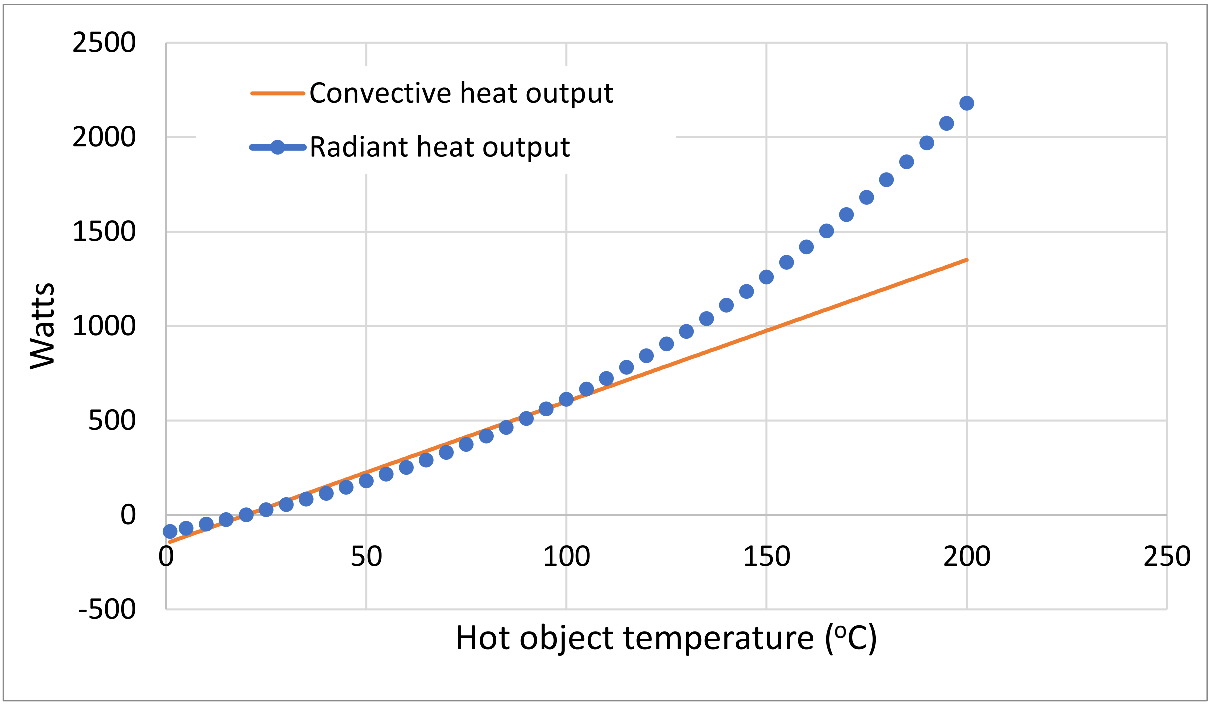


Figure 141: Convective heat output and radiant heat output showing overview of outputs in watts against temperature 0-200°C, for a hot object with a surface area of 1m² and a background temperature of 20°C (convective heat transfer coefficient 7.5, emissivity coefficient 0.9)(CIBSE 2001,Web Reference 1).

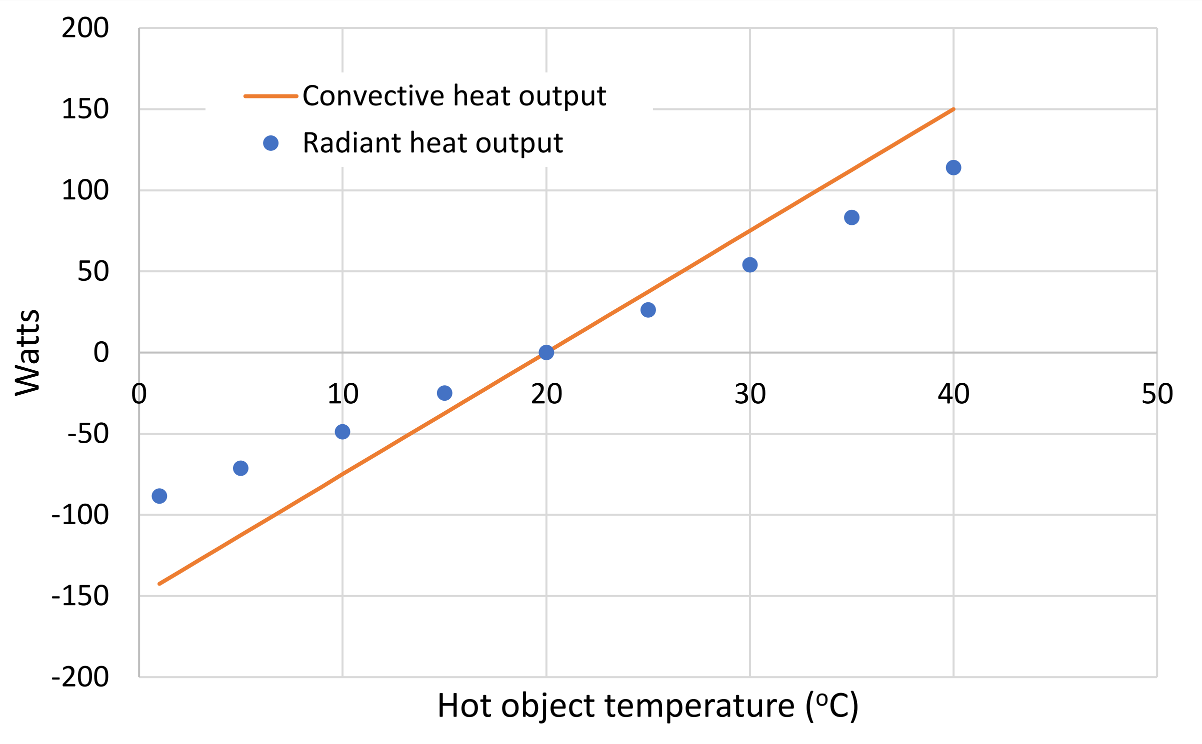


Figure 142: Convective heat output and radiant heat output showing overview of outputs in watts against temperature 0-40°C, for a hot object with a surface area of 1m^2 and a background temperature of 20°C (convective heat transfer coefficient 7.5, emissivity coefficient 0.9) (CIBSE 2001,Web Reference 1).

Assessing the heat from the appliance as a whole is not easy as there are a great number of variables, such as ash-pit heat losses, flue gas losses (Weston 1949, 255). It was also not possible to take thermal images of the fire at the same time as the chimney breast due to limitations of the camera thermal scale, thereby making it difficult to assess heat output of the fire itself. However, with the data for the chimney breast temperature it is possible to calculate its heat output and use the result to calculate from that certain efficiencies may be calculated using published figures, thermal images of the fire, and fuel rate consumption. The result will offer some general insight into heat output from the chimney breast but cannot be considered an absolute value.

Calculating heat output for chimney breast:

The chimney breast area above the mantel shelf is 2.89m^2. If a peak from the first week is selected as an example (20:56 Experiment 1, day 1), using the infrared camera, the average temperature for that area is 36.8°C. The air temperature is difficult to assess due to the intense radiant heat hitting the loggers within the room, coupled with the fact that they are matt black, therefore the loggers give the radiant temperature rather than the air temperature. As such, the logger from upstairs is utilised to give the air temperature as it is not within the path of the fire, there is no door between the two rooms and the staircase is within the room. The air temperature was 17.35°C.

Calculations: chimney breast in room

Radiant heat

Radiant heat output from the chimney breast is calculated using the Stefan-Boltzmann Constant, derived from the Stefan-Boltzmann law regarding radiation from a black body (CIBSE 2001, 3:10):

$q = \sigma T^4 A$

where

q = heat transfer per unit time (W)

$\sigma = 5.6703\ 10^{-8}\ (W/m^2K^4)$ *- The Stefan-Boltzmann Constant*

T = absolute temperature in kelvins (K)

A = area of the emitting body (m^2)

Thus using the following equation, the wattage may be calculated:

$q = \varepsilon\ \sigma\ (T_h^4 - T_c^4)\ A_h$

where

T_h *= hot body absolute temperature (K)*

T_c *= cold surroundings absolute temperature (K)*

A_h *= area of the hot object (m²)*

ε *= emissivity coefficient of the object*

The emissivity of a smooth plaster wall may be taken to be 0.9

In the case of 21/11/2017 8:56PM

$T_h = 309.95\ K$

$T_c = 290.5\ K$

$A_h = 2.89\ m^2$

$\varepsilon = 0.9$

Thus:

$q= (0.9x(5.6703x10^{-8}))\ (309.95^4-290.5^4)\ x2.89^2 = 310.829$ *watts*

Convected heat

To calculate the convected heat from the chimney breast the formula for Convective Heat Transfer must be used (CIBSE,2001,3:4). This is based upon convective heat transfer coefficients. The equation for convection can be expressed as:

$q = hc\ A\ dT$

where

q = heat transferred per unit time (W/hr)

A = heat transfer area of the surface (m^2)

hc = convective heat transfer coefficient of the process (W/m^2 °C)

dT = temperature difference between the surface and the bulk fluid (°C)

The heat transfer efficiency may be taken to be between 5 and 10, a halfway point of 7.5 being selected as a best fit of the scenario (ASHRAE 1997 Handbook Fundamental).

In the case of 21/11/2017 8:56PM

A = 2.89m^2

hc = 7.5 W/m^2 °C

dT =19.45 °C

Thus:

q = 7x2.89x19.45 =

421.87 watts

Radiant and convected heat total

The total radiant and convective heat output of the chimney breast is calculated to be:

310.8 + 421.9 = 732.7 watts

This figure does not include external portion of the chimney breast (Figure 143).

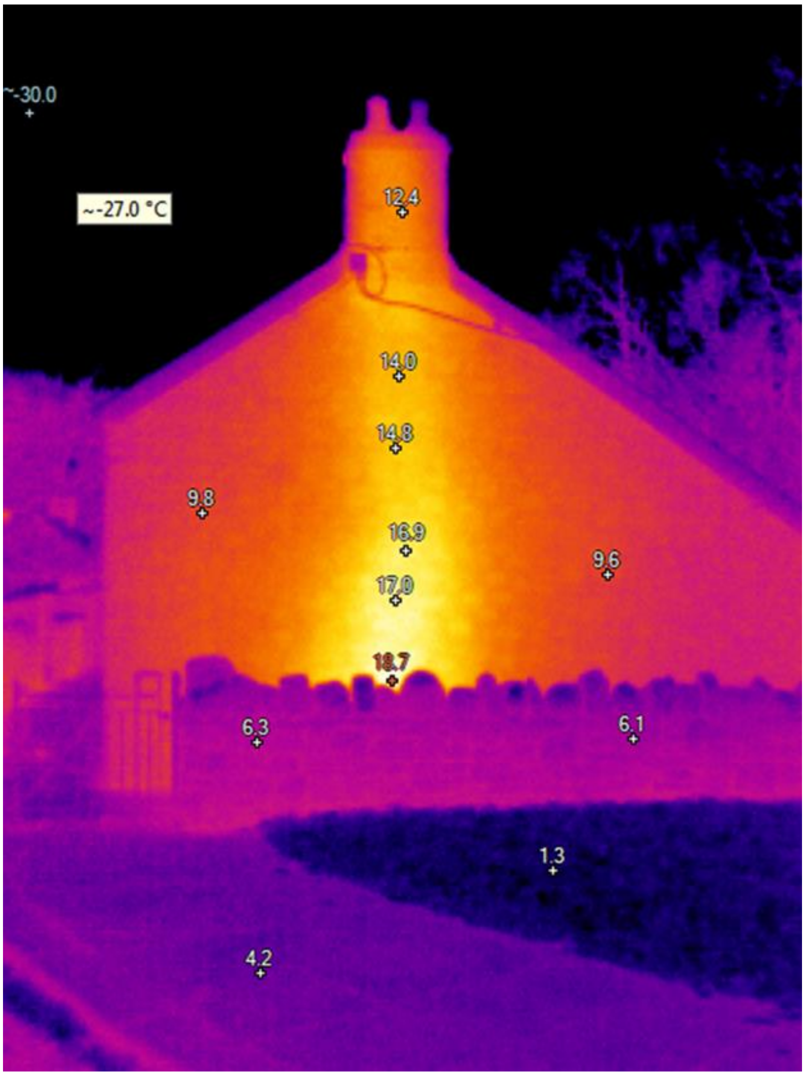


Figure 143: Infrared imagine of the pine end of Rhyd-Y-Car No.6, showing the heat from chimney.

Infrared imaging suggests a similar figure to the internal chimneybreast temperature (Figure 143) and if this house were one of the others in the row then the figure could be doubled for an internal chimney. This demonstrates the benefit of heating between properties in a terrace.

Furthermore, this figure does not include the upstairs part of the chimney, which is a lower temperature, but likely to still be providing some heat output and is discussed later. Bedford

(1948) suggests 25% of the potential heat from the fuel is gained by the chimney, and experiments by Weston (1949 ,254) concur with this.

Data collected is used to assess whether this figure of 25% was achieved in the study. If the radiant efficiency of an open fire is 25% (Shaw, 1955 gives 24%; Fishenden, 1920 gives 22%; BCURA 2016 gives 30.8%; Wilson 2020 gives 26%) and at 8:58PM 21/11/2019 the fire was burning at a rate of 5kg of coal per 4 hours, there was approx. 1.25kg of coal burned over one hour. Bituminous coal is 8kw/kg x 1.25kg=10kw of energy in the fireplace and 25% was radiant heat into the room= 2.5kw/h. 25% of 10=2.5kw.

Taking the figure for the heat output of the chimney breast in the room calculated earlier in this chapter, 732.7 watts. Doubling it to account for the portion facing the outside of the building 732.7x2= 1465.4 watts.

The upstairs portion of the chimney breast must be accounted for, it measured 26.16°C (20:56, Experiment 1, Day 2 21/11/2017) at the ledge. Assigning this to be a centre point to produce an average overall temperature of the chimney breast, it is 1m from the timber floor, so the area may be calculated 2m high (which is 0.5m short of the ceiling apex, so is a slight under-representation due to the logger location). The flue in the chimney is narrower at this point, so the area calculation is based on a width of 50cm wide to match the heat distribution. This gives an area of $1m^{2.}$ utilising the previous formulae, taking the average temperature of the chimney breast to be 26.16°C the radiant heat output is 47.9 watts and the convected heat output is 64 watts, totalling 111.9 watts. Doubling this for both sides of the chimney the heat output is 223.8 watts. Adding this to the downstairs chimney breast heat output the total chimney heat output is:

1465.4 + 223.8 = 1689.2 watts

This gives the percentage of heat output from the chimney breast as 17%, which is lower than the 25% suggested by Weston (1949, 254). This may be because the sides of the chimney are also part of the wall, rather than projecting into the room.

If the chimney breast sides were the standard 45cm (4” brick end + 9” brick front + 4” brick end) both downstairs and upstairs are the same height, this would give an area of 0.9m x 2m = 1.8m^{2},. The downstairs average surface temperature recorded by the thermal imaging camera was 36.8^{o}C, giving a radiant heat output of 198 watts and a convective value of 245 watts, totalling 443 watts.

Upstairs the average area temperature is 26.16°C, 82.9 watts for radiant, 111 watts for convective, totalling 193.9 watts.

Upstairs and downstairs total 636.9 watts. Added to the previous figure for chimney breast heat output may be put at 2326.098 watts. This is 23% of the total fuel in the fire and a much closer average to the one suggested by Weston (1949, 254).

However, Rhyd-y-Car No6 lacks an internal and projecting chimney breast, so it is likely to be half of the 17% figure at 8.5%, the other half being lost to the externally exposed chimney.

The other chimneys in the Rhyd-y-Car row likely gain between 17% and 23% of the calorific value of the fuel from their chimneys as they are internal.

Thermal capacity of the chimney breast

The usefulness of the thermal capacity of the chimney breast is important in the room environment when considering periods of low fire burning, or when the fire is out. To analyse its impact, the time taken for the chimney breast to reach a peak temperature was analysed. This may be seen as the minimum 'charge' period for warming up the chimney to store the heat for the rest of the day.

There were several peaks in temperature for the chimney breast during a day, the largest occurred in the early afternoon after the second re-fuelling of the fire (Figure 126 - Figure 130), these figures were averaged to produce Table 5.

		Average time for max. peak (hours)					
Experiment	**Fire type**	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Weekly**	**Average**
1	**Banked**	5	5	8	7	**6.25**	**6.25**
2		9	5	5	5	**6**	
3		8	7	4	7	**6.5**	
4	**Daily**	5	7	4	3	**4.75**	**5.87**
5		7	5	6	10	**7**	

Table 5: Average time for maximum peak after fire revived or relit in morning.

When the fire reaches a peak it is emitting a large amount of radiant heat to the room. Due to the design of the fireplace throat (Chapter 2, Figure 6 and Figure 7) most of the heat entering the chimney flue will be from convection from the combustion gases. The warm products of combustion and air are in contact with the internal side of the brickwork forming the flue, which absorbs the heat whilst it passes at a rate of 216 cubic meters an hour (Venerables 1957a, 4). The rate at which the brickwork absorbs the heat and conducts it to the room surface through the brick and plasterwork is slower than the immediate heat gained from the fire as radiant energy. The brickwork reaches a peak in temperature after the fire has died down to some degree. For the fire in this study, the delay in the desorption/emittance is 85 minutes as an average, which was calculated by the time difference between a temperature peak recorded at logger B3 in front of the fire, and a peak for the logger on the upstairs chimney breast.

Sixteen hours after the fire has gone out, the chimney is emitting between 258 and 183 watts, an average of 220 watts (Figure 129 and Figure 130). How long the heat is of benefit to the relative humidity in the room is difficult to calculate and depends on the door being open and the room accessed. It would not be enough to mitigate against the door being open all day with no fire burning, as is the present practice. Figure 144 shows that three days after the fire, the chimney breast has no real heating benefit to the room, it presents itself at slightly above the wall temperature by 1-1.5°C, which could be because of the insulating impact of the air-gap in the chimneybreast, as opposed to the solid wall. Figure 145 shows that 20 hours after the fire has gone out, the chimney breast sits at around room temperature. This overall suggests a time frame between 16 and 20 hours for stored heat in the chimney breast.

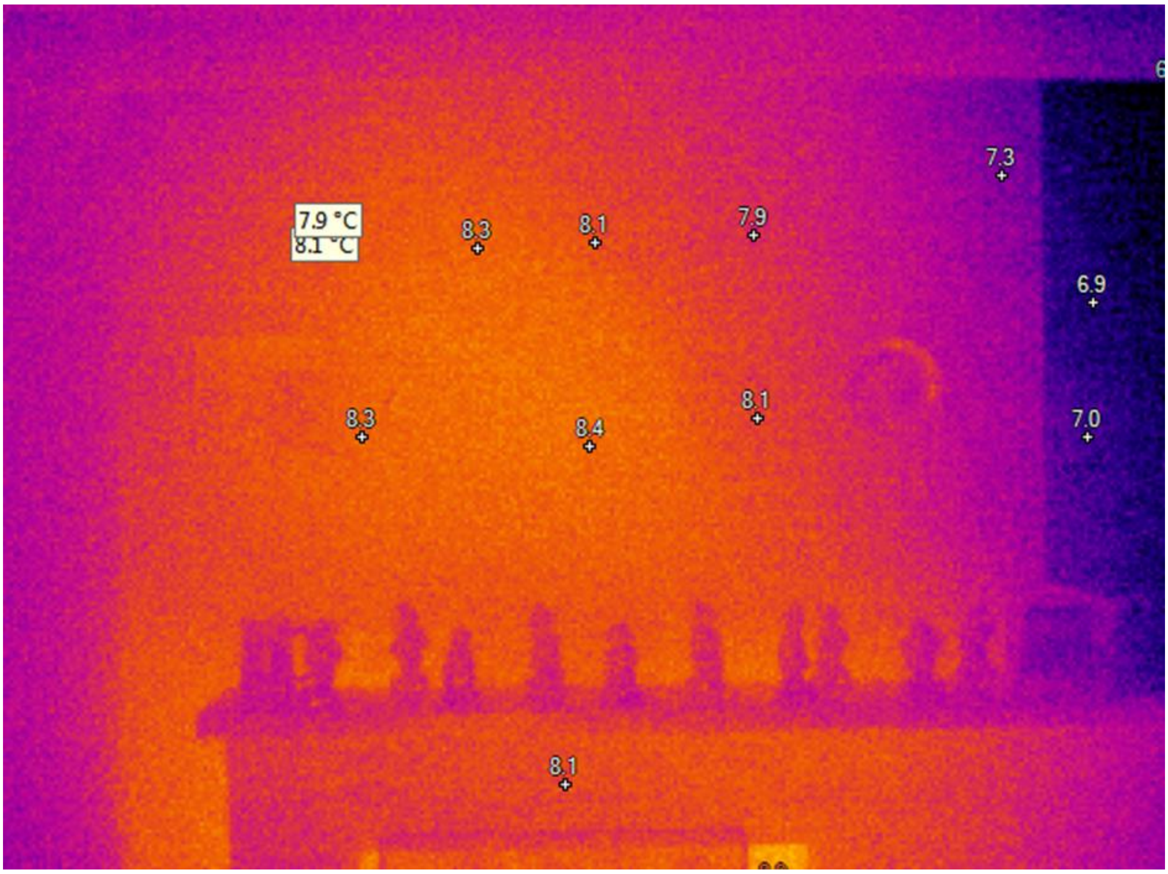


Figure 144: Chimney breast temperature three days after fire has gone out.

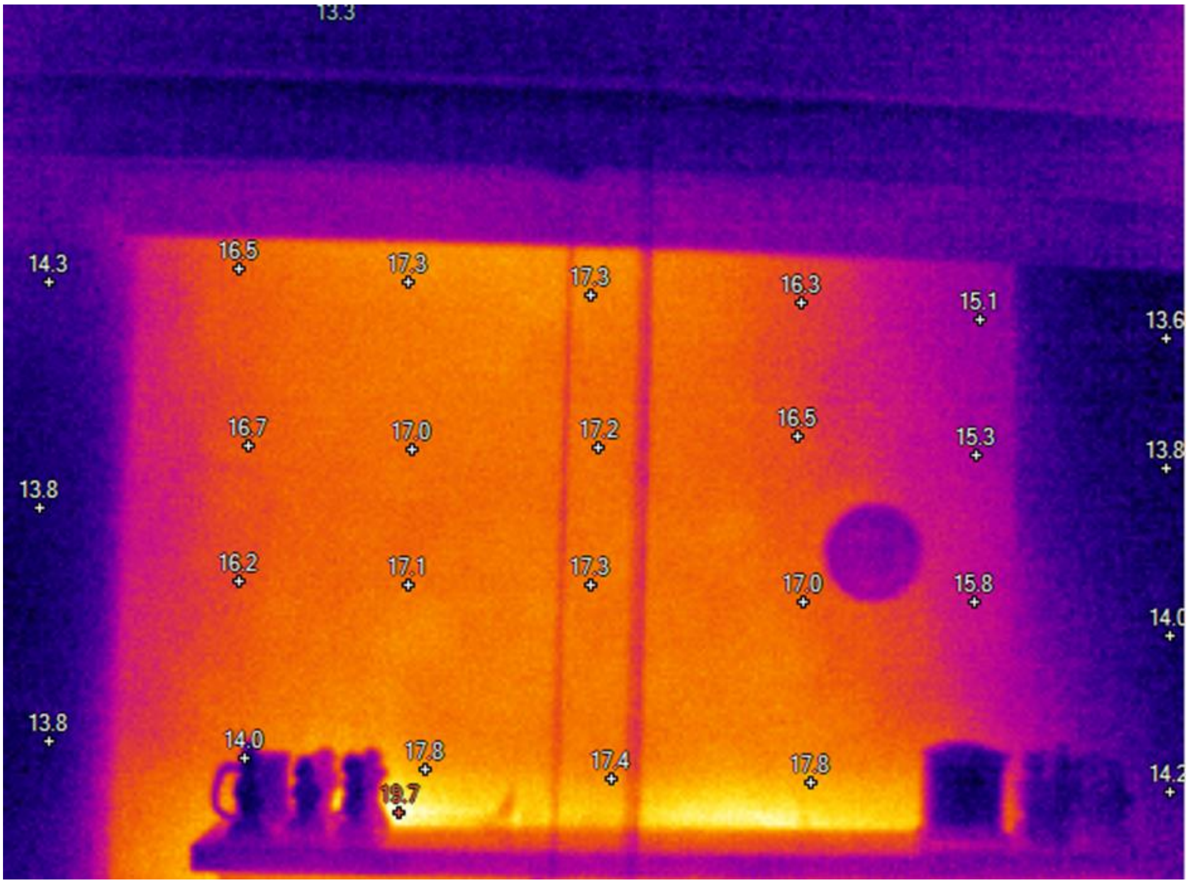


Figure 145: Chimney breast temperature 20 hours after the fire has gone out.

If the heat decay from the chimney breast is plotted on a graph a logarithmic curve can be produced (Figure 146). It is not a perfect fit, but R^2=0.945 is a close fit and visualises how the remaining stored heat tails off.

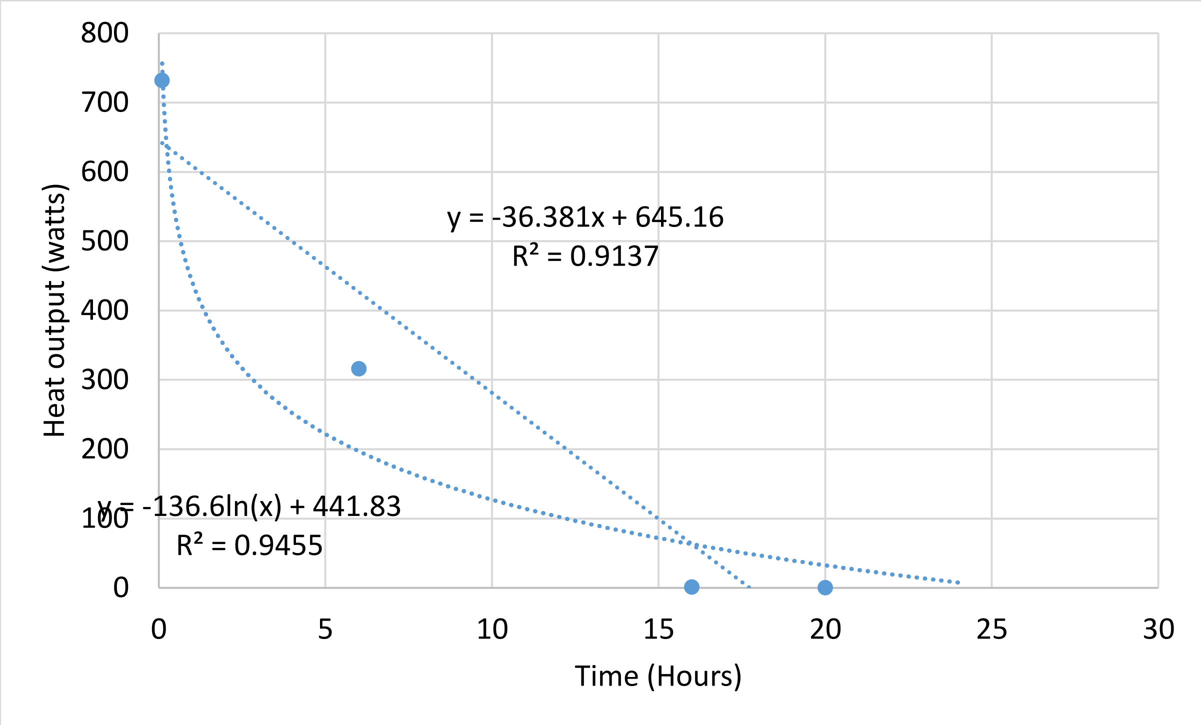


Figure 146: Heat decay from chimney breast to room. Clear that half-life of first 6 hours is of most benefit. Logarithmic line showing best R^2. Maximum watts taken from theoretical calculations on heat output later in chapter (which are in line with observed readings for Experiment 1 day 2).

If temperature parity with air temperature is seen to be the point at which the chimney breast stops emitting heat, then the chimney breast continues to emit for 20 hours. To the end point the output may be considered negligible in heating terms, but as a major part of the building fabric it would reduce the heat losses from the room considerably and avoid condensation problems. Whilst this may have a limited impact on thermal comfort, it is likely to be part of the reason RH remains under 50%RH 20 hours after the fire has gone out (as in Experiment 5).

As cold, high RH air enters the building it is warmed and its RH is lowered; for example, 90% RH 5°C air being warmed to 12°C gives 55.7%RH. This demonstrates that a great deal of heating is not required to maintain an acceptable internal environment for the majority of objects after the thermal inertia has been charged to a high degree.

7.1.2 Thermal capacity and emittance of chimney breast

For all experiments the data consistently shows that the humidity pattern created by refuelling the fire is repeated daily, but that the second and third day are overall 5-10 %RH lower and the overall room temperature increases by 5-10°C. This rarely continues past the third day, suggesting the building fabric ‘equilibrium’, for the thermal mass reaching an optimum temperature and moisture content. The raising of temperature after fuel addition is visible as a step function and the initial weeks also show a daily step function.

At 08.39 Experiment 2, day 1 (i.e. before the fire is alight) the watts output for the chimney breast is in negative, i.e. below air temperature at -3.9 watts, indicating that the thermal mass from the week previously does not continue throughout the weekend.

Given that radiant heating heats the fabric of the room and then the air, after an experimental run the thermal mass of the walls should be at a high level. If the walls are warmer than the air, and remain in this state for a time after the fire is out, then they are contributing the heat of the room. The wall temperature was not recorded dynamically during the experiment other than by the spot use of the thermal camera to record the chimney breast temperature. These images also show the wall temperature in the left-hand corner, which is the coldest part of the room. This is because it has a larger external surface area (Figure 147) offering two sides to the external environment, subject to the cooling by temperature differentials, wind, and precipitation.

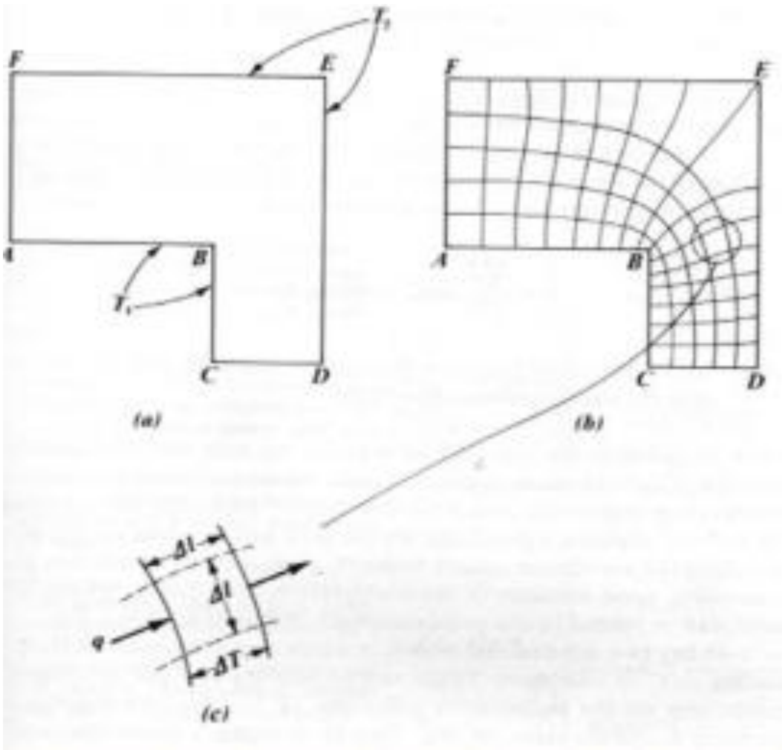


Figure 147: Diagram showing heat transfer of a corner, how the external surface area is larger than the internal surface area (Kreith 1973).

By taking the wall temperature at the point, the temperature for the other walls in the room can be considered to be either at this level or slightly higher than it. From this it can be determine if wall temperature exceeds room air temperature. From this the thermal mass of the walls can be broadly assessed. Figure 148 and Figure 149 show the wall temperature during Experiment 5, ten and twenty hours after the fire has gone out. In Figure 148 the wall to the left and right of the chimney breast is at between 14.2°C and 16.7°C. The air temperature recorded at the room centre on logger E2 (Figure 138) is 12°C at this time, showing that the walls are still offering a warming effect.

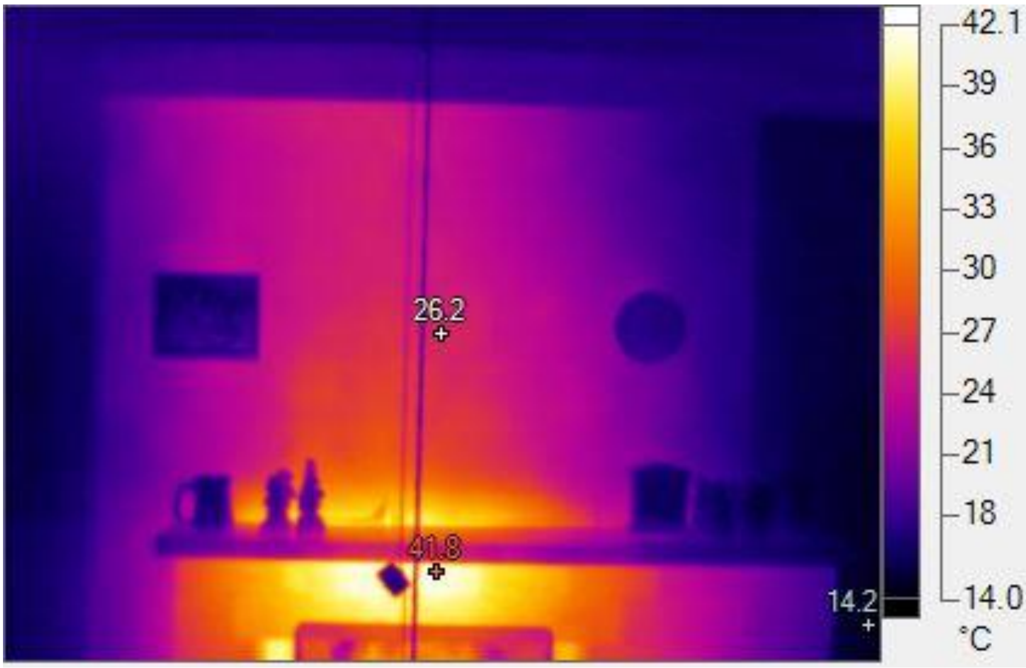


Figure 148: Experiment 4 day 4, 10 hours after the fire is out. Room centre temperature 11°C

Figure 149 shows that whilst the air temperature recorded on logger E2 (room centre) was 9.6°C the wall was slightly warmer at 11-12°C. This is only slightly above air temperature but suggest why the room air stays below 52%RH at this point, despite no heating for 20 hours.

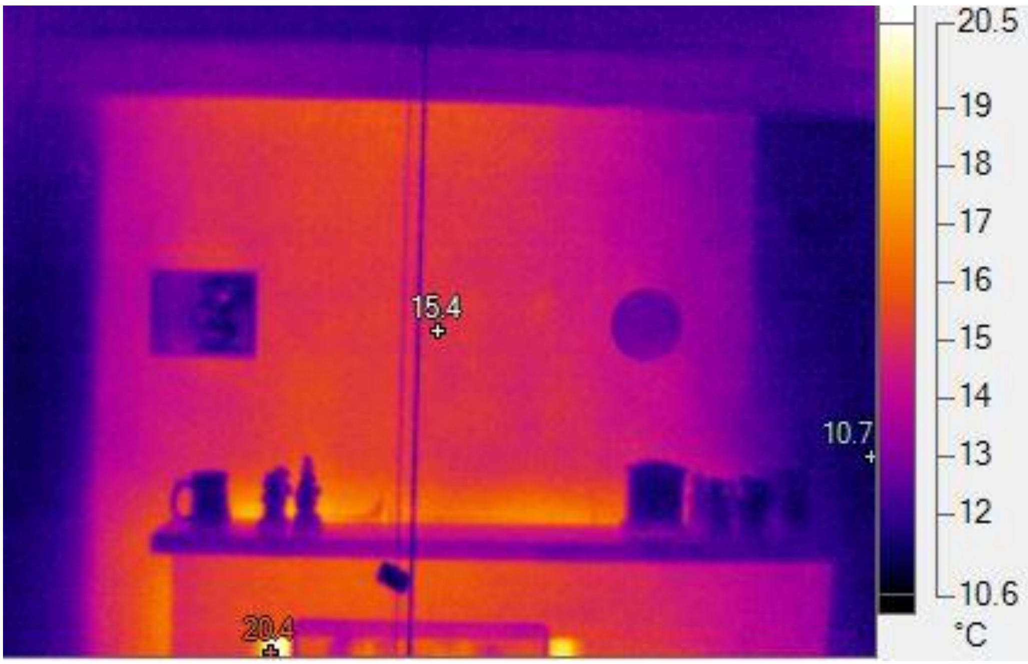


Figure 149: Experiment 4 day 4, 20 hours after the fire is out. Room centre temperature 9.6°C

7.1.3 Thermal mass of chimney breast

To calculate the thermal mass of the chimney breast is calculated by assessing the mass and specific heat capacity of the brickwork. On the inside of the chimney the temperature of the flue gasses can be estimated from published values. Fishenden took measurements at ceiling level of the chimney flue gas temperature, her maximum flue gas temperature for a similar fireplace with no damper restriction is 51.1°C (Fishenden 1925, 116). BCURA figures give 68°C (Venables 1957a) and Post War Building Studies reports flue gas temperatures between 60°C and 88°C (Post War Building Studies 10 1945, 44). The room temperature is known, and therefore the temperature of the brickwork can be calculated using its U-value. With the U-Value of a 4" brick as 3.3 W/m^2K (without plaster) and with the chimney heat area and output the same as calculated earlier in Chapter 7, the average flue gas temperature is likely to be 50°C above air temperature of the room. From this figure, the likely stored heat of the chimney breast may be calculated. The area of the chimney breast is required for this calculation and is given in Table 6.

Chimney component	Area (m^2)
Chimney breast downstairs (front)	2.89
Chimney breast downstairs (back)	2.89
Chimney breast upstairs (back)	1
Chimney breast upstairs (back)	1
Chimney breast sides (right)	0.091

Chimney breast sides (left)	0.091
Total	9.6

Table 6: Area of chimney breast.

Given a chimney wall thickness of 0.102m, the volume of chimney breast substance is:

$0.102 \times 9.6 = 0.98m^3$

Thermal energy is stored as sensible heat in the brickwork. This may be calculated using the following formula (Engineering ToolBox 2009):

$q = V \rho \, cp \, dt$

$= m \, cp \, dt$

where

q = sensible heat stored in the material (J)

V = volume of substance (m^3)

ρ = density of substance (kg/m^3)

m = mass of substance (kg)

cp = specific heat of substance (J/kg°C)

dt = temperature change (°C)

Density of brick 1969 kg/m^3 with a specific heat of 921 j/kg°C and an energy density of 1813kj/m^3°C

Substituting room air temperature 20°C and the flue gas temperature 50°C

$q = (0.98m^3)\ (1969\ kg/m^3)\ (921\ j/kg°C)\ ((50°C-20°C))$

$=53315400.6\ J$

$53315400.6J = 2.777778 \cdot 10\text{-}7kWh = 14.8kW$

Appliance efficiency

Researching the impact the fire has on the environment inside the building has delivered figures which may be utilised to calculate the overall appliance efficiency and produce a simple cost analysis. The overall efficiency of the appliance in situ at Rhyd-y-Car No.6 is 25% for radiant room efficiency and 8.5% for chimney heat gain=33.5%. The other houses on the row with internal chimneys probably sit between 42%-48% overall efficiency.

7.1.4 Cost analysis

- For a simple cost analysis for Rhyd-y-Car No6, at £8.50 per 25kg of house coal, this breaks down to 13 pence per useful kW. The banked in fires on average burn 89.33 kg coal a week banked in. The fire running time is 100 hours, this breaks down as 0.89kg coal/hour, which equates to 30p/h over the period as a whole.
- Daily fires burned 74.5kg over the week (on average). 16 hours of fire running a day, gives 64 hours a week. 1.16kg coal/hour, which equates to 39p/hour.
- If the cleaners light the fire at 7:00 and it is out at 17:00 then the fire costs about £7.02 a day to run giving 54kW of useful heat over ten hours at usual burning rates (5.4kW/h).

As the thermal mass has been shown to be effective at keeping a stable RH environment throughout the night without a banked in fire, it would be cheaper to run the fires not banked in. It is interesting to note that the overnight banked in fire running costs are less than the daily lighting regime due to the slumbering fire lowering the average fuel consumption. It is a possibility that to lower fuel consumption, aspects of the method to bank the fire could be utilised in the day. When the fire is burning well, adding a layer of small coal/ashes would slow combustion but this would require further measurement of the impact of this on the environment in the room.

Carbon Emissions

From the fuel consumption the CO_2 emissions may be calculated. If bituminous coal is taken to have a CO_2 content of 2.38kg per 1kg (engineering toolbox)

- Per useful KW

  If the overall appliance efficiency is taken at 33.5% and then 400g of coal are required per useful kw, giving 0.95kg CO_2/KW useful heat.
- Banked in fires burned 89.33 kg coal a week

  89.33X2.38=212.6kg CO_2
- Daily fires burned 74.5kg over the week

  74.5X2.38=177.31kg CO_2

Overall building heat loss

SAP test results give a total heat loss for building fabric, which may be seen as W/K, K being thermal conductivity based upon the temperature difference on each surface. Here it is the difference between inside and outside temperature (See appendix 2, Lannon 2019):

213.1 W/K

So if the indoor temperature is 20°C and the outside is 0°C then the heat loss is:

213.1W x 20ºC= 4262 Watts

Experiment 5 day 4 at 19:00 the outside temperature was 4.9°C and the indoor air temperature was 14.5ºC, giving a K of 9.8°C.

9.82C X 213.1W/K = 2091.6 Watts.

If a winter scenario of -2°C is calculated for, and the indoor temperature is required to be 18ºC:

20 X 213.1W/K = 4262 Watts.

This scenario is within the limits a lit fire to achieve, as displayed earlier. However, the ability of the stored or latent heat in the chimney breast to mitigate against this level of heat loss is not possible. However, the figures to calculate the heat loss would have included the wall that makes up the chimney breast. This is in fact passing heat to the room, so would lessen the W/K value. Similarly, if the next-door house were heated, the W/K value would be less again, and further to that, if the walls are above air temperature the general thermal mass of the walls will mitigate against initial heat loss from the air to a certain degree. It is unfortunate that no accurate calculations may be made for this, but if further studies were to be carried out then the utilisation of several infrared cameras facing the surfaces of the room would provide accurate data from which one could calculate the length of time the thermal mass took to cool. Heat flux plates could also have been used for measuring the heat flow in the wall, and are used for measuring U-values laid out in BS ISO 9869-1:2014. The only data for this in the present study comes from the chimney breast wall of the house and the length of time it remains warmer than air has been discussed earlier in this chapter. This is relevant when thinking about the external air entering the building.

Summary

The experiments confirmed that when the open fire was in use it acted as a ventilator as well as heat-emitter. It should be taken into consideration that an open fire will constantly replenish the air in the room with new air. The experiment showed that without a banked in fire overnight the room was drier and a small, slow burning fire, induced an intake of external air whilst not offering enough heat to mitigate against a corresponding RH rise.

One of the most overlooked aspects of the open fire has been its heat output from the chimney breast and its thermal storage capacity. This investigation found that an internal chimney can add 17% to the radiant efficiency of the fireplace and offer 1.6kW. These results were encouraging but are dependant on room temperature, as the flue gasses from an open fire are so heavily diluted by additional air they are not at a high temperature. Therefore, they do not exceed room air temperature greatly and thus the heat output per square metre of chimney breast is not large.

The potential for stored heat within the thermal mass of the chimney breast was calculated at more than 14kW, a seemingly high figure but the heat would not be conducted in its entirety into the room, some of it is lost via the rear wall of the chimney. Once a fire is allowed to go out, the cooling of the chimney breast causes a reduction of heat output over time. Based on the experimental data, a logarithmic curve would suggest that over a 24 hour period, almost 7kW was emitted by the chimney breast into the room with the first 6 hours providing 4.4kW. This is a figure half that expected when calculating the potential heat that is stored in the thermal mass, but with losses to the outside and to air going up the chimney the figure is logical and is significant for the environment in the room and informs on best procedure for how to treat the fire at the end of a day as the building is closed.

The Egerton report (Post War Building Studies, Heating and Ventilation of Buildings, 1945) states that traditionally built dwellings (solid walls) require continual heating even at background level to expel water vapor from the building fabric and guard against condensation. These experiments have shown this to largely be true, but that the residual heat in the thermal mass of the room is enough to maintain a low RH throughout the night, and that the only benefits from overnight banking of the fire would be the human comfort levels. If continual heating is defined as all day, every day, but not all night then it may be said that it is necessary to have continual heating for solid wall buildings.

This is reflected in the building enthalpy, at K+5°C in 90%RH conditions at 0°C, 5°C and 10°C give under 65% RH inside with the same air from outside. The relatively low background heat in the thermal mass has a large impact on RH. The use of relative humidity is standard practice in conservation for recording environmental conditions in buildings, however, due to the nature of the temperature differentials apparent between internal and external conditions, and air ingress to the inside of the building, there is merit in the use of specific humidity alongside relative humidity. This would be of benefit for future studies to include.

The thermal mass of the building takes a great deal of time to reach its maximum thermal inertia. A symptom of short period heating is the building quickly returning to being cold with high RH as soon as the heating is removed/reduced, suggesting that only the surface layers of the walls and floor are initially warmed and that the bulk of the mass requires much longer to warm up.

Utilising the 3D graphs and thermal images, the rate at which individual components of the room respond differently to the heat output. The floorboards that comprise the ceiling are the first to warm up, as they gain some of the highest levels of direct radiation (Figure 94 - Figure 95). The walls are next (not including chimney breast) and the floor to some degree, though due to conduction with the earth this quickly dissipates (Figure 110). The radiant heat raises temperature within the room to comfortable levels within a short space of time. For the daily fire lighting cycles refuelling and the dip in radiant heat output, suddenly creates a higher RH environment (Figure 126 - Figure 130) but overall there is a trend of decreasing average daily humidity and increasing average temperature over the first three days of the fires being run, but this does not happen on the fourth day. The chimney breast and fireplace warm up within 6 hours of the fire being lit but the building (particularly the walls) take between 48 and 72 hours to reach their optimum for thermal mass contribution to heating the room. The banking in of fires appears to make little difference to this pattern and do not offer advantages for creating a more even RH, likely having a negative effect. The daily lighting of fires creates a more even environment overall. Residual warmth in the building fabric overnight is more than enough to cope with the issues of condensation and mould growth overnight, with RH being under 60% at 08:00 and fewer RH fluctuations and a more even drier atmosphere across the whole room. If one lived inside the cottage, waking up to a warmer room and not having to light the fire would be of benefit. However, for collections this warmer environment offers no appreciable benefit, especially considering the RH is in a more even state. In contrast, the banked in fire cycles produce high RH levels of above 70% at 08:00 in contrast to the high of 60% RH from a non-banked fire (Figure 99 and Figure 111). As the museum is open every day of the week, a cooling period that would normally occur over a weekend when fires are not lit is avoided.

It has been noted that figures for solid wall U-values are likely better than previous calculations have given, and that the transmittance of heat through the walls may not be as great as SAP calculations suggest (Rd**SAP** 2012 version 9.94; Baker,2011,II). This may, to a certain extent, be an explanation for why the energy within the thermal mass of the building lasts longer than theoretical calculations would have suggested.

It is worth noting that the fire can create extremes of low RH, the high levels of radiation directed forward and upwards from the fire create high temperatures and very low RH levels, under 30%, in these areas (Figure 94). These extremes, and fluctuations are of consideration in the next section when looking at the response of timber objects to them.

8 Wood response experiments

Rationale

The detailed study of the use of fires in daily or continuous burning cycles identified the range of RH values that these practices may produce during winter months and their distribution within the room. Of primary concern is the effect of these RH values on organic materials that absorb and desorb water. Wood is the obvious organic to consider, as it is extensively used in furniture. Its rigid cellular structure, anisotropy and various orientations within the construction of furniture can result in physical damage from absorption and desorption of water. Of primary concern is the rate at which water is adsorbed and desorbed relative to the range and rate of RH fluctuations that occur. The data collected from the heating experiments can be used to investigate this with the results offering guidance on where furniture can be placed relative to the heat source to minimise risk of damage.

Environmental fluctuations and the rate at which the furniture absorbs/desorbs moisture relates to the cell structure of the timber, the type of timber, the cut of the timber, and its finish, as discussed in chapter three. To understand the rate at which timber from historic furniture reacts to water vapour in the air a series of experiments were devised. In particular, to investigate a relationship between the environmental conditions recorded from the historic heating experiments, and historic timber with its original coatings.

A 2018 paper by Luimes et al. researched the response of oak cabinet doors to RH changes. Using strain gauges it provided results for strain across joints and other areas of a reconstructed oak-cabinet door exposed to different environmental conditions within a climatic chamber. Similarly, the dimensional changes of furniture when responding to RH were recorded by Knight and Thickett (2017). They utilised a linear variable differential transformer to measure small dimensional changes to the crack width of a piece of furniture in a fluctuating environment within a historic building.

Melin et al. (2017) researched the response of wood to RH and temperature changes simulating indoor environments of historic buildings and museums, specifically the depth to which the changes could be recorded inside the sample, producing moisture gradients for the timber. This study utilised small RH and temperature sensors that were inserted into a hole in the sample, which was plugged with the same wood. One surface of the sample was exposed, the remainder coated with aluminium foil. The data recorded by the sensors was that of the air inside the cavities within the sample, rather than the actual moisture content of the wood, which was later calculated.

This PhD seeks to determine the response of the historic timber samples that retain their original coatings, and the covering of the faces with aluminium foil would be a way to ensure that moisture could only access the sample through the exposed surface. However, aluminium foil lacks the ability to move with the sample, so an alternative was found with two-part silicone, which offers superior flexibility.

It is possible to calculate the dimensional change of timber by knowing its moisture content. There are several methods to calculate this, one of the most accurate is the distillation method. However, this required the destruction of the sample and was therefore rejected, as the sample would be required for further testing (Desch et al. 1996, 84).

Another is the oven dry method. This involves drying the samples in an oven at 60°C for several hours, then raising the temperature to 105°C and leaving at that temperature. The sample is then weighed and returned to the oven. this is repeated until the difference is less than 0.2% (Desch et al. 1996, 83).

Arends et al. (2019, 104) utilised a gravimetric method of analysis for recording the relationship of an oak sample to RH, this was part of a paper researching the response of panel paintings to environmental conditions inside historic buildings and museums. The moisture content of the timber can be calculated by knowing its mass, and its dry mass. This use of balances was considered a practical methodology for recording the moisture gain and loss to samples through environmental changes set by the climatic chamber. After the experiments the dry mass was then be calculated utilising the 'oven dry method', and this was used to calculate figures for moisture content of the sample. This was then related to dimensional change and which was used to consider potential damage to furniture.

In order to examine the impact of environments created by open fires on the moisture response of wood, several sets of experiments were devised to:

- Determine the equilibrium moisture content of historic wood samples at various RH values to create a standardisation curve for the experiments that followed.
- Determine moisture gain loss from historic wood samples in the fluctuating RH conditions fires produce in a room.
- Determine the response of wood to equal and opposite fluctuations in RH to assess how surface coatings influence adsorption and desorption of water.

For all the experiments, historic oak timber samples were selected from pieces of furniture and cut into regular sizes. These were used to investigate the impact of original coatings on moisture sorption/desorption.

Sample sets

8.1.1 Sample origins

Samples were selected as advised by Senior Furniture Conservator, Emyr Davies at St Fagans (Figure 150). These were all plain sawn oak, one is a late Victorian/Edwardian dressing table, one is a drawer front from a chest of drawers c.1800 and another is a back panel also c.1800. Samples were straight grained, tracheids more or less parallel.

Figure 150: 1) Sample 1, Later Victoria/Edwardian dressing table top, oak; 2) Sample 2, Georgian drawer front, oak; 3) Sample 3, Georgian backboard, oak.

8.1.2 Characteristics of sample coatings

Samples 1 and 2 have been coated during their working life. Sample 3 had no obvious coating, therefore was utilised as a control to assess the response of uncoated timber.

Fourier-transform infrared spectroscopy (FTIR) is a suitable method to identify organic polymer structures due to its ability to detect functional groups by their molecular vibrations (Stuart,B.2004,2). The unique pattern of a material in the complex fingerprint region of the spectrum makes it possible to designate the resulting peaks to a particular material. Samples of the coatings from Samples 1 and 2 were taken with a clean scalpel blade for analysis.

Spectra were acquired using Perkin-Elmer Spectrum One FTIR-ATR with a diamond crystal in the mid-IR region between 4000-450cm^{-1}. The crystal was cleaned with industrial methylated spirits (IMS) to avoid contamination before analysis took place. To avoid atmospheric interference the background was collected in Perkin Elmer Spectrum 10 (30 scans) and subtracted from subsequent readings. The sample was placed to cover the window of the crystal and the pressure arm was applied to ensure close contact between it and the crystal to minimise background noise. 30 scans were collected to minimise background noise. No software manipulation of the spectra was undertaken.

No clear results were obtained from Sample 1 but Sample 2 produced a clear spectrum (Figure 151; Table 7).

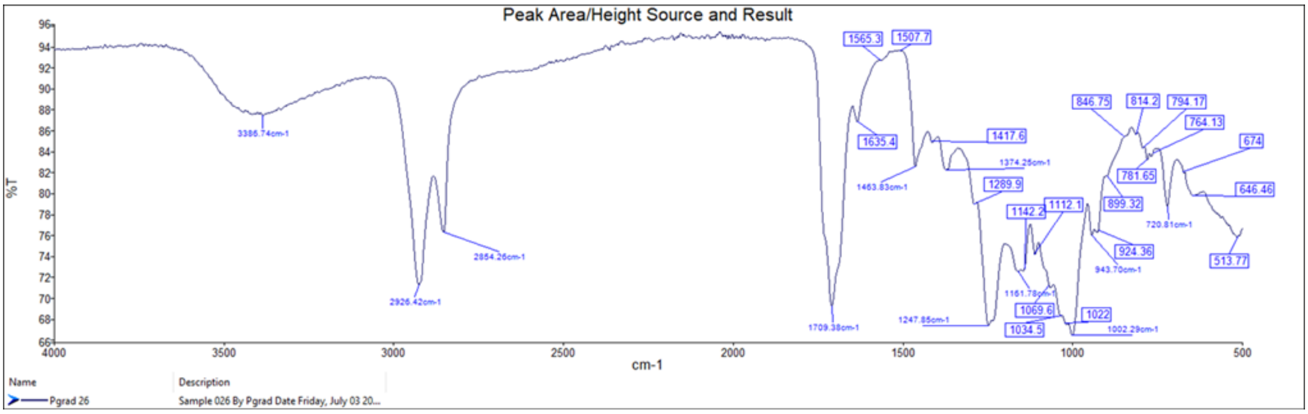


Figure 151: FTIR of coating from Sample 2.

Wavelength	Assignment
3385	OH
2926	C-H
2854	C-H
1709	C=O
1635	C=C
1463	C-CH_3
1417	CH_2
1374	C-CH_3
1289	
1247	O-H/C-O
1161	O-H-C-O
1142	
1112	O-H/C-O-C
1069	C-C
1034	C-O
1022	C-O
1002	C-O
943	C-CH_3/C=C-H?
924	C-H/CH_2
899	
846	

814	
794	
781	
764	
720	C-H, C=C-H? CH_2 rocking
674	
646	

Table 7: Showing spectra peaks from FTIR analysis of coating from Sample 2.

The spectrum displays a broad hydroxyl O-H band around 3385cm^{-1} and aliphatic symmetric and asymmetric CH_2 and CH_3 groups at 2926cm^{-1} and 2854cm^{-1} respectively. C=O stretching is present at 1709 cm^{-1}, indicating the presence of ester groups in the polymer structure with a C=C shoulder at 1635 cm^{-1} (Sarkar, Shrivastava 1997). CH_2 and CH_3 asymmetric and symmetric bending/deformation groups are present at 1463cm^{-1} and 1374 cm^{-1}as well as a weak CH_2 signal at 1417cm^{-1} (Brajnikov et al 2018). O-H and C-H groups are present at 1161cm^{-1}, 1112cm^{-1}. 1034cm^{-1} and at the doublet peak at 943cm^{-1}-924cm^{-1}. C-H out of plane bending can be seen at 720 cm^{-1}. Stretching C-O bands are present at 1247cm$^{-1,}$ 1034cm^{-1}, 1022cm^{-1} and 1002cm^{-1} and stretching C-C band at 1069cm^{-1} (Casanova *et al.* 2016).

The position of the peaks display a good agreement with a lac resin (Figure 152). Lacs are complex natural polymers that are made by the insect Kerria lacca. The insect is a parasite to a range of host-trees and leaves secretion on twigs. The coated twigs are mixed into stick-lac and is then refined to different levels to produce seed-lack or shellac (Rivers, Umney 1974). While it is difficult to differentiate between the lacs using FTIR (Derry 2012) it is likely that shellac has been used on the drawer front to varnish the surface using the French polish method consistent with the methods of the period.

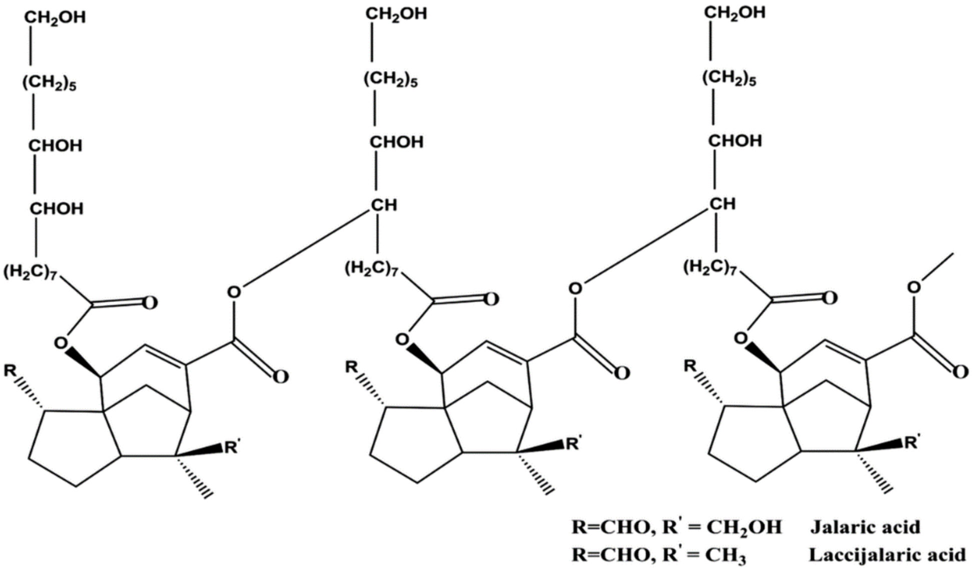


Figure 152: Structure of lac.

While the exact composition of the lac will vary with the host tree of Kerria lacca, shellac can broadly be defined as a mixture of soft and hard resin (70-80%), wax (6-7%) and dyestuff (4-8%) (Tamburini et al. 2017). The soft (30%) and hard (70%) resins are essentially differentiated by their molecular weights (Rivers,1974) but have very similar composition of different mono and polyesters of hydroxyaliphatic acids. These include primarily a mixture of 9,10,16-trihydroxyhexadecanoic (aleuritic) acids, 6-hydroxytetradecanoic (butolic) acids and sesquiterpenoid acids (jalaric and laccijalaric) with other minor compounds (Tamburini et al. 2017).

The dyestuff is primarily made of laccaic acids (A,B,C and D oxy-anthraquinone) and produces the range of yellow-orange colours that is normally associated with shellac due to the chromophore group within the structure. Wax will influence the clarity of the final resin, as light will interfere with the long polymer chains present. The composition of the wax is reflected in the CH_2 and CH_3 stretchings, representing higher alcohols fatty acids and straight chain hydrocarbons (Sarkar 1997).

A Nikon Eclipse ME600 research microscope was used to record a cross section of the coating on Sample 2 (Figure 153). The cross section was produced from an offcut after the sample set from the drawer front was taken and was polished using grit 800 wet and dry paper and then a buffing pad. The picture shows the surface layer and the thickness of the coating, which is around 0.25mm.

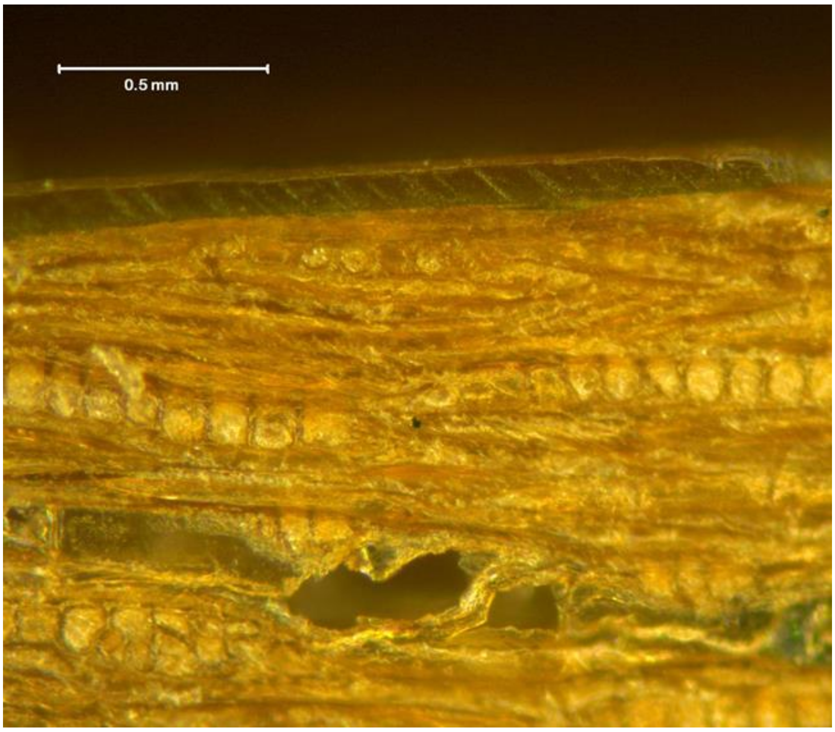


Figure 153: Microscope image of sample cross section from sample 2, showing the shellac layer

8.1.3 Sample preparation

The samples were cut into 7cm x 7cm squares (+/-4mm), the thickness of the wood being left to retain original finishes (25mm thick Sample 1, 19mm Sample 2, 12.5mm Sample 3). Nine samples from each piece of wood were used, in total there were 27 samples (Figure

154; Table 8). So that the impact of the original finishes could be measured, a coating was applied to the sides of the samples, and also the rear or front face. Two-part 1:1 silicone (Platsil-gel 10 from Mouldlife Limited, Polytek Development Corp) was used as the coating as it is impervious to moisture and flexible, allowing for sample movement. Out of each sample set, three were coated to leave the front (polished face) of the sample exposed, three to leave the rear (interior of furniture face) of the sample exposed. Three had both faces exposed, all samples had their sides coated with silicone. The sides of the samples were coated to simulate the fact that only the faces of the furniture are exposed to the environment. The end grain of timber is the most reactive to moisture and would make the test on the impact of the original coatings difficult to quantify.

Figure 154: Samples during coating with two-part silicone.

Sample	Timber source	Overview	Condition	Dimensions (mm)
1 A,B,C	Dressing table top. Late Victorian/ Edwardian.	Shellac finish on the room facing surface, internal finish woodstain.	Shellac face and stained face exposed. All edges covered.	70x70x25
1 D,E,F			Shellac surface exposed, all other faces covered.	
1 G,H,I			Stained face exposed, all other faces covered.	
2 A,B,C	Chest of drawers, draw front. Georgian.	Shellac finish on the room front of the drawer, internal finish woodstain.	Shellac face and stained face exposed. All edges covered.	70x70x19
2 D,E,F			Shellac surface exposed, all other faces covered.	
2 G,H,I			Stained face exposed, all other faces covered.	
3 A,B,C	Oak back board. Georgian.	Woodstain on front and rear face.	Both stained faces exposed.	70x70x12.5
3 D,E,F			One stained face exposed, all other covered.	
3 G,H,I			One stained face exposed, all other faces covered	

Table 8: Overview of sample source, dimensions and faces coated.

Overview of experimental methods

An outline of the method for each experiment is given below (Outline of experiment numbers and description. Later in the chapter each experimental method is offered in detail.

Experiment	Title
7	Equilibrium Moisture Content (EMC) reference experiment
8	RH fluctuations experiment
9	Balance fluctuations experiment
10	Coatings experiment
11	Radiant heat experiment

Table 9: Outline of experiment numbers and description.

8.1.4 Experiment 7: Equilibrium Moisture Content (EMC) reference experiments

Initial EMC of the wooden samples was determined for a range of RH values to provide a calibration curve for the experiments with fluctuating RH. The mass of the samples was dynamically recorded as they responded to RH and temperature set points. The set points for the environmental conditions were initially set at steady reference points so the moisture content of the samples would be known at particular RH.

8.1.5 Experiment 8: RH Fluctuation experiments: heating sequences

Thereafter, the climate chamber was programmed to repeat a 24 hour heating sequence (temperature and humidity) from within the cottage when heated by the banked open fire, thus giving the response of the object to the environment. This was selected before detailed three-dimensional analysis of the data showed that non-banked in fires likely provide a better environment for the objects.

8.1.6 Experiment 9: Balanced fluctuations experiments

After the heating sequence experiments a new fluctuation RH sequence was utilised, with a larger sample set. These fluctuations involved three and six hour stepped changes in RH on repeat. This allowed for interpretation of the response of objects to many fluctuations of a large magnitude, which can be related to the use of intermittent heating in historic buildings. It also allowed for more accurate interpretation of the response rate of the samples to environmental changes.

8.1.7 Experiment 10: Coatings as moisture barriers

Investigating the response of wood with different original surface coatings utilised the mass change data from Experiment 9 with three and six-hour RH fluctuations and related these to the presence or absence of original shellac coating on the samples.

8.1.8 Experiment 11: Radiant heat experiment

The climatic chamber was set to a RH of 60% and 14°C. The sample was placed on a balance and then exposed to a set radiant temperature from a heating element, controlled with an electronic controller via a matt black thermocouple. This investigated low level background temperature, higher ambient RH levels and radiant heating, a scenario which is often found when heating traditional buildings with high thermal mass levels and radiant heating systems, such as open fires.

Experiment 7: EMC reference experiments

8.1.9 Experimental set up

Samples 1A and 2A were each placed on a Sartorius Secura 225D-1S Semi-Micro Analytical Balance (with a repeatability of 7E-05 grams and a linearity of 0.0002 grams) within a Binder KBF240 climatic chamber at (≤2 ± % RH and 0.1 to 0.5 ±°C) to record continuous gravimetric readings, logging mass dynamically every 2.5 minutes on a Microsoft Excel spreadsheet. The climatic chamber was maintained at 30%RH and 20°C until the mass of the samples stabilised at which point the RH was increased to 40%RH. The process was repeated in 10% increments to 60%RH. The remaining samples were stored in the same climate chamber to undergo the same equilibration process to 60%RH (Figure 155). The potential influence of vibration from the climate chamber on the balance readings was mitigated by a damping mat beneath each balance. Dataloggers (MadgeTech 101A ±3%RH ±0.5°C) inside the chamber recorded the humidity and temperature to verify maintenance of the RH and temperature set points during the study. Balance drift was tested with a 100gram weight with fluctuating environmental conditions for 25 days and found to be within ±0.002grams, (Appendix 3).

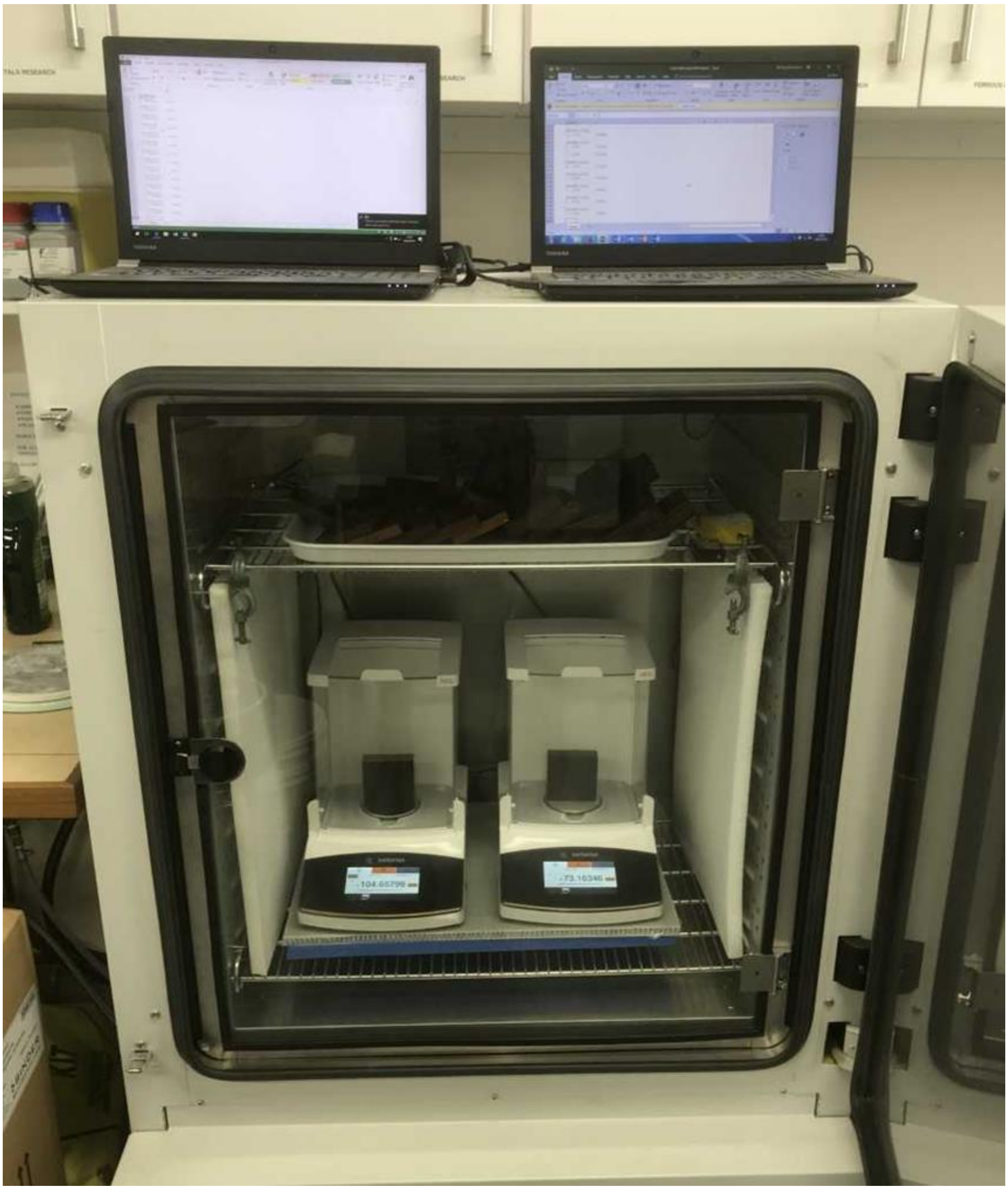


Figure 155: Experimental set up, Sample 1 and 2A in the climatic chamber on balances, with remaining samples above on tray.

8.1.10EMC reference experiment set points

The initial experiment recorded the static mass of the samples at different RH values to identify their EMC equilibrium point. This produced a reference scale of mass at the set RH points. The initial set point was 30% RH and 20°C (temperature was maintained at 20 °C for all the EMC RH set points). When the samples desorbed moisture to 30% RH, the humidity was increased to 40% RH, later 50%, the final set point being 60% RH. This period was broken by the necessity to stop the experimental run due to a laboratory refit (during the 50 to 60% RH range). This required the 60% RH samples to be equilibrated by placing them inside a sealed plastic container with silica-gel that had been conditioned to 60% RH.

8.1.11 Oven-dry method for sample moisture content

The oven-dry method was utilised after the experiment to determine the moisture content of the samples, the sample is weighed then dried in an oven at 60C for 24 hours to mitigate against case-hardening. Thereafter the oven is set to 103 +/-2°C and after 12 hours the samples are weighed and returned to the oven. Thereafter the sample is regularly weighed until the difference between the last weighing is less than 0.2% within two hours (Desch et al. 1996, 83; BSI 2002).

$$Mc\ (\%) = \frac{\text{Mini}-\text{Mod}}{\text{Mod}}\text{x}100$$

Where: M_{ini} = Initial mass of sample (g) and Mod =Oven-dry mass of sample (g)

Oven dry masses, Sample A1; 66.5166G Sample B1; 97.0906G

8.1.12 Results EMC equilibration tests

The initial observation of the results for sample 1A and 2A is length of time taken for the sample mass to flatline after an RH change (Figure 156 and Figure 157) and how small the mass change is. The response of the timber to the RH change is logarithmic and after the initial, near period of absorption the rate decreases to an extremely slow figure.

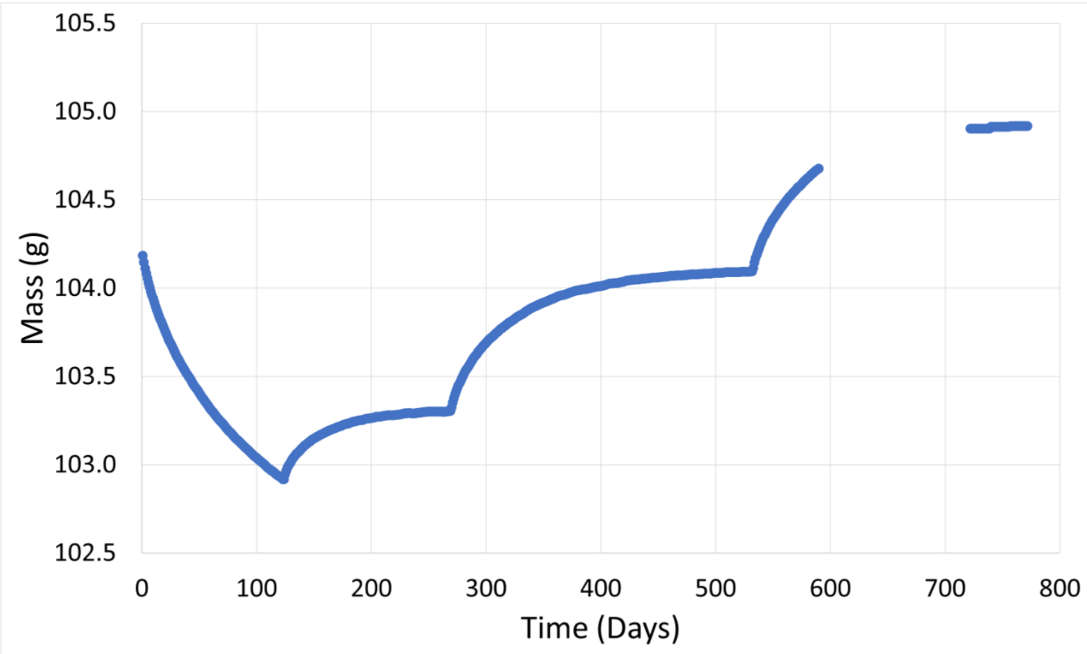


Figure 156: showing sample 1A mass from the ambient room RH to 30% RH, 40%RH, 50%RH, 60%RH.

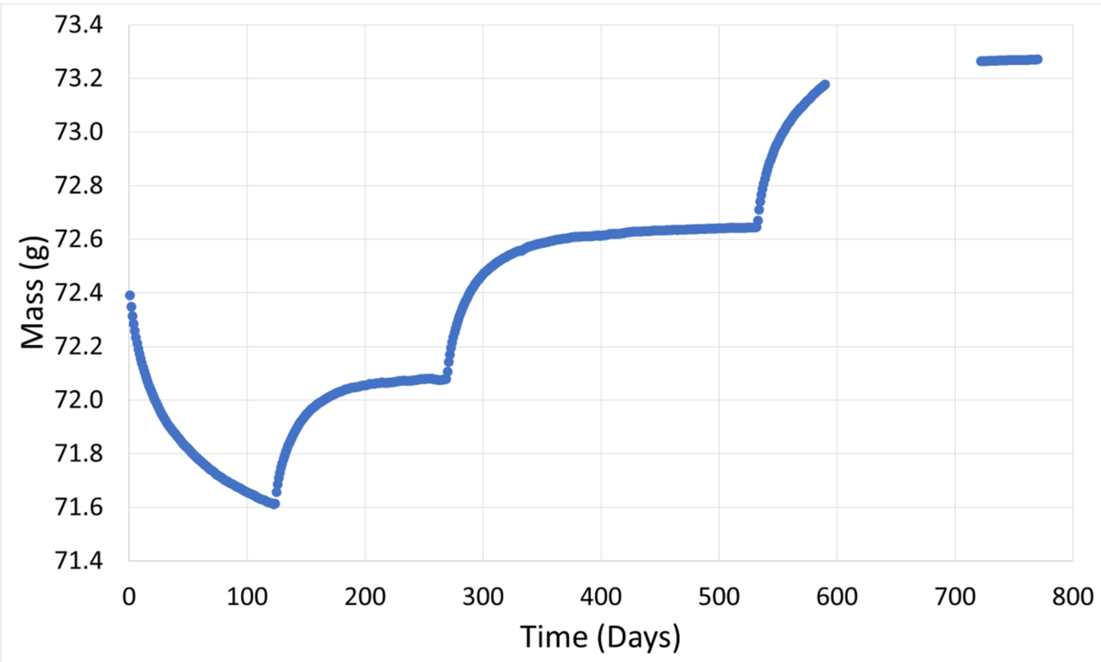


Figure 157: showing sample 2A mass from the ambient room RH to 30% RH, 40%RH, 50%RH, 60%RH.

During the 60% RH equilibrium run the laboratory was refurbished. The samples were taken out of the climatic chamber and kept in a stable environment with conditioned silica gel to 60%RH. After this period they were returned to the climatic chamber and balances. During this period out of the chamber, no mass were recorded. A line of best fit was utilised from the data before and after the lab refit.

8.1.13 Discussion

8.1.13.1 A method for identifying the attainment of Equilibrium Moisture Content

The mass readings of the samples show that moisture gain or loss slows down over time as can be seen by calculating the rate of change in mass as a percentage, both daily and weekly (Figure 158 and Figure 159).

The selection of a period of time between two masses is key. Over a day, there is a small a rate of change in mass making it difficult to visualise the overall rate (Figure 158). Using a longer period of seven days gave greater clarity, which can be seen in Figure 159.

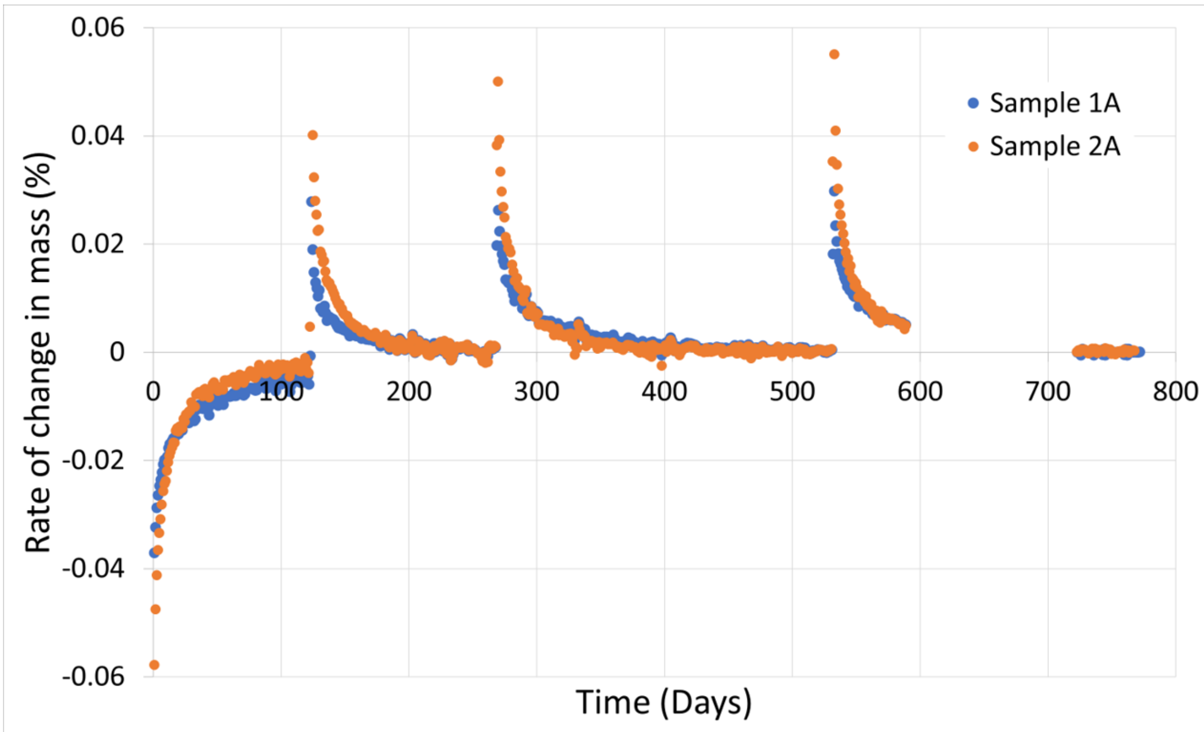


Figure 158: Daily rate of sample mass-change (%).

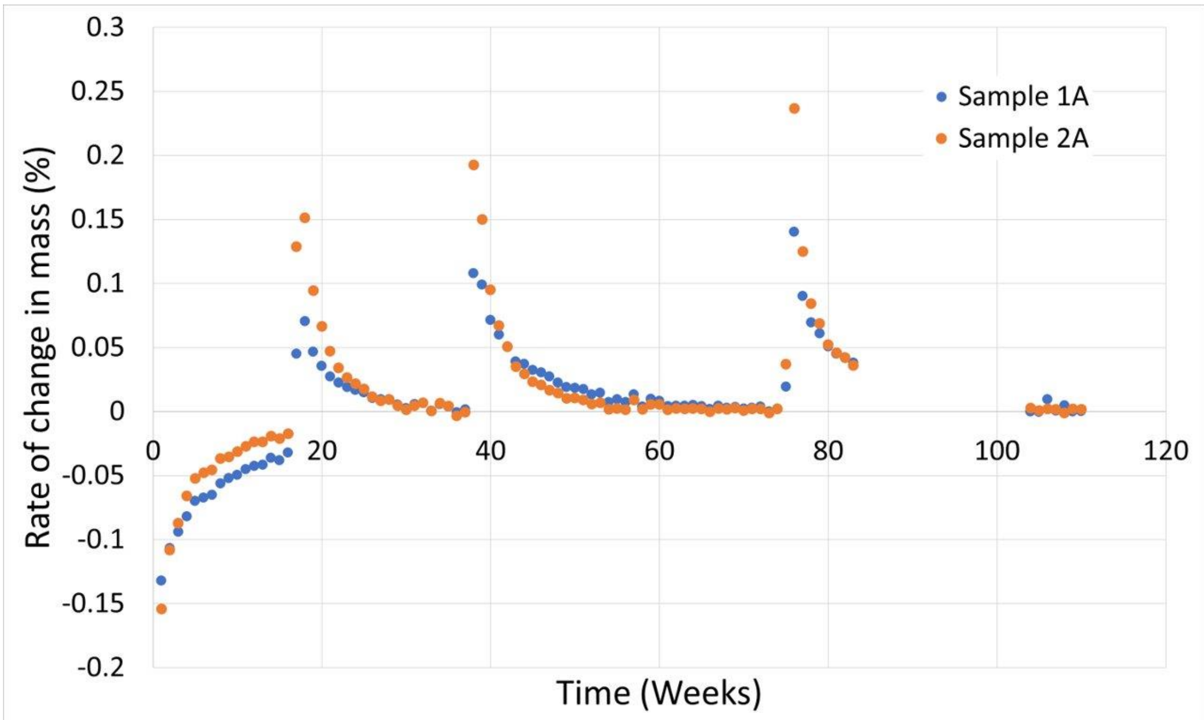


Figure 159: Weekly rate of sample mass-change (%).

The results of weekly rate of mass change is recorded as a percentage, with 0.02% being the value for determining end point for EMC.

Utilising the weekly rate of change method to identify the sample EMC for sample 1A at 50% RH (the longest run between RH changes) the time saved from the experiment as it stands would have been 20 weeks. This would have been 0.1% different from the figure as the experiment stands, and utilised the weekly rate of change identifier of 0.015%. It is suggested that for the future this might be the best figure to select.

Appendix 3 shows the drift of the balance with a 100gram weight, showing deviation of 0.002g. This gives a percentage error of 0.002%, which would have a negligible impact on results. Both samples respond in a similar manner.

8.1.13.2 Equilibrium Moisture Content of samples

The EMC for the following tables and graph were calculated using the 0.02% weekly rate of mass change to determine when a sample had reach equilibrium with its RH. The oven dry mass was then used to calculated the EMC figure and plot Figure 160 and produce Table 10 and Table 11. Columns (Table 10 and Table 11) show the time taken to reach the EMC, and also 90% of the EMC figure, 75%, and 50%. This shows the exponential nature of the curve impacts the time for timber to respond, and how the response is weighted to the initial period of RH change. Dimensional change has been calculated based upon 10cm, this was chosen as an easy figure to visualise, multiply, and add other figures to (for example, if the dimensional change from 30% to 60% RH is wanted then all figures can be added together).

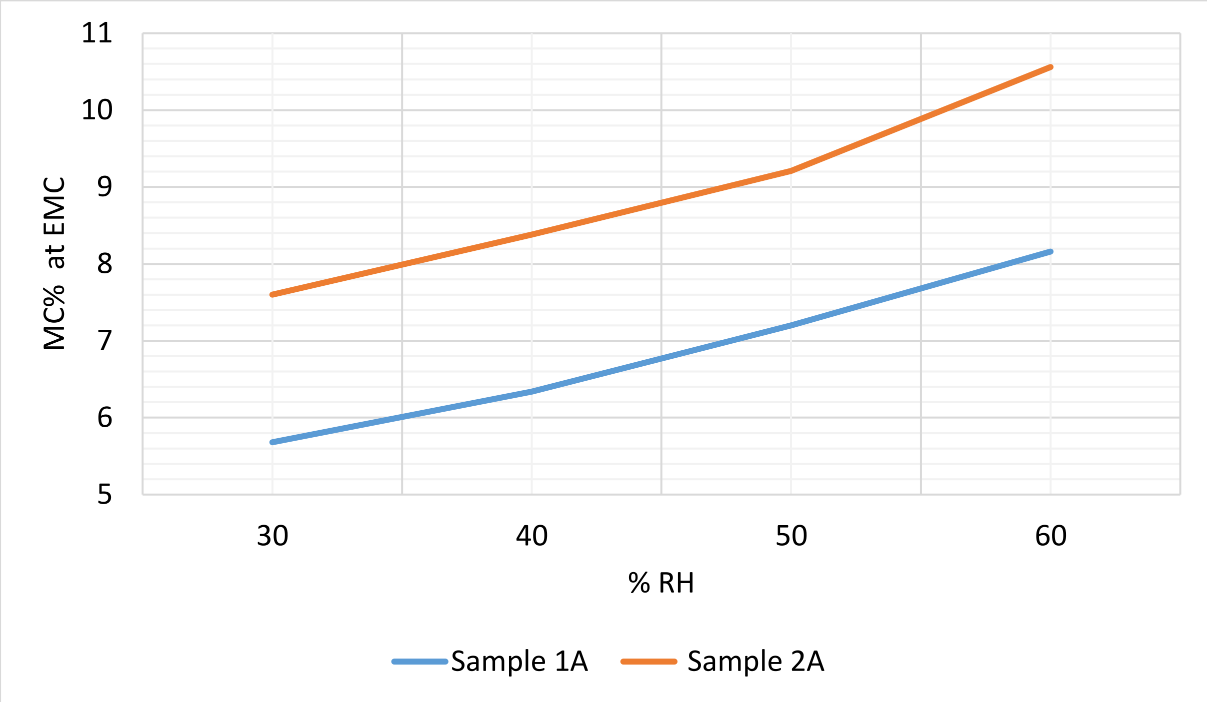


Figure 160: Equilibrium moisture content of timber samples 1A and 2A at 30, 40, 50 and 60% RH.

RH change	Time taken to reach EMC (days)	Time taken to reach 90% of total change (days)	Time taken to reach 75% of total change (days)	Time taken to reach 50% of total change (days)	Calculated total tangential dimensional change for 10cm sample
30% to 40%	50	36	24	10	0.12mm/10cm
40% to 50%	69	55	39	20	0.28mm/10cm
50% to 60%	196 days (Lab refit impact)	226	Estimate: 74	38	0.5mm/10cm Total overall dimensional change 30%-60%RH =0.9mm/10cm

Table 10: Time for sample 1A to reach EMC of RH points, and time taken to reach 90%, 75% and 50% of the total change. Showing the weighting to the earlier stages of an RH change.

RH change	Time taken to reach EMC	Time take to reach 90% of total change EMC (days)	Time taken to reach 75% of total change (days)	Time taken to reach 50% of total change (days)	Calculated total tangential dimensional change for 10cm sample
30% to 40%	56	38	23	12	0.26mm/10cm
40% to 50%	89	48	27	13	0.33mm/10cm
50% to 60%	197 (lab refit impact)	211	56	21	0.49mm/10cm Overall from 30 to 60% RH 1.2mm/10cm

Table 11: Time for sample 2A to reach EMC of RH points, and time taken to reach 90%, 75% and 50% of the total change. Showing the weighting to the earlier stages of an RH change.

8.1.13.3 Sample moisture content and dimensional changes

It is possible to calculate dimensional change of oak based on the moisture content of the timber and utilising a set of average dimensional change figures for a number of samples (Simpson 2001, 3-7). This will be useful for understanding the relationship between moisture and potential damage.

Formulae for calculating dimensional change of dry timber are given in Wood Handbook and based upon the dimensional change coefficient, which is calculated from the wet to dry shrinkage figures of specific tree species. Figures for European oak (*Quercus robur*) are not included in Wood Handbook, these are found in Wood Structure and Properties pp84,

(1998) and Conservation of Marine Archaeology, (1987) pp63 which provides respectively tangential 9.09% radial 5.04% and tangential 9.5% radial 4.9% from green to dry. These figures are utilised to create the 'dimensional change co-efficient' of *Quercus robur* from Wood Handbook pp3-9 and pp12-15 as tangential 0.00230 and radial 0.00423.

Thus utilising the formula given in Wood Handbook:

$\Delta D = D_I[C_T(M_F - M_I)]$

ΔD is change in dimension,

D_I dimension in units of length at start of change,

C_T dimensional change coefficient tangential direction (for radial direction, use CR),

M_F moisture content (%) at end of change,

M_I moisture content (%) at start of change.

Example calculation:

For a 10cm sample, moving from 7% MC to 9% MC (30%RH to 60%RH) (Utilising data from historic sample experiments Fig 158) this would mean:

10 [0.000230 (2)]

10 [0.000460]

0.00460cm

Which is 0.46mm per 100mm (tangential).

Experiment 8: RH fluctuations experiment

A series of experiments were developed to investigate the impact of RH fluctuations on timber objects. The frequency and magnitude of fluctuations is important in understanding timber response. This investigation simulated:

- fluctuations designed to mimic the environment from the heating experiments and the impact of coatings on timber samples in relation to their moisture uptake.
- fluctuations that are regular and balanced.

8.1.14 RH and temperature fluctuations based on data from fire experiments

A programme for the climatic chamber was developed to mimic the environmental conditions inside the house when heated by the banked in open fire and was repeated automatically every 24 hours (Figure 161). The set points reproduce an average daily RH pattern for the open fire for banked in experiments, showing the initial dip in the morning when the fire is lit, a small rise when refuelled and another repetition of this twice until the banked in period of the night (see Chapter 6 for heating experiment results).

Samples 1A and 2A from the initial equilibrium set points experiments were utilised for the open fire fluctuations test. The method was the same as detailed in 7.2. They were previously equilibrated at a 60%RH equilibrium.

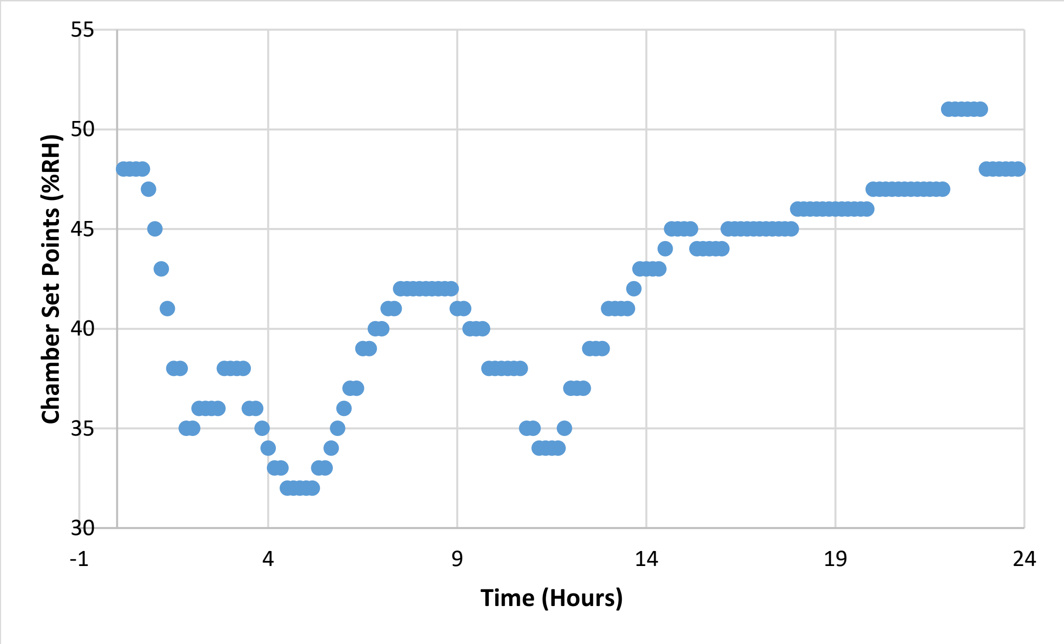


Figure 161: Climatic chamber set points for banked in fires model run over 24 hours and repeated thereafter.

8.1.15 Results

As the samples were equilibrated to 60% RH when the new RH pattern started, their initial response was moisture loss, as might be expected at the start of a fire lighting regime following an unheated period (Figure 82). Their mass decreased overall, but with small periods of mass gain in every daily cycle, representing the RH spikes from the daily fluctuations (Figure 163 and Figure 164). After four days the samples began to slow their mass loss and the daily spikes became more visible, as the daily loss of moisture lessened. It is possible to pinpoint the time of day and burn cycles from the peaks and troughs of the mass. After 40 days the daily mass loss was beginning to equal that of the mass gain overnight to produce a near repetition of the day before. It was at this point the experiment was ended.

The moisture content in sample 1A goes from 8.17% at the start of the experiment to at the end a daily fluctuation between 7.25% and 7.21%. Overall a drop of 0.9%, which is replicated in sample 2A which drops from a starting weight of 10.23% to an end weight which fluctuated with the RH pattern to between 9.10% and 9.01%.

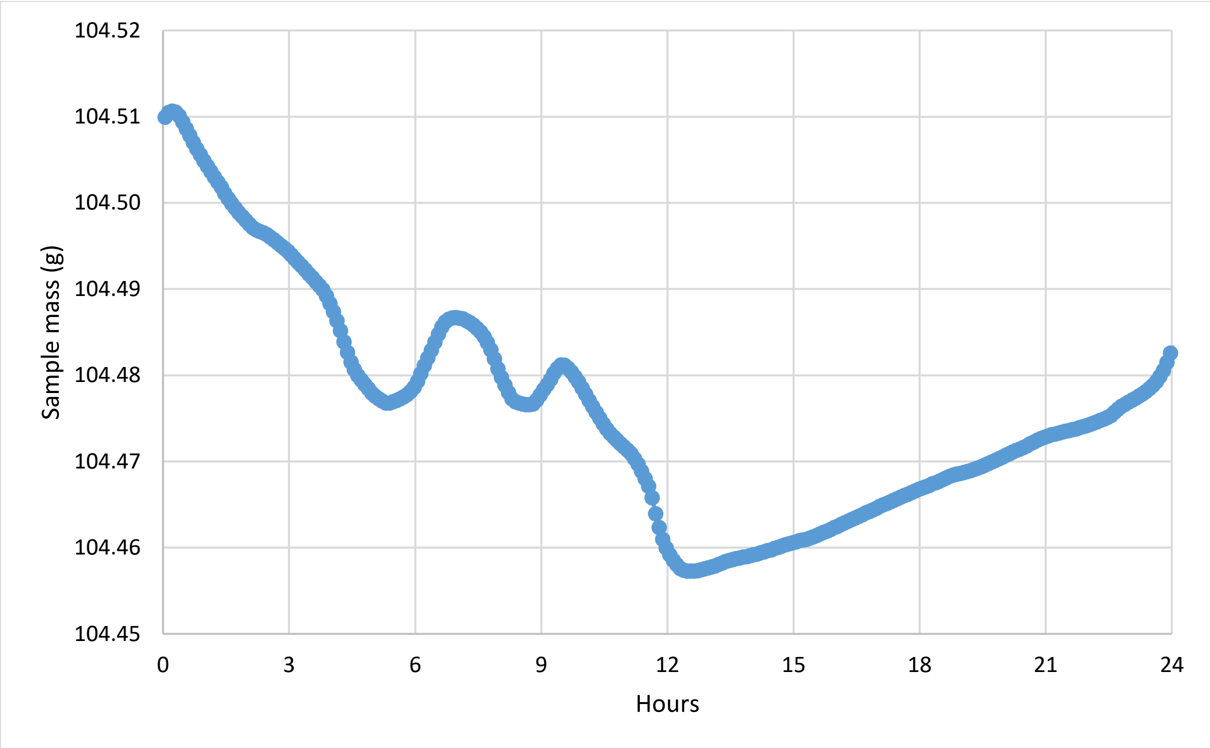


Figure 162: A close up of a section from Figure 163, sample 1A weight during one of the 24 hour fluctuation RH cycles, showing how closely it follows the RH pattern in Figure 161.

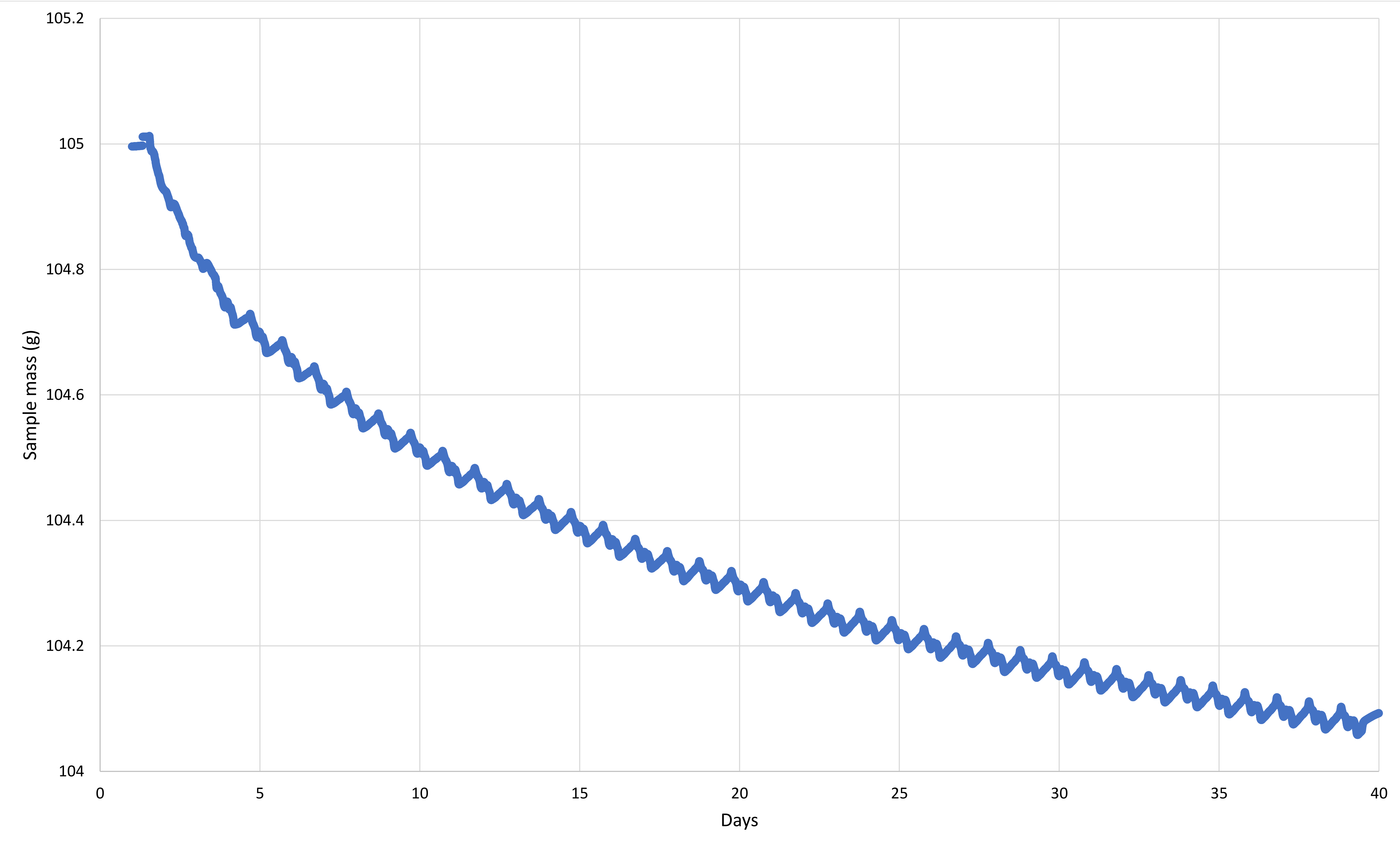


Figure 163: Sample 1A, mass of sample responding to daily RH fluctuations.

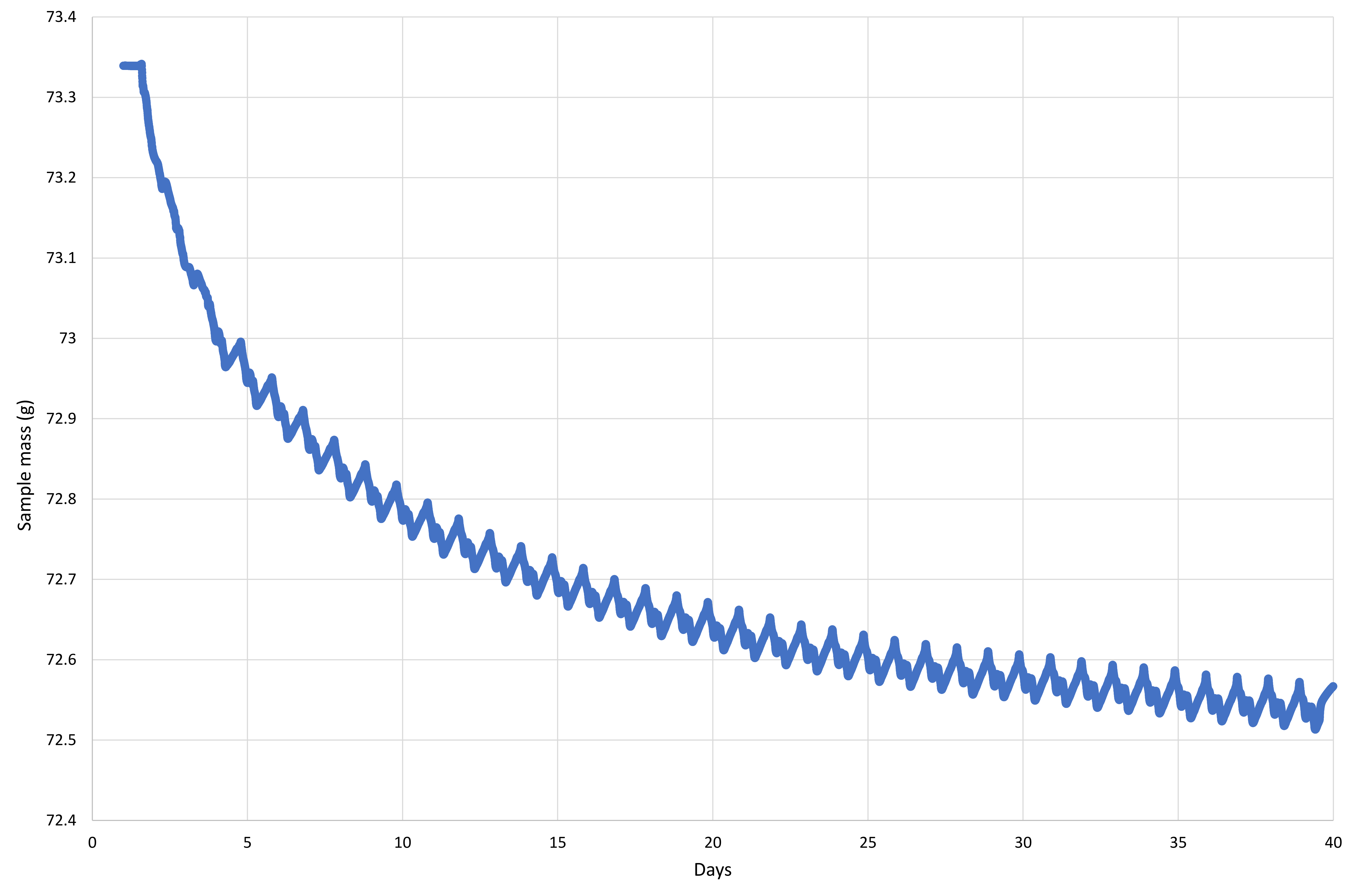


Figure 164: Sample 2A, mass of sample responding to daily RH fluctuations.

8.1.16 Discussion

By the end of this experiment, the samples appeared to be approaching equilibrium. Minor daily fluctuations which correspond to the climatic chamber set points are visible (Figure 163 and Figure 164). Taking the daily set points for the climatic chamber and averaging them gives a figure of 41.5% RH. Comparing this to the end sample mass, sample mass of 1A is 104.1g which using Figure 160 indicates an EMC RH of 46%. Sample 2A weighs 72.55g, the EMC of the sample is 9.07%, which using the EMC reference data in Figure 161 is an RH of 42%.

It seems that Sample 1A had yet to fully reach equilibirum, as evidenced in the continued downward trend of mass in Figure 163. The higher mass of Sample 1A, due to it being thicker, has likely contributed to this. The thickness of the sample suggests a longer time for moisture vapour to penetrate the structure. As such, the higher RH suggested by the end EMC is likely to have eventually reached similar levels to that of Sample 2A. Sample 2A appears to have reached an approximate equilibrium with the time-weighted average RH (41.5%) in the climate chamber. This gives an indication of the likely behaviour of wooden objects in a room heated by banked in fires with EMC corresponding to the average RH over the day where cycles are regular.

Likely daily dimensional changes of the timber given changes in mass of less than 0.1g in a day for samples of this size are small enough to not be of general concern. The small mass changes follow the RH changes very accurately (**Figure 161** - Figure 164). The slow response of the timber to RH as a whole suggests that if daily fluctuations are repeated they can be averaged and the sample will sit at that figure, with minor fluctuations of little consequence.

Experiment 9: Balanced RH fluctuations experiment

Samples	Sample coatings	RH Fluctuations until sample equilibrium (3 and 6 hour tests)
2 B	Shellac face and stained face exposed. All edges covered.	
2 C	Shellac face and stained face exposed. All edges covered.	
2 D	Shellac surface exposed, all other faces covered.	
2 E	Shellac surface exposed, all other faces covered.	
2 G	Stained face exposed, all other faces covered.	
2 H	Stained face exposed, all other faces covered.	
3 A	Both stained faces exposed.	X
3 B	Both stained faces exposed.	X

Table 12: Details of samples utilised for fluctuation experiments.

Samples were equilibrated at 60% RH, fluctuations from this point were determined according to controlled ambient RH. A series of 3-hour long RH fluctuations took place 10%

above and beneath a mid point of 60% RH in such a way that it was symmetrical, with set points of 70% and 50% max/min (Figure 165). In a 24 hour period there would be 2 cycles and this was continued for 17 days. The temperature was constant at 25°C.

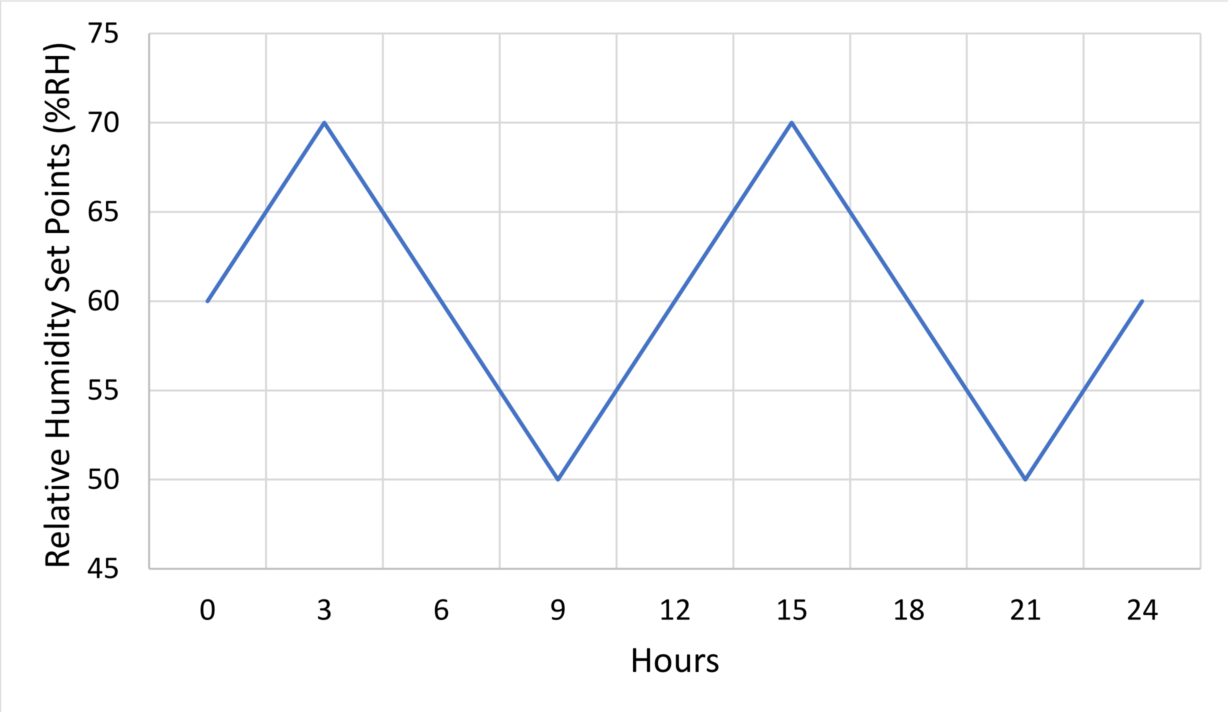


Figure 165: Climatic chamber set points for three house tests.

A further series of fluctuation experiments also took place whereby the 3 hours were increased to 6 such that in 24 hours 1 cycle was experienced, as seen in Figure 166.

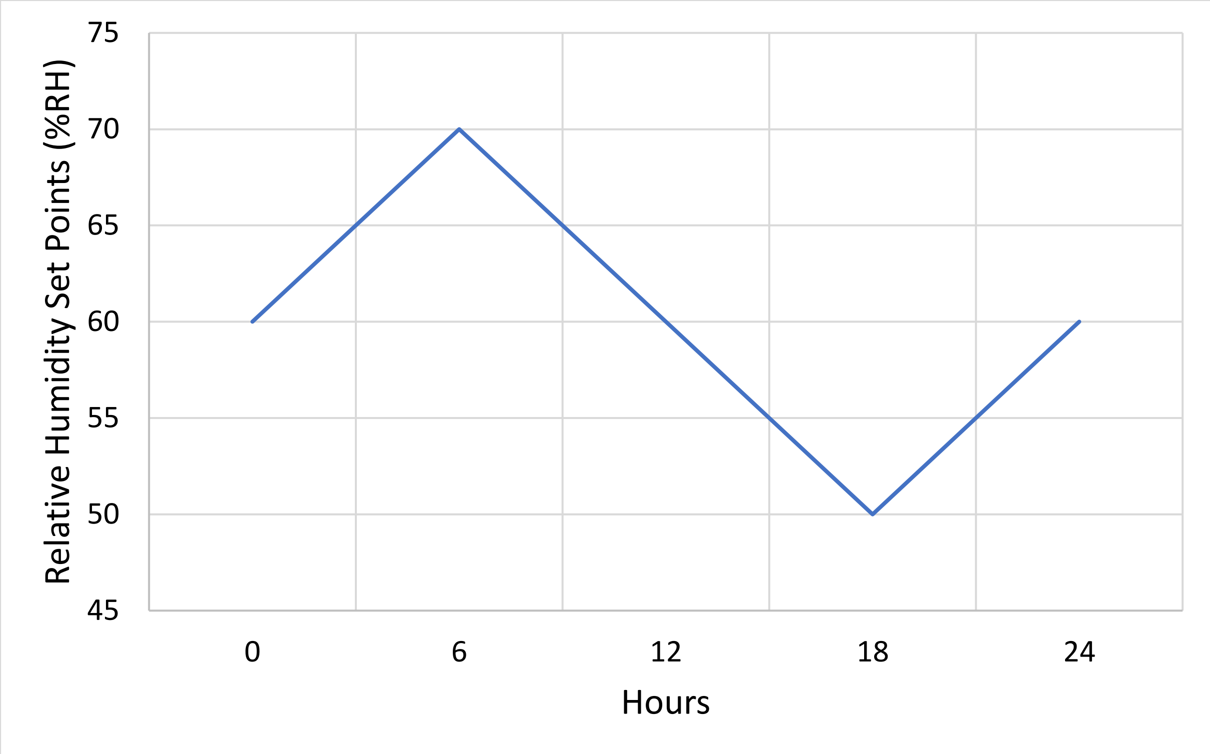


Figure 166: Climatic chamber set points for six hour fluctuation tests.

These fluctuation set points are displayed side by side in Figure 167, giving a clear overview of the difference the two fluctuations lengths have on the set points over 24 hours.

The samples were placed within the climatic chamber on balances in the same setup as discussed in Chapter 8.4. Samples were the same as those described earlier (Chapter 8.2), with the same two-part silicone covering sides and faces to give results for different finishes.

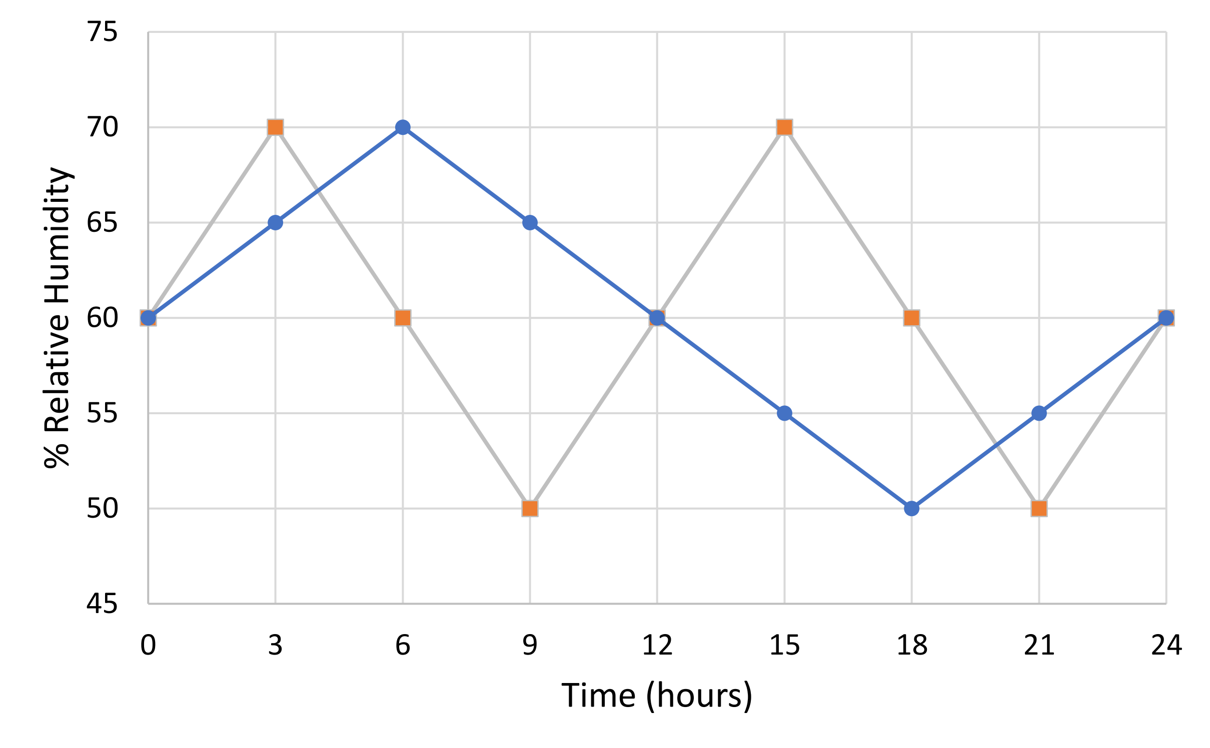


Figure 167: Climate chamber set points for three (orange) and six (blue) hour fluctuations.

8.1.17 Results

The first two samples investigated in this manner were 3A and 3B, which have only stain and no coating on either face (Table 12). The graphs of their masses and moisture contents are given in Figure 168 and Figure 169. Initially, one sample gained a small amount of mass during each cycle whilst the other lost a small amount on each cycle. As desorption is usually slightly larger than sorption it was expected both samples would lose mass after each cycle. However, neither sample was far away from reaching a point where it was balanced within the cyclical hysteresis, gaining and losing moisture equally. After 150 hours the change was negligible.

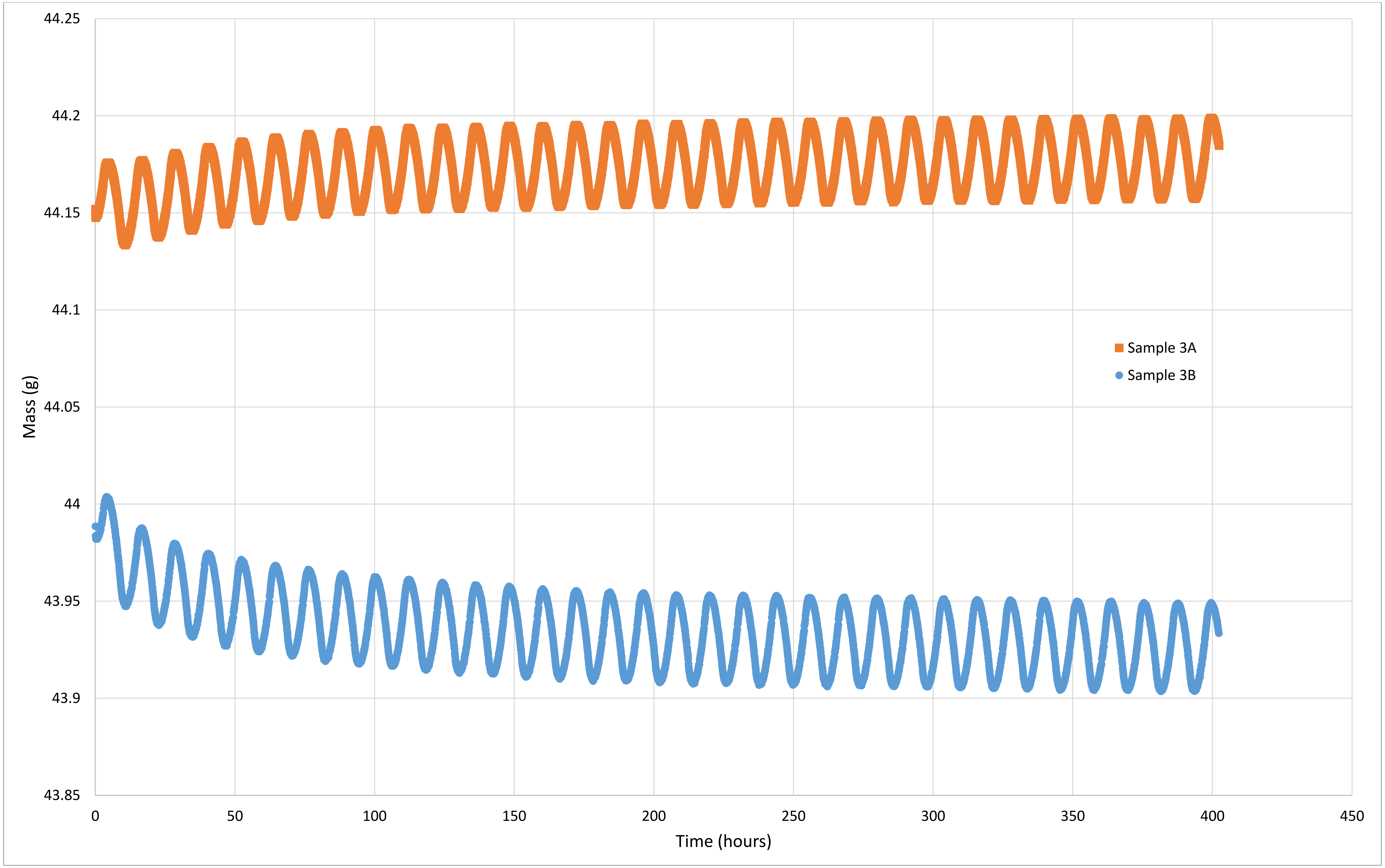


Figure 168: Timber sample RH% fluctuation response showing mass for samples 3A and 3B.

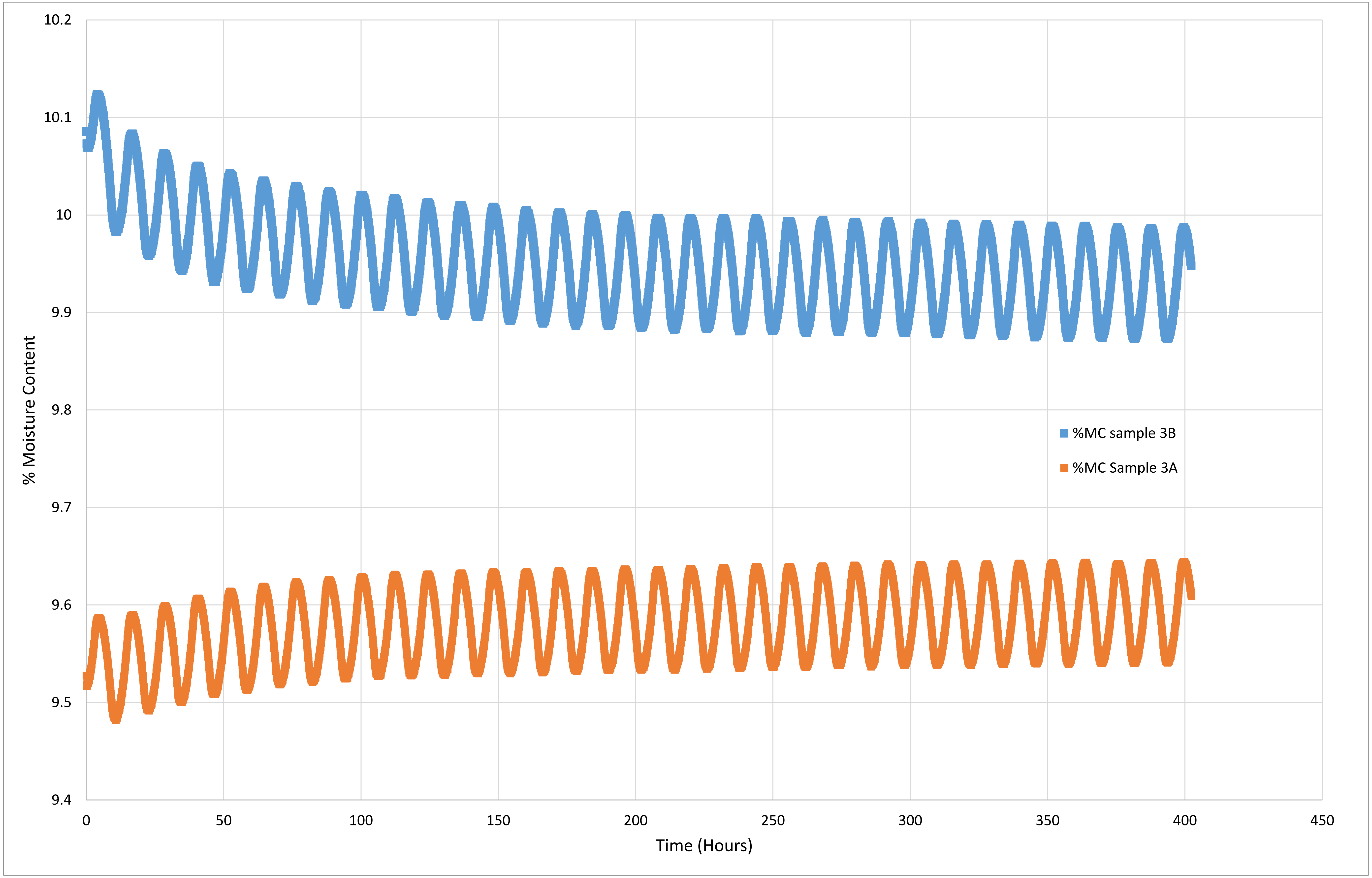


Figure 169: Change in Moisture Content (%) for samples during fluctuations for samples 3A and 3B.

8.1.18 Discussion

By comparing the mass of each sample with its dry mass, the EMC could be calculated and assessed against known EMCs at given RH% levels. An average of the moisture content of Sample 3A and Sample 3B at 60%RH at the termination of the experiment was determined to be 9.78% MC. The EMC for European oak (*Quercus robur*) given by Farmer (1972) and Rijsdijk et al. (1994) in Figure 51 suggest that this MC corresponds with an RH of 46%. Comparison to the EMC reference experiment results (Figure 160) gives an RH of c.60% RH. It is possible to suggest that the historic samples have lower EMC than newer ones although the experimental EMC reference data was from Sample 1A and Sample 2A rather than 3A and 3B.

The daily MC change of the samples in over 6 hours from 50%RH to 70% RH is less than 0.1%MC, which will have a very small impact on the dimensional change of the sample. Overall, though it is clear that an equilibrium is reached in each sample, the change is little more than 0.1%MC from the start point to end point of the experiment.

The mass gain and loss of timber samples to the six hour fluctuations has proven to be, over a 24 hour period, of the same magnitude as the three hour fluctuations (Figure 170). The samples follow the pattern of the fluctuations closely, but it appears that the time frame is not large enough to allow the sample to absord or desorb moisture more quickly. In comparison to the time taken to reach EMC in the initial experiments at different set points, the number of days to reach half of the end EMC took samples between 18-45 days at various RH figures. These smaller fluctuations that last a few hours are buidling-blocks upon which larger movement can happen, but there is a ratio between being below and above a set RH point that will lead the samples to find their own equilibirum in a fluctuating environment.

Experiment 10: Coatings as moisture barriers

Samples	Sample coatings	RH fluctuations to investigate coating impact on sample response (3 and 6 hour tests)
2 B	Shellac face and stained face exposed. All edges covered.	X
2 C	Shellac face and stained face exposed. All edges covered.	X
2 D	Shellac surface exposed, all other faces	X

	covered.	
2 E	Shellac surface exposed, all other faces covered.	X
2 G	Stained face exposed, all other faces covered.	X
2 H	Stained face exposed, all other faces covered.	X
3 A	Both stained faces exposed.	X
3 B	Both stained faces exposed.	X

Table 13 Details of samples utilised for fluctuation experiments.

The purpose of this experiment was to highlight the fluctuation range according to the type of finish applied to the wood. Each historic sample had a different surface finish (Table 123). Several of the wooden samples were put through a short cycle of three-hour and six-hour fluctuations following the pattern described earlier in Figure 165 and Figure 166. Gravimetric readings were recorded and the results are shown in Figure 171 and Figure 172 as an hourly percentage mass increase/decrease and in Figure 173 and Figure 174 as hourly percentage increase/decrease mass in hysteresis. The difference between a stain finish, a shellac finish, and a sample with both finishes is shown in both three-hour and six-hour format.

8.1.19 Results

The initial results show that the magnitude of the moisture gain/loss between the 6 hour and the 3 hour experiment is essentially the same (Fiure 169).

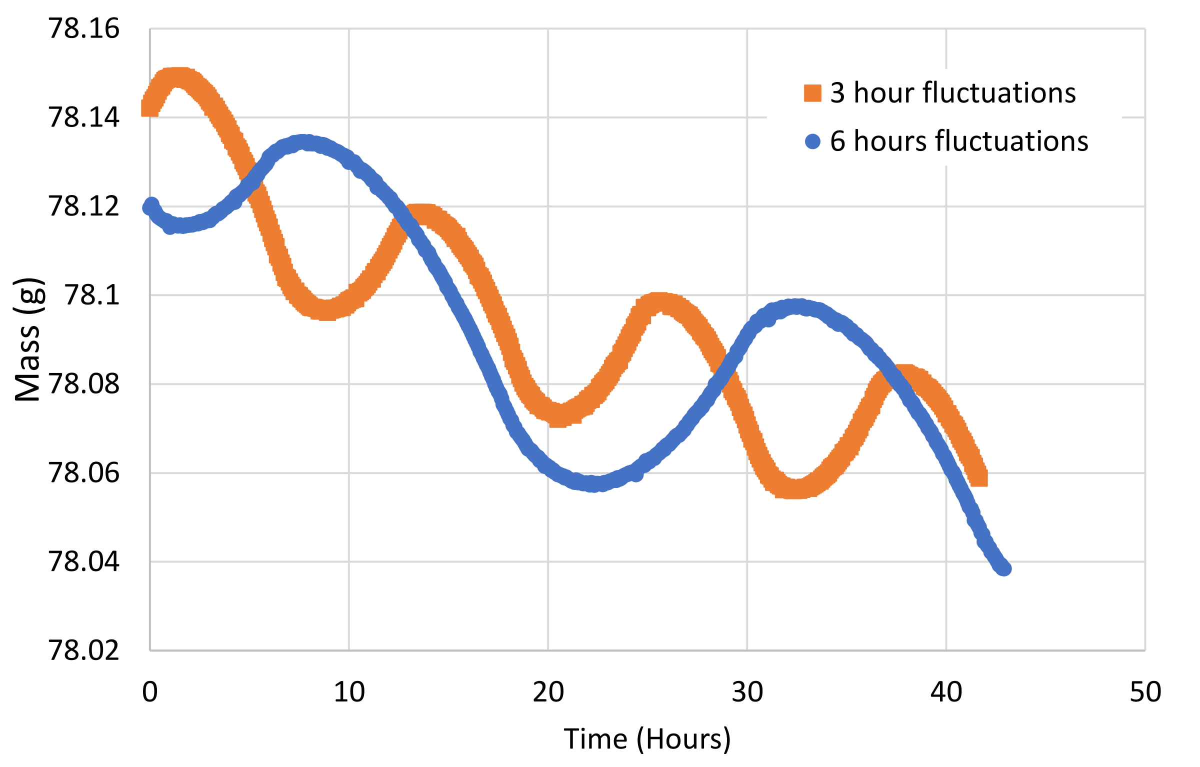


Figure 170: Response of timber sample to RH fluctuations for sample 2D.

The impact of finishes is also clear, as the shellac finish responds at a rate up to 50% slower than the stain finish. The response of shellac face and stain face exposed is slightly less than that of the stain only faces exposed. Figure 173 and Figure 174 show the hysteresis loop from the 3 and 6 hour fluctuation tests. It is notable that whilst the RH patterns were equally balanced, the hysteresis loops are weighted towards moisture desorption. The hysteresis loop is narrower for the 3 hour fluctuation, overall it is likely that all moisture gain or loss over these short spans is limited to the surface layers.

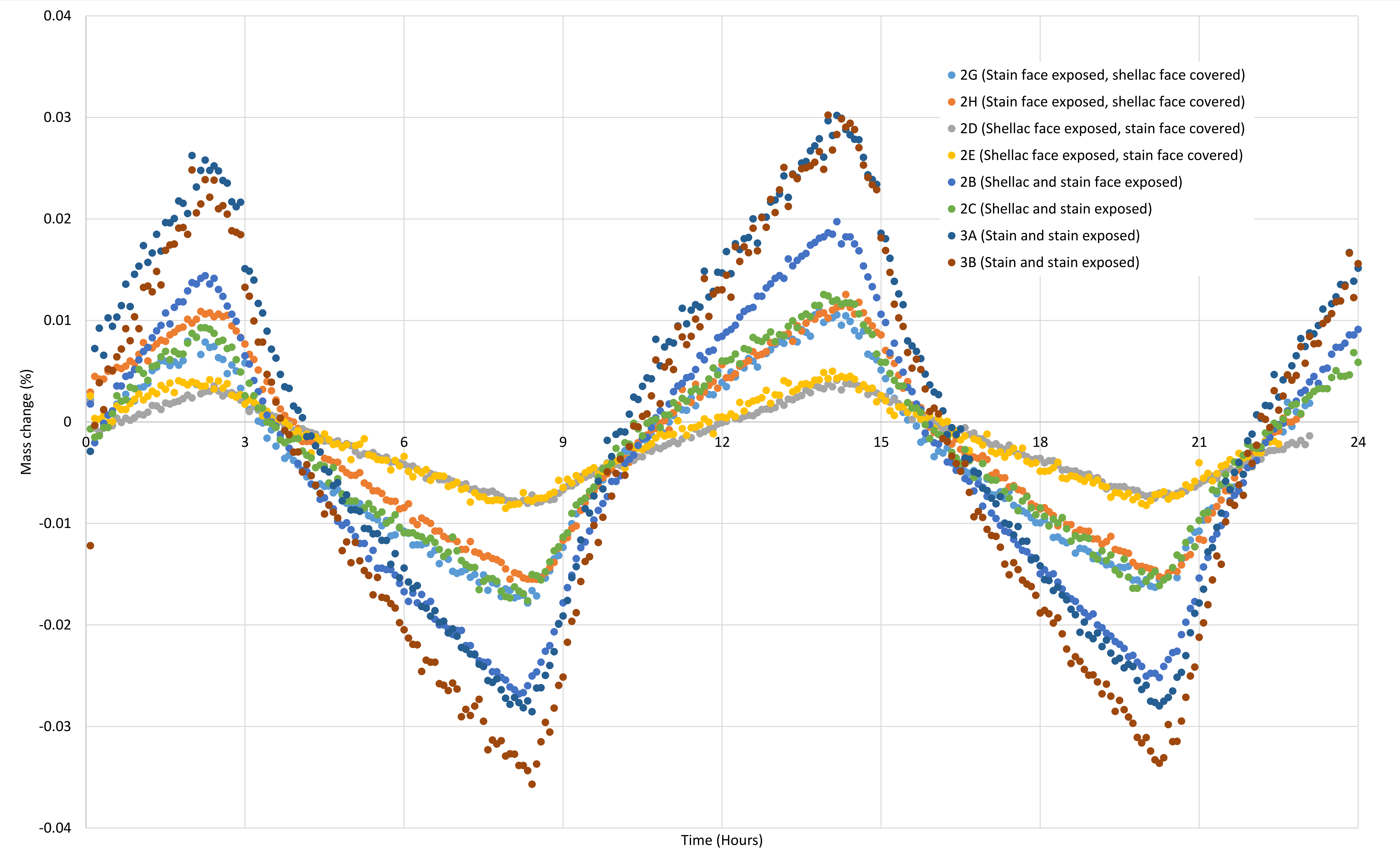


Figure 171: Hourly percentage mass gain/loss of samples over three hour fluctuations over 24 hours.

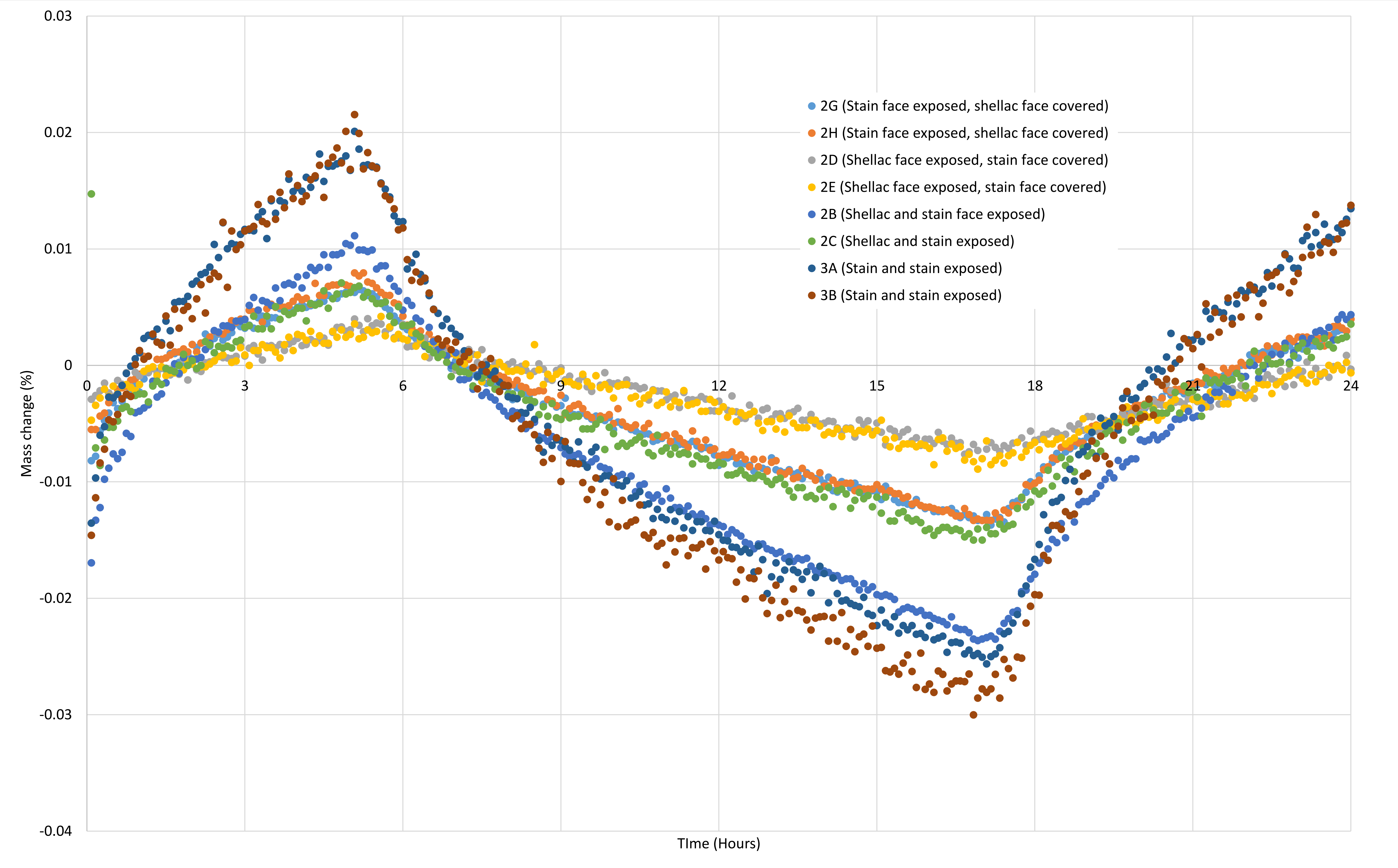


Figure 172: Hourly percentage mass gain/loss of sample over 6 hour fluctuations over 24 hours.

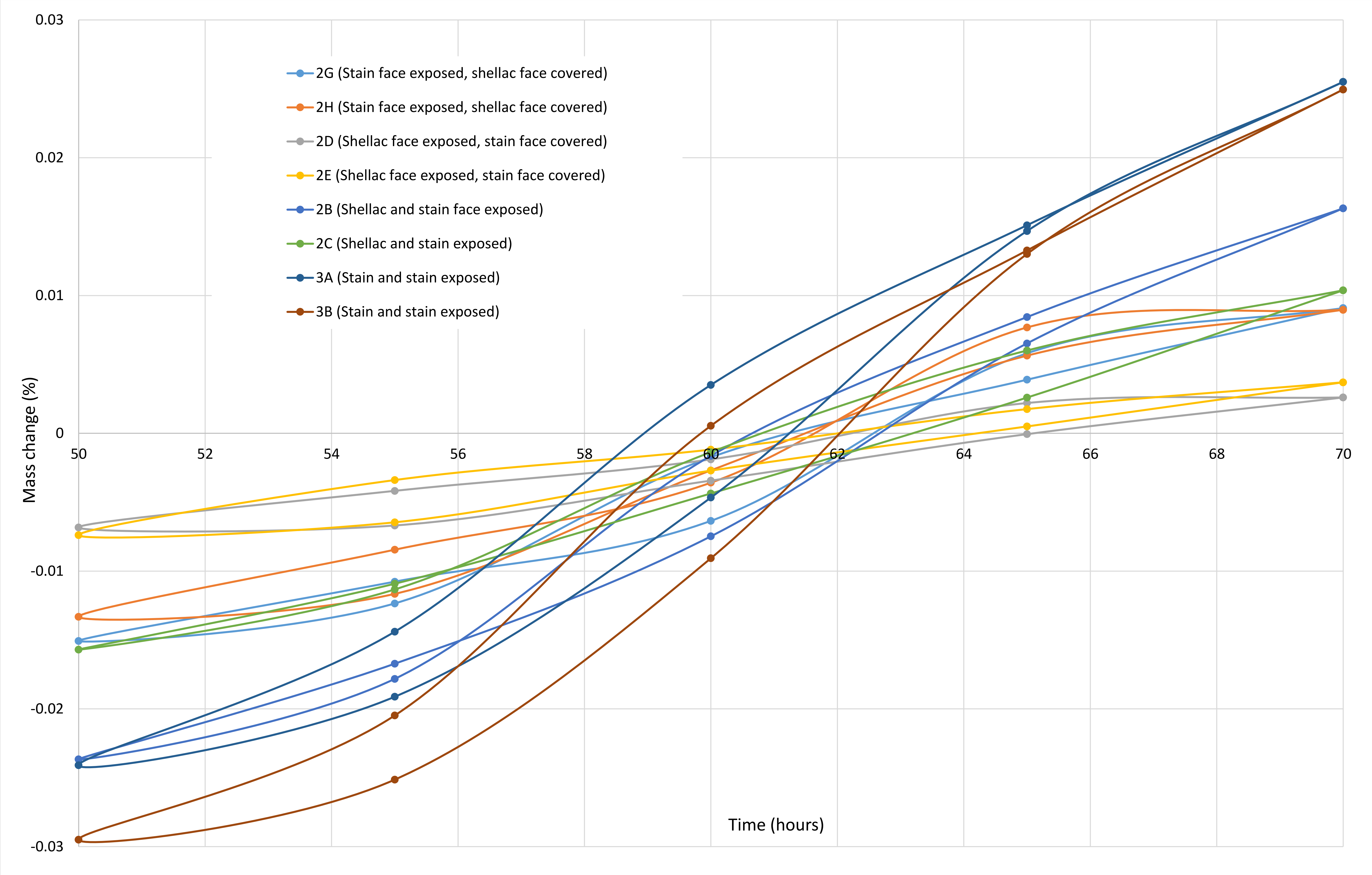


Figure 173: Hysteresis loop for three hour fluctuations, showing hourly percentage mass gain/loss at different RH points for samples..

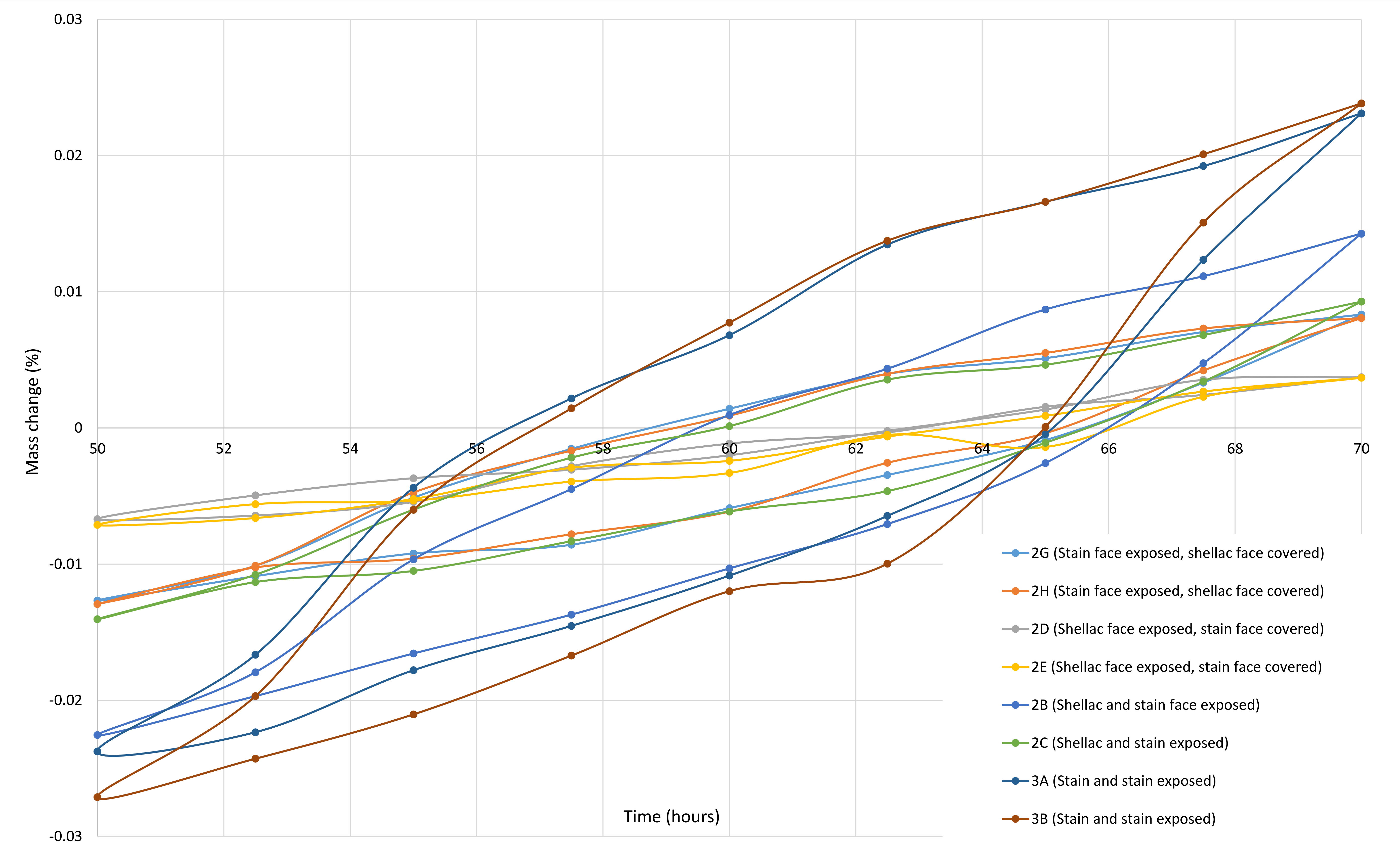


Figure 174: Hysteresis loop for six hour fluctuations, showing hourly percentage mass gain/loss at different RH points for samples.

8.1.20 Discussion

The difference in fluctuation time seems to have limited impact on the magnitude of percentage mass gain or loss (Figure 171: Hourly percentage mass gain/loss of samples over three hour fluctuations over 24 hours., Figure 172: Hourly percentage mass gain/loss of sample over 6 hour fluctuations over 24 hours., Figure 172 and Figure 173). It is possible that the small amount of bonded moisture gain in this timeframe happens within the shorter fluctuation and that initial gain of vapour on the most active sites, i.e. the surface, is a short-term process. Whereas longer term moisture transfer to beneath the surface into the solid matrix of the timber, through the cellular structure, is slower than can be seen within short term fluctuations under a ¼ day (Bahar et al. 2016, 1548). This suggests that fluctuation time is key to the response of timber.

The stain only samples with both faces exposed (3A and 3B, Figure 173 and Figure 174) had the highest rate of sorption/desorption. This is a result of the lack of coating on these samples, but there is the factor of this sample being thinner than the rest. Sample 3A and 3B both have a mass of 44g and had a maximum moisture gain of 0.8g and 0.9g. Sample 2B and 2C both have a mass of 73g and had a maximum moisture gain of 0.14g and 0.065g. Despite the differences in mass of samples due to thickness (Sample 2 group 19mm, Sample 3 group 12.5mm), it appears to be likely that the difference in mass change is related to the lack of coating on the two exposed faces of samples 3A and 3B. These two samples show good agreement with each other and (when mass differences are accounted for) also with Sample 2B which had one shellac and one stained face exposed.

Within the Sample 2B-2G group, there is good agreement between Samples 2D and 2E with one exposed shellac face and between 2G and 2H with one exposed stained face. These show the expected smaller mass % response of the shellac coated faces. The poor agreement between samples 2B and 2C limits meaningful discussion of the effect of a stained and shellac face both being exposed.

Unbleached shellac cast in alcohol is known to have a lower permeability to moisture vapour than cellulose, at 0.9-3.8 g mm/kPa h m^2 and beeswax has a slightly lower MVP factor than shellac, if this was applied as a later polish (Hahenmaier et al. 1991, 828-829; Talen et al. 2005, 243; Donhowe et al. 1993, 867). It is likely that the coatings control absorption/desorption rates rather than sample thickness. Sample weight gain has shown that the fluctuations are too rapid to allow the moisture vapour time to penetrate beyond the initial surface layers, and therefore the thickness of the sample is of little consequence to the response of the timber. The permeability of oak is also highly variable depending upon location relative to the sapwood/heartwood. If the sample were from the sapwood of the timber it would also display increased reactivity in comparison to samples closer to the heartwood (Domone et al. 2010, 430). This is highly unlikely given that heartwood is usually selected for furniture, but biological variation of the timber is a consideration.

The movement of the water vapour has to follow cellular pathways and, in the case of these samples, cannot move in the axial direction and must move transversely through the cell lumens. Capillary condensation may occur yet is unlikely in these samples as capillaries are open to the end grain, and therefore not exposed during these experiments, and this phenomenon is also generally believed to have little impact under 99.9% RH (Hansmann et al. 2002, 3-4; Skaar 1988, 54; Domone et al. 2010, 432; Wang et al. 2014, 331-332). It is likely due to the nature of oak, the tyloses impeding the path of the lateral moisture movement from pits (Figure 175) that the vapor did not reach very far into the samples.

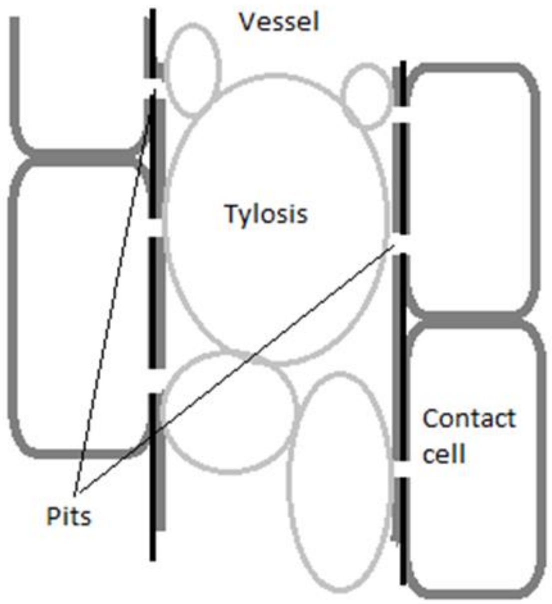


Figure 175: Figure showing vessel element blocked by tylosis, based on diagram from Micco et al. 2016, 191.

Examining the results for mass change in samples 2D and 2E (shellac exposed) compared to 2G and 2H (stain exposed), a difference between the water vapour uptake by the two surface types can be identified. The results indicate the stain finish has a 50% greater moisture uptake than the shellac. Extrapolating this to a scenario in which a piece of furniture with a polished face externally and a plain stained face internally is subject to RH fluctuation, it might be expected that the unequal moisture uptake could lead to physical effects due to differential dimensional change in the two faces (Figure 176).

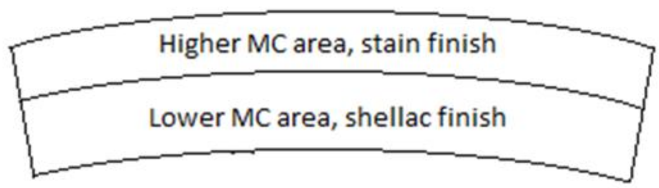


Figure 176: End grain view of timber board with shellac and stain finish exposed to high RH levels for 30 days.

Within a chest or closed piece of furniture, there is perhaps some buffering on the internal surface, as displayed in experiments by Luimes (2018). This may impact the response of furniture if the polished front is on the exterior, and the stain finish the interior, the buffering properties of the timber itself may produce a steady internal environment which would mitigate against the different absorption rates of the finishes. However, for a table top or similar piece of furniture with one polished face, one bare face, both in the same environment, this would not be the case. Thickness of the timber would be an important factor here, as it would influence the ability to buffer. This is, however, not borne out by anecdotal observation of the furniture within Rhyd-y-Car No. 6.

Experiment 11: Radiant heat experiment

As the open fire delivers most of its heat via radiation, the air in the immediate locality can have a very low RH. A simple experiment was devised to measure the impact of radiant heat upon the timber samples.

8.1.21 Method

A 150 watt nickel-chrome spiral heating element set in a circular refractory housing with a mica sheet cover was utilised at mains voltage (240V AC, 50Hz) and wired via a XH-W3001 temperature controller (Figure 177 and Figure 178). The thermocouple was painted matt black to ensure radiant temperature was detected, this fed into the microcontroller turning the element on or off to within 0.5°C of a given temperature. The non-sequential memory allows the device to store the set points even if the power is interrupted.

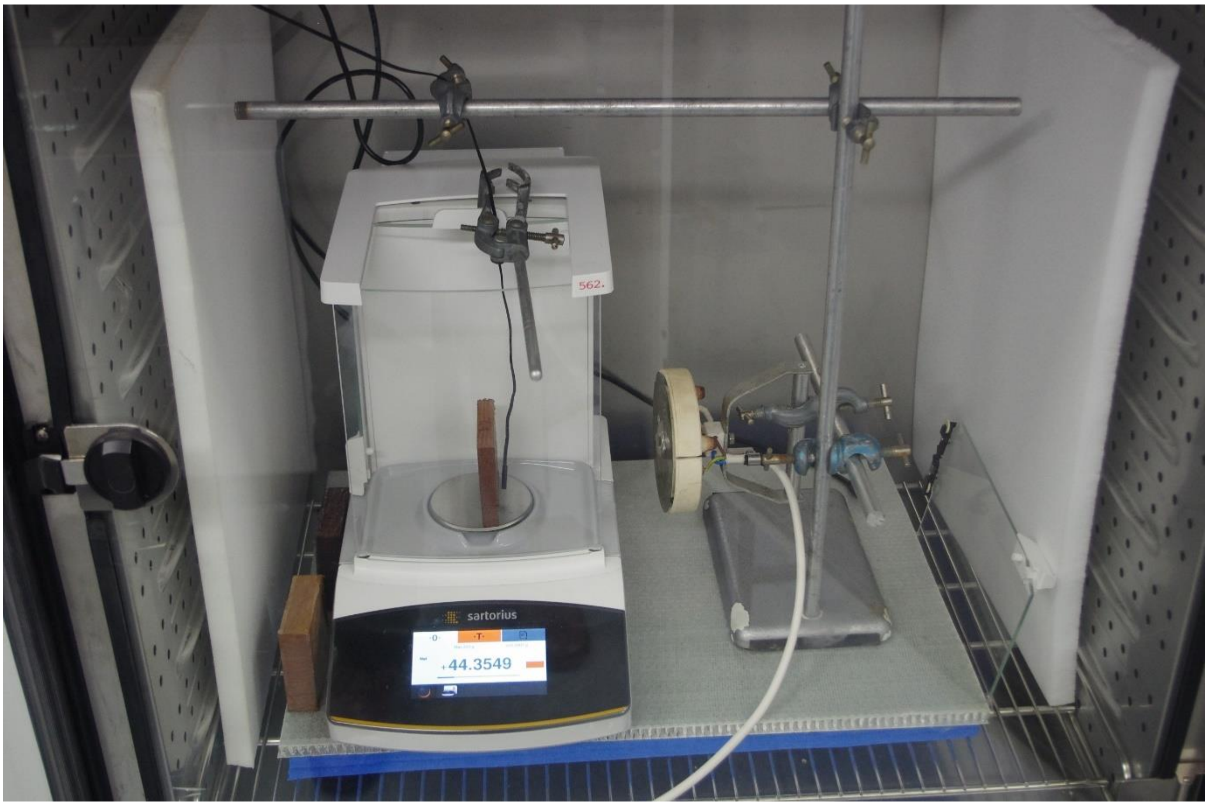


Figure 177: Radiant heat experimental setup. Showing sample on balance in climatic chamber, with heating element and thermostat sensor in front of sample.

Figure 178: Thermostat microcontroller for switching the element on and off.

A laboratory retort-stand held the element so that it may easily be adjusted to the desired height. The element was placed within the Binder climatic chamber, the balance was set up on foam boarding to minimise vibrational impact. The timber sample 2B (equilibrated to 60%RH prior to this experiment) was placed on the balance in such a way that one surface faced the heating element. Next to, but not touching (under 10mm), the timber sample was placed the thermocouple. All the sides and the top of the balance were open, and the side facing the heater element was removed entirely.

The climatic chamber was set to 60%RH and 14°C, replicating the background conditions of the cottage when the fire is first lit. The temperature controller was set to 25°C, however the surface temperature on the front surface of the sample was spot checked utilising a Fluke laser thermometer. The front measured 33.5°C, and at the rear of the sample 25.8°C, (producing an average sample temperature of 29.7°C). This is with the temperature controller reading 25°C, the thermocouple being less than 1cm from the surface of the wooden sample. This radiant temperature level was experienced within the room when heated by the open fire at numerous locations, so did not impact the validity of the experiment.

8.1.22 Results

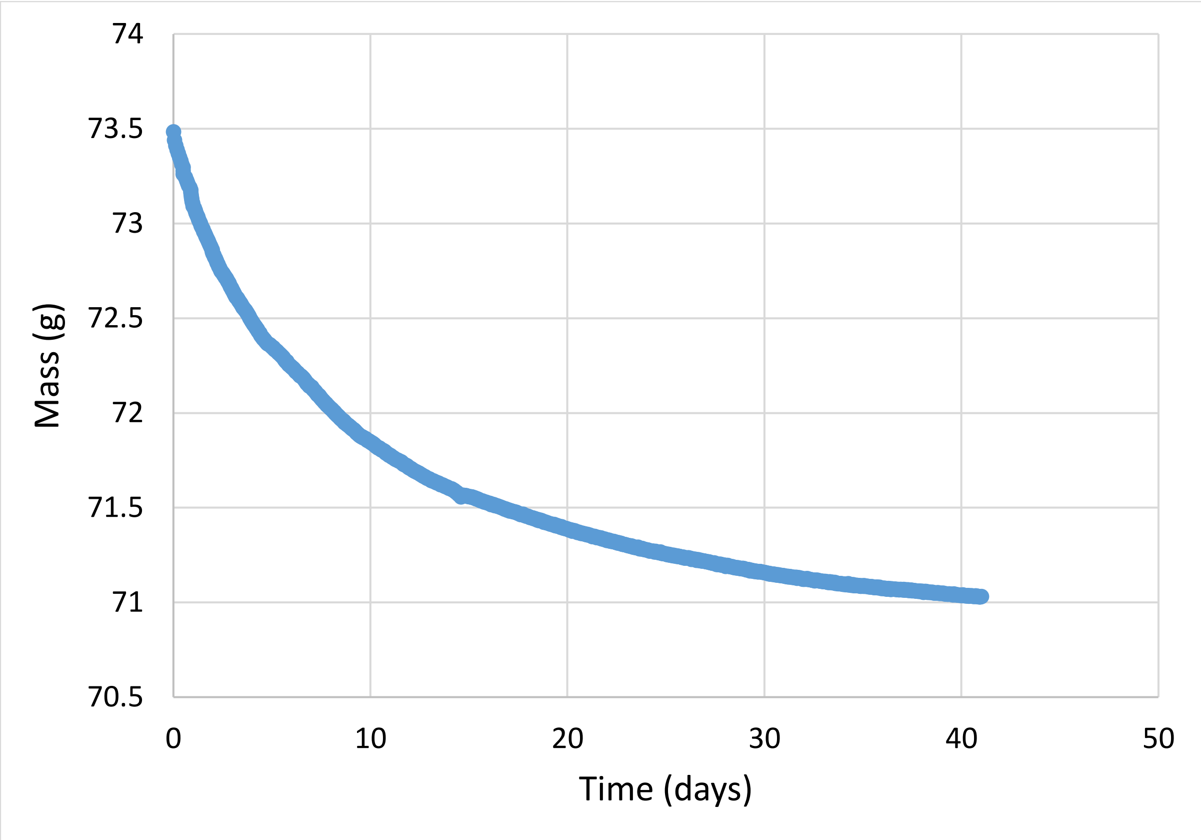


Figure 179: Mass of timber Sample 2B (*Quercus robus*) when exposed to radiant heat source at background of 60%RH 14°C.

The results (Figure 179) show that Sample 2B lost mass over the duration of the exposure to the heating element with the rate of mass loss falling off over time to come close to an equilibrium point. After the experiment the dry mass of the sample was taken utilising the oven dry method detailed earlier. After two days at 104°C, the sample lost a further 4.68g (from 70.70g to 66.02g).

At the start of this radiant heat experiment, the MC of Sample 2B was 10.6%, at the end of the experiment its MC was 7.07%. Looking at Figure 160 10.6% is equal to 60% RH (which the sample was acclimatised to) with the 7.07% MC suggests an RH of 26%.

8.1.23 Discussion

The temperature across the sample is not constant, one side is higher than the other. The side exposed to the element measured 33.5°C, this would give an RH of 18.9%. The opposite side measured 25°C, giving an RH of 32.2%. This average is 25.5% and is less than half a percentage from the value calculated from the sample mass. This could produce an uneven gradient of moisture through the sample, influenced by the temperature gradient. With furniture exposed to radiant heat from a fire, as with this sample, there will be a temperature gradient throughout the timber. The extent of this gradient will be based on the U-value of the timber, the room air temperature, and the surface temperature of the exposed timber face. This will produce different RH values for different surfaces depending on their temperature values. As discussed above, this may have consequences for differential dimensional changes within a piece of furniture and has the potential to result in physical damage.

Summary of humidity response tests

Whilst small fluctuations in RH result in a near instant change in mass of the wooden samples, the overall change is small in comparison to that recorded over a longer time period. Mass change can readily be related to RH by the peaks and troughs produced but for a sample to change its EMC due the impact of RH, took over a month in these experiments. Modelling the environmental changes caused by fire lighting demonstrated that the short-lived fluctuations in RH produce only small changes (in the samples, less than 0.1g in 24 hours) in moisture content with the magnitude of the hysteresis loops indicating that these have minimal impact on the EMC of the sample. This can be extrapolated to mean that dimensional change is expected to be negligible. Over a period of a day, several RH fluctuations of +/-30% RH can take place. If these are balanced so that there is no net change in humidity, the wood is unlikely to change its EMC beyond 0.1%. Luxford et al. (2013, 4) have suggested that these small daily fluctuations mean that a wooden object is unlikely to reach an equilibrium in the constantly changing environmental conditions within a historic building. The data from these experiments indicates that objects may respond dynamically to shorter fluctuations whilst reaching an overall equilibrium over longer periods of time.

It is clear is that if an RH loop exists over a period of time, then it may be averaged to work out what the EMC of timber exposed to it may be. It took 40 days for sample 1A to reach its EMC under the open fire cycles, a change of around 20%RH which resulted in an average calculated dimension change tangentially of -0.25mm and radially -0.47mm (for a 10cm theoretical sample size). As the hysteresis is exponential, the quickest part of the cycle is the initial change. In experiment 8 sample 2A (Figure 164) has reached just short of its end mass after seven days, which would result in a dimensional change of 0.2mm for 10cm radially. If RH patterns are balanced (fluctuating evenly around an average point) within a number of days the physical impact of a fluctuation of ±20% RH is likely to be negligible.

Seasonal variations are of a greater concern than daily or weekly fluctuations, as they have the scope to impact wooden objects over a longer period of time. Bratasz et al. (2007, 205) suggests that only the outer layer of a few mm of a polychrome wooden sculpture in a church is likely to be impacted by short term fluctuations, and that only seasonal variations will impact the moisture content of the whole object. This appears to align with the data collected in this PhD. The experiments into the response of the oak samples show that if a daily fluctuation is repeated then the sample will, over time, reach a moisture content that is an average of that daily pattern, with only the outer layers responding to the small daily fluctuations. Further climate chamber experiments over a year, using data that has been collected in the building throughout the four seasons of the year, would identify if this predicted minimal impact follows through a whole year.

The experiments investigating the impact of coatings showed that a shellac finish reduces the rate of adsorption and desorption by 50% in comparison to a stained finish within the same sample material (Sample 2). There is limited research into the impact of traditional coatings on timber samples, leaving scope for further investigation in this area. It is also interesting to note that the EMC figures for the samples used in the coatings studies here were lower than that of Farmer (Figure 51) for *Quercus robur*. This may imply that historic timber can become less responsive over time, though it could be the result of a natural variation in the amount of sub or semi crystallised zones within the timber structure. However, Gereke et al. (2011) suggests that age has little impact on the EMC of timber, and that surface coatings are the main factor. It may be that wood with original coatings have a lower EMC.

The high degree of radiant heat output from open fires was shown to reduce the RH at the surface of a sample as compared to the RH of the room more generally. In effect, radiant heat creates a localised low RH zone at the surface of an object. On a spring day if the doors to the cottage are open and the fire is blazing, air at 15°C and 80%RH may be entering the building, whereas an object exposed to radiant heat from the fire may have its surface temperature raised to 20ºC and will consequently experience an RH of 55%. One side of the object will be warmer than the other with the conduct of heat energy through the wood being determined by its R value. Within time a uniform temperature and humidity gradient will be established through the wood. This has the potential to generate stresses where one side is much drier than the other.

Another problem may arise where an object, such as a chest of drawers, is positioned against a wall. Radiant heat would not reach the back of an object in this circumstance and would create a cold spot on the wall. This may impact the thermal mass of the building, particularly when large pieces of furniture make it unlikely that the walls are warmed by radiant heat, thus increasing the likelihood of condensation behind furniture. This is more likely on external walls and corners, and in particular areas on the same wall as a fireplace, such as either side of the chimney breast. These areas gain the least radiant heat, despite being some of the closest to the fire.

9 Conclusion

Summary of findings

It has been demonstrated that radiant heat from an open fire can create internal environments which are 40%RH lower than the external environments recorded in this study. Due to the high levels of heat stored in the thermal mass of traditional buildings, RH can remain below 60% for at least 20 hours following a fire. It has also been shown that the RH is highly dependent upon the nature of coal combustion and consequent radiant heat output from the fire, meaning the RH across a room varies. This can be based upon distance from the fire, height and location within the room in relation to other objects (i.e. a direct path to the fire being blocked by furniture or room design). The fire itself burns with a natural cycle of peaks and troughs in heat output based on refuelling patterns, subjecting objects within a room to a wide variety of different temperatures within the heating period and, consequently, a range of RH values.

The heated thermal mass of the room effectively allows a chimney breast to contribute to the conservation heating to manage the RH of a room (Staniforth 2007, 7) for a considerable period after the fire has gone out. It has also been calculated that the chimney adds 17% efficiency to the open fire tested in the scenario in this study. The effects of open fires on RH depend on their lighting regimes. Overnight, a slow burning fire will induce more air into the room and up the chimney, creating higher RH zones around ingress points than if no fire were alight but will maintain higher air temperatures until the morning. Daily fires create a less varied internal RH, and with no fire burning in the grate induce less external air into the building during the night and early morning, creating a more even RH throughout the room.

The thermal mass of the building, heated by the radiant heat, can keep the room under 55%RH for 24 hours after the fire has been refuelled and the door to the building shut.

The response of oak timber objects with coatings has shown that traditional shellac finishes can slow the rate of mass gain of the wood from moisture uptake with RH fluctuations by up to 50%. It has also been found that the moisture content of wooden objects (as measured by mass) respond to the daily fluctuations that an open fire produces, but that this is minimal and is likely to produce negligible dimensional change. Overall, it takes around one month for wooden objects to acclimatise to new RH values. A week may be considered the longest point a wooden object should be kept at a radically different RH to which it is acclimatised due to the highly logarithmic nature of the timber-moisture hysteresis.

Within a room heated solely by an open fire, the short-term nature of fluctuations have a limited impact upon them, and longer-term patterns of RH should be considered when looking at significant damage to timber objects.

Fire usage recommendations and collections impact

The following recommendations are for the running of the National Museum of Wales St Fagans, but have further benefit to other organisations and individuals outside the museum. As such certain aspects of the recommendations may be interpreted for different scenarios.

Changes to the daily fire-use routine have the potential to improve management of the internal environment of some historic buildings at St Fagans. Currently, cleaners open the buildings at the start of the day around 7:00, opening the doors and allowing external high RH air to enter the buildings as floors are swept and mopped. The fires are often lit at this time and, with the doors still open, this draws more external air into the building. This is the period during which condensation risk inside a building is highest; the external air can be at a higher temperature than the internal surfaces, as this is when the heat remaining in the thermal mass of a building is at its lowest point (Chapter 1.1.3).

A warden takes over responsibility for the building during the opening hours of the museum and the doors are generally left open to signal to visitors that buildings are open. Again, this causes a high air exchange rate and one which the heating capacity of a fire is unlikely to be able to mitigate. Contrasting the measurements of RH in Rhy-y-Car No.6 during normal opening (70-90% Figure 5) and during Experiment 2 (consistently under 50% Figure 102 to Figure 111) suggests two possible causes of reduced RH: closure of the door during the day and refuelling of the fire to bank in overnight rather than going out by 17:00.

In daily use, if the warden were to keep the fire burning throughout the day and refuel the fire before locking up at 17:00 then this would ensure that the heat levels stored in the thermal mass was given a final boost for the night, with the fire likely going out at around 21:30.

If no fire is to be lit in the building the next day, as is the present ‘one day on one day off’ practice, then it is suggested that the door is opened as little as possible. The of the thermal mass of the room is low 20 hours after the fire goes out, but manages to keep the RH levels under 60%. The stored heat in the chimney breast at 8:00 the next morning is around 100watts, and whilst this is a small part of the overall potential heat that can be stored within thermal mass of the building, it could not mitigate against the effect on RH of having the door open (Figure 146).

As the heating of the thermal mass of the building is cumulative over two to three days, it is of benefit to run a fire in a building consecutively for this period, rather than the day-on day-off practice. This also impacts moisture within the building materials, such as the joists, floorboards, plasterwork and mortar. A two- or three-day heating cycle would provide lower moisture levels within the building on the next unheated day.

When the fires are in use they can create low RH zones, especially within a radius of around 1.8-2m. RH levels can be a minimum of 20%, and temperature a high of 30°C, but more usually c.35-50%RH and temperature c.15-25°C (Figure 138). This area should be reserved for the display of collection that are more likely to withstand prolonged exposure to low RH levels and higher temperatures. This is likely the ideal place for visitors to be allowed to warm themselves.

Localised RH zones are created by fire use (Chapter 0), the fire draws in external air and higher RH zones are created along the path this air takes. Furniture placed in this zone would experience prolonged periods of higher RH air at lower levels around from the floor to 35cm. These areas can be avoided by placement of objects outside obvious routes that the air takes.

It has been demonstrated that timber surface temperature, due to the radiant heat, is relative to the RH of the room. Spot checks with a laser thermometer and a RH reading shielded from the radiant heat source in the room can be utilised to calculate the RH experienced by an object on its surface (Chapter 0).

The response of the timber samples has highlighted the slow physical response of oak to environmental changes. Response rates demonstrate that a shellac finish may reduce moisture gain/loss by up to 50% in comparison to unfinished samples (Chapter 0). Moisture gain is slow and appears to be limited to the surface layers of the timber during the initial period of an ambient RH change. 75% of change in moisture content happens within the first 50% of the total time frame, which is usually between three and four weeks (Chapter 8.1.12). Shorter fluctuations within a day are of smaller consequence with tests showing minimal moisture gain/loss possible within that timespan. Daily fluctuations should be considered as part of the larger weekly average.

For an object such as an oak chest of drawers in a room heated for two days by an open fire followed by a day with no fire with the door open (and an RH of above 80%, Figure 5), the primary risks are surface mould and condensation rather than dimensional change. Despite the large differences in RH between the days, they will average out and be limited to the surface of the timber.

It should be noted that these observations are based upon the results of the solid oak samples. Objects which are veneered, or with finer detailing and layers (marquetry, gilt object, polychrome sculptures) the response to these RH changes is likely to be different, and as the RH changes appears to create an EMC difference between external surfaces and internal area of the timber, these shorter-term fluctuations are more likely to cause damage.

The nature of the radiant heating means that there is a risk of the creation of low temperature areas on walls and behind pieces of furniture, especially in corners. This presents a risk of condensation and different EMC's across one piece of furniture. If the air in the room is kept at a low RH by maintaining a lower air exchange rate, these risks can be minimised. At present, with the doors to the property open, lower RH values are achieved through direct radiant heat rather than dry air.

Overall:

- Keep the door to the property closed as much as possible.
- Light the fire daily, and ensure it burns all day.
- Refuel the fire at the end of the day, ensure the fireguard is in place and lock-up.
- With doors shut, a two day lit and one day unlit pattern should offer favourable conditions.
- Avoid placing wooden furniture within 2m of the fire. Consider this area for visitor use.
- Avoid placing wooden furniture at low level between air entry points and the fire.
- Avoid placing furniture or objects in corners of external walls.
- Ensure solid oak objects do not experience RH fluctuations of more than 30%RH for more than 1 week.

10 Glossary

- Anastomosis; A connecting link.
- Anhydro glucose unit; Single sugar molecule in a polymer.
- Anisotropic; Properties of material in relation to direction.
- Ash-pit; The space beneath a fire for the collection of ashes.
- Bonded; A lasting link which forms a chemical compound.
- Chimneybreast; The portion of brickwork which contains the fireplace and flue.
- Chimneystack, The external portion of a chimney, normally above the roof.
- Covalent bond; Chemical bond via shared electron pairs
- Crystalline; The order of atoms, ions or molecules in a material that form a unit cell which is part of a symmetrical repeating pattern
- Equilibrium Moisture Content; The point at which a hygroscopic material neither gains or looses moisture
- Fibril; A component of biological nanostructure, similar to, but much smaller than, a fibre.
- Flue; The duct inside a chimneybreast/stack that extends from the fireplace to the external air.
- Galactose; a simple sugar which belongs to a simple carbohydrate.
- Glucomannan; water soluble polysaccharide, a component of hemicellulose in cell walls.
- Grate; The perforated base upon which a fire is made, usually steel, iron or cast iron.
- Hemicelluloses; a component of cell walls along with cellulose. Random amorphous structure with little strength.

- Hydrophobic; A water repelling molecule
- Hydrophilic; A molecule attracted to water
- Hydroscopic; Attracting and holding water
- Intermolecular; Between molecules
- Intramolecular; Inside molecules
- Lamella; A thin layer
- Lumen; A tube like structure
- Mannose; A sugar that forms some carbohydrates
- Medullary; Radial structure perpendicular to growth rings, appear in some oak cuts as rings or stripes.
- Microfibril; A very fine fibril
- Moisture Content; The amount of water contained in a material
- Monosaccharaide; The simplest form of sugars, smallest part of carbohydrates. They form disaccharides such as sucrose and lactose, a polysaccharides such as cellulose and starch.
- Parenchyma;
- Phenylpropanoid; a large diverse family of organic compounds that includes compounds in the structure of trees that form polymers such as lignin.
- Polysaccharides; chains of monosaccharides such as cellulose and starch.
- Pyranose ring; saccharides that include a six sided ring of five carbon atoms and one oxygen atom.
- Relative Humidity; The amount of water in a certain amount of air.

- SAP rating; 'Standard Assessment Procedure' a government approved system for calculating energy performance of buildings.
- Throat; The opening between a fireplace and a chimney
- Tyloses; Outgrowths from parenchyma cells into vessels.
- Van der Waals forces; A weak form of bonding between atoms and molecules based upon distance rather than electronic bond.
- Xylan; A polysaccharide found in wood cell walls.
- Xylose; A monosaccharide found in wood cell walls.

11 Appendices

Appendix 1; Fuel use during heating experiments

Experiment	Date	Time and Date	Kg Coal Applied	Action
1	20th Nov	20/11/2017 09:03	2	Fire lit
		10:01	3	
		10:28		
		13:40	1.5	
		14:00	3	
		18:00	7	
		21:55	4	Banked over with 2.5kg small coal
	21st Nov	21/11/2017 08:10		Poked through and riddled
		08:13	5	
		11:56	4.5	
		15:55	4	
		19:00	6	
		22:30	3.5	Banked over with 1.5kg small coal

22nd Nov	22/11/2017 08:55	3.5	Poked through and riddled
	12:55	4	
	17:00	4	
	21:00	5.5	Banked over with 2kg small coal
23rd Nov	23/11/2017	4	Poked through and riddled
	12:00	4.5	
	16:00	4.5	
	19:00	3	
	22:50	3.5	Banked over with 2kg small coal
24th Nov	24/11/2017 08:40	2.5	
	17:10		Fire seems to have been sluggish throughout day, much unburnt clinker.
			82.5
			Total, including small coal = 90.5
2			
27th Nov	27/11/2017 08:25	1.5	Fire lit
	08:45	3.5	
	12:15	6.5	
	04:45	6	
	07:15	5	
	10:20	5	Banked over with 1.5kg small coal
28th Nov	28/11/2017 08:30	1	Sticks and paper required, fire practically out in morning.
	08:50	4	
	11:45	6	
	16:00	4	
	19:30	5.5	
	22:15	4	Banked over with 2.5kg small coal.

29th Nov	29/11/2017	6	Some stick to get going, but did re-ignite self
	11:40	6.5	
	16:00	6	
	20:00	2	
	22:00	4	Banked over with 2kg small coal
30th Nov	30/11/2017		Much material left, required paper over fireplace to 'get going'.
	08:10	3	
	11:55	4	
	16:00	5	
	19:45	2	
	22:00	4	Banked over 3kg small coal
1st Dec	01/12/2017 07:50		Fire poked
	08:05	1.6	
			96.1
			Total including small coal=105.1
3			
11th Dec	11/12/2017 08:20	1	Fire lit
	08:32	5	
	12:24	5.5	
	16:01	5	
	19:30	5	
	22:30	1	Fire low, sticks added to get going,
	22:55		3Kg small coal
12th Dec	12/12/2017 08:03		Fire poked through, large glowing mass.
	08:20	3	
	11:45	4.5	
	15:50	5	
	19:50	4	
	22:12	4.5	Banked over with 2kg small

				coal
	13th Dec	13/12/2017		Fire poked, newspaper held over to draw
		08:35	2	
		11:00	2.5	
		15:10	4	15:00, paper to draw, grate clocked with clinker
		16:00	2	
		20:45	2	
		22:15	2.5	Banked over with 4kg small coal
	14th Dec	14/12/2017 08:00		Fire poked
		08:10	2.5	
		12:00	2	
		16:00	3	
		19:50	3	
		22:00	1.5	Banked over with 4kg small coal
	15th Dec	15/12/2017 08:00	3	Good fire in morning
				73.5
				Total including small coal=86.5
4				
	8th Jan	08/01/2018 07:51	3	Fire lit
		08:12	4	
		11:30	6	
		15:48	5	
	9th Jan	09/01/2018 08:05	4	Fire lit
		11:52	6	
		16:02	6	
	10th Jan	10-Jan	7	Fire lit
		11:49	7	
		15:54	6	

11th Jan	08:05	7	Fire lit
	11:53	7	
	15:55	7	
			Total=
			75
5			
15th Jan	15/01/2017 07:51	1.5	Fire lit
	08:05	4	
	11:52	7	
	15:52	6.5	
16th Jan	08:10	1.5	Fire lit
	08:20	5	
	11:50	4	
	15:44	5	
17th Jan	17/01/2017 08:14	3	Fire lit
	08:24	4	
	11:50	7	
	15:44	7	
18th Jan	18/01/2017	7	Fire lit
	11:55	6	
	15:56	6	
			Total=
			74.5

Appendix 2; Results for SAP 2012 version 9.92 Calculations

Rhyd-Y-Car no.6 by Welsh School of Architecture

Dwelling volume (m^3)	124.3
Effective air change rate	1.3
Ventilation type	24d

Fabric heat loss (W/K)	202.3
Total fabric heat loss (W/K)	218.1
HLP (W/m²K)	4.7
Heat gains from water heating, (kWh)	438.2
Average Internal gains (W)	423.9
Average Solar gains (W)	46.6
Mean Internal temperature (C°)	18.9
Space heating requirement in kWh2/m2/year	264.5
Efficiency of main space heating system 1 (in %)	50.0%
Efficiency of water heater	50.0%
Fuel for water heating, kWh	2635.5
Electricity for pumps, fans and electric keep-hot	0.0
Electricity for lighting (calculated in Appendix L)	720.6
Energy saving/generation technologies	0.0
Average Fuel costs (p)	9.4
Additional standing charges	£120
Total energy cost	£1,428
SAP rating	24.2
Average Co2 emission factor	0.468
Dwelling CO2 Emission Rate	232.97

Appendix 3;Results of Air Blower test of Rhyd-Y-Car No. 5 and 6 by Welsh School of Architecture

	N.o 5	No. 6	No. 5 and No. 6
Air Permeability Index ($m^3/h/m^2$)	12.5	7.2	6.8
Estimated expected infiltration rate (/hr)	0.91	0.52	0.49

Appendix 4; Balance drift test

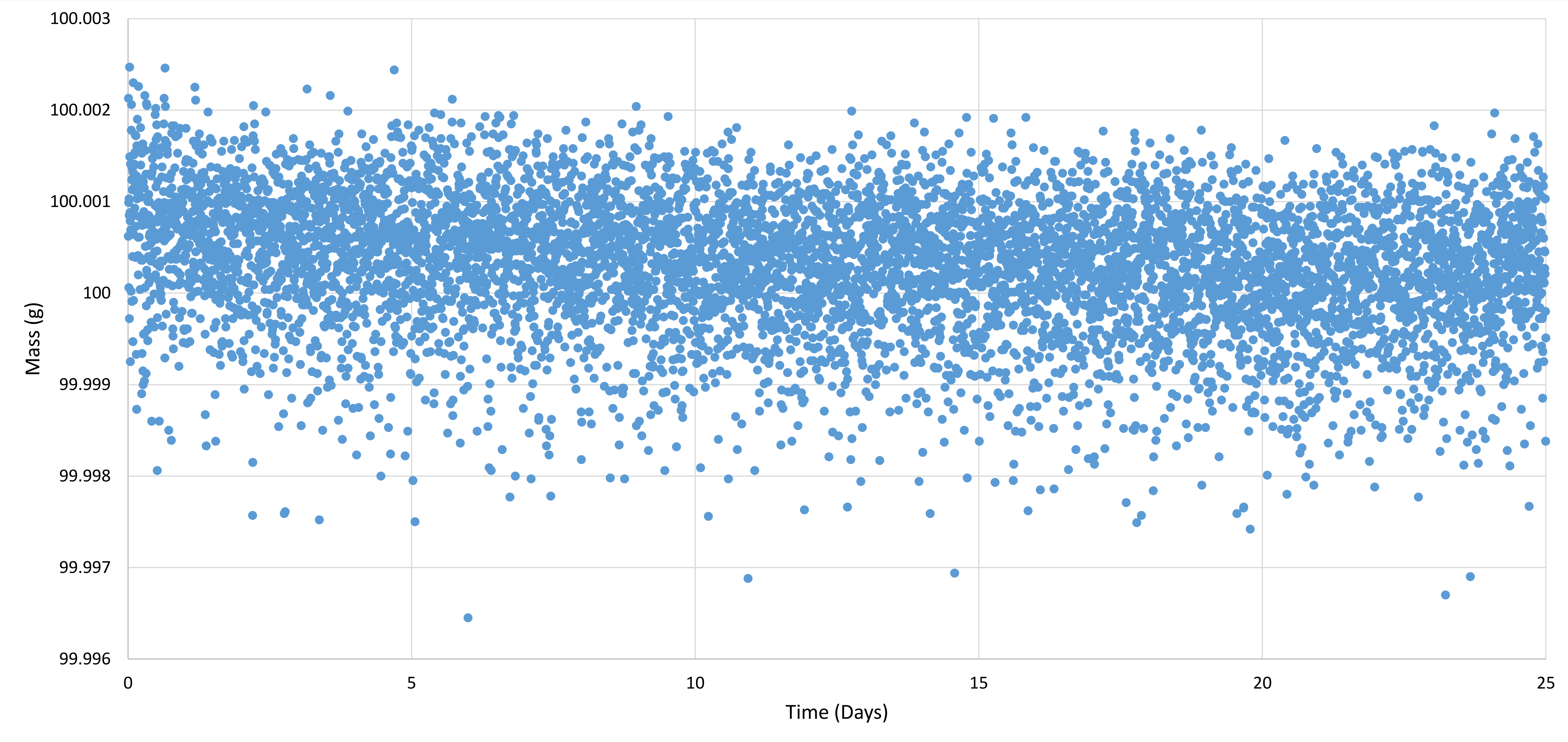
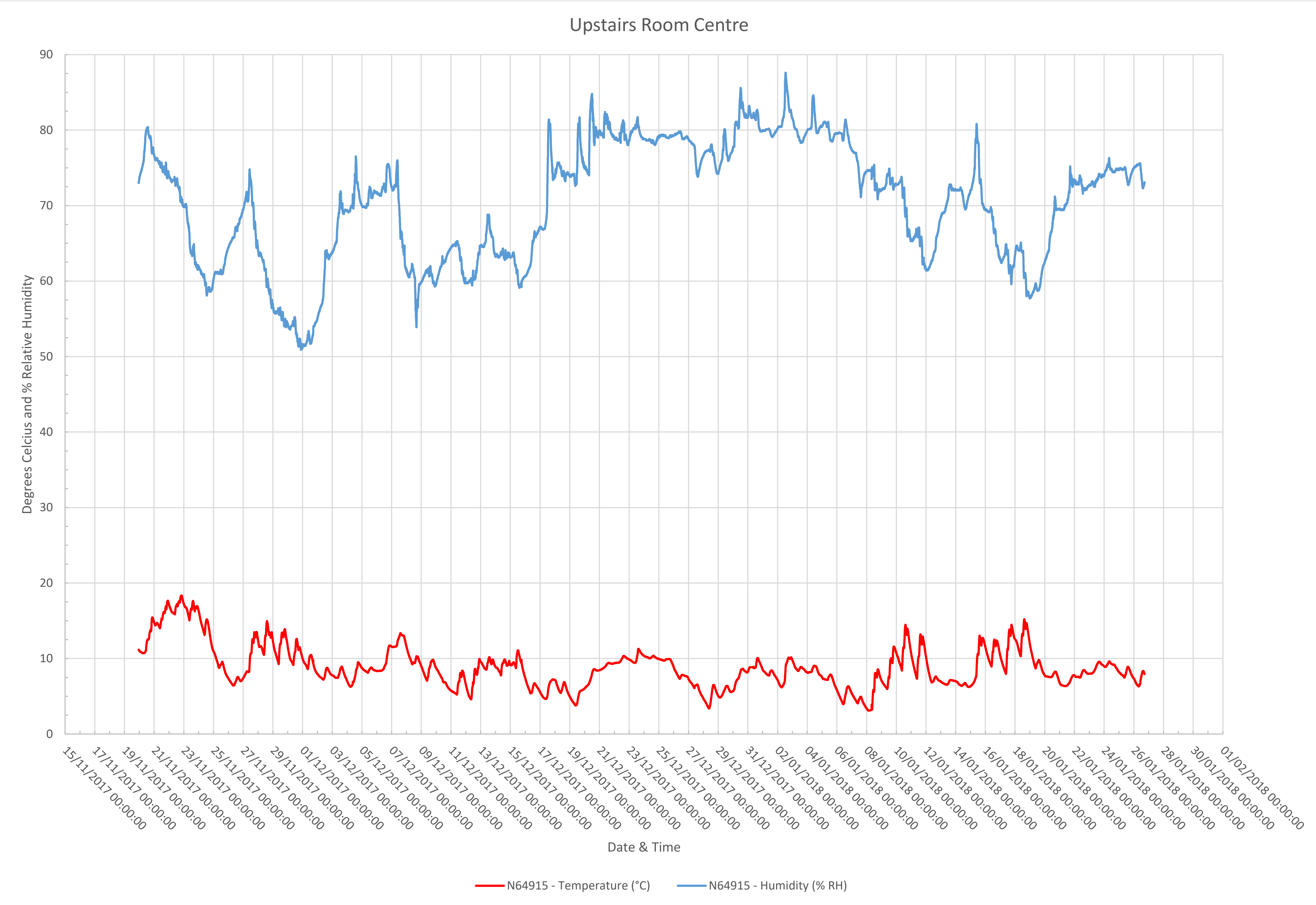


Figure 180: 100gram weight on balance in climatic chamber as experimental set up chapter 8.3. Three-hour fluctuations as described in chapter 8.5.1

Appendix 5; Environmental data for all heating experiments upstairs



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