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Conserving the historic environment: thermal monitoring of The Hill House, by Charles Rennie Mackintosh

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ABSTRACT

The Hill House is celebrated as Charles Rennie Mackintosh and Margaret Macdonald's most significant residential work. It embodies their total design philosophy, reflecting the unique atmosphere of its site in every detail. This study examines the house's thermal environment, comparing temperature and humidity data before and after construction of a protective shelter, 'the Box'. Analysing historic evidence alongside contemporary Building Management System (BMS) data, the research evaluates the house's original design and present condition. Findings reveal the original radiator system and fireplaces could provide comfortable conditions year-round. The new BMS and electric radiators offer more precise humidity control. 'The Box' stabilises internal temperatures, minimising the influence of external weather. The study concludes that the house was finely tuned to its environment, offering a unique, weather-responsive experience. Preserving these characteristics is crucial, as a record of life at the turn of the century, and as a testament to Mackintosh's architectural ingenuity.

ARTICLE HISTORY

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Charles Rennie Mackintosh; Hill House; environmental design; environmental history; thermal comfort; conservation; fireplaces

1. Introduction

Completed in 1904, The Hill House in Helensburgh is the most significant surviving work by Scottish architect Charles Rennie Mackintosh and artist Margaret Macdonald (Figures 1 and 2) (Howarth 1952). Its design is a harmony of exterior form and interior furnishings and fittings, reflecting the architectural ideals of the Arts and Crafts movement (Davey 1980). The house embodies the prosperity of Glasgow's turn-of-the-century merchant class, exemplified by client Walter Blackie and his family (Blackie 1959).

Born in 1868, Charles Rennie Mackintosh enrolled at the Glasgow School of Art in 1884, where he met his future wife and collaborator, Margaret Macdonald. Apprenticing in the office of Honeyman and Keppie in 1889, Mackintosh quickly made a name for himself, designing both the Glasgow Herald Building and Martyrs School, completed in 1895, and winning the commission for the new Glasgow School of Art in 1896 (Howarth 1952). This project was notable for its innovative use of electric lighting, and a mechanical heating and ventilation system (Lawrence 2020).

Following his success, Mackintosh received private commissions, including Windyhill, a villa in Kilmacolm designed in 1900. This home, with its L-shaped plan, roughcast exterior, and sloping roofs, served as a clear prototype for his later, more famous work, The Hill House. Windyhill's design demonstrates Mackintosh's Arts and Crafts sensibilities, particularly in his use of fireplaces and bay windows to enhance warmth and natural light (Davidson 1968).

Mackintosh's work was influenced by M. H. Baillie Scott, a leading figure in the Arts and Crafts movement. Scott's designs, such as Blackwell, above Lake Windermere, and White House,

also in Helensburgh, embraced the natural environment, orientating key living spaces toward the sun (Hawkes 2012). In his essay, 'An Ideal Suburban House', Baillie Scott described how the 'delicacy and daintiness' of the drawing room should be set against the 'broad and homely character' of the hallway (Baillie Scott 1894). This could easily be a description of the contrasting yet complementary rooms of The Hill House.

With scenic views to the south over the Clyde estuary, The Hill House manifests a desire to escape the noise and pollution of the industrial city. Mackintosh designed the south front and east and west wings of the house to exploit the horizontal light of the latitude of 56° North to maximum effect. For example, the oriel window of the school room captures morning light, while the bay window in the Drawing Room tracks the sun as it moves across the sky (Figure 3). The projecting window of the dressing room catches the evening sun; architectural adaptations that reflect the site's unique context and climate (Macaulay 1994).

In recent years, The Hill House has faced significant structural issues due to the use of Portland cement in the exterior harling roughcast, trapping moisture and causing damage to the interior structure (Wright 2012). To address this, a protective shelter, 'the Box', was constructed in 2018 to shield the building from rain and wind, enabling the interior to dry out and necessary repairs to be carried out effectively (Figure 4; Dickson, Houston, and Reid 2020).

Environmental conservation

Conservation efforts at The Hill House, all the more important following the recent fires at Mackintosh's Glasgow School of Art and pressing concerns about climate change, reflect the



Figure 1. The Hill House, west front. Author.



Figure 2. The Hill House, south front. Author.

heritage value of the house as well as the need to better understand the original environmental design intentions of its architect.

Conservation literature for historic buildings typically focuses on technical solutions from conservators and engineers designed to improve energy efficiency and prevent cycles of 'reactive repair' without compromising heritage value. For instance,

Cassar (2009) has established standards for English Heritage that include using Building Management Systems to regulate indoor climate.

However, a growing body of research advocates for a more historical perspective. For example, in their study of Brodsworth Hall (architect: Philip Wilkinson, 1863), Cassar and Taylor (2010) illustrate how archives can supplement modern temperature



Figure 3. The Drawing Room. National Trust for Scotland.



Figure 4. 'The Box'. National Trust for Scotland.

data to help reconstruct past indoor conditions. Similarly, in their study of Hardwick Hall (architect: Robert Smythson, 1598), Lawrence and Hawkes (2021) emphasize the importance of constructing a more accurate description of historic indoor environments both to improve 'our understanding of people's lives in the past and significant historical events', as well as the 'relationship between people and climate, and how this has changed over time'. Their study employed thermal monitoring over an annual cycle, together with archival investigations, to show how life in the Elizabethan age was 'both defined and circumscribed by the changing weather and climate'.

The importance of a historical perspective is also highlighted by Eriksdotter and Legnér (2015), who studied how Burmeister House in Visby, Sweden, was adapted in response to its climate over 250 years. They argue that the building's design, which oriented rooms to the sun, employing features like fireplaces and shutters, links the material culture of a single home to broader climate changes, such as the Little Ice Age. Today's reliance on technology for comfort can diminish our appreciation for how significant seasonal changes were in the past, when indoor and outdoor environments were far less distinct.

In this context, the principles of adaptive thermal comfort are particularly relevant. Historically, people used adaptive behavioural strategies – such as adjusting their clothing or the use of fireplaces and curtains – to control their surroundings (English Heritage 2014). This aligns with evidence from environmental psychology, that people prefer retaining direct control over their environment and experiencing more 'natural' conditions that reflect the outdoors (Humphreys, Nicol, and Roaf 2015). While modern interventions are often necessary, they risk altering the environmental experience of historic structures (Adams et al. 2014; Cassar 2009). This article aims to examine these issues in the context of the conservation of The Hill House, reflecting on Mackintosh's original design aspirations and the balance between preservation and environmental adaptation.

Heating The Hill House

The Hill House represents a transition point from the traditional heating of country houses by fireplaces, to the widespread use of central heating. While central heating was first developed in the nineteenth-century, its domestic application was initially limited to retrofitting older, larger stately homes. The Hill House is a significant, yet overlooked, example of a home designed with central heating from its inception, marking an important shift in the history of domestic architecture.

Central heating would go on to liberate architectural design from the compact, thermally massive construction of the past, paving the way for many twentieth-century architectural revolutions. The Hill House is representative of a transitional phase, combining a central heating system for day-to-day comfort in the main living rooms with smaller, supplementary fireplaces for use in winter (Figures 5 and 6).

Very little information is available on the heating of The Hill House in the existing literature. An accompanying article discusses the development of the design and Mackintosh's environmental considerations in some detail (Lawrence, *forthcoming*). Mackintosh selected James Cormack & Sons for the central heating installation, likely due to their experience with similar systems, including their work at the Glasgow School of Art (Lawrence 2020). The final bill for the heating equipment was £116, with additional costs for grates and garden heating ('Honeyman, Keppie & Mackintosh Job Book' n.d.).

The Hill House utilized separate heating systems: an oil-fired boiler for central heating, and a 'Sunbeam' kitchen range and coal-fired boiler for domestic hot water. The boiler for the central heating was housed in a dedicated heating room at the base of the spiral stair tower in the south-east corner of the plan, with an external oil tank located outside the east wing of the house.



Figure 5. Radiators; left to right: Hallway, Dining Room, Library. Author.



Figure 6. Fireplaces; left to right: Hallway, Library, Drawing Room. Author.

While designing the house, Mackintosh likely consulted contemporary resources including the six-volume publication 'The Principles and Practice of Modern House-Construction', edited by the architect G. Lister Sutcliffe, and published by Blackie in 1899 (Figure 7), which promoted central heating's ease of use and low maintenance, suggesting that it could be maintained by domestic servants (Sutcliffe 1899, 108). The author recommended that radiators be positioned underneath windows 'so that an upward current of warmed air may be produced, in the very place whence a cold draught usually proceeds'. As a compromise, the author suggests that there is no reason 'why a combined system of open fires and hot water heating should not be used. The flue of the fireplace might then be used as an outlet for the vitiated air' (Sutcliffe 1899, 109).

Mackintosh's heating design at The Hill House included a loop of radiators on the ground floor, relying on fireplaces for warmth upstairs. The Crane radiators, common for the period, are inefficient by modern standards but typical of low-pressure convection systems (Figure 5). The relative size of the radiators, together with their assumed heat output, is outlined in Table 1. There is no record of how the radiator sizes were arrived at in relation to room size or function, but contemporaneous manuals offered various methods of calculation (Gwilt 1903, 750). A large radiator was placed under the window in the Hallway, which would warm the upstairs by convection (Figure 8). Mackintosh also employed large-diameter pipes under the bay window seat in the Drawing Room, providing both draught protection and radiant warmth for those enjoying the view (Figure 3).

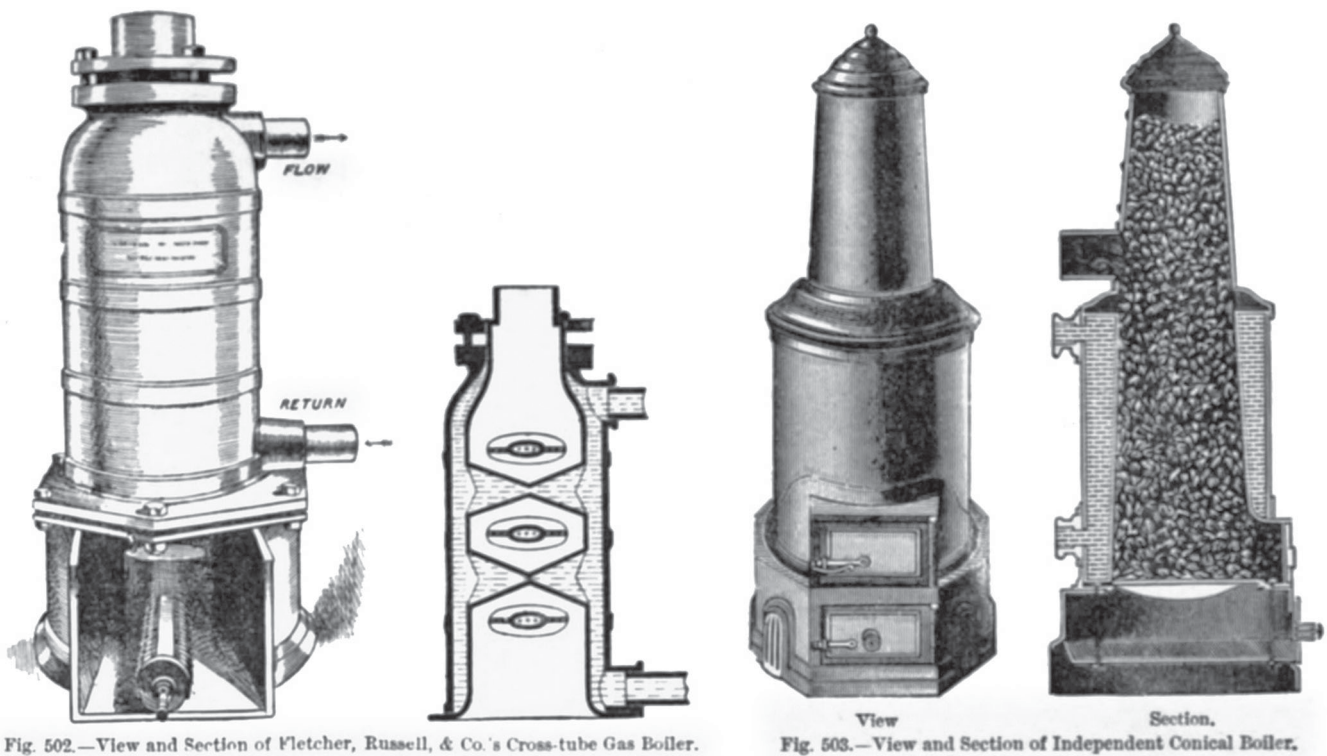


Figure 7. Illustrations of boilers, from G. Lister Sutcliffe, *The Principles and Practice of Modern House-Construction* (Blackie, 1899).

Table 1. Radiators at The Hill House.

Location	Type	Sections / length	Assumed heat output
Hallway	2 columns	9 sections	800W
Cloak Room	2 × 4 ¹ / ₂ " cast iron pipes	6 feet	400W
Library	6 tubes	18 sections	2,400W
Foot of stairs	2 columns	13 sections	1,100W
Drawing Room	2 × 4 ¹ / ₂ " cast iron pipes	12 feet	800W
Drawing Room	6 tubes	18 sections	1,400W
Dining room	2 columns	15 sections	1,300W
Bathroom	Towel rail	3 bars	300W

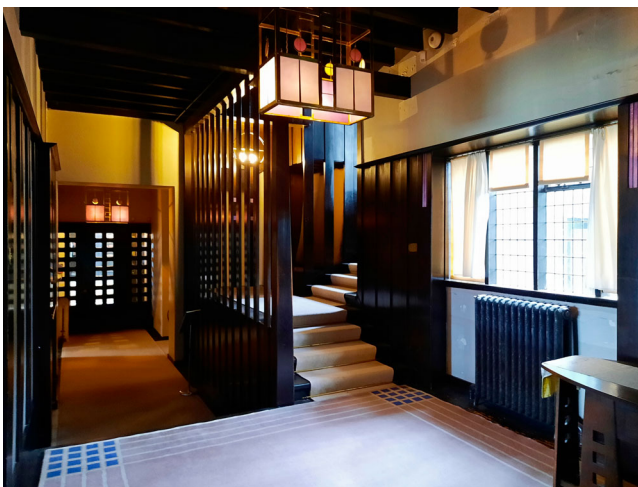


Figure 8. The Hallway. Author.

Methodology

The thermal monitoring programme described by this paper compares three sets of data recording air temperature and relative humidity levels at key locations within the house, compared

with an external reference. The aim of the monitoring was to make a quantitative survey of the thermal environment of the house, both to evaluate the condition of the house in the present and, it is hoped, provide data to further our understanding of the environment of the building as originally constructed. While a Building Management System (BMS) is used for day-to-day management of the house and its environmental systems, this project represented the first time that historic data extraction was employed to take a long view of the thermal performance of the house reflecting seasonal changes over several calendar years.

Data collection

Annual datasets from 2021 to 2022 and 2022 to 2023 data were collected concurrently, reflecting environmental conditions inside the house in its present condition. Following this data collection, historical data from 2018 was extracted from the BMS to compare conditions inside the house before and after construction of 'the Box'.

The monitoring devices employed were Hanwell Pro Precision RH/T wireless loggers. These have an operating temperature

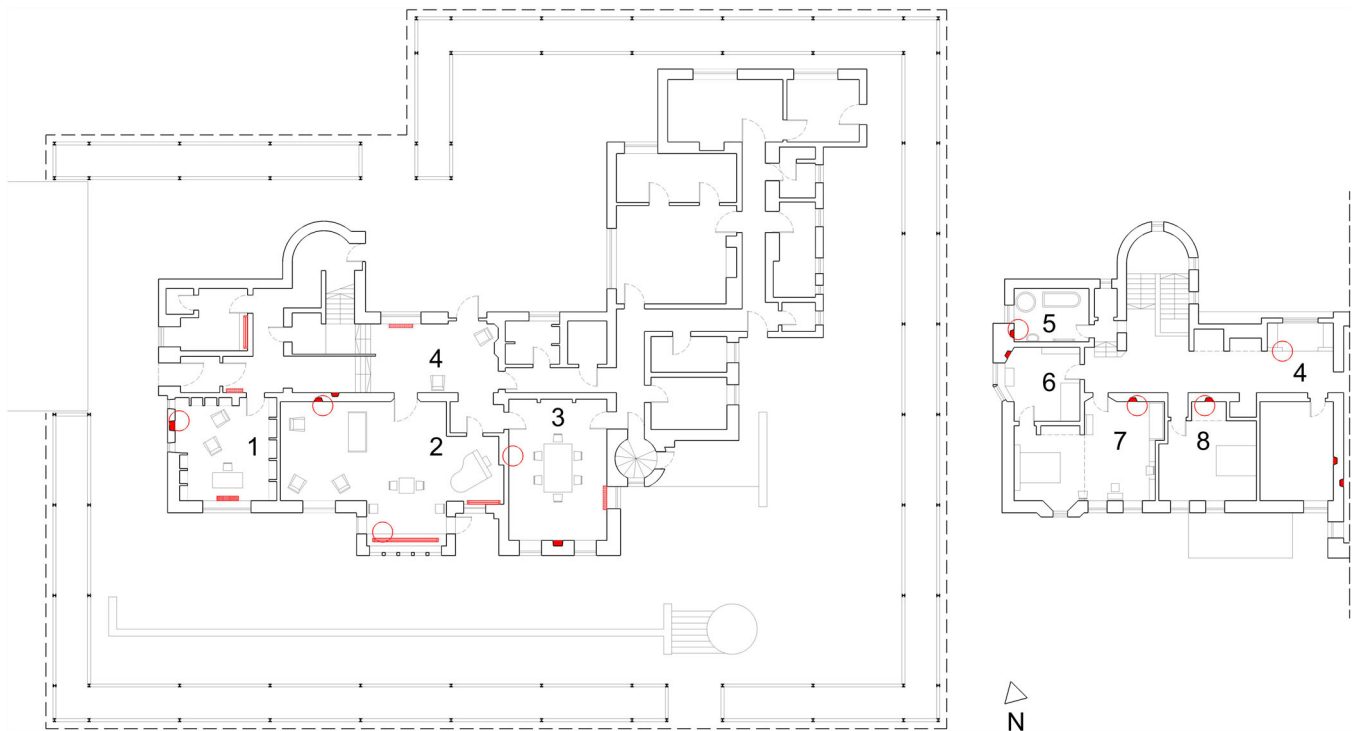


Figure 9. Ground and part-first floor plan of The Hill House and 'The Box', with fireplaces and radiators highlighted in red. The locations of wireless data loggers are circled. Key: 1. Library; 2. Drawing Room; 3. Dining Room; 4. Hallway; 5. Bathroom; 6. Dressing Room; 7. The White Bedroom; 8. Second Bedroom.



Figure 10. Locations of wireless data loggers. Clockwise from top left: Library; Drawing Room fireplace; Drawing Room bay window; Dining Room; Hallway; Bathroom; The White Bedroom; Second Bedroom.

range of -40° to $+60^{\circ}\text{C}$, with a resolution of 0.1°C , and a RH range from 0 to 100%, with a resolution of 0.1%. Accuracy for temperature is $\pm 0.1^{\circ}\text{C}$. Supplementary monitoring was undertaken utilizing two-channel HOBO U10-003 Temperature-RH model loggers. These have an operating temperature range of -20° to $+70^{\circ}\text{C}$, with a resolution of 0.02°C , and a RH range from 0 to 95%, with a resolution of 0.1%. Both logger types comply with the ranges and accuracy levels specified in Standard ISO 7726 for measuring the physical variables of the environment (ISO 1998). Measurements of temperature and RH were taken at each location at max. 30 min intervals. The monitoring locations are indicated in Figures 9 and 10.

The loggers were positioned at a height of approx. 1–1.5 m from the floor (representing air temperature for a standing subject). As far as possible the loggers were positioned in locations representative of the original inhabitation of the house: e.g. on the mantelpiece, where this is the focus of the original seating arrangement; on the sideboard next to the dining table; or next to the benches in the Drawing Room bay window and in the Hallway. Positions near radiators were avoided, with the exception of the Drawing Room bay window (data was only collected at this location following decommissioning of the hot water pipes located underneath the window seat).

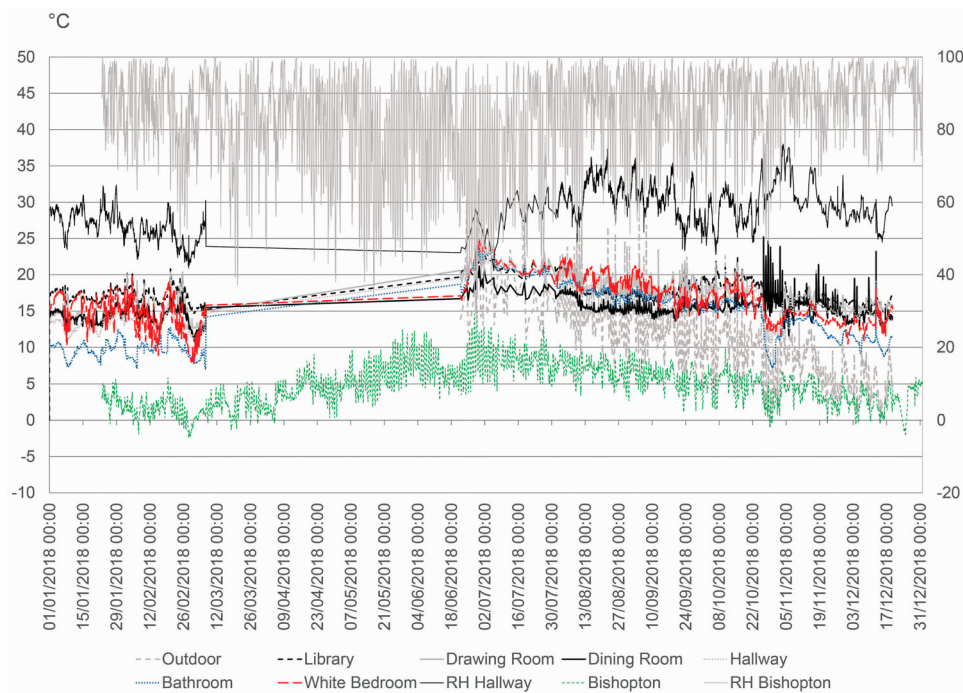


Figure 11. Temperatures and RH, January – December 2018. Data obtained from: Met Office and Economic and Social Research Council, 'Met Office: Observations Data, 2022' [data collection], University of Glasgow – Urban Big Data Centre.

To provide a broader background to the monitored data, a complete meteorological data set was obtained from the Meteorological Office for the weather station at Bishopton, located approximately 14 miles south-east of The Hill House, near Glasgow Airport.

The first dataset covers a period from January to December 2018, illustrating environmental conditions within the house prior to the construction of 'the Box' (Figure 11). This includes a period from March to June 2018, when an hourly monitoring system installed in 2004 was replaced by the new Hanwell BMS, recording data approximately every five minutes. The calibration of this system occurred during June and July, during which period the system was turned off at night-time. The data was interrupted again in December, coinciding with the beginning of construction of 'the Box'.

The second dataset covers a period from August 2021 to August 2022, following construction of 'the Box' (Figure 12). During this period, the original water radiator system inside the house was decommissioned. Also, during this period, the installation of new electric heating led to a system overload, resulting in all heating in the house being turned off as a precautionary measure for a period of several months. It has therefore been possible to gather data from the house 'free running', without any additional heating across a wide range of weather conditions, establishing a baseline for the thermal performance of the building upon which different historic heating methods can be accurately modelled.

The third dataset covers a period from August 2022 to August 2023, with the house heated by portable electric radiators, controlled by the Hanwell BMS (Building Management System) (Figure 13). The system is employed to control humidity rather than temperature, to protect the internal collections and assist with the 'drying-out' of the house.

Infrared photographs of the interior of the house were captured utilizing a Flir One thermal imaging camera in December 2023, utilizing Multi-Spectral Dynamic Imaging technology. This camera has an ambient operating temperature range of 0° to +35°C, with a scene operating temperature of -20° to +120°C, with a resolution of ±3%.

Taken together, the three datasets and thermographic imagery permit comparisons to be made of the thermal performance of the House:

- In its current condition, and prior to the construction of 'the Box'.
- Operating with the original water radiator system, and the new electrical humidity-control system.
- 'Free running', without any mechanical heating.

Calculation of heat output

Following the data collection, the radiant heat output of the fireplaces and radiators were calculated in order to visualize the original heating of the house. The radiant heat release rate of the fireplaces was estimated based on experimental data collected by Margaret Fishenden for the Air Pollution Advisory Board at the University of Manchester between 1916 and 1919 (Fishenden and Air Pollution Advisory Board 1920). Fishenden's experiments measured the heat absorbed from a variety of fireplace designs and sizes. The data that has been utilized here is based on 'a small modern fire grate, open, barless and with a raised hearth', with 'a small fender, with adjustable doors for draught regulation' underneath (Fishenden and Air Pollution Advisory Board 1920, 9). The fireplace in Fishenden's experiment was centred on the short wall of a room measuring 5 × 3.5 m. One long wall of the room was an external wall of approx. 800 mm thickness.

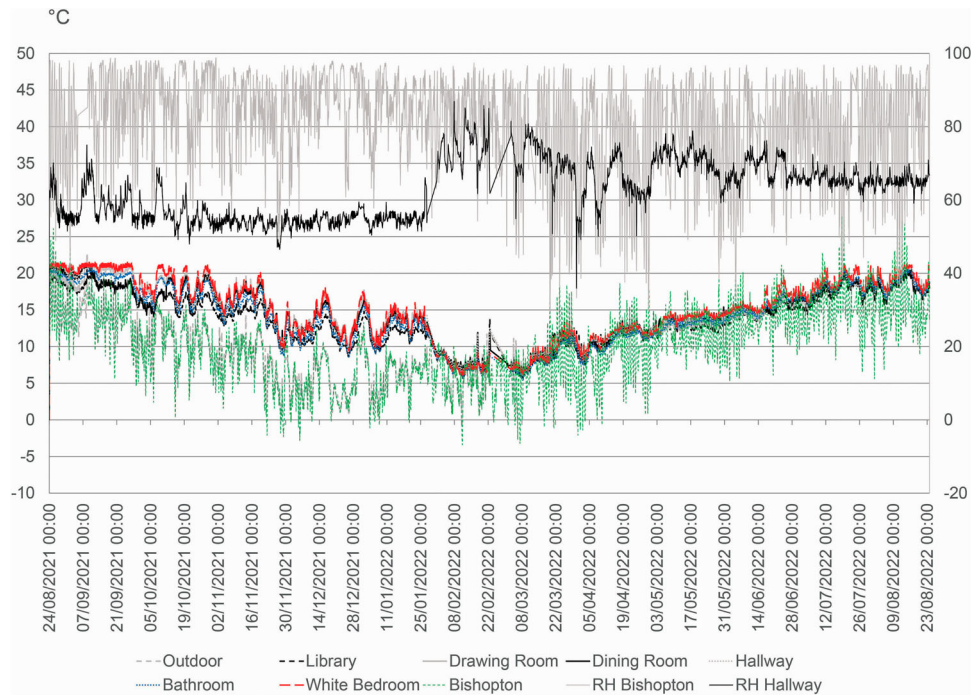


Figure 12. Temperatures and RH, August 2021 – August 2022. Data obtained from: Met Office and Economic and Social Research Council, 'Met Office: Observations Data, 2022' [data collection], University of Glasgow – Urban Big Data Centre.

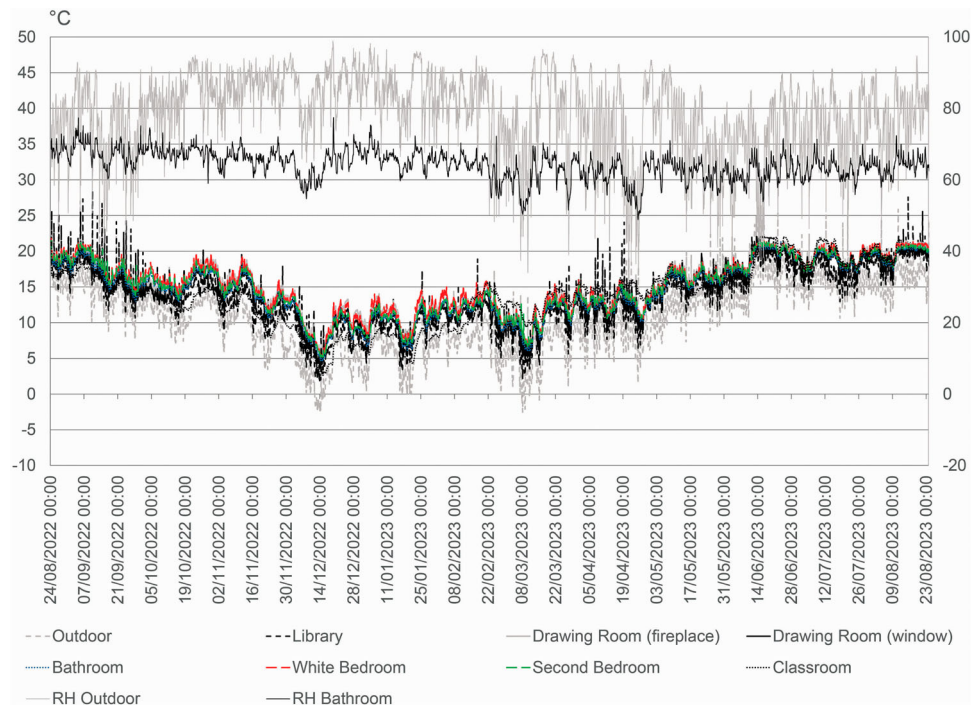


Figure 13. Temperatures and RH, August 2022 – August 2023.

The size and style of the fireplace, together with the construction of the room, provide a relevant comparison for The Hill House fireplaces.

Summary of thermal monitoring data

1.1. data

The coldest day from the 2018 monitored period was 28 February, where external temperatures recorded at the weather

station at Bishopton, 18 km to the south-west, fell to a low of -4.9°C at 6am (Figure 14). Within the house, temperatures remain relatively stable, with the warmest temperatures in the Library, falling from around 17°C at midday on the 27 February to a low of 15°C lasting for the duration of the 1 March. Temperatures in the other rooms follow a similar trajectory, from around 15°C to 13°C , over the same period in the Drawing Room and Dining Room. Upstairs, temperatures in the White Bedroom and Bathroom fell from around 9°C to 8°C . The difference in temperatures between the rooms reflects the varied influence of the

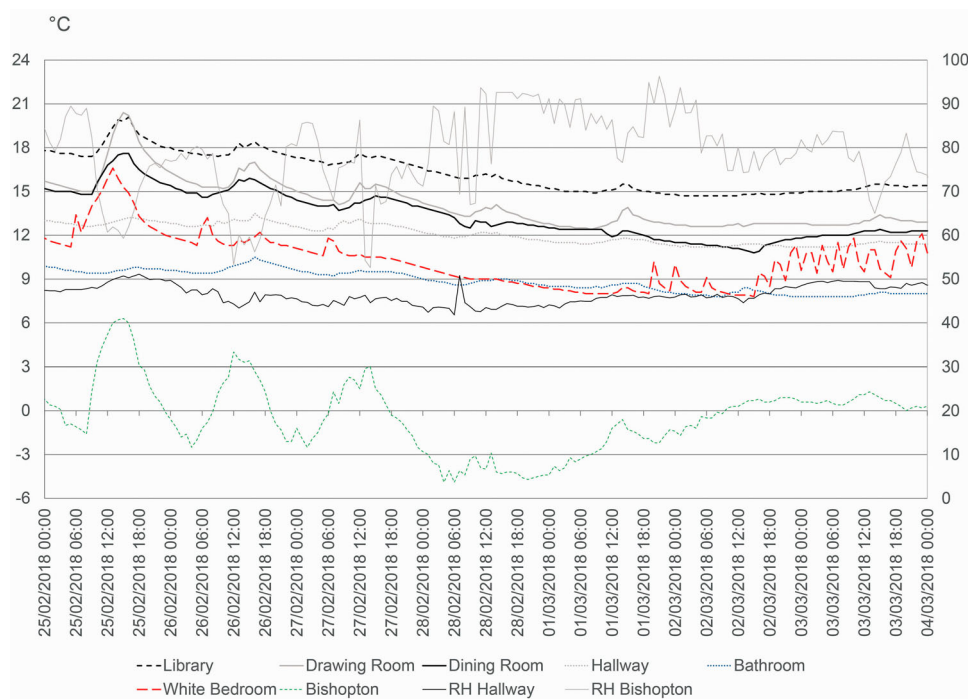


Figure 14. Temperatures and RH, 25 February – 4 March 2018. Data obtained from: Met Office and Economic and Social Research Council, 'Met Office: Observations Data, 2022' [data collection], University of Glasgow – Urban Big Data Centre.

water radiator system, with additional portable heating in the White Bedroom from the evening of the 1 March leading to a flutter pattern of around ± 2 K approximately every 3 h. Small peaks in temperature can be observed around the middle of the day from 26 February – 1 March. Larger internal peaks are observed on 25 February, where temperatures in the Drawing Room increase from 15°C to 20°C from 10am to 4pm. This reflects the influence of solar gains in the south facing rooms, particularly the large bay window in the Drawing Room, overlooking the Clyde. According to the data from Bishopton Weather Station, the 25 February was a sunny day followed by a clear night. By contrast the 26 February was overcast and cloudy, followed by rain showers on 27 February and light to heavy snowfall from 28 February to 1 March.

Looking at data from 7 January to 7 March, internal temperature spikes associated with sunny days are clearly discernible over the longer period (Figure 15).

1.2. data

An electrical fault that occurred around 27 January 2022 led to all heating in the house being switched off for a period lasting several months. This led to a drop in internal monitored temperatures together with a significant rise in internal humidity for the rest of the winter period (Figure 12).

The coldest day from the 2021 to 2022 monitored period was 11 February, where external temperatures at Bishopton fell to -3.4°C at 6am (Figure 16). This occurred during the period without internal heating. We can see remarkably constant internal temperatures of around $6\text{--}7^{\circ}\text{C}$ in all rooms on 11 February, rising to $7\text{--}8^{\circ}\text{C}$ on the warmer days preceding and following. While there are regular diurnal peaks reflecting daytime hours, these rarely exceed 2 K. Unlike the 2018 data, external

weather conditions are more difficult to discern, reflecting the construction of 'the Box', shading the house from the influence of solar gains.

Following the heating failure RH increased from its controlled level in the interior of around 50–60% in the Hallway to around 70–80%, following exterior levels. The influence of the electric heating can be detected as it is turned on for safety checks following the electrical failure. The heating was turned on from 20 to 21 March, coinciding with a dip in external night time temperatures from around 3°C to below 0°C , over which time internal temperatures stratified according to the presence of radiators, rising from around 9°C on the 20 March to $11\text{--}12^{\circ}\text{C}$ in the Library and White Bedroom, and $10\text{--}11^{\circ}\text{C}$ in the Drawing Room and Hallway (Figure 17). Temperatures in the Dining Room and Bathroom remained consistent, suggesting no heating was turned on in these spaces. Simultaneously, internal RH fell from over 70% to close to 60%, where the feathering pattern indicates the presence of thermostatic control.

The hottest day of the 2021–2022 monitored period was 19 July, where external temperatures at Bishopton peaked at 28.6°C at 1pm (Figure 18). Remarkably, internal temperatures in all monitored rooms barely rise above 21°C , or fall below 18°C in the days preceding and following, despite night time external lows of $12\text{--}15^{\circ}\text{C}$. The period from 17 to 20 July was sunny, with some cloud cover in the early mornings.

1.3. data

The coldest period from the 2022–2023 monitored period was 13 December, where external temperatures fell to a low of -2.2°C at 2am, remaining sub-zero until late morning on 14 December (Figure 19). Within the house, temperatures remained

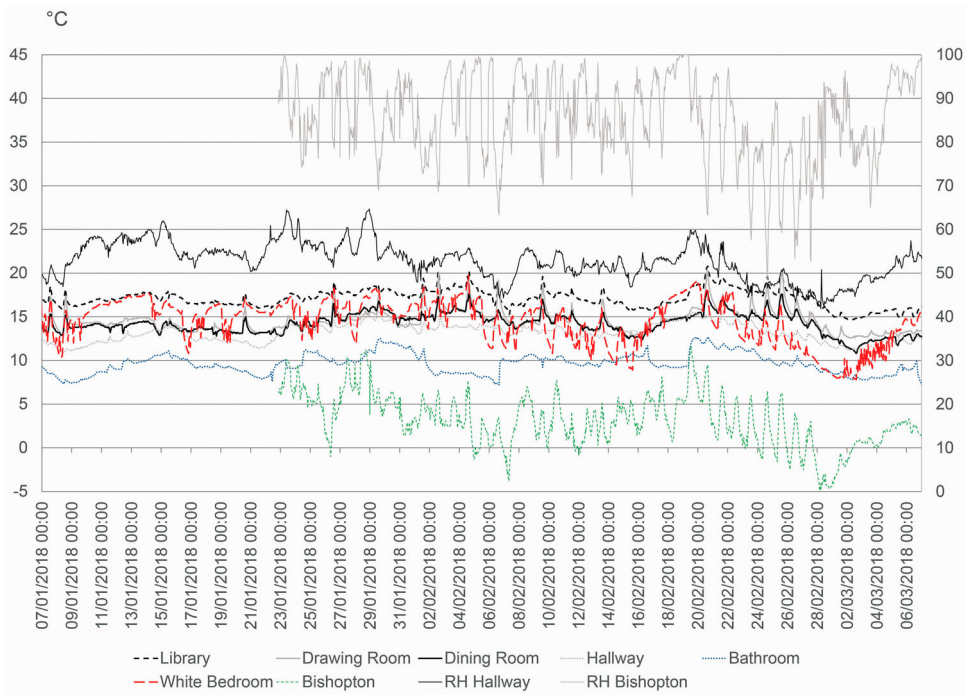


Figure 15. Temperatures and RH, 7 January – 6 March 2018. Data obtained from: Met Office and Economic and Social Research Council, ‘Met Office: Observations Data, 2022’ [data collection], University of Glasgow – Urban Big Data Centre.

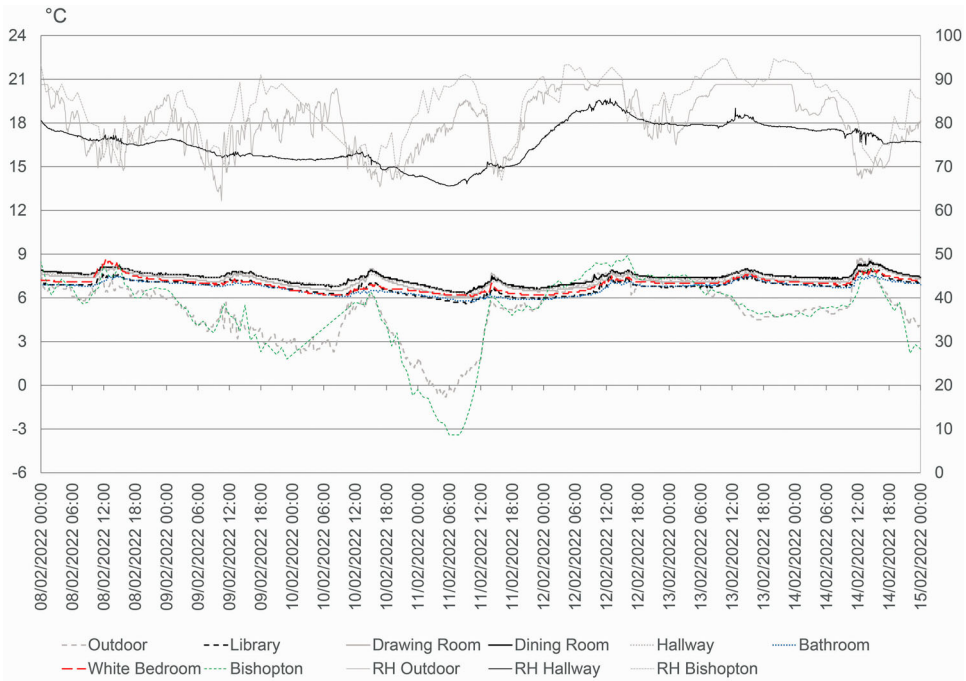


Figure 16. Temperatures and RH, 8 February – 15 February 2022. Data obtained from: Met Office and Economic and Social Research Council, ‘Met Office: Observations Data, 2022’ [data collection], University of Glasgow – Urban Big Data Centre.

relatively stable, with temperatures in the White Bedroom, Second Bedroom and Drawing Room, near the fireplace on the spine wall, falling from around 6.5°C at 12am on 13 December to 5°C at 12pm on 14 December. An additional datalogger placed in the bay window of the Drawing Room recorded colder temperatures, falling from 4.5°C to 3.5°C over the same period, with a small peak of 5°C corresponding to the afternoon sun between 2pm and 5pm on 13 December. The Library is the coldest room,

with temperatures falling from 3°C to 2°C over the same period, peaking at 4°C in the afternoon.

As with the 2021–2022 data, the influence of external weather conditions is reduced by ‘the Box’, with the exception of the Library, where pronounced peaks of up to +6 K can be seen, corresponding with afternoon solar gains, for example on 11, 14 and 15 December. This reflects the geometry of the Library window, with a lintel 3.1 m above the floor allowing the sun to

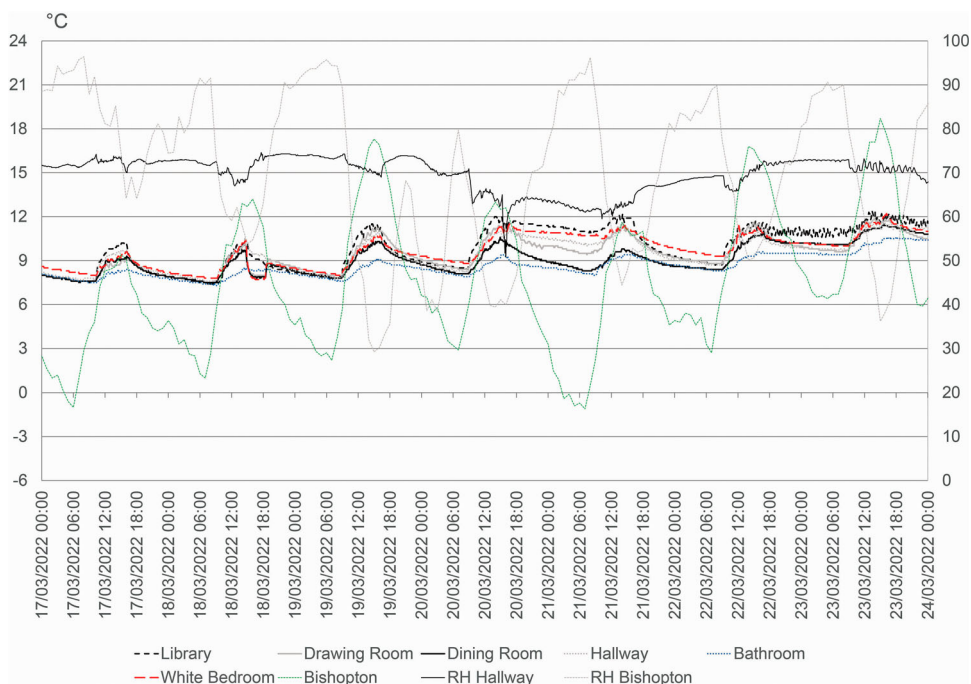


Figure 17. Temperatures and RH, 17 March – 24 March 2022. Data obtained from: Met Office and Economic and Social Research Council, 'Met Office: Observations Data, 2022' [data collection], University of Glasgow – Urban Big Data Centre.

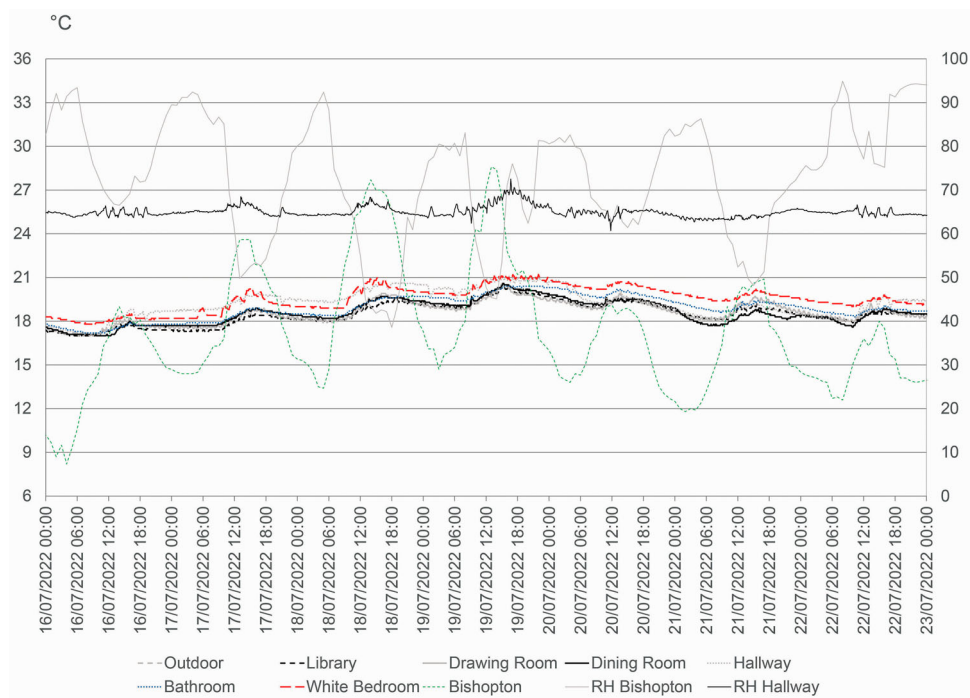


Figure 18. Temperatures and RH, 16 July – 23 July 2022. Data obtained from: Met Office and Economic and Social Research Council, 'Met Office: Observations Data, 2022' [data collection], University of Glasgow – Urban Big Data Centre.

project deep into the room around the winter solstice, when the sun is at an altitude of barely 10 degrees at midday.

The low temperatures observed in all rooms, in a pattern closely following external temperatures, also visible over the full annual monitoring period, shows the reduced influence of the electric radiators on heating the space compared with the original central heating system. It can also be observed that internal relative humidity levels are maintained broadly at 60–70% across the year. This is somewhat higher than before the old

heating system was turned off, when humidity was broadly maintained at 50–60%, rising to 70–80% on occasion.

Equinox data

A comparison of the data from the period around the autumn equinoxes in 2018, 2021, and 2022 is illustrative of the changes to the internal environment of the house in response to the

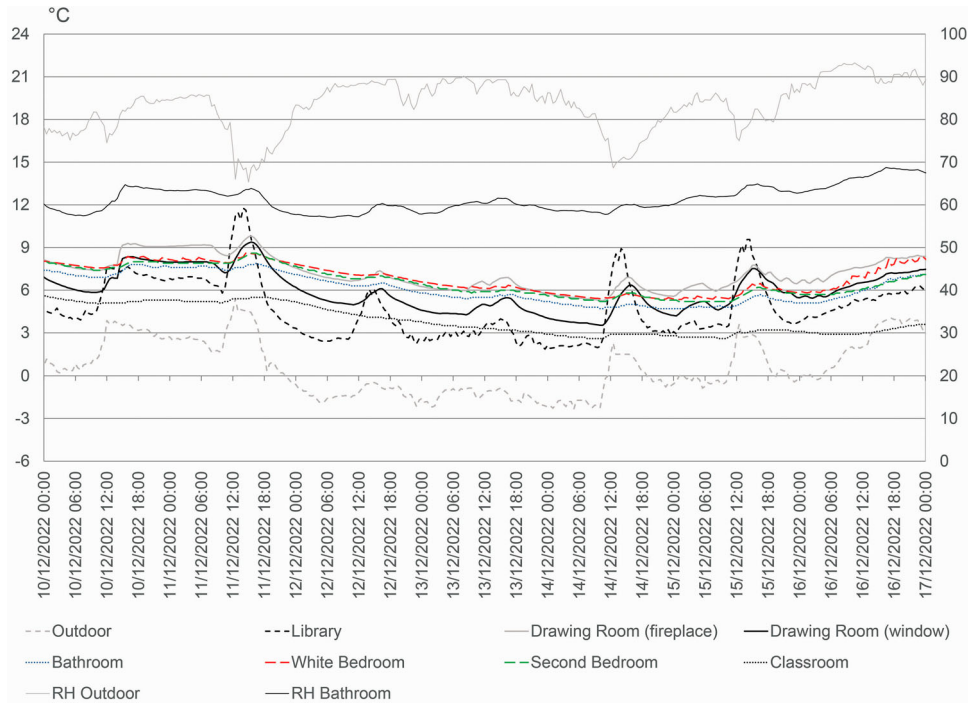


Figure 19. Temperatures and RH, 10 December – 17 December 2022.

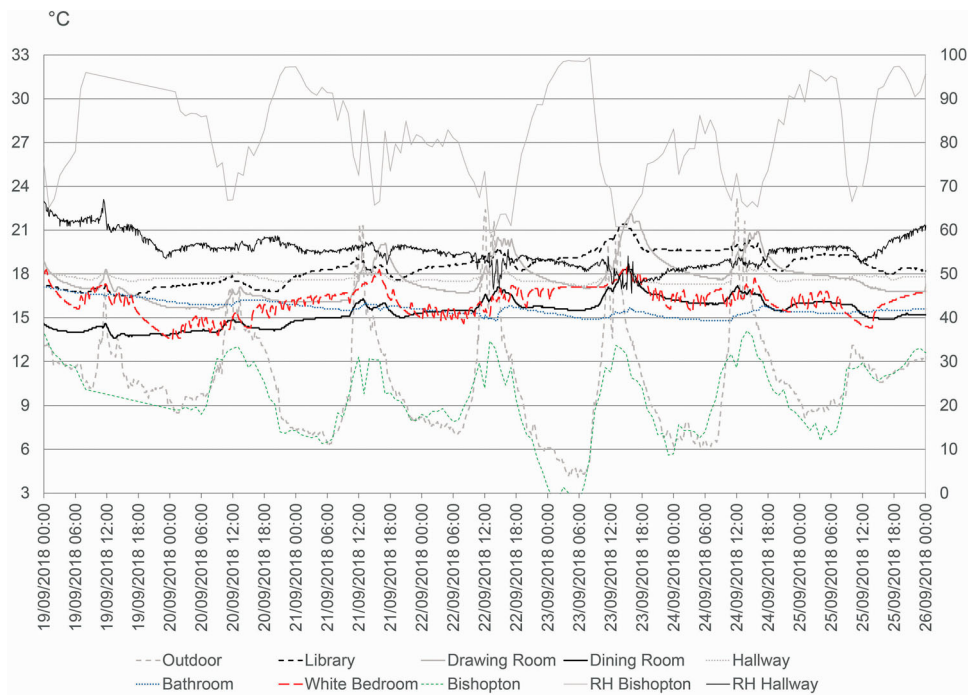


Figure 20. Temperatures and RH, 19 September – 26 September 2018. Data obtained from: Met Office and Economic and Social Research Council, ‘Met Office: Observations Data, 2022’ [data collection], University of Glasgow – Urban Big Data Centre.

construction of ‘the Box’, combined with the changes to the heating regime.

In 2018, the equinox itself (23 September), was cloudy and overcast in the morning, with sun and part cloud from 2pm until sunset (Figure 20). Conditions were similar on the days preceding and following, with part cloud and occasional showers on the 21 September, part cloud and sun in the early morning and late afternoon on 22 September, and clear skies in the morning

followed by part cloud in the afternoon on 24 September. Temperatures recorded at Bishopton peaked at around 13–14°C on these days, with the external reference at The Hill House peaking much higher at 21–22°C, likely indicating sunshine hitting the instrument. The biggest response to the weather conditions is again observed in the Drawing Room, where internal temperatures rise daily from 17°C overnight to 22°C on the equinox itself. Temperatures in the Dining Room and Library rise from around

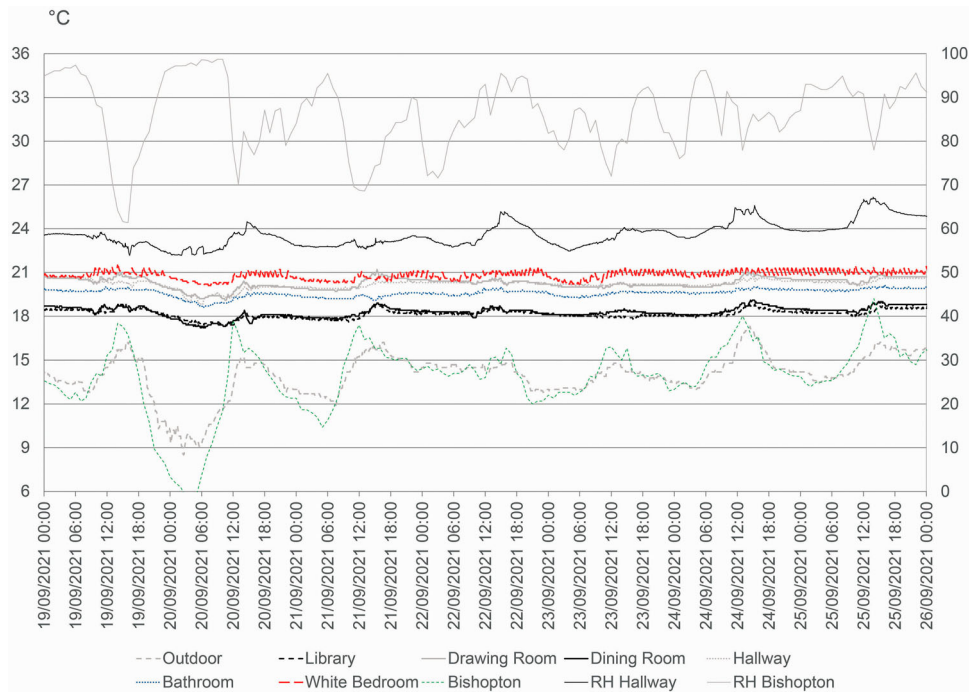


Figure 21. Temperatures and RH, 19 September – 26 September 2021. Data obtained from: Met Office and Economic and Social Research Council, 'Met Office: Observations Data, 2022' [data collection], University of Glasgow – Urban Big Data Centre.

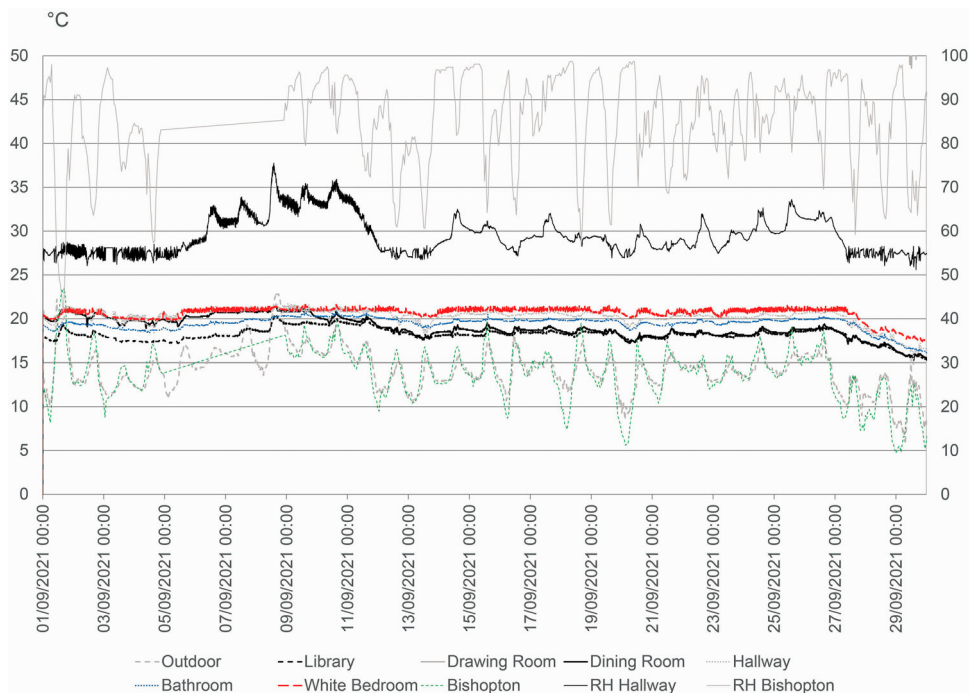


Figure 22. Temperatures and RH, 1 September – 30 September 2021. Data obtained from: Met Office and Economic and Social Research Council, 'Met Office: Observations Data, 2022' [data collection], University of Glasgow – Urban Big Data Centre.

19°C to 21°C and 16°C to 18°C respectively. On the north side of the house, temperatures in the Hallway (around 17°C) and Bathroom (around 15°C) barely register the diurnal change in temperature.

In 2021, the equinox (22 September) was overcast with light showers, with external temperatures hovering around 15°C (Figure 21). The 21 September was also cloudy. The mornings

of 19 and 20 September were clearer with sunshine breaking through early morning mist. This is reflected in exterior temperatures at Bishopton reaching around 17°C on each day by the early afternoon. However these changes in weather barely register on internal measurements. From the graph covering September 2021, we can see internal temperatures are steady around a band of 19°C to 21°C until 27 September, when the BMS

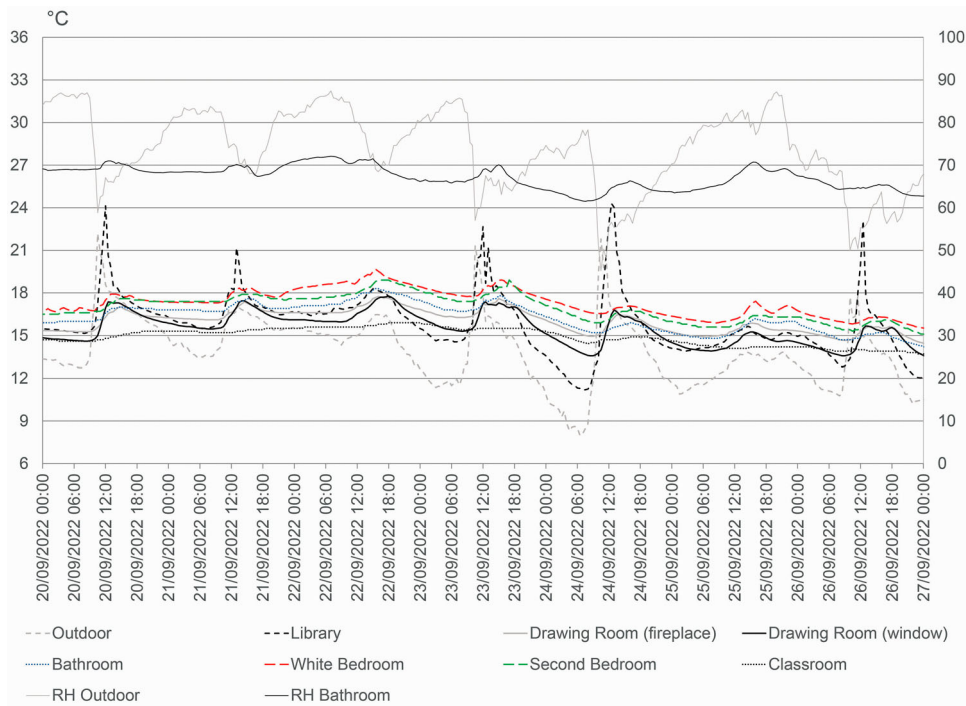


Figure 23. Temperatures and RH, 20 September – 27 September 2022. Data obtained from: Met Office and Economic and Social Research Council, 'Met Office: Observations Data, 2022' [data collection], University of Glasgow – Urban Big Data Centre.

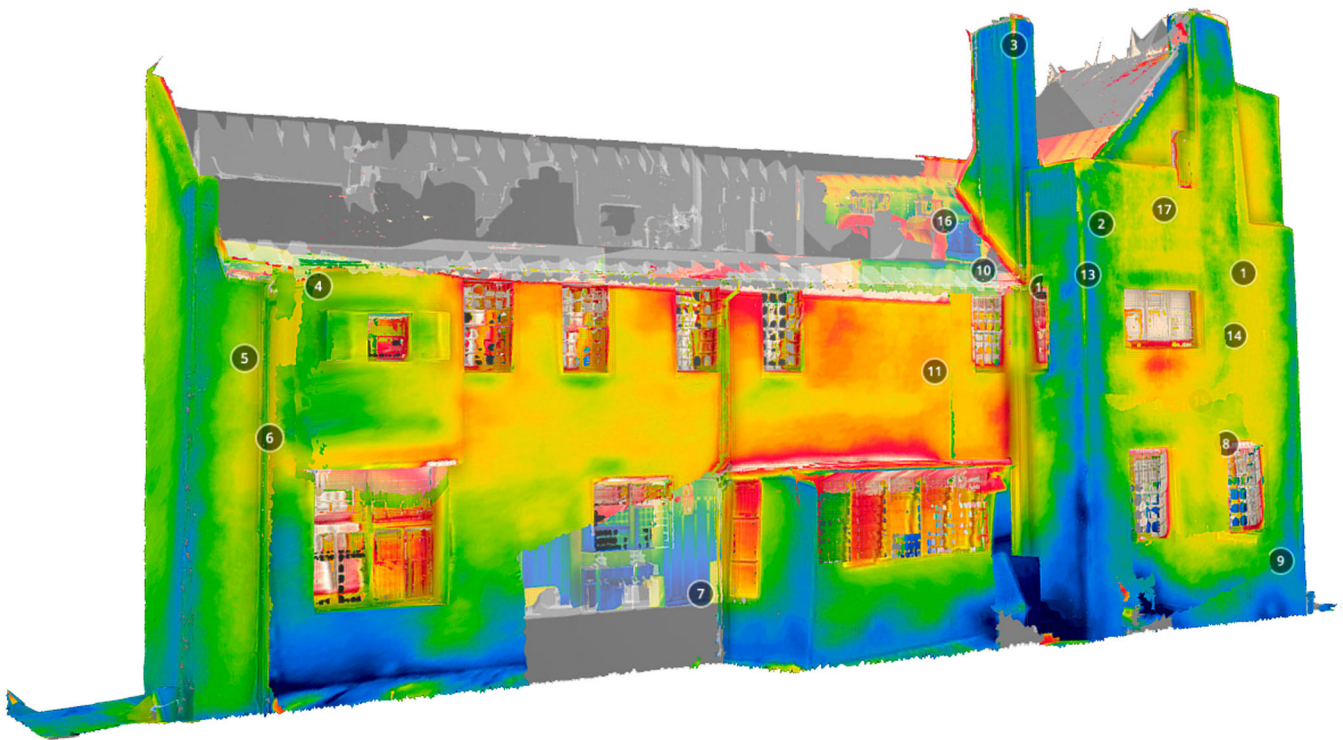


Figure 24. Thermographic survey. Historic Environment Scotland.

settings appear to have been adjusted to control RH at a band of 50–60%, allowing temperatures to drop into the winter period (Figure 22).

In 2022, the morning of the equinox (23 September) was overcast, clearing to sunshine in late morning, followed by light showers at midday and cloudy conditions in the afternoon (Figure 23). Temperatures at Bishopton were around 14–15°C

during the day, falling to 7–8°C overnight. The external reference at The Hill House again peaked at 21–22°C on 23 and 24 September, likely indicating sunshine hitting the instrument. The biggest response to the weather conditions is observed in the Library, with internal temperatures rising to 23–24°C in the afternoon on 23 and 24 September (it is likely this also indicates sunshine falling on the datalogger), but falling to 11°C on

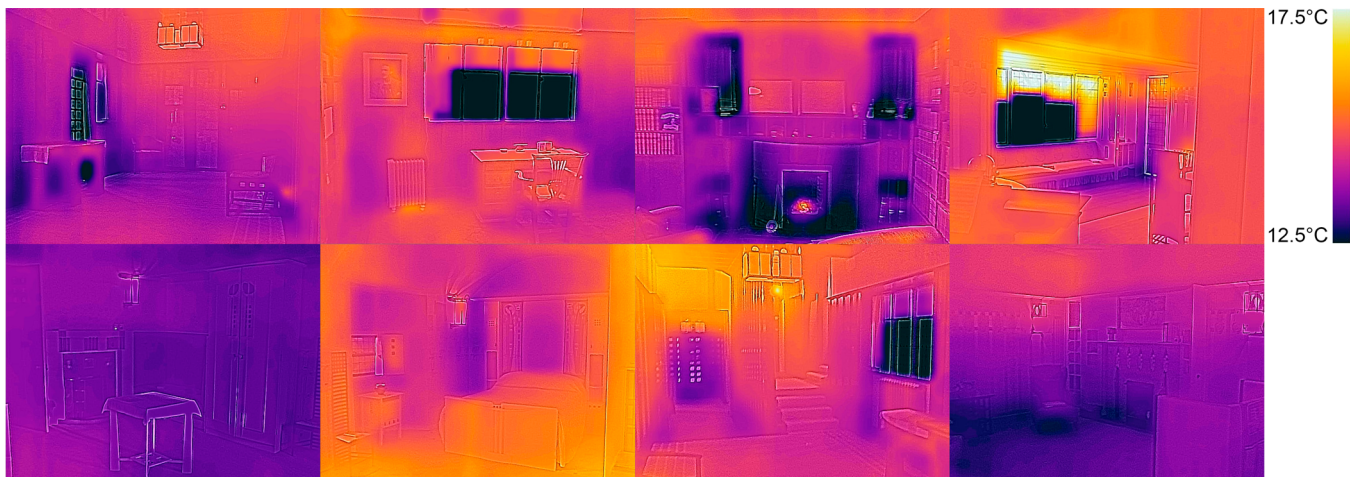


Figure 25. Infrared images. Clockwise from top left: Hallway from entrance; Library desk; Library fireplace; Drawing Room bay window; Drawing Room fireplace; Hallway looking towards staircase; White Bedroom bed; White Bedroom fireplace.



Figure 26. The White Bedroom. Author.

the morning of 24 September, while temperatures in the other rooms only fell to 15–17°C. The datalogger placed in the bay window of the Drawing Room also recorded temperatures 1–2 K lower than the datalogger on the spine wall.

Thermographic imaging

A thermographic survey undertaken by Historic Environment Scotland following construction of ‘the Box’ in 2019 reveals the extent of moisture retention behind the harling roughcast (Figure 24). Patches of green and blue indicate the presence of dampness, tracing the path of the fireplace flues, underneath the windows, and in the corners of the construction. Preliminary analysis indicates that moisture levels have reduced between 2019 and 2023, with clear evidence of drying in locations that were suffering from the highest levels of water ingress prior to construction of ‘the Box’ (Young, 2024).

To investigate the influence of ‘the Box’ and electric radiators on the present-day thermal experience of the interior of the house, an infrared survey of key rooms was undertaken on 21

December 2023, when external ambient temperatures remained stable at around approximately 9–11°C.

The monitored air temperatures of the house reflected the external conditions, with temperatures in the drawing room bay window of around 14°C, and 15°C next to the fireplace in the centre of the house plan. Air temperatures in the other monitored spaces fell within this range, although the library was slightly warmer at 15.5°C. The infrared images show how the physical building fabric responds to the prevailing atmospheric conditions (Figure 25).

Viewed from the entrance the Hallway exhibits thermal stability, with noticeable cool areas around the north facing windows. In the Library, the warmth from an electric radiator warms the ceiling. This radiator is placed just to the left of the original radiator, which was centred under the window behind the desk. The fireplace on the west wall, together with the small windows to either side of the chimney breast, appear as cold patches on the book-lined walls. If the fire was lit the thermal experience of this space would be quite different, offering a welcome retreat from the weather outside.

In the Drawing Room, the bay window exhibits dynamic thermal qualities, warmed by an electric radiator in one corner. The window bay was originally warmed by hot water pipes running underneath the cushioned seat, offering an unexpectedly comfortable place to rest in what is otherwise an exposed vantage point projecting beyond the envelope of the rest of the house. When the sun is shining, the sitter would benefit from the solar gains through the window overlooking the garden and Clyde estuary to the south. Looking back towards the sitting area a temperature gradient across the room is revealed, from the window bay projecting outside the stone envelope of the house, to the fireplace located on the thermally massive spine wall around which the plan is organized.

Moving back into the Hallway, the pools of warmth which would be created by the original water radiators are absent – for example next to the front door, offering respite on entry from the west-of-Scotland weather, and underneath the window at the foot of the stairs.

Upstairs, in the White Bedroom, the smaller volumes of the vaulted bed space and the seating area next to the fire offered

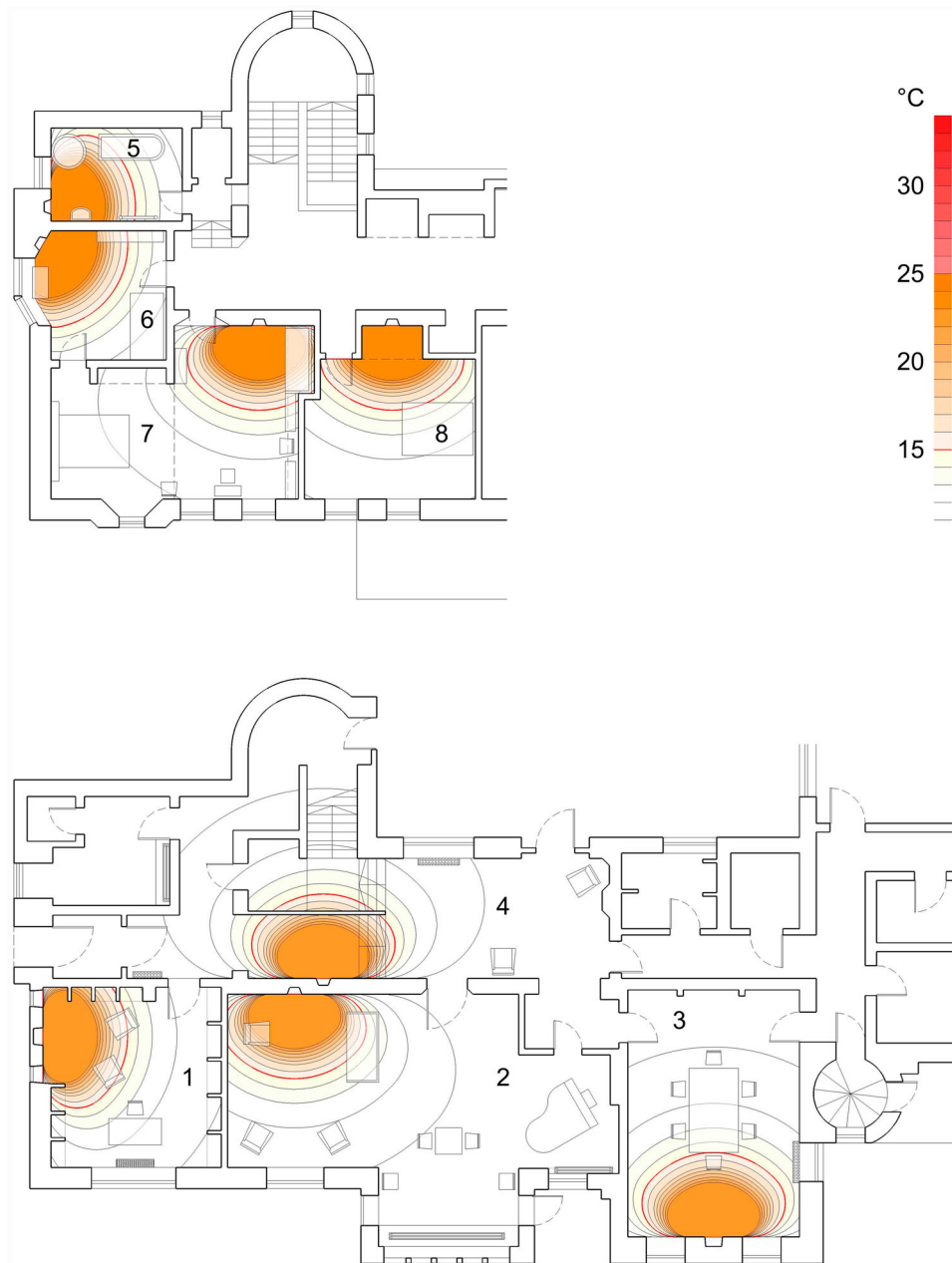


Figure 27. Floor plans with isotherms indicating operative temperature around fireplaces on 11 February 2022. Key: 1. Library; 2. Drawing Room; 3. Dining Room; 4. Hallway; 5. Bathroom; 6. Dressing Room; 7. The White Bedroom; 8. Second Bedroom.

a retreat from the larger rooms downstairs. On cold nights, the bedroom would have been warmed quite efficiently by the small fire (Figure 26).

Today, the thermal experience of the interior is remarkably consistent, except for the influence of the electric radiators.

Visualizing fireplaces and radiators

To visualize the warming effect of the fireplaces and radiators on the internal environment of the house as originally constructed, the radiant heat output of each heat source was calculated, and plans annotated with isotherms to show the spatial variation of operative temperature (a proxy for thermal comfort combining Mean Radiant Temperature and air temperature, adjusted to account for convection heating of the room).

Detailed information about the calculation method can be found in Appendices A and B.

Figure 27 shows the effect of the fireplaces on operative temperatures in The Hill House given an external temperature equivalent to the coldest day in the 2021–2022 monitoring period, 11 February, when internal temperatures stabilized at around 7°C without any heating, with external temperatures in a range of 0–6°C. Air temperature has been adjusted by +3 K to account for convection from the fireplace, based on Fishenden's experiments. The comfort zone (15–22°C) has been outlined in red, based on the Adaptive Comfort Model, which calculates comfort temperatures as a product of the prevailing mean outdoor temperature (ASHRAE 2004).

Figure 28 shows the effect of the water radiators on operative temperatures given the same external temperature. It is

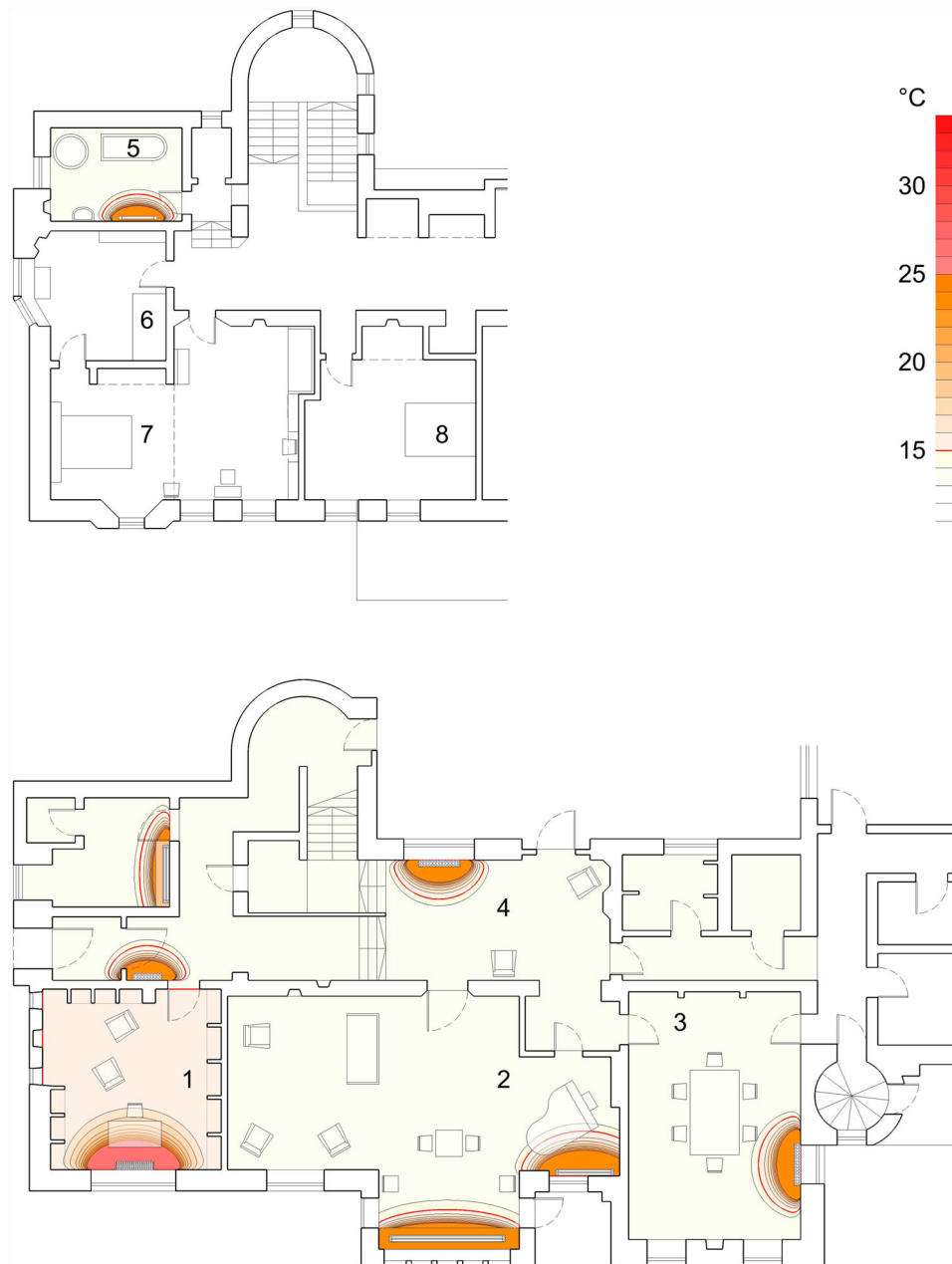


Figure 28. Floor plans with isotherms indicating operative temperature around radiators on 28 February 2018. Key: 1. Library; 2. Drawing Room; 3. Dining Room; 4. Hallway; 5. Bathroom; 6. Dressing Room; 7. The White Bedroom; 8. Second Bedroom.

important to note that despite their name, the principal mode of heat transfer from radiators is by convection. Based on data from the coldest day in the 2018 monitored period, 28 February, when the original central heating system was still operational, air temperature has been adjusted to account for convection from the radiators by +6 K in the downstairs rooms, except for the Library which has been adjusted by +8 K; and by +2 K in the upstairs rooms, which were not fitted with radiators, but still benefitted from warmth rising from the ground floor.

Figure 29 shows the effect of solar gains on operative temperatures given the same external temperature, on the winter solstice. This is calculated based on the effective radiant flux, accounting for solar and window geometry, anthropometric

dimensions, and the reflectance of internal surfaces (Arens et al. 2015; Lawrence and Hawkes 2021). The figure displays solar geometry at both solar noon (10.6° altitude, 180° azimuth) and late afternoon (2.4° altitude, 220° azimuth). Detailed information about the calculation method can be found in Appendix C.

Figure 30 depicts the combined warming influence of fireplaces, radiators, and solar gains at midday on the winter solstice, assuming an external diurnal air temperature range of 0–6°C. All downstairs rooms achieve comfort conditions, but the Library is excessively warm. The Drawing Room exhibits warm pockets by the fireplace, bay window, and piano alcove, with temperatures of 17–20°C in the centre of the room. The table area in the Dining Room shows comparable temperatures.

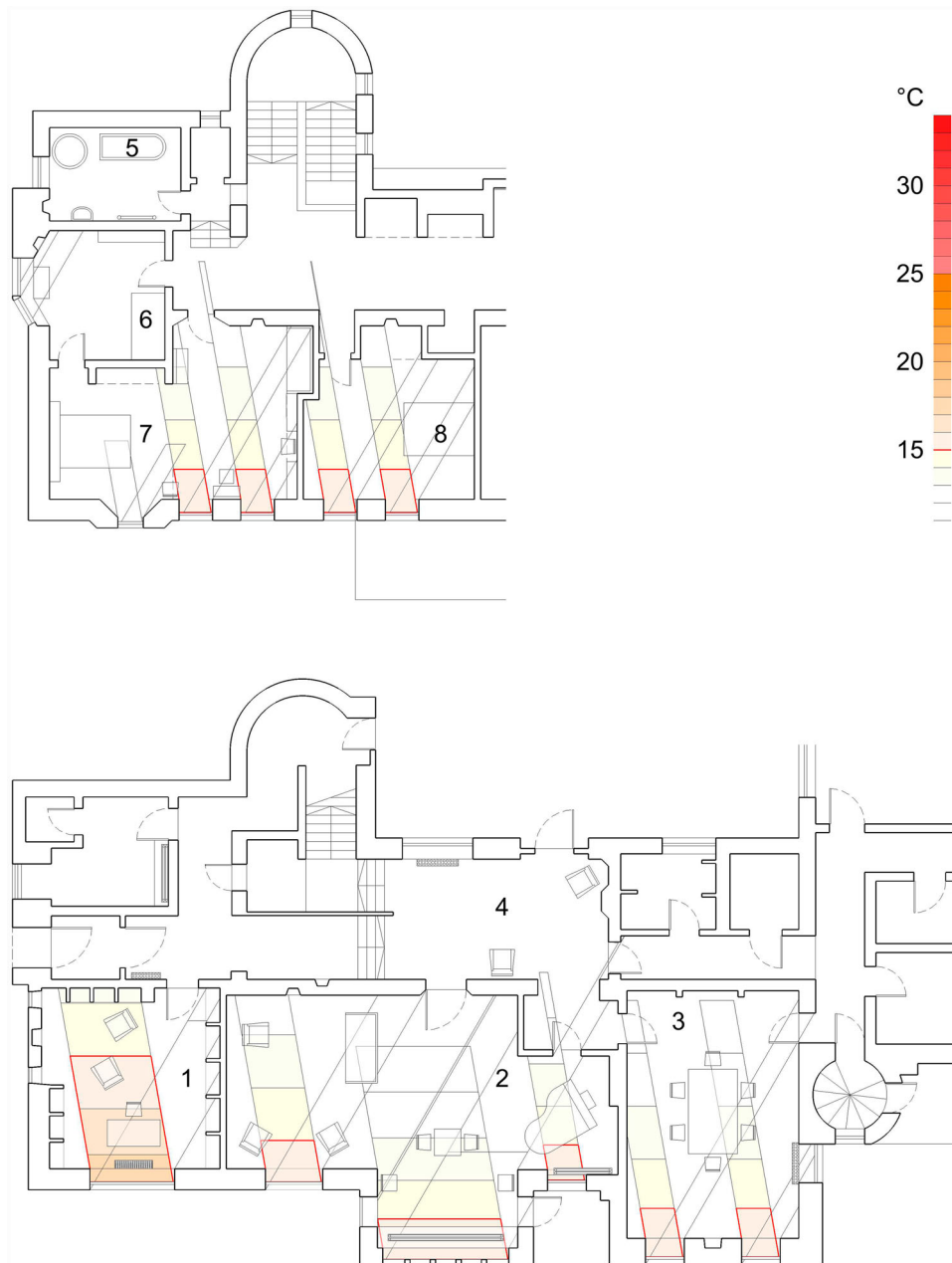


Figure 29. Floor plans with isotherms indicating operative temperature due to solar gains on the winter solstice. Key: 1. Library; 2. Drawing Room; 3. Dining Room; 4. Hallway; 5. Bathroom; 6. Dressing Room; 7. The White Bedroom; 8. Second Bedroom.

Interpretation of thermal data analysis

Analysis of the monitoring data and the subsequent thermal modelling reveals the changing nature of the indoor environment at the transition from fireplaces to central heating. This shift marked a significant change in domestic comfort, providing more stable temperatures, while strategically placed fireplaces were employed for localized warmth, complementing Mackintosh and Macdonald's carefully designed interiors.

Examination of the data reveals the relative effectiveness of the original water radiator system and the new electrical humidity-control system. By comparing datasets from 2018, 2021–2022, and 2022–2023 with thermal imagery, four key observations emerge:

- **Heat Output:** The original water radiator system delivered more heat, especially to the main downstairs rooms, than the replacement electric radiators.
- **Humidity Control:** The current setup, which combines a new Hanwell BMS system with electric radiators, provides more precise and effective humidity regulation compared to the older water system.
- **Climate Stability:** The construction of 'the Box' has proven effective in minimizing the impact of daily weather fluctuations and room orientation on the internal climate.
- **Temperature Consistency:** Internal temperatures now closely align with long-term seasonal averages. In winter, they approach 'free-running' temperatures, without active heating.



Figure 30. Floor plans with isotherms indicating operative temperature due to fireplaces, radiators and solar gains on the winter solstice. Key: 1. Library; 2. Drawing Room; 3. Dining Room; 4. Hallway; 5. Bathroom; 6. Dressing Room; 7. The White Bedroom; 8. Second Bedroom.

The role of fireplaces and thermal mass

In mild seasons, heating strategies would be adapted to the weather and the occupants' activities. While central heating alone could comfortably warm the Library, the Drawing Room fireplace might also be lit for social events. At night, the central heating would warm the bedrooms by around +2 K from the floor below, but the fireplaces would probably be lit into early spring. The spine wall (Figure 31) functions as a thermally massive element, effectively acting as the building's hearth. This wall provides warmth from the flues in winter and coolness in summer, complementing the solar gains from the south-facing windows.

The fireplaces were central to the spatial design and played an important role in the thermal form of the house. However,

fireplaces would result in significant temperature asymmetries exceeding that permitted by modern comfort standards. ASHRAE Standard 55 sets a 23°C limit for temperature asymmetry from a warm wall, beyond which 5% of people may feel discomfort (ASHRAE 2020). In the Drawing Room, this limit would likely be reached 1.5-2 metres from the fireplace (Ghali, Ghaddar, and Salloum, 2008).¹

The shift from dynamic to uniform environments

The changing nature of the indoor environment at The Hill House highlights a broader shift in domestic comfort. While modern interventions often aim for uniform temperatures, studies suggest that overly uniform environments can increase

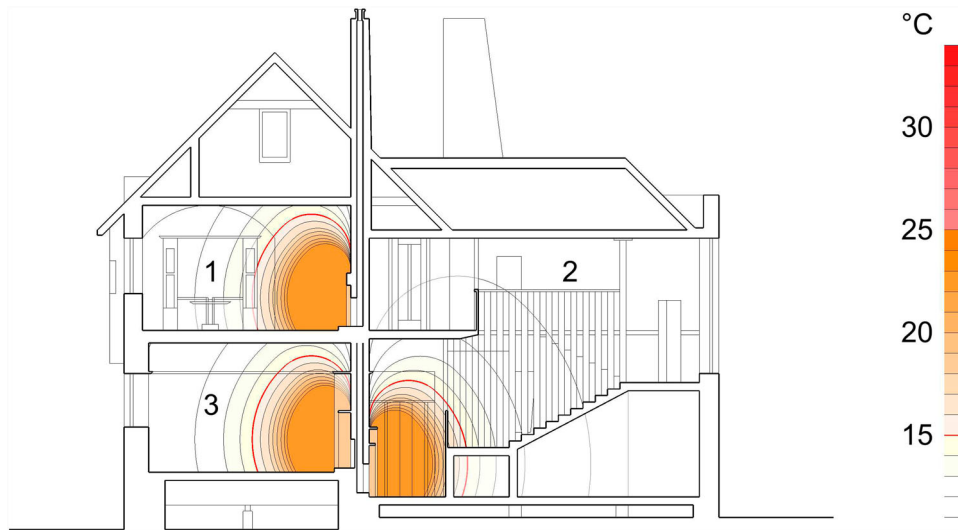


Figure 31. Section with isotherms indicating operative temperature around fireplaces on 11 February 2022. Key: 1. The White Bedroom; 2. Hallway; 3. Drawing Room.

discomfort by limiting thermal stimulation (Mishra, Loomans, and Hensen 2016; Zhu et al. 2016). In contrast, varied indoor spaces with gradual thermal transitions encourage adaptation to changing seasons. This aligns with the concept of thermal alliesthesia (Parkinson and de Dear 2015), encompassing the pleasure of dynamic thermal sensations. Mackintosh's design for The Hill House embraced this, exploiting the dynamic qualities of a range of natural and artificial thermal stimuli, so that the sensory experience is inextricably linked with the spatial form.

Conclusion

This project represented the first time that historic data extraction was employed to take a long view of the thermal performance of The Hill House, reflecting recent changes that have been made to its environmental management. The thermal monitoring programme, combining three datasets with a thermographic survey, provides an important foundation for the conservation of the house. It demonstrates how the design of the house, including its original heating strategy, created a dynamic thermal experience far removed from modern uniformity.

The research reveals that the original water radiator system provided more heat, particularly in the main downstairs rooms, compared to the replacement electric heaters. The new Hanwell BMS system, combined with electric radiators, offers more precise and effective humidity regulation than the original water system.

The temporary shelter, 'the Box', has significantly contributed to the drying of the house and stabilizing its internal climate, minimizing external influences. However, The Hill House's original design was deeply integrated with its environmental context, calibrated to the weather, the movement of the sun across the sky, and the day-to-day life of its occupants. This sensitivity is a core aspect of its heritage value.

To preserve the original character of the house, the National Trust for Scotland has recently been awarded a grant from the National Lottery Heritage Fund to remove 'the Box' in 2028. This will restore the house to its original condition and reconnect it with its surrounding landscape. Future exploratory work

will investigate heating and lighting strategies that preserve the unique architectural qualities of The Hill House, reflecting the contrast between light and dark, warm and cold, refuge and prospect, and its connection to the landscape. It is hoped that the findings from this research can also serve as a guide for reconciling modern conservation needs with the preservation of the interior environment of other important historic works of architecture.

Note

1. While this paper reports on thermal asymmetry from a domestic stove, the overall effect on the radiative field of the greater surface area of a stove at a lower radiative temperature will be similar to that of an open fire.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References

- Adams, Charlotte, Rachel Douglas-Jones, Adrian Green, Quentin Lewis, and Thomas Yarrow. 2014. "Building with History: Exploring the Relationship between Heritage and Energy in Institutionally Managed Buildings." *The Historic Environment: Policy & Practice* 5 (2): 2. <https://doi.org/10.1179/1756750514Z.00000000053>.

- Arens, Edward, Tyler Hoyt, Xin Zhou, Li Huang, Hui Zhang, and Stefano Schiavon. 2015. "Modeling the Comfort Effects of Short-Wave Solar Radiation Indoors." *Building and Environment* 88 (June): 3–9. <https://doi.org/10.1016/j.buildenv.2014.09.004>
- ASHRAE. 1993. *Fundamentals*. Atlanta, GA: American Society of Heating Refrigerating and Air-Conditioning Engineers.
- ASHRAE. 2004. "ISO 7730: Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria." ISO. <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/91/39155.html>.
- ASHRAE. 2020. *Standard 55 – Thermal Environmental Conditions for Human Occupancy*. Atlanta, GA: American Society of Heating Refrigerating and Air-Conditioning Engineers. <https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy>.
- Baillie Scott, M. H. 1894. "An Ideal Suburban House." *The Studio* 4:127–132.
- Blackie, Agnes A. C. 1959. *Blackie & Son, 1809-1959: A Short History of the Firm. With Internet Archive*. London: Blackie.
- Cassar, May. 2009. *Environmental Management Performance Standards: Guidelines for Historic Buildings*. Swindon: English Heritage.
- Cassar, May, and Joel Taylor. 2010. "A Cross-Disciplinary Approach to the Use of Archives as Evidence of Past Indoor Environments in Historic Buildings." *Journal of the Society of Archivists* 25 (2): 2. <https://doi.org/10.1080/0037981042000271484>.
- Davey, Peter. 1980. *Arts and Crafts Architecture: The Search for Earthly Paradise*. London: Architectural Press.
- Davidson, Hamish R. 1968. "Memories of Charles Rennie Mackintosh." *Scottish Art Review* 11 (4): 6–11.
- Dickson, Bryan, Mel Houston, and Suzanne Reid. 2020. "The External and Internal Decorative Finishes of the Hill House, Helensburgh: Challenges of an Early Twentieth-Century Dwelling House." *Studies in Conservation* 65 (sup1): 70–74. <https://doi.org/10.1080/00393630.2020.1779522>.
- Drysdale, Dougal. 1998. *An Introduction to Fire Dynamics*. 2nd ed. Chichester: John Wiley & Sons.
- Du Bois, D., and E. F. Du Bois. 1916. "A Formula to Estimate the Approximate Surface Area If Height and Weight Be Known." *Archives of Internal Medicine* 17 (6_2): 863–871. <https://doi.org/10.1001/archinte.1916.00080130010002>
- English Heritage. 2014. *Practical Building Conservation: Building Environment*. Abingdon: Routledge.
- Eriksdotter, Gunhild, and Mattias Legnér. 2015. "Indoor Climate and Thermal Comfort from a Long-Term Perspective." *Home Cultures* 12 (1): 1. <https://doi.org/10.2752/175174215X14171914084692>.
- Fanger, P. O. 1972. *Thermal Comfort – Analysis and Applications in Environmental Engineering*. New York: McGraw-Hill Book Company.
- Fishenden, Margaret White and Air Pollution Advisory Board. 1920. *The Coal Fire*. London: H. M. Stationery Office.
- Ghali, K., N. Ghaddar, and M. Salloum. 2008. "Effect of Stove Asymmetric Radiation Field on Thermal Comfort Using a Multisegmented Bioheat Model." *Building and Environment* 43 (7): 1241–1249. <https://doi.org/10.1016/j.buildenv.2007.03.008>.
- Gwilt, Joseph. 1903. *An Encyclopedia of Architecture, Historical, Theoretical, and Practical*. London: Longmans, Green & Co.
- Hawkes, Dean. 2012. *Architecture and Climate: An Environmental History of British Architecture, 1600-2000*. London: Routledge.
- Honeyman, Keppie & Mackintosh Job Book'. n.d. GLAHA 53061. Glasgow: The Hunterian, University of Glasgow.
- Howarth, Thomas. 1952. *Charles Rennie Mackintosh and the Modern Movement*. With Charles Rennie Mackintosh. London: Routledge and Kegan Paul.
- Humphreys, Michael, Fergus Nicol, and Susan Roaf. 2015. *Adaptive Thermal Comfort: Foundations and Analysis*. Abingdon: Routledge.
- ISO. 1998. *ISO 7726: Ergonomics of the Thermal Environment – Instruments for Measuring Physical Quantities*. Geneva: ISO.
- Lawrence, Ranald. 2020. *The Victorian Art School: Architecture, History, Environment*.
- Lawrence, Ranald. Forthcoming. "A Dwelling House Under a Murky Sky: The Internal Environment of The Hill House, by Charles Rennie Mackintosh." *The Journal of Architecture*.
- Lawrence, Ranald, and Dean Hawkes. 2021. "Describing the Historic Indoor Climate: Thermal Monitoring at Hardwick Hall." *Architectural Science Review* 64 (3). <https://doi.org/10.1080/00038628.2020.1856032>.
- Macaulay, James. 1994. "Hill House: Charles Rennie Mackintosh." *With Charles Rennie Mackintosh. Architecture in Detail*. Phaidon.
- Mishra, A. K., M. G. L. C. Loomans, and J. L. M. Hensen. 2016. "Thermal Comfort of Heterogeneous and Dynamic Indoor Conditions – An Overview." *Building and Environment* 109 (November): 82–100. <https://doi.org/10.1016/j.buildenv.2016.09.016>.
- Parkinson, Thomas, and Richard de Dear. 2015. "Thermal Pleasure in Built Environments: Physiology of Alliesthesia." *Building Research & Information* 43 (3): 3. <https://doi.org/10.1080/09613218.2015.989662>.
- Sutcliffe, G. Lister. 1899. *The Principles and Practice of Modern House-Construction*. Vol. 4. London: Blackie.
- Wright, Andrew. 2012. *The Hill House, Helensburgh: Evaluation of Condition and Significance*. Edinburgh: National Trust for Scotland.
- Young, Maureen. 2024. *Hill House, Helensburgh: Preliminary Results from Microwave Moisture Analysis Comparing Data From 2018-2023*. Edinburgh: Historic Environment Scotland.
- Zhu, Y., Q. Ouyang, B. Cao, X. Zhou, and J. Yu. 2016. "Dynamic Thermal Environment and Thermal Comfort." *Indoor Air* 26 (1): 125–137. <https://doi.org/10.1111/ina.12233>.

Appendix

Appendix A

Mean operative temperature can be approximated by the equation:

$$T_o = (T_a + MRT)/2 \quad (A1)$$

Mean radiant temperature (MRT) can be calculated by rearranging this equation as follows:

$$MRT = 2 T_o - T_a \quad (A2)$$

MRT is estimated from effective radiant flux, q_{eff} , by the equation:

$$MRT = (q_{eff}/f_{eff}h_r) + T_a \quad (A3)$$

The value for the effective radiation fraction for a body (f_{eff}) is 0.725 for a standing pose, and the radiant heat transfer coefficient (h_r) is 4.7W/m² (ASHRAE 1993).

Effective radiant flux, q_{eff} , can therefore be calculated by rearranging this equation as follows:

$$q_{eff} = (MRT - T_a) f_{eff} h_r \quad (A4)$$

Appendix B

To calculate distance of isotherms from fireplaces / radiators:

Radiant flux q'' can be calculated from the effective radiant flux by adjusting for the fraction of the body surface area facing the heat source (f):

$$q'' = q_{eff} f \quad (B1)$$

where $f = 0.29$ (Du Bois and Du Bois 1916)

The radiant heat release rate is estimated by the equation:

$$Q_r = q'' 4\pi R^2 \quad (B2)$$

(Drysdale 1998)

Distance R can be estimated by rearranging this equation as follows:

$$R = \sqrt{(Q_r/q'' 4\pi)} \quad (B3)$$

Appendix C

To calculate impact of solar gains on thermal comfort:

Effective radiant flux, q_{eff} , adjusted for the fraction of the body exposed to the sun (f_{bes}), is calculated by the equation:

$$q_{eff} = (0.5 f_{eff} f_{svv} (I_{diff} + I_{TH} R_{floor}) + f_{eff} f_{p} f_{bes} I_{dir}) T_{sol} (a_{SW}/a_{LW}) \quad (C1)$$

Total outdoor irradiance (I_{TH}) is a product of direct beam solar radiation (I_{dir}) and diffuse sky irradiance (I_{diff}), which vary according to solar altitude β .

The fraction of the sky vault in view of the subject (f_{svv}) is a property of the width (w) and height (h) of the window, and the distance from the window to the subject (d):

$$f_{svv} = (\tan^{-1}(w/2d) \tan^{-1}(h/2d))/16,200 \quad (C2)$$

The energy flux absorbed by the body varies according to long and short-wave absorptivity (a_{LW} and a_{SW}), estimated to be 0.95 and 0.7 respectively.

The radiant flux reflected onto the subject from the floor varies with the reflectance of the floor (R_{floor}), estimated to be 0.5. The projected area factor of a body facing the sun (f_p) varies with solar altitude and azimuth, but is estimated to be 0.3 for a subject facing the sun with solar altitude $< 45^\circ$ (Fanger 1972). The fraction of the body exposed to the sun (f_{bes}) will be affected by shading from the window reveals (varying with solar azimuth).