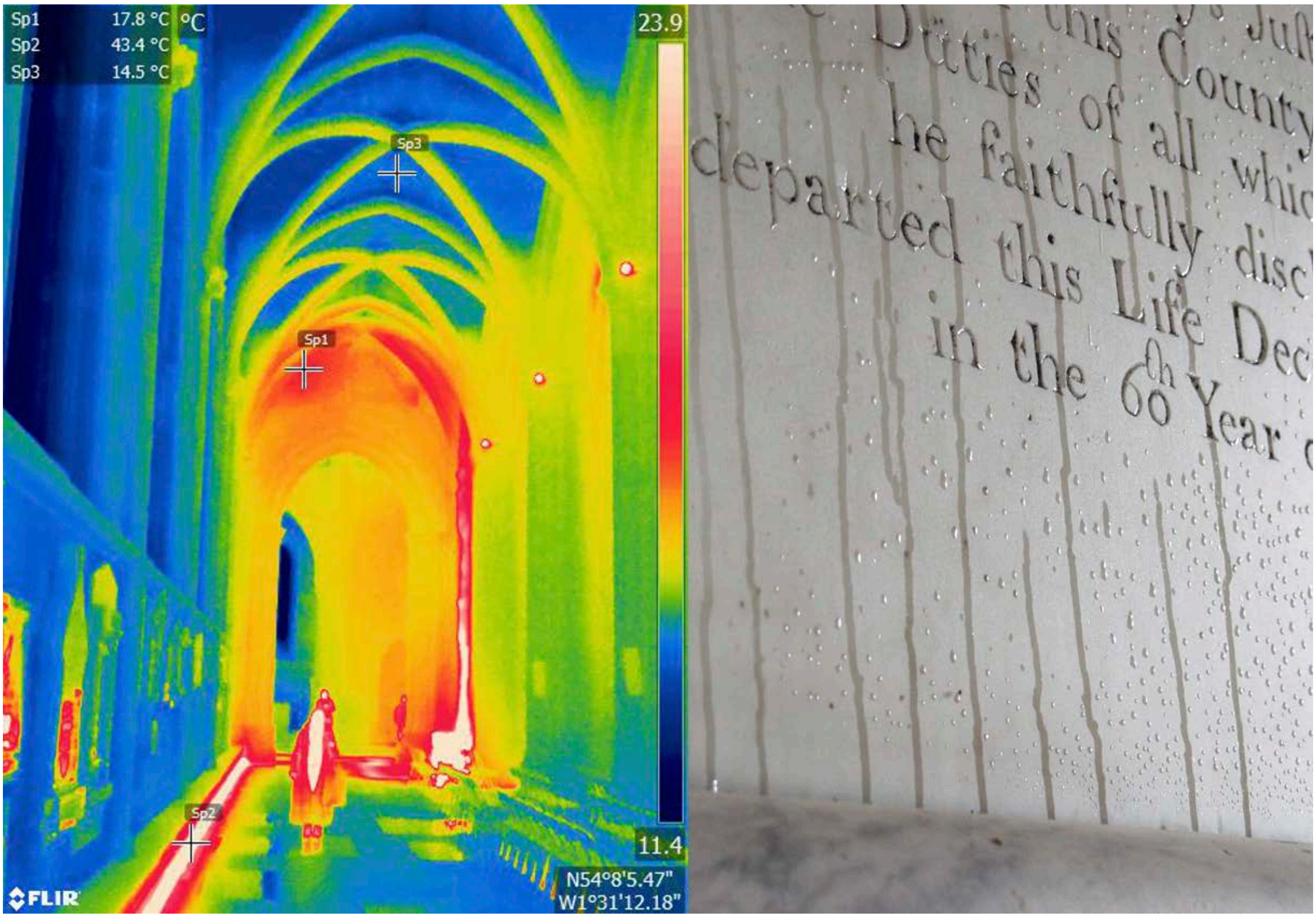
Historic England

Understanding the Environmental Performance of Historic Buildings for Conservation



Summary

Every building has its own internal microclimate, known as the 'building environment'. This is a product of the way the building envelope buffers external environmental conditions, the mechanical services used within and the building occupants. It depends on many factors, including the building's form, materials and condition; the type of services; and the way the building is occupied and used. The building environment affects the condition of the building fabric and contents, and their pattern and rate of deterioration. Understanding these interrelated factors will, therefore, inform options for measures to control and address deterioration. It is important to understand the building environment for all buildings, but it is particularly vital for historic buildings of traditional construction because their fabric – and their contents, too – may hold significance beyond their functional value. Furthermore, such buildings are often particularly vulnerable to deterioration caused by environmental factors.

You may want simply to conserve your historic building in its existing form. In this case, a building environmental performance assessment (BEPA) will not only help to identify areas that may need repair or require further investigations, but it will also provide a benchmark to measure the effectiveness of repairs once they have been implemented. Alternatively, you may want to adapt your historic building to allow new uses, broaden access or make it warmer and more comfortable to live or work in, while also addressing its energy efficiency. Such changes may involve internal alterations to the layout and installing facilities such as toilets and kitchens, as well as updating heating systems. Before you begin, it is important to understand how the building envelope performs currently, how the building performance affects the internal building environment and how the situation will be changed by

Front cover: The building environment affects the condition of the building substrates and contents. A building environmental performance assessment will help to identify areas that need repair or further investigations. Thermal imaging (left) is a helpful investigation tool, as well as recording observed condition phenomena such as condensation (right). © Tobit Curteis Associates the proposed project. This knowledge will help to ensure that the alterations do not result in any unintended effects on the condition of the building fabric and contents, or the level of comfort of any occupants. It will also allow you to balance the conservation needs of the building fabric and contents with the needs of the people using the building.

This guidance describes the factors that affect the internal environment of a historic building of traditional construction – its 'environmental performance' – and how the environmental performance, in turn, affects the condition of the building fabric and contents. It also outlines the steps needed to minimise the risk of environmental deterioration to building fabric and contents when planning remedial work, upgrades or alterations. The guidance is aimed at building professionals, custodians and owners of all types of historic buildings who are planning repair or alteration projects.

The term 'environmental performance' is commonly used to refer to the thermal efficiency of a building, and a building performance evaluation is often carried out when considering upgrading the thermal performance of a building. Although heating and insulation are discussed in this document, they are considered in relation to the conservation of a historic building's fabric and contents rather than in terms of the thermal comfort of building occupants or energy efficiency. See our Technical Guidance pages for more information on these topics.

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Contents

1. What is the ‘building environment’ and why does it matter?

The ‘building environment’ can be described as the environmental parameters to which a building’s structure, contents and users are exposed. These commonly include air temperature, water (in all its states: liquid, vapour, solid), light (visible light, ultraviolet [UV] and infrared [IR] radiation) and air quality.

1.1 The importance of managing environmental conditions

The environmental conditions – especially humidity, temperature and light – in a historic building are key factors in its long-term conservation and in the preservation of its contents. If conditions are good, deterioration will be slow. Conversely, if environmental conditions are poor, deterioration can be swift, costly to repair or, in many cases, irreversible. Typical environmental damage includes crumbling and flaking of stone, plaster or wall paintings; movement and cracking of timber structures; stained glass deterioration; mould and rot of organic materials; and metal corrosion. A poor building environment also creates uncomfortable living and working conditions.

Common forms of deterioration associated with poor environmental conditions are illustrated below.

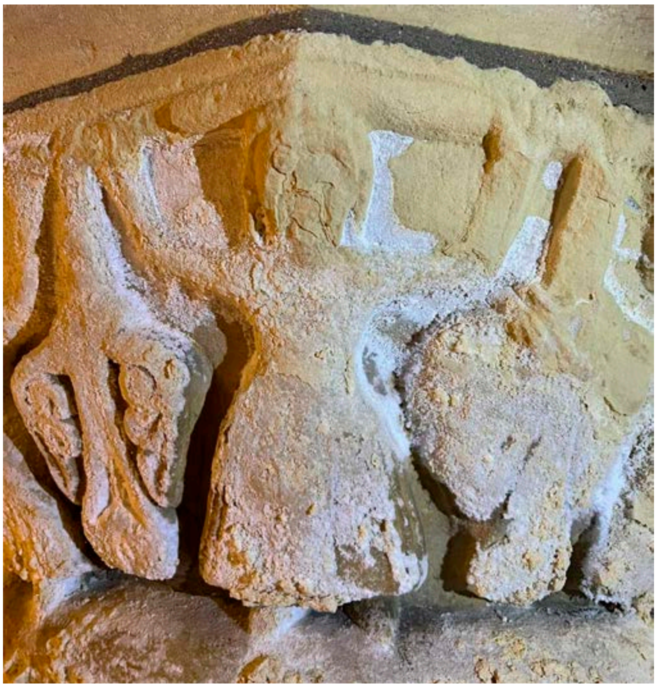


Figure 1: Salt activity causing the deterioration and loss of surface of medieval limestone carving.
© Tobit Curteis Associates

Figure 2: Distortion of the painting on canvas due to high and unstable relative humidity.
© Sally Woodcock

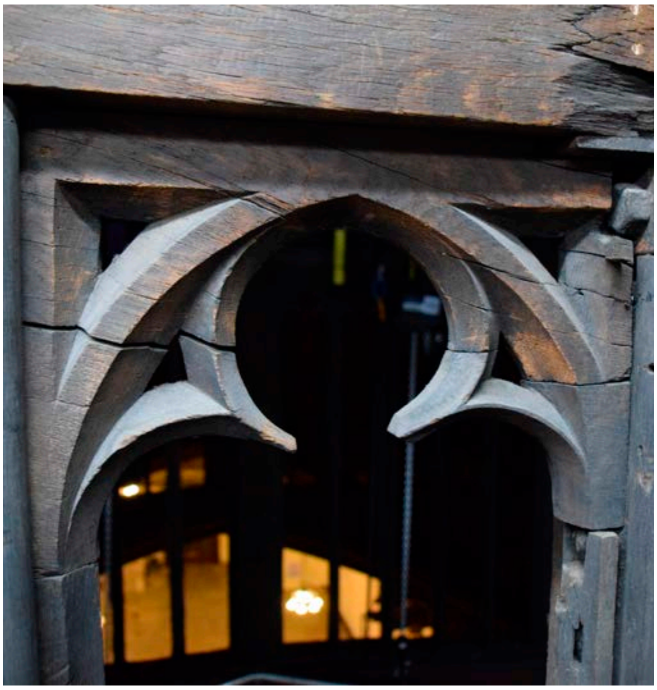


Figure 3: Long-term exposure to changing temperatures and humidity levels may cause timber to split. © Dale Perrin, by kind permission of Strategic Estates, Parliament

Figure 4: Delamination and flaking of the paint surface resulting from expansion and contraction in the timber panel, due to heating.
© Tobit Curteis Associates

Figure 5: Microbiological growth on internal brickwork due to high moisture levels caused by water ingress. © Tobit Curteis Associates

Figure 6: Sunlight falling across wall paintings, leading to delamination and flaking. © Tobit Curteis Associates

Understanding how a building performs before undertaking a programme of repairs will help identify what work is necessary and will also provide a means for measuring the effectiveness of the project. Before introducing significant changes, such as modifying the layout, improving thermal insulation or introducing new services – or, indeed, leaving a building unoccupied for an extended period – it is essential to understand a building's environmental performance so that you can anticipate how the changes may influence deterioration patterns and rates of the fabric and contents. Measures can then be designed to control the risks.

1.2 The building performance triangle

Three key factors affect the environmental performance of a historic building (that is, the level of buffering between the external and internal environments) and, therefore, the success of many conservation and alteration projects. They are referred to as the 'building performance triangle':

- **Building fabric** (the building's construction, materials and condition)
- **People** (those using the building and how they are managing their uses)
- **Services** (the equipment added to improve building usability, such as lighting, heating, cooling and mechanical ventilation)

The three factors are interconnected and need to be considered together; a change to one affects the other two.

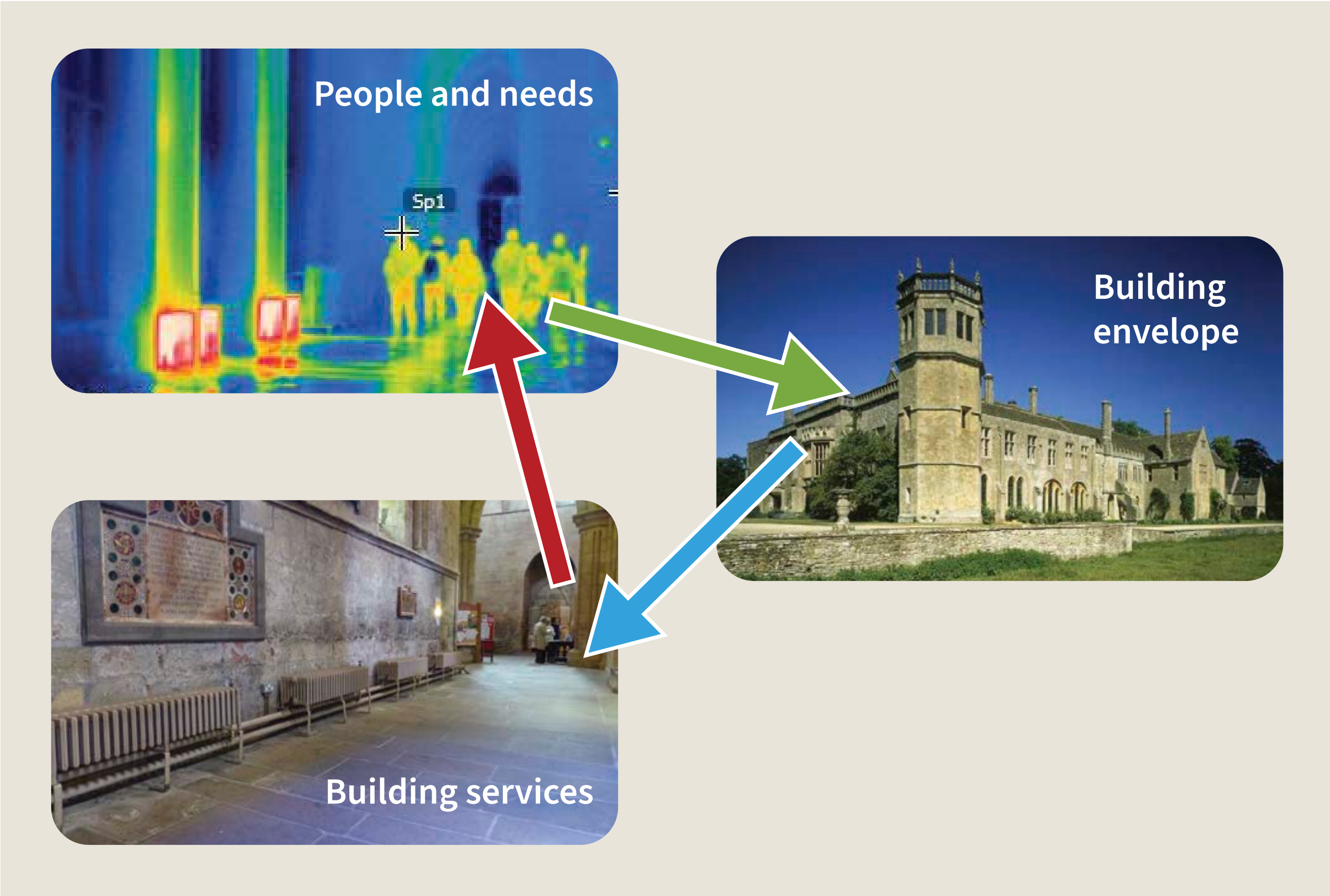


Figure 7: Three key factors affect the level of buffering between the external and internal environments: the building performance triangle showing the interaction between the building envelope, building services and people using the building. © Tobit Curteis Associates

It is common for a project to focus on one factor of the building performance triangle only, but this approach will likely fail to achieve the best outcome. For example, if a project to improve thermal comfort focuses on the heating system only and does not address the causes of heat loss or take into account where and why building users are uncomfortable, it may not effectively reduce user discomfort. This is particularly true in buildings that are poorly maintained, where water ingress may be contributing to the causes of discomfort. In these cases, the proposed heating system may result in condensation forming on the historic fabric – increasing deterioration – and may also create convection currents that are uncomfortable for users.

We have published more detailed information on the building performance triangle in Historic England's Building Environment volume of the Practical Building Conservation series. See also our webpage on Heating Design Considerations.

2. Understanding environmental parameters

Many environmental parameters have an impact on building fabric and contents. Temperature, water, and light (both visible and UV radiation) are the most common.

2.1 Temperature

Temperature has a direct effect on building materials and also influences relative humidity. Although most building materials and contents are tolerant of moderate variations in temperature, significant heating and cooling causes some materials, such as metals, to expand and contract. This can affect structural stability.

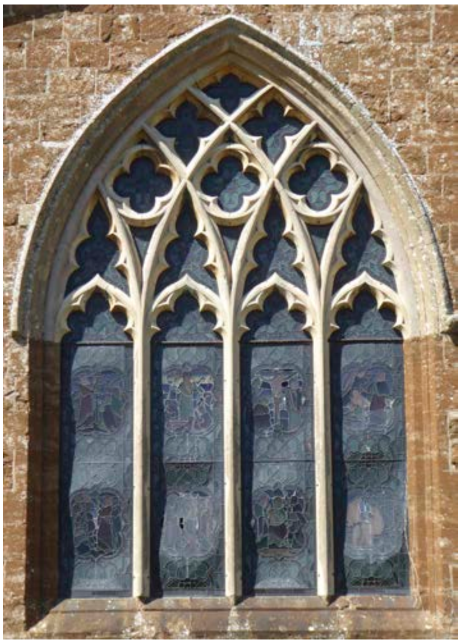


Figure 8: Deformation of stained glass and cracking of lead cames is due to thermal expansion and contraction combined with wind loading. Detail (right) showing resulting gaps forming between the glass and lead cames. © Tobit Curteis Associates

Temperature variations also cause the moisture content of building materials to change, resulting in expansion and contraction of organic materials and salt activity in inorganic materials, a process discussed in detail in 2.2 Water.

Temperature can be a significant factor during building alterations or repairs, particularly in the way it influences the drying of materials. Sudden changes in temperature and the resultant fluctuation in relative humidity can cause many previously stable materials, such as timber, to expand and contract, resulting in deformation and cracking, or flaking of painted surfaces. For example, where water penetration has caused ceiling laths to decay, significant room heating could cause them to shrink and, potentially, the ceiling to collapse.

Temperature has a direct effect on air buoyancy. Because warm air rises, environmental conditions at floor level and at ceiling level can differ significantly, especially if the room is tall. If the temperature at floor level is increased to make it comfortable for users, the temperature at height will be greater and may create harmful conditions for sensitive fabric such as timber roofs or ceiling paintings.

2.2 Water

Most of the materials from which historic buildings and contents are made are more sensitive to water than they are to temperature. For inorganic materials such as stone and plaster, changes in moisture content cause contaminant salts to crystallise or dissolve (with associated changes in size). As a result, masonry can lose cohesion and become powdery, or delamination and flaking can occur between plaster and paint layers.

Figure 9: Delamination and flaking of paint layer caused by salt activity. © Tobit Curteis Associates

For many organic materials, such as timber and textiles, fluctuating moisture content causes expansion and contraction, which can lead to distortion or cracking. The speed at which changes occur is significant: if the temperature change is slow enough to allow materials to adjust, they can often tolerate the variation without significant risk. On the other hand, a small temperature change can cause serious damage if it happens swiftly and the material structure has no time to adjust. Elevated moisture levels also allow fungi and insects to attack organic materials.

Figure 10: Dry rot caused by high moisture levels resulting from water ingress. © Tobit Curteis Associates

Liquid water

Poorly managed liquid water is one of the major causes of serious damage to historic buildings (including eventual structural collapse if left untreated). Water ingress can cause direct damage to the fabric where it penetrates, and more widespread damage as it evaporates and raises the humidity within the building. This can also make the building feel uncomfortable for occupants. Problems caused by liquid water are generally linked to specific and recognisable sources, including:

- Rainwater ingress through defects in the building envelope, typically because the features intended to control the rain are poorly designed, poorly maintained or both
- Lateral penetration of groundwater into walls if the internal floor level is lower than the ground level outside
- Capillary rise from groundwater, including that caused by damaged drains or water mains
- Lateral penetration into walls from surface water run-off or flooding – often associated with impermeable ground surfaces or surfaces that slope towards the building

- Lateral penetration from splash-back of rainwater, especially where the ground at the base of the wall is covered with an impermeable finish
- Damage to internal plumbing, causing either slow leaks or sudden flooding
- Cleaning (for example, washing windows and floors with large quantities of water)

Liquid water damage is often exacerbated by low-porosity wall finishes, such as cement-based renders or some modern emulsion paints (acrylic polymer-bound), which reduce or prevent evaporation.

For above-ground water, designing appropriate repair and control methods is usually relatively straightforward. Below-ground water is more complex to deal with because the specific source is not always obvious and is often inaccessible.

Water vapour

The sources and effects of water vapour within a historic building are more difficult to identify and understand than those of liquid water, not least because temperature plays a major role.

In most buildings of traditional construction, the primary long-term influence on internal air moisture content is the external air. External humidity and temperature fluctuate significantly during the day, in a way that would be damaging to sensitive building fabric and contents. The building envelope (the walls and roof that form the enclosed building) provides a level of buffering between internal and external conditions, limiting air exchange and the transfer of water vapour. The thermal inertia of the building envelope (variable depending on construction type) also provides improved internal stability. As a result, the internal building environment will be more stable than the external environment and will be more conducive to preserving sensitive building fabric and contents.

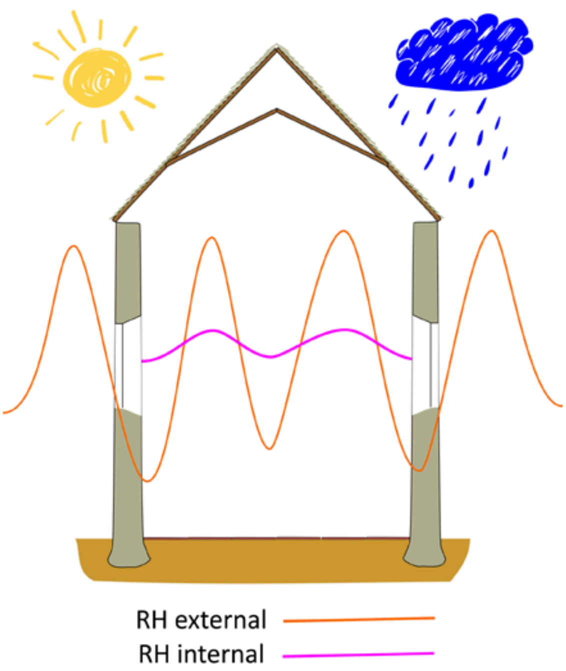


Figure 11: The building envelope provides both thermal and hygral buffering between internal and external temperature and humidity with the result that large fluctuations in the external conditions are reflected by far smaller fluctuations within the building. © Tobit Curteis Associates

When we discuss humidity in this context, we are generally referring to a parameter known as relative humidity. When air is supporting the maximum amount of water at a given temperature, it is said to be saturated and the relative humidity is 100 per cent. At 50 per cent relative humidity, the air is holding half of the water it could hold at that temperature. At 100 per cent relative humidity, condensation takes place and water droplets form on cold surfaces (*see* Condensation, below).

Warmer air can support more water vapour than cooler air, so relative humidity can fluctuate if the temperature of the air rises or falls. It will also vary if the actual number of water molecules in the air changes. In practical terms, this means that unstable internal air moisture content can be caused either by an intermittent source of water (such as evaporation from a tea urn, using a bath or shower, faulty rainwater goods causing water ingress when it rains, or an open window allowing in external air with a different moisture content), or by space heating or cooling, which changes the air temperature inside the building. Unstable internal air moisture content is generally damaging to sensitive hygroscopic (water-attracting) building fabric and artefacts.

Figure 12: Distortion of tapestry due to expansion and contraction of the fibres resulting from fluctuating temperature and humidity.
© Tobit Curteis Associates

Many sources of water vapour are obvious, including:

- Evaporation from wet walls and floors
- Water vapour escaping from cooking facilities and bathrooms
- Drying laundry
- Damp air blowing in through open doors and windows
- People with wet shoes, clothing and umbrellas

People also produce water vapour and radiate heat all the time. Estimated metabolic rates suggest that an average person generates about 30 to 70 grammes of water vapour per hour and 100 watts of heat, depending on their physical activity. These amounts are not especially high compared to other sources in buildings. However, when large numbers of people are gathered in a small space for an extended period, the amounts can be significant.

Condensation

When the air temperature drops below what is known as the dew point temperature, it is no longer able to support the water vapour it already holds and the vapour will condense.

In buildings, this situation often occurs when warm humid air strikes a cold surface, such as a windowpane, cold wall or the underside of roof slates or tiles. However, condensation can form on any part of the structure where the temperature is below the dew point. On low porosity surfaces, including glass, ceramic tiles, metal and walls covered with impermeable paint, liquid condensation is visible as water droplets. If enough droplets accumulate, they coalesce and run or drip down. On porous materials, such as stone and plaster, condensation may occur on the surface, but it is quickly absorbed and so may not be visible. Depending on the temperature and relative humidity, condensation can also occur within the pores of building materials, rather than on the surface. This is known as ‘interstitial condensation’. It is important, therefore, not to interpret the absence of visible condensation as evidence that no condensation has formed.

A particular condensation pattern can occur when large numbers of people congregate for an event, such as a concert, in a historic building that is only occasionally used and heated. For the event, the heating is turned on, which encourages water to evaporate from the building fabric. The people attending the event breathe moisture into the warmed air. When the people leave and the heating is turned off, the air cools and is unable to hold the increased levels of water vapour, so condensation forms after the building is closed.

Another common condensation pattern occurs when a building has been closed for the winter and/or the masonry structure has cooled. If windows and doors are opened on a warm spring day, when the air outside has a high moisture load due to the sun causing evaporation from the ground, the warm and moist air will cool in the building to the level where the air can no longer hold the water vapour. Condensation will then occur on any cold surfaces, such as walls and monuments.

Just like liquid water, cycles of condensation and drying activate soluble salt deterioration and the expansion/contraction of materials such as timber. Such cycles can cause these materials to deteriorate.

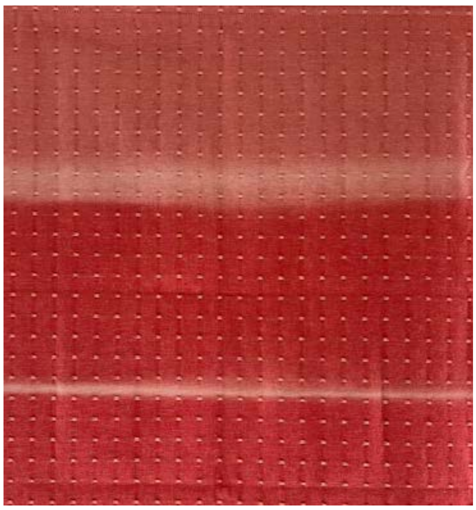
Figure 13: Condensation on wall paintings caused by ingress of warm, humid spring air striking cold surfaces. Condensation accumulates on the non-porous section of oil painting, but is absorbed into the porous limewash section. This may give the impression that no condensation is happening on the limewash while in fact the same level of condensation is happening (see surfaces with beading condensation vs those with none visible, in both pictures). © Tobit Curteis Associates

2.3 Light

Many organic materials are photosensitive – that is, they are vulnerable to damage when exposed to certain wavelengths on the electromagnetic spectrum: typically, UV, IR and visible light. Photodeterioration may cause a change in appearance (fading of textiles, paints or timber surfaces) or, sometimes, weakening of structural integrity. The effect of exposure is cumulative.

The outer surface of a structure is most at risk, and the penetration level of the radiation is often very limited. For example, the impact on the structural core of a timber post can be minimal, even when the damage to the outer surface is significant. For textiles, though, surface damage may have more serious consequences, as threads become brittle.

Figure 14: (left) Discolouration and degradation of leather bindings due to exposure to high levels of visible light and UV radiation. © Caroline Bendix (right) Discolouration of a textile blind due to exposure to high levels of visible light and UV radiation. © Tobit Curteis Associates



Daylight rather than artificial light generally carries the greater risk for photosensitive materials. Whether direct or diffuse, daylight contains high levels of UV radiation and so, in conservation terms, it can be particularly damaging, especially when surfaces are exposed to direct sunlight. IR radiation in sunlight heats building materials and contents, which can result in the type of temperature changes and associated humidity issues discussed in 2.1 Temperature.

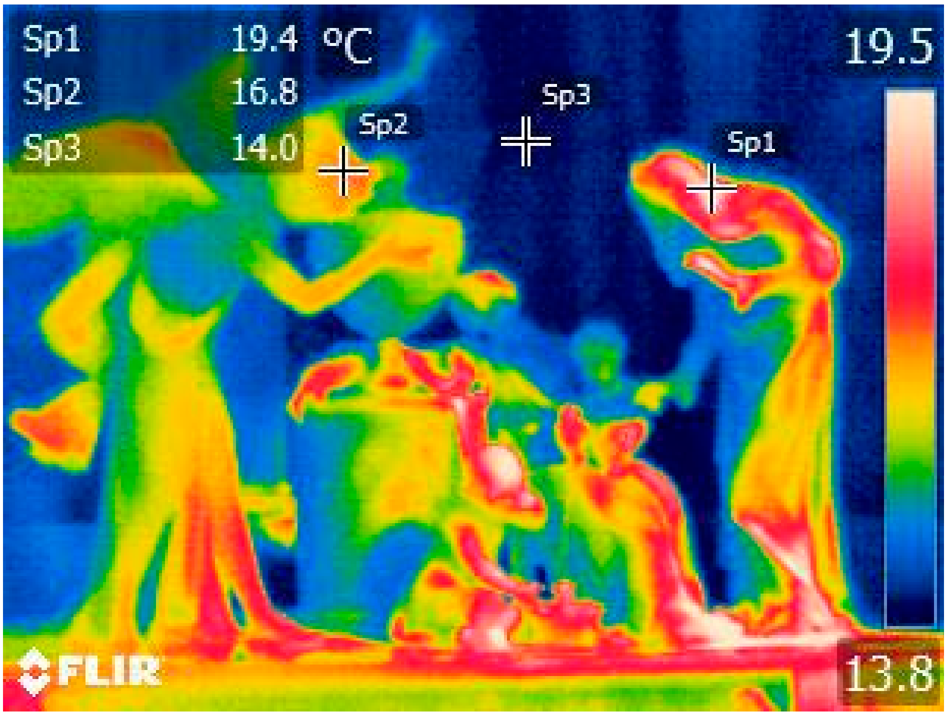


Figure 15: (top) Marble monument exposed to direct sunlight (seen in normal light). (bottom) Thermal image showing differential heating on the marble monument exposed to direct sunlight. © Tobit Curteis Associates

Coatings such as paints and varnishes can protect sensitive organic structures from the effects of sunlight. Historically, this is one of the reasons why timber building elements were often painted.

Artificial lighting can also cause damage, but it is generally simpler to control. Depending on the light source, levels of UV radiation can be minimised at source or filtered out. With the increasing use of LED lighting (which is far more restricted in the wavelengths it emits and uses less energy), the risk to sensitive materials has greatly decreased. It is important, though, that the correct LED is selected for the particular situation.

3. Understanding the inherent building environmental performance

Understanding the inherent building environment, and how it affects us, is the essential first step before seeking any modification (*see* 4 Modifying the building environment). This chapter focuses on the inherent (natural or 'passive') performance of the building envelope: that is, the level of buffering it provides between the external and internal environments.

3.1 Inherent environmental building performance

External environmental conditions vary enormously during the day and throughout the year. In winter, even weak sunlight can provide significant warming, and temperatures can drop sharply on a clear night. However, it is in spring and summer that the greatest fluctuations in temperature and humidity, and hence the most unstable exterior conditions, occur. When the external temperature rises in the spring, evaporation takes place from ground that remains wet after the winter, increasing the volume of water vapour in the air. Because the air is warm, it can hold a large amount of water vapour, so even with additional water vapour from the ground, the relative humidity can remain low and the air 'feels' dry. When the temperature drops at night, the air is unable to support as much moisture and water vapour is reabsorbed into the ground, often through condensation.

Because of its thermal mass and the way it limits air exchange, the building envelope provides a separation – or buffer – between the unstable temperature and moisture conditions outside, and the more stable interior. Sensitive building fabric and contents generally require environmental stability for their effective conservation and so perform better in a building with a high level of buffering.

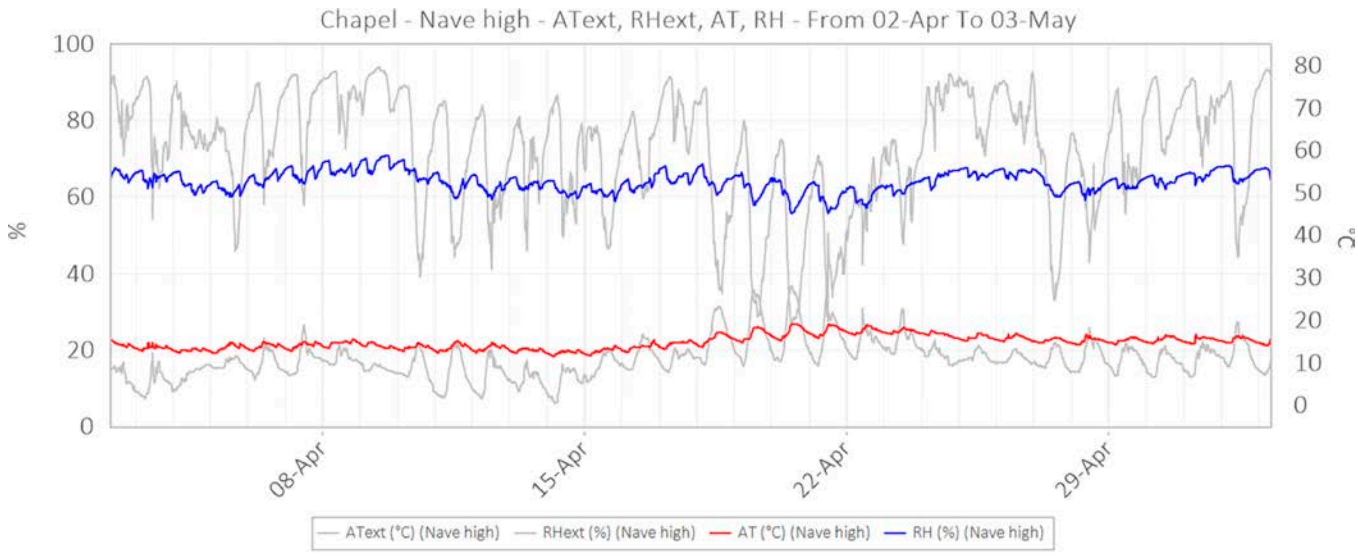


Figure 16: The chart shows that the internal relative humidity (blue line) and temperature (red line) are relatively stable, despite the unstable external conditions (grey lines), because of the passive buffering provided by the building envelope. © Tobit Curteis Associates

The passive buffering provided by the building envelope between internal and external conditions can be separated into water vapour (hygral) buffering and temperature (thermal) buffering. To illustrate the difference, consider how a sealed glass box containing nothing but air would perform in these terms. An increase or decrease in the water vapour content in the air outside would not affect the air within the box. In other words, the glass box provides a very high level of *hygral* buffering. However, glass is thermally inefficient, with a low thermal mass, so heat will pass through the glass as a result of radiation. So, if there is a high temperature outside the glass box, it will become hot inside the box. In other words, the glass box provides a low level of *thermal* buffering.

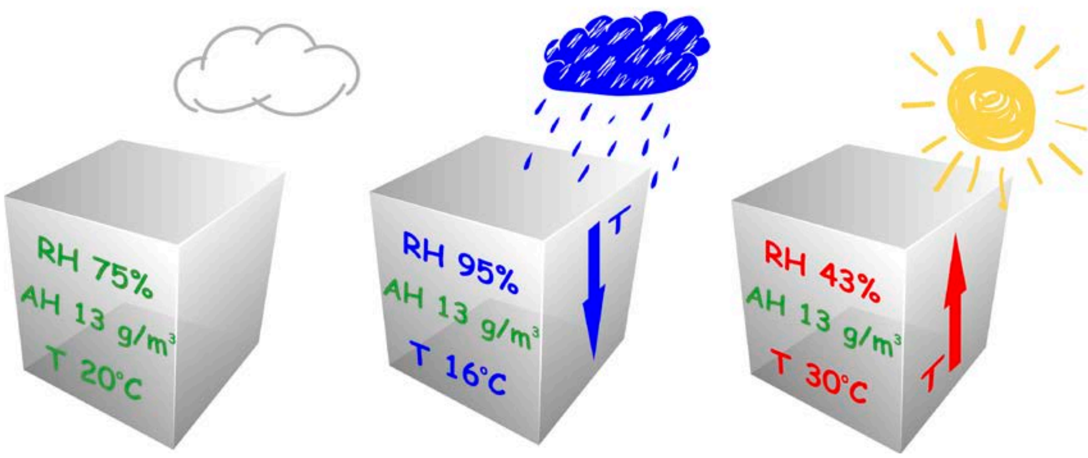


Figure 17: The glass box represents a building with very high hygral buffering (water vapour cannot enter or leave the box) but very poor thermal buffering (glass provides minimal thermal insulation). When the weather outside changes, the temperature (T) and relative humidity (RH) in the glass box will increase or decrease (in inverse proportion) but the absolute humidity (AH) will remain the same. © Tobit Curteis Associates

In traditional buildings, thermal and hygral buffering depend on the building's construction materials and condition. Thin timber-framed walls are far less thermally efficient than thick masonry walls because they transmit heat more quickly. Air leakage through timber-framed walls (which will further reduce thermal buffering) will also reduce hygral buffering efficiency. Thick well-constructed masonry walls may be inherently more efficient, but buffering is often compromised by air leaking around poorly fitting details such as doors and roofs.

Figure 18: (left) Timber frame with lath-and-plaster construction. (right) Thermal imaging showing the significant heat loss which can take place through insubstantial lath-and-plaster structures. [Note: The base of the wall, affected by damp, appears cooler.] © Tobit Curteis Associates

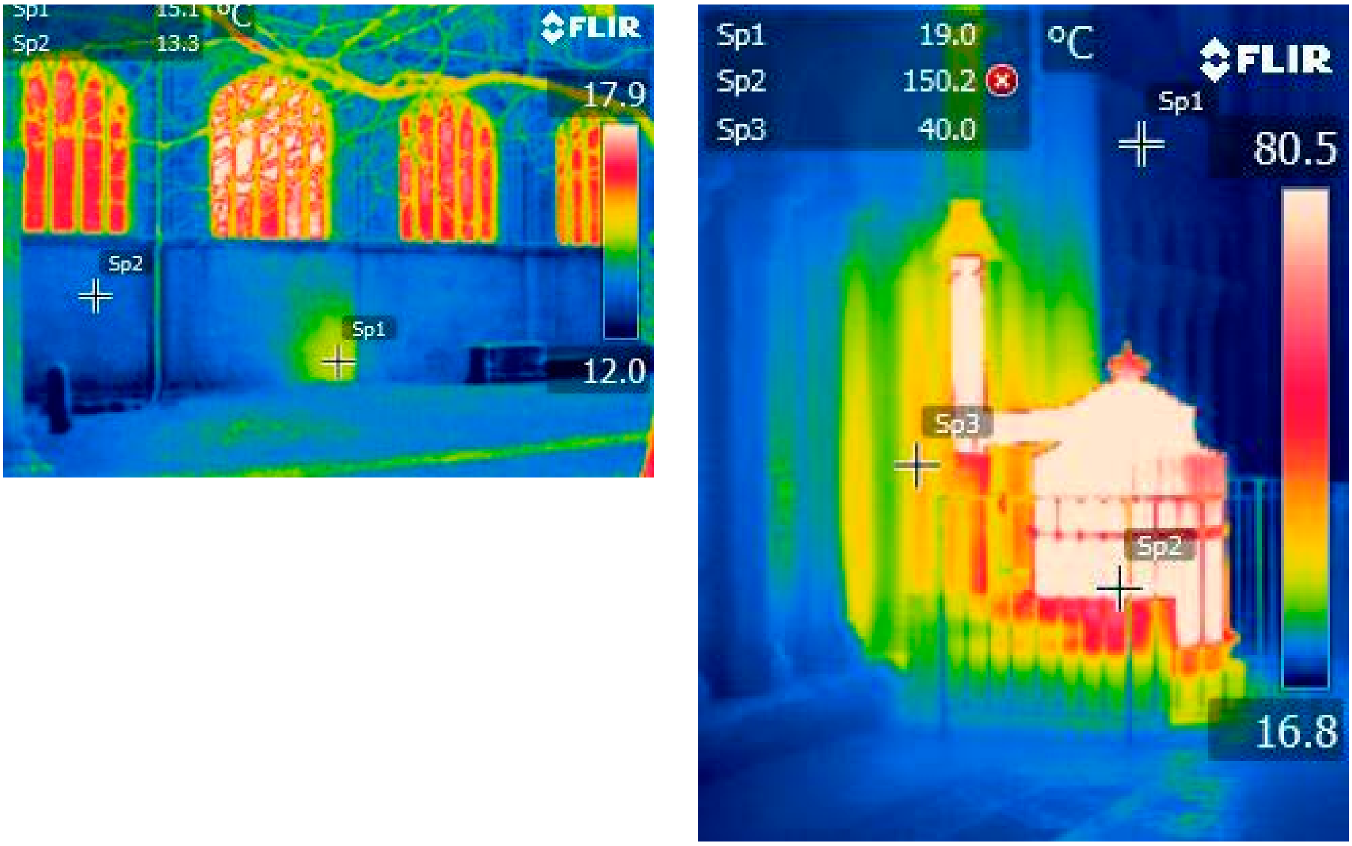


Figure 19: Thermal imaging showing the limited heat loss which occurs through thick masonry walls (left), even when the level of heating adjacent to the wall is extremely high (inside view, right). © Tobit Curteis Associates

Traditional architectural details, such as eaves on roofs and hood mouldings on windows, were often intended to protect a building from rainwater ingress. Further protection was provided by materials such as lime render, which allowed rainwater to be absorbed and then re-evaporated once rain stopped, rather than running down the surface of the building. Alterations, reliance on damp-proof systems, the use of modern materials and poor maintenance have often made traditional buildings less efficient in the way that they resist and remove water. As a result, water either penetrates the building envelope above the ground or is absorbed into the below-ground structure. This liquid water will, in turn, evaporate into the interior space, causing unsuitable conditions both in terms of conserving the fabric and providing comfort and usability.

4. Modifying the building environment

We generally try to modify the building environment to improve the usability of a building for the occupants rather than to benefit the building itself or its contents. There is, however, the potential to cause unintended harm when modifying the building environment, so it is important at the outset to clarify: why modifications are needed; the effect they may have on building users, fabric and contents; and how to control potentially damaging effects.

Thermal comfort

In a traditional building, the indoor environment should balance the occupants' comfort and health requirements with the conservation requirements of the building and its contents.

Many parameters affect a person's 'thermal comfort', including air temperature, mean radiant temperature, air velocity (draughts) and relative humidity – as well as loss of body heat, type of clothing and metabolic rate. Research has demonstrated that the level of personal control over the thermal environment has a significant effect on 'perceived comfort'. If a building user is able to do something to relieve their discomfort (for example, open a window), they feel far more comfortable – even if they do not actually change anything significantly.

Understanding why body heat is being lost and how this can be reduced should be the first point of focus. For example, a person will lose less heat when sitting on a cushion or an upholstered chair than on a cold timber or plastic seat. Conversely, when it is very hot, sitting on a cold surface may help a person feel more comfortable. Addressing loss of body heat is generally relatively inexpensive and carries negligible risk to the building fabric. Only after implementing measures to reduce loss of body heat should installing or modifying a heating system be considered.

Heat gain from solar radiation through glazed openings can cause discomfort through overheating. Flexible means such as awnings, blinds, shutters or screens to address or moderate how the internal space heats up also need to be considered.

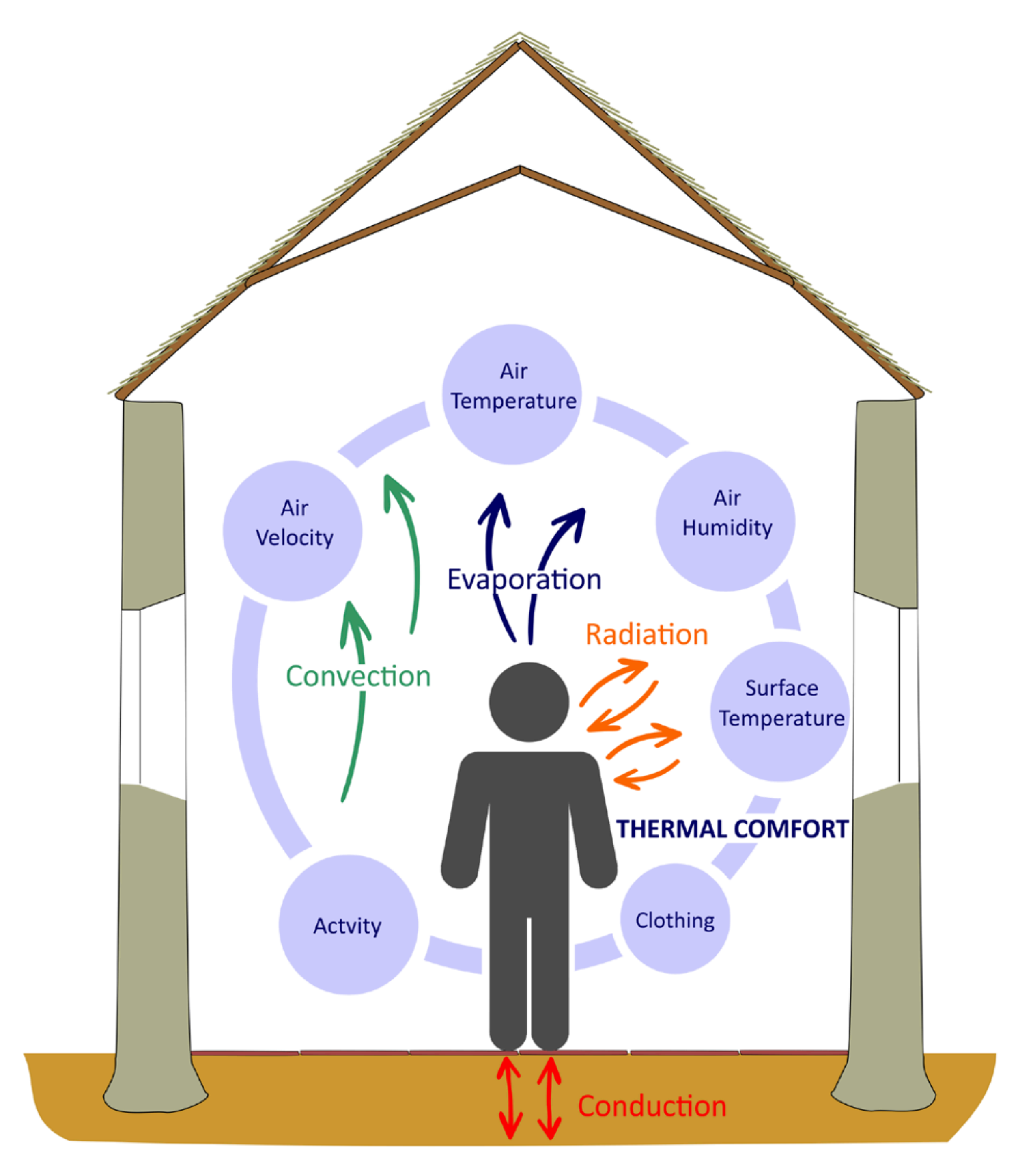


Figure 20: The parameters affecting a person's sense of thermal comfort. © Tobit Curteis Associates

4.1 Improving the inherent environmental building performance

For many traditional buildings, improving their inherent (passive) environmental building performance will improve occupants' thermal comfort. It can also reduce the need to install or upgrade artificial controls. These often have a high carbon footprint to install and run, and they can be a risk to the building fabric and contents. In most cases, the environmental conditions in a historic building deteriorate because the level of inherent buffering provided by the building envelope has reduced for some reason. So, working out what has changed and then reversing it may improve performance. For example, removing lath-and-plaster ceilings in churches in the 19th century (an intervention commonly carried out for archaeological interest) exposed roughly constructed and very air-leaky roofs, and undermined the buffering provided by the building envelope. Similarly, replacing lime plaster with modern cement or gypsum-based materials can also reduce buffering. In such cases, reinstating the ceilings or traditional interior finishes may be the most effective way to improve the passive building performance, both in terms of maintaining the building fabric and improving thermal comfort.

Figure 21: Traditional methods of reducing heat loss from the occupants to the building envelope included the use of hanging fabrics (top), panelling and shutters (bottom). © Tobit Curteis Associates

Improving the inherent building performance generally means increasing the level of buffering provided by the building envelope. However, in some cases, improving passive performance may involve changing the current form or detailing, which could affect the significance of the building itself. This is often the case with buildings that are missing some traditional functional details, such as overhanging eaves or gutters, because they were removed in the past or were originally excluded for design reasons. With creative solutions, the impact of improved detailing or design change on significance may be minimised, and the change justified by the reduced rate of deterioration of the building fabric and contents.

Some changes, such as thermal insulation, may have little effect on a building's significance and appear benign, but they could still have hidden risks. For example, thermal insulation may increase the moisture content of a wall or contribute to overheating.

Controlling liquid water

To successfully manage the building environment, all sources of liquid water must be controlled effectively. Failing to address liquid water sources will undermine any environmental control and improvement measures. On the wider site, addressing liquid moisture sources may involve dealing with problems of surface water run-off through actions such as re-landscaping or land drainage, or installing measures to reduce flood risk.

The building envelope itself must be in good order, with no water ingress through poorly designed architectural details, and no areas of damage or inappropriate alterations. The rainwater disposal system – both the above-ground rainwater goods and the below-ground drainage – must be well designed, have sufficient capacity for the size of the building and be in good condition. The system also needs to be able to cope with the increased volumes and frequency of rainfall that have been occurring in recent years. Any new internal and external plumbing should be routed to avoid sensitive or significant material, in case of failure. In practical terms, this means ensuring that water and drainage pipes do not run above sensitive fabric, such as wall paintings or historic collections. Risks associated with washing floors or other internal water usage can be addressed by effective building management.

Figure 22: Damage to the base of the wall caused by a burst water pipe. © Clews Architects

Figure 23: The use of liberal amounts of water when washing floors can cause salt activity and damage to the historic fabric. [Here, three crewmen scrubbing the floor of the 'Ritz' onboard the Endurance – Jock Wordie the expedition geologist on the left, with Third Officer Alfred Cheetham in the centre, and Alexander Macklin the ship's doctor on the right]. © Scott Polar Research Institute, University of Cambridge/Hulton Archive/Getty Images

Increasing thermal buffering

Understanding heat loss and heat gain is necessary to safely and effectively improve the thermal performance of a building for the comfort of users and the conservation of the fabric. It is also necessary to achieve improvements in energy efficiency. Reducing heat loss and heat gain by improving the inherent performance of the building envelope can reduce the need for mechanical systems that may be expensive to install, may use a significant amount of energy to operate, and may require regular maintenance and eventual replacement. However, changing the environmental performance of the building envelope has inherent risks. These need to be understood and addressed to avoid introducing unwanted effects. For example, if insulation is applied to an external wall (whether to the internal or external face), condensation may form at the interface and lead to mould growth. Water may also become trapped within the building fabric. If a ceiling is insulated to prevent heat escaping into the roof space, this will result in a colder roof space, possibly leading to greater levels of condensation and the need for improved ventilation to control associated damage. Most of the potential problems are predictable, and environmental testing and materials performance calculations can be undertaken to assess the risk and inform the design of mitigation measures.

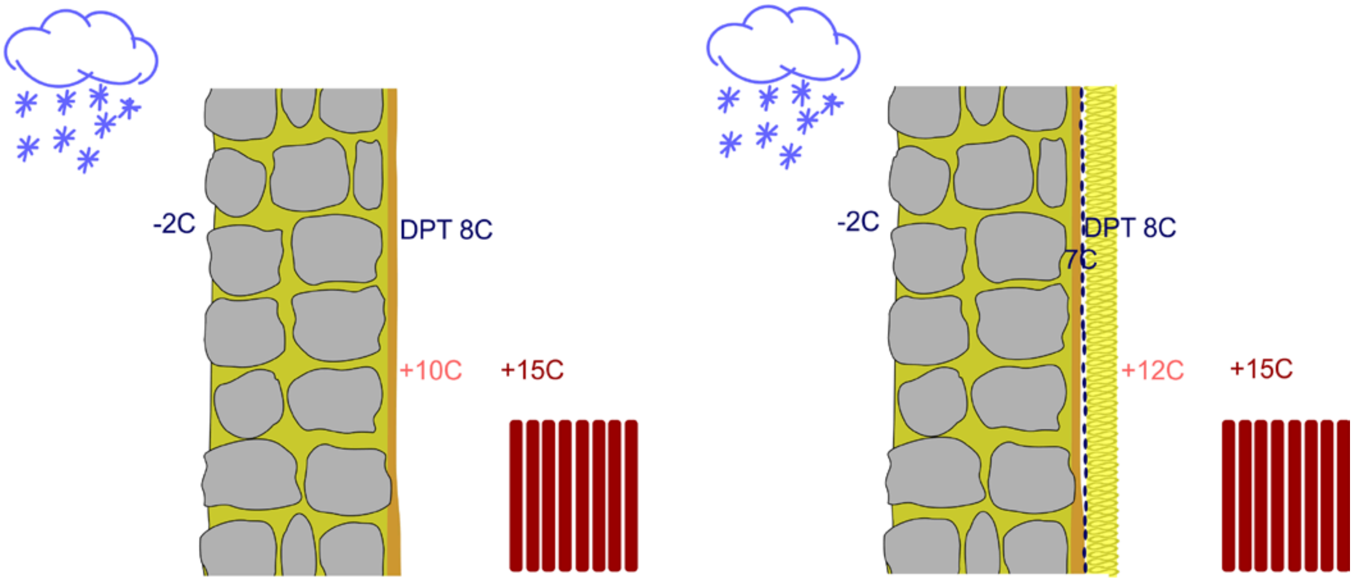


Figure 24: Measures to improve the thermal performance of both traditional and modern buildings need to be carefully designed to avoid risks associated with condensation due to temperatures differential. Here, the risk of interstitial condensation with the addition of an insulation layer. Condensation will take place when the air temperature drops below the dew point temperature (DPT) © Tobit Curteis Associates

See also Historic England’s technical guidance and webinars on [responding to climate change](#) through mitigation and adaptation.

Heat transfer

Heat gain and heat loss can take place through three interrelated processes: radiation, convection and conduction.

- **Radiation** occurs through the transfer of (electromagnetic) energy. Heat gain and heat loss take place through thermally inefficient elements of the building structure, such as single-glazed windows or uninsulated roofs, when the temperature outside differs from that within. Radiant heat gain or heat loss to or from a person occurs when we stand close to a surface that has a higher or lower temperature than we do, such as a wall or window, which is either losing heat to or gaining heat from the exterior.
- **Convection** occurs via air of different temperatures. Heat gain or heat loss to the air can take place because of air exchange with the exterior. This may be caused by loose-fitting architectural elements (for example, doors, windows and roofs), but it may also be caused by intentional ventilation (through an open window or door). Although draughts may be uncomfortable in the winter, they can be useful in the summer to reduce heat gain. Convective heat gain or heat loss to or from a person occurs when we are surrounded by air that is either warmer or cooler than our body and we are wearing unsuitable clothing.
- **Conduction** (heat transfer by direct contact) occurs when we touch a cold or hot surface. Examples include standing on a cold floor in poorly insulated footwear or sitting on cold seating without a cushion. Similarly, conductive heat gain occurs when we touch a warm surface: for example, leaning against a radiator or sitting on a heated cushion.

Whatever the process, heat will always travel from the hotter body, architectural feature or surface to the cooler one. By pinning down the causes of discomfort and heat loss or heat gain, appropriate solutions usually become apparent.

Common approaches to controlling heat loss or heat gain include:

- Locating sources of draughts or heat gain and either mitigating them or positioning activities so that people are kept away from them
- Locating seating and activities away from cold surfaces, such as external walls
- Partitioning spaces both horizontally and vertically, using permanent partitions (such as ceilings or walls) or moveable partitions (such as draught screens or curtains)
- Using insulating layers on floors and seating (for example, mats, carpets or cushions)
- Ensuring that users are aware of conditions and dress appropriately

If heat loss and heat gain from both people and the building fabric can be effectively moderated, the use of mechanical controls such as heating and cooling systems can be reduced.

For further information on heat gain mitigation, building regulations and overheating in historic buildings, see our Technical Guidance pages.

Roofs and ceilings

Although a historic roof may be weathertight, it is often thermally inefficient because it was not designed to retain high levels of internally generated heat. As a result, heat generated by space-heating systems is often lost via the roof (as well as through walls, windows and doors). Installing insulation can reduce heat loss considerably. However, great care has to be taken to prevent unexpected and damaging side effects, such as condensation. This could promote mould growth, and could cause roof coverings, in particular lead, to deteriorate or timber structures to become susceptible to insect attack.

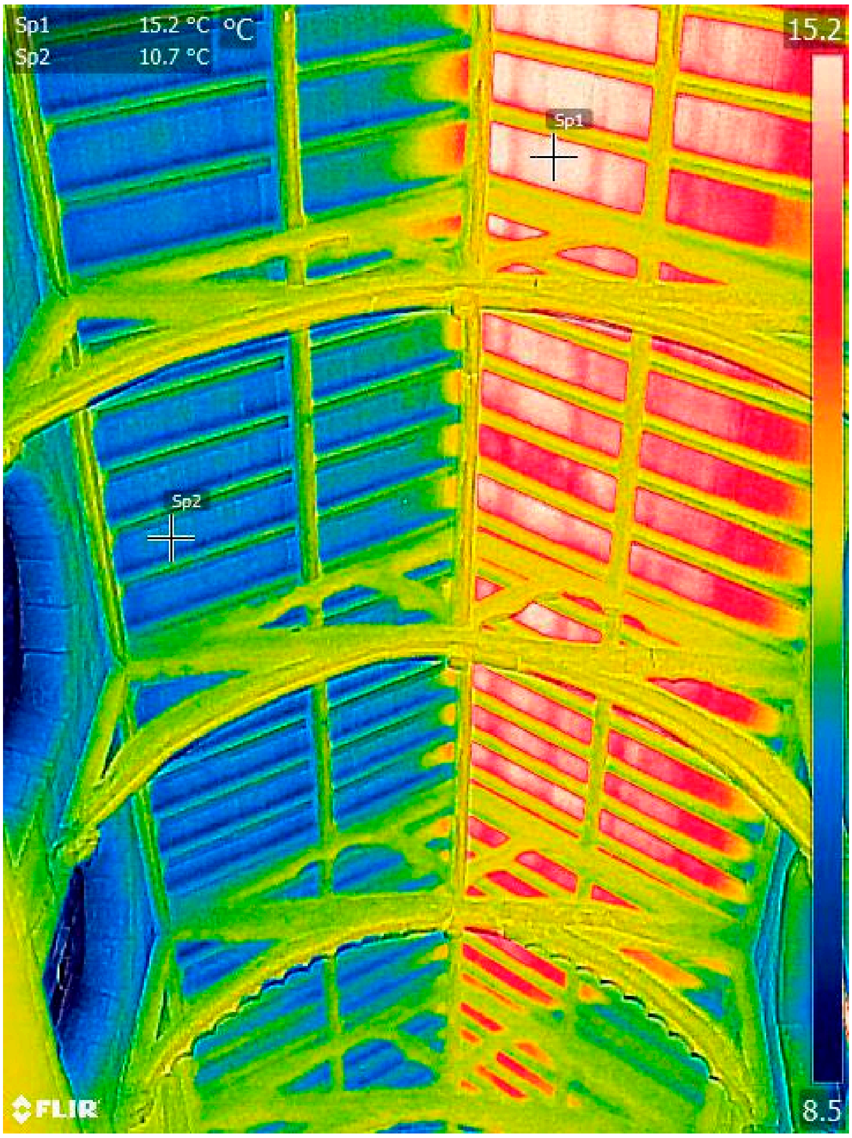


Figure 25: In many buildings of traditional construction, the roof is one of the largest sources of heat loss and gain. Here, low thermal buffering results in the north pitch of the roof being cool while the south pitch heats due to solar gain.
© Tobit Curteis Associates

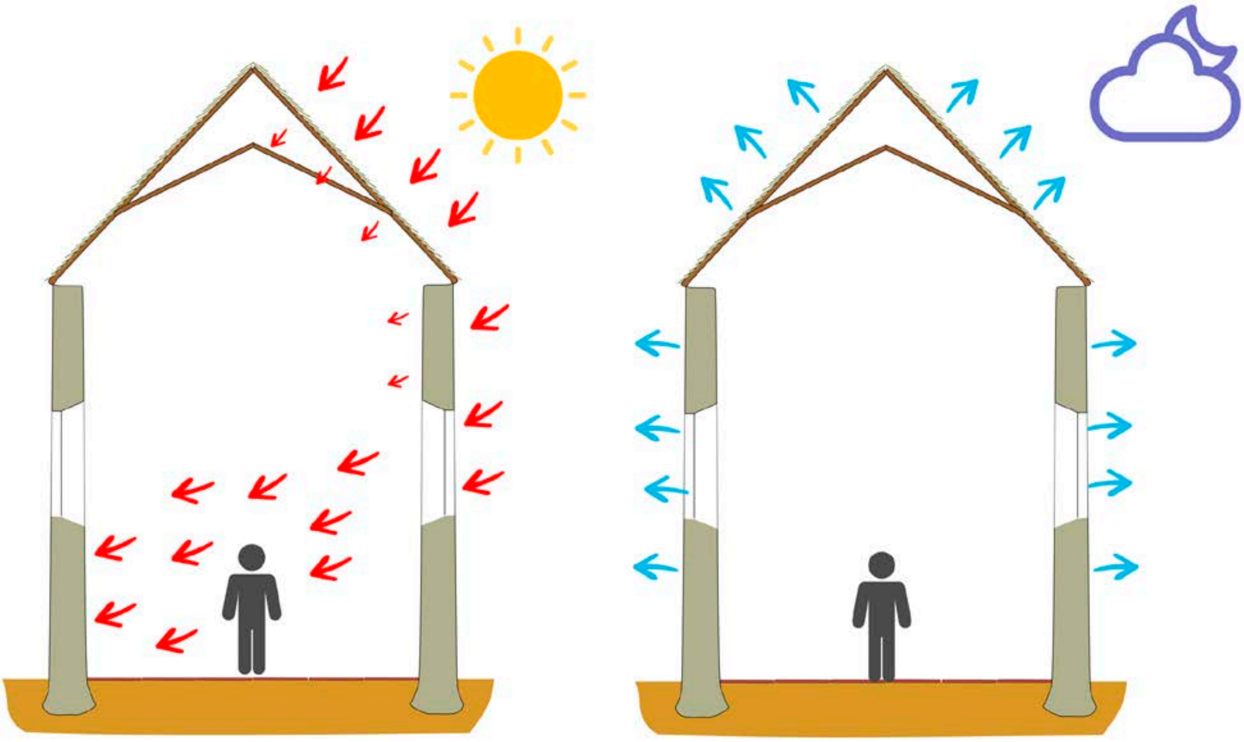


Figure 26: Heat gain in buildings (left) and heat loss in buildings (right). © Tobit Curteis Associates

Figure 27: Simple insulation measures can improve the thermal performance of the ceiling and roof space but care is required to avoid condensation both on the ceiling and within the roof space which will be colder as a result of the intervention. Thermal imaging (left) showing the underside of a vaulted ceiling, and view from above the vault, showing subsequent installation of insulation (right) © Tobit Curteis Associates

A lath-and-plaster ceiling below a roof will generally reduce radiant heat gain and heat loss. It will also reduce the level of air exchange and will, therefore, considerably improve the buffering performance of the building envelope.

See also Historic England’s guidance on [improving energy efficiency] and [adaptation for climate change].

Double-door systems, lobbies and air curtains

With single-door systems (commonly found in traditional buildings), internal/external air exchange is inevitable when the door is opened. The amount of exchange can be considerable if the door is used frequently or is left open, perhaps to allow large numbers of people to pass through. If two or more doors in different areas of the building are open at the same time and cross ventilation occurs, the loss of internal warmed air can be significant. Porches and double-door systems have been used for centuries to reduce this air exchange. The development of modern architectural glass allows designs that are efficient and less obtrusive. However, the environmental performance of glazing is very different to that of traditional wall construction materials, so the effect of the specific design must be assessed to ensure that the environmental impact will be as expected.

Figure 28: Glazed lobbies can be an effective method of reducing air leakage and improving the thermal performance of the space. (left) Digital visualisation of the proposed lobby at Ripon Cathedral and (right) thermal imaging of the actual lobby.
© Caroe Architecture Ltd with artworks by Sally Scott (left)
© Tobit Curteis Associates (right)

Adding a lobby will create a separate building environment. If well designed and managed, it can benefit the fabric, but if poorly designed or used, it may create damaging conditions. For example, if the main door is left open for long periods, decorative stonework on internal walls around the door may be exposed to external temperature and humidity, thus increasing condensation risks. Consequently, it is important to evaluate the effect of installing a lobby early in the design process. Generally, this involves assessing the current environmental performance of the building envelope and the likely changes the lobby will create.

Heat curtains (bands of hot air generated by high-speed convective units located over doors), such as those used in shops where doors remain open, are occasionally suggested as an alternative to a lobby, but they are unsuitable for the majority of historic buildings. While these systems offer some level of thermal comfort, by reducing cold air ingress, they are highly inefficient in terms of energy use and vulnerable to prevailing weather conditions. Furthermore, they do not provide the humidity buffering generally required for effective conservation environmental control. There is also considerable risk to the building fabric from evaporation caused by high-speed warm air blowing over sensitive surfaces.

Room compartmentation

Most traditional buildings have internal walls, partitions and ceilings. These allow different sets of environmental conditions to co-exist in different parts of the building, largely by passive means. The walls of the compartment provide hygral and thermal buffering between spaces. For example, walls and partitions allow you to heat your living room but keep an unused room next door much cooler; they also prevent the humidity in a bathroom from raising humidity in adjacent rooms.

In some historic buildings, the main spaces are large and interconnected, either because that is how they were constructed or because historic partitioning has been removed. Consequently, achieving different environmental conditions in different locations may not be straightforward.

Introducing (or reintroducing) carefully designed internal partitions and ceilings can limit the level of air exchange and thermal transmittance between different areas. By enclosing a small space, it is possible to produce comfort heating in that particular location, without needing to heat the rest of the space. Traditional furnishings such as box pews or timber screens combined with curtains were designed with this in mind. Compartmentation can also be designed to be temporary, flexible or even reversible, should occupants wish to use the space differently (for example, modern pods inserted in old buildings).

Enclosing a space within a compartment can pose a risk if the microclimate within is poor. For example, enclosing an area already affected by high humidity caused by water ingress will further increase the relative humidity. This may lead to a more uncomfortable and more damaging building environment, rather than the anticipated improvements. Air quality in a space with reduced air movement should also be considered from the occupants' perspective.

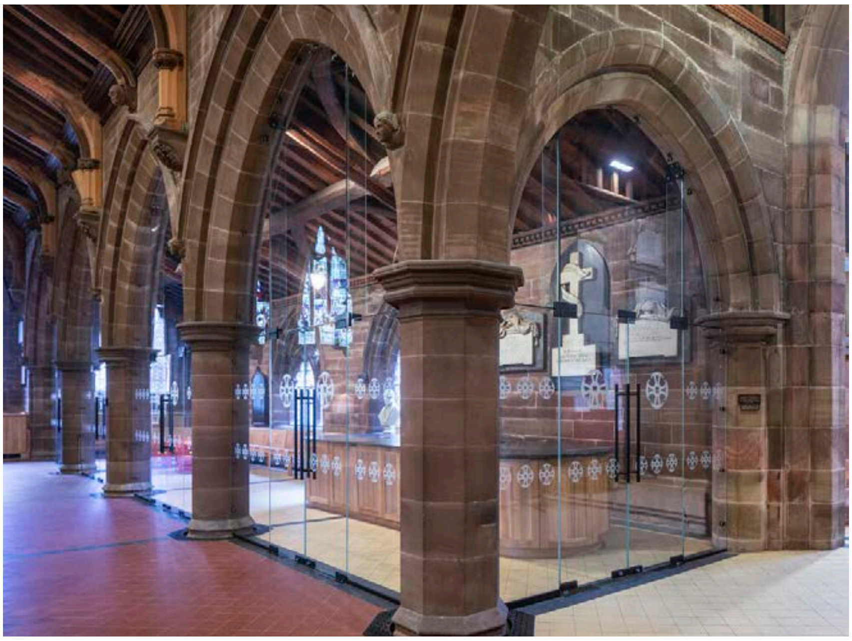


Figure 29: The introduction of internal partitions allows different areas of large open-spaced buildings to be used and heated in different ways. © Clews Architects, photography Andy Marshall

Figure 30: In the 19th century, ceilings in churches were often removed to expose the architectural structure, making the building far less thermally efficient. The reinstatement of ceilings reduces air leakage and improves thermal buffering resulting in a more stable and efficient space. St Botolph's church, Hardham in 1995, without its internal ceiling (left), and the church with its ceiling reinstated (right).
© Tobit Curteis Associates (left) © Historic England Archive (right)

Fixtures, fittings and furnishings

Traditional buildings employed many features to improve building use and comfort (some of which have continued to be included in more recent constructions). External and internal shutters were commonly used in buildings until the 19th century. They improved the thermal efficiency of windows by offering a significant reduction in radiant heat loss in winter and heat gain in summer. External awnings, another common design feature in the 19th century, reduced solar gain. Some were designed to work with sash windows to increase airflow through the building. Sliding sash windows could be opened at the top of the building to allow 'night flushing': removing summer heat from the room before it could warm the fabric. Once glass became cheaper in the 19th century, secondary glazing became common in colder climates.

In addition to shutters, windows were equipped internally with blinds and curtains. In winter, these stopped draughts and reduced heat transfer or loss through the glass. Exterior doors also had curtains to prevent winter draughts.

On wooden floors, rugs and carpets reduced both draughts and conductive body heat loss via feet. Walls were sometimes hung with fabric or covered with wooden panelling for the same reason. Tapestries and curtains were also hung over doors in partitions and internal walls to cut draughts.

Most of these features had the great advantage of being flexible: occupants could adjust them in response to the weather and level of discomfort. House records show that tapestries and rugs were used in winter and then taken down and stored in summer, when occupants were glad to lose body heat into the walls.

With changes in architectural fashion, shutters and awnings were removed from many historic buildings in the 20th century. In some cases, reinstating these features would improve the internal building environment.

Figure 31: Simple physical control measures, such as using awnings, shutters and blinds, were common in traditional building design. A Buckingham Palace garden party in 1897, with all the window awnings down on the south-west elevation to reduce heat gain. Image: Wikimedia Commons.

Figure 32: A Victorian advertisement for domestic awnings and blinds.

Many traditional passive control designs are now regaining popularity for new buildings as 21st-century building designers begin to re-examine low-cost and carbon-efficient systems for maintaining a comfortable internal environment.

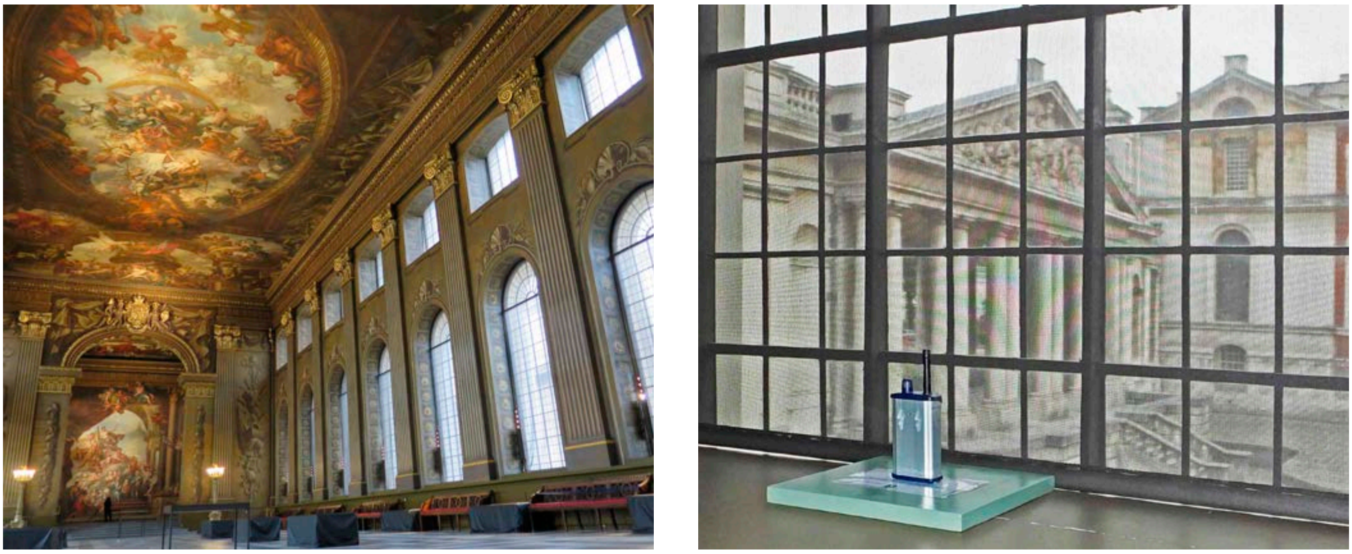


Figure 33: Light-control mesh is commonly used in historic buildings to reduce exposure of photosensitive materials as well as to control heat (left). Detail (right) showing llight-control mesh and how it allows those inside the building to see through the window. © Tobit Curteis Associates by kind permission of The Greenwich Foundation for the ORNC

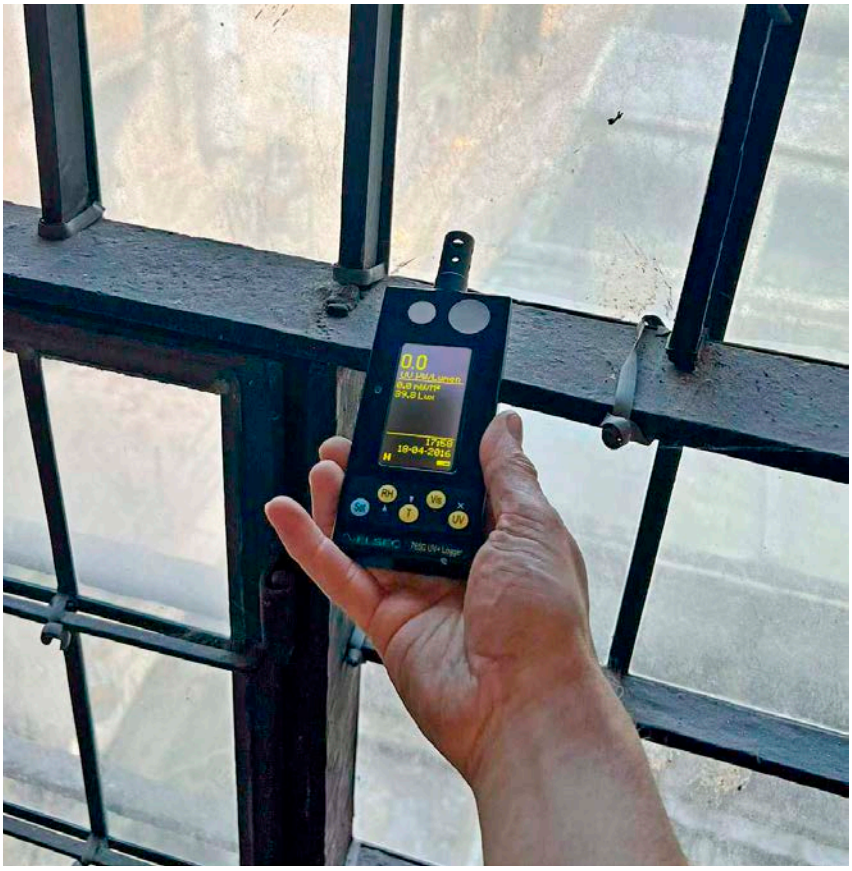


Figure 34: UV control film is often applied to glazing to protect photosensitive historic materials. © Tobit Curteis Associates

Special modern types of window glass can be used to filter out damaging UV radiation or UV absorbing film can be applied to the glass surface.

4.2 Artificial controls: Heating

Mechanical systems are used to modify the internal microclimate created by the building envelope. In the UK, the most common system is heating of the general air mass (space heating). Heating will usually require a high-energy input, commonly supplied directly or indirectly by fossil fuels. It is, therefore, all the more important to reduce waste by making sure that heated air is not lost to the exterior.

Space heating is generally introduced in an historic building to improve thermal comfort for users. Systems need to be designed to take account of the people being heated, when they will require the heat, and what they are doing. For example, visitors to a historic building are often there for a short time, moving around in many areas and wearing outdoor clothing. By contrast, the audience at a concert sit in a fixed location for a long period of time and usually remove their outerwear.

As heat also affects humidity and air circulation, it can influence environmental conditions in unpredictable ways. But ‘heating’ does not have to mean space heating: there are alternative systems that can produce more effective thermal comfort at much less risk to the building fabric and contents and at much lower energy costs, as discussed below.

To design and use heating most effectively, it is important to establish how the space is used (*see* 6.4 Thermal improvements: Defining needs and risks). It is also necessary to understand the different principles of the two main heating types in historic buildings: convective heating and radiant heating.

Convective heating

Most space heating in historic buildings is provided through convective systems. Convective heating has been used in buildings since the 19th century, but it became common in the mid-20th century with the widespread introduction of domestic central heating.

The simplicity of convective space heating and the possibility of maintaining a common temperature throughout a space offer many advantages. For historic buildings, however, there are some significant disadvantages: a common problem for tall rooms is that it is necessary to heat the whole air mass to benefit from an increase in temperature in the lowest two metres, where thermal comfort is required. This is not energy efficient, and it is also often difficult to achieve because of the thermal inefficiency of the building.

Because warm air rises, the temperature at the top of the building can be much greater than that at the bottom. This can cause uncomfortable air movement and draughts. It also means that the relative humidity at height will be significantly reduced, possibly causing stresses to timber structures and salt activity in masonry. If heating is used only when the building is occupied, both temperature and humidity will fluctuate widely, placing increased stress on the sensitive historic fabric.

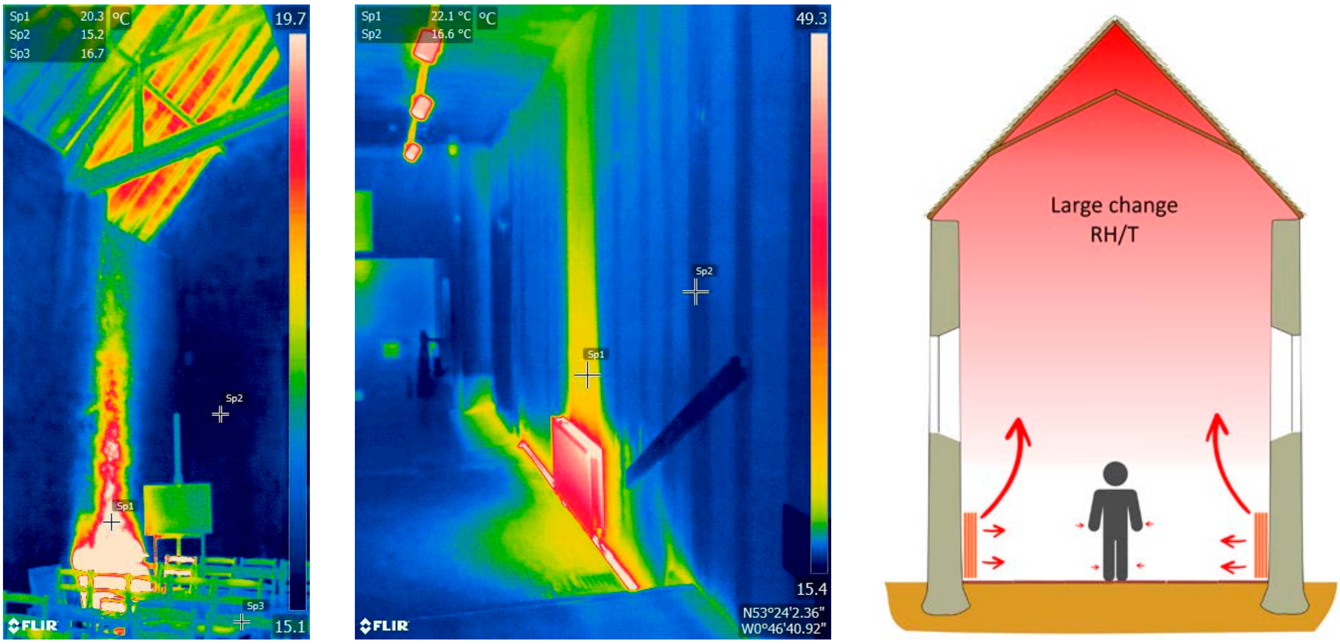


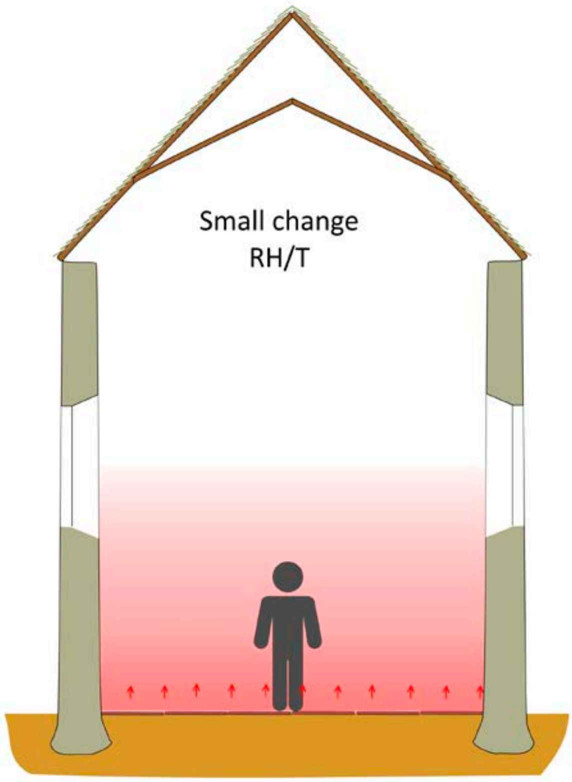
Figure 35: Thermal images (left and centre) showing buoyant air rising from convective heaters. The effects of convective heating on temperature and relative humidity inside a building (right). © Tobit Curteis Associates

Radiant heating

Radiant heating uses IR radiation to heat surfaces rather than air. Many traditional heating systems, such as open fires, are primarily radiant in effect (although as the surrounding surfaces warm up and then, indirectly, warm the air, such systems will also have a convective effect). Modern radiant heating systems come in many types, including electric radiant panels, chandeliers and floor heating (also known as underfloor heating). The last uses the floor surface itself as the heat emitter, and heat is provided either by electrical heating elements or water pipes below or embedded in the floor.

Radiant heating can provide thermal comfort for users close to the heat emitter, with minimal effect on the overall air mass in the room. This limits the fluctuations in relative humidity that are typical of space heating.

Underfloor heating uses a mix of radiant heating and convective heating. Installing underfloor heating transforms a source of heat loss into a source of heat gain. Electric underfloor heating usually gives a higher output than a hot water system, but it is much more expensive to run and so needs to be used very sparingly, and only where no other heating system is appropriate. Installing underfloor heating is costly and requires large interventions, which can have adverse effects on sub-floor archaeological material. In addition, the insulation and other materials needed for an effective underfloor heating system can disturb the movement of groundwater, which in itself can damage the building fabric. These problems are not necessarily insurmountable, but they must be investigated before underfloor heating is installed.



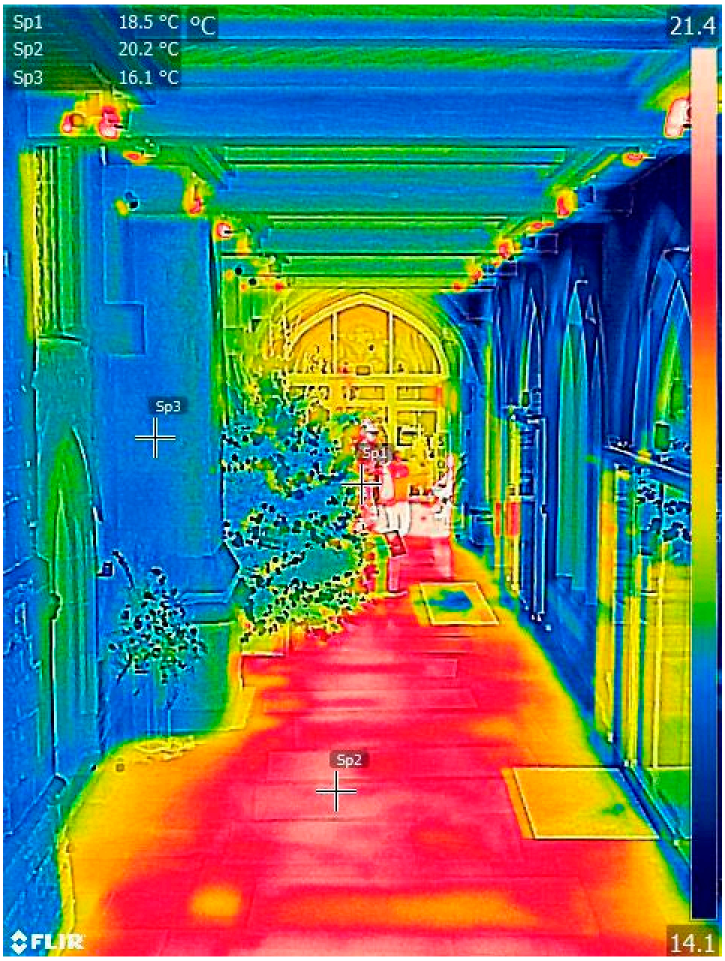


Figure 36: Underfloor heating providing largely radiant warmth at low level: normal light (top left) and thermal image (bottom left). Heat distribution inside a building with underfloor heating, illustrating only limited change of temperature and relative humidity at height (top right). © Tobit Curteis Associates

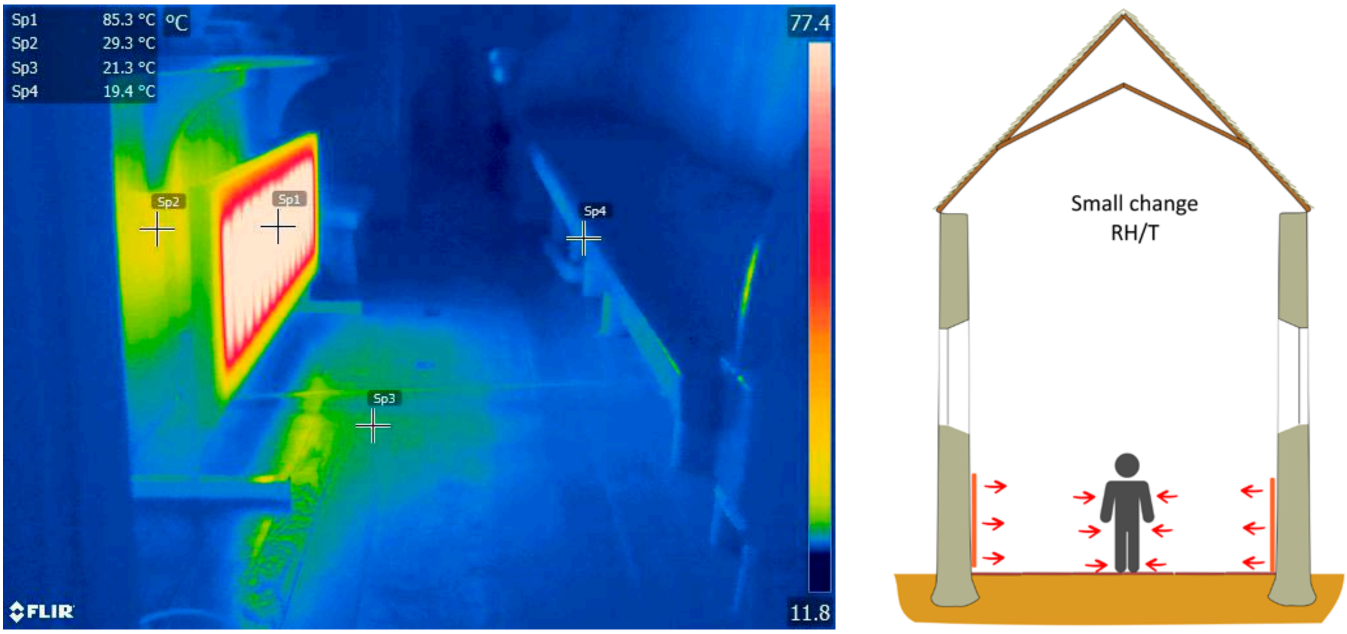


Figure 37: Thermal image showing radiant panel providing heating to adjacent seating (left). Heat distribution associated with radiant heating panels (right). © Tobit Curteis Associates

Radiant heating systems based on a number of small locally positioned units (for example, pew heaters) can be very effective. Heating panels correctly located within fixed seating can provide efficient local heating at a relatively low cost. They can be used in conjunction with overhead radiant heaters (wall-mounted or chandeliers), which are nowadays both efficient and fairly unobtrusive. In some circumstances, radiant panels can also be fitted to moveable partitions and screens to provide temporary heating in areas where specific activities take place. Under-carpet heating (electrical heat emitters below or manufactured within carpets or floor mats) offers more flexibility and is relatively easy to install. As with fixed underfloor heating, under-carpet heating both reduces loss of body heat and warms the person.

Because radiant heaters need to be positioned close to the people who require heat, it is necessary to understand how the building is used and position the heaters accordingly. For temporary heating locations, electrical power outlets need to be situated in the correct positions. As the infrastructure for most radiant heating systems (apart from hot water underfloor heating) is electrical, installing such systems is usually far less disruptive to a sensitive building than putting in hot water heating routes, assuming that sufficient electrical power is available.

Another advantage is that control systems for electric radiant heating offer flexibility and can allow different areas to be turned on or off depending on patterns of use.

Wall- or ceiling-mounted radiant systems are most efficient when they are used for limited periods: for example, just before and during an event. This way, heat is generated and transferred to the body with minimal effect on the larger air mass and, thus, on any sensitive building fabric or contents. Used correctly, radiant systems can be very energy efficient. It is important, however, that heaters are pointed away from sensitive fabric so that it is not inadvertently heated alongside the people.

Underfloor heating generally requires a long heat-up time. However, because of the thermal mass of the floor, it tends to provide stable and efficient radiant heat output, and also has a convective effect.

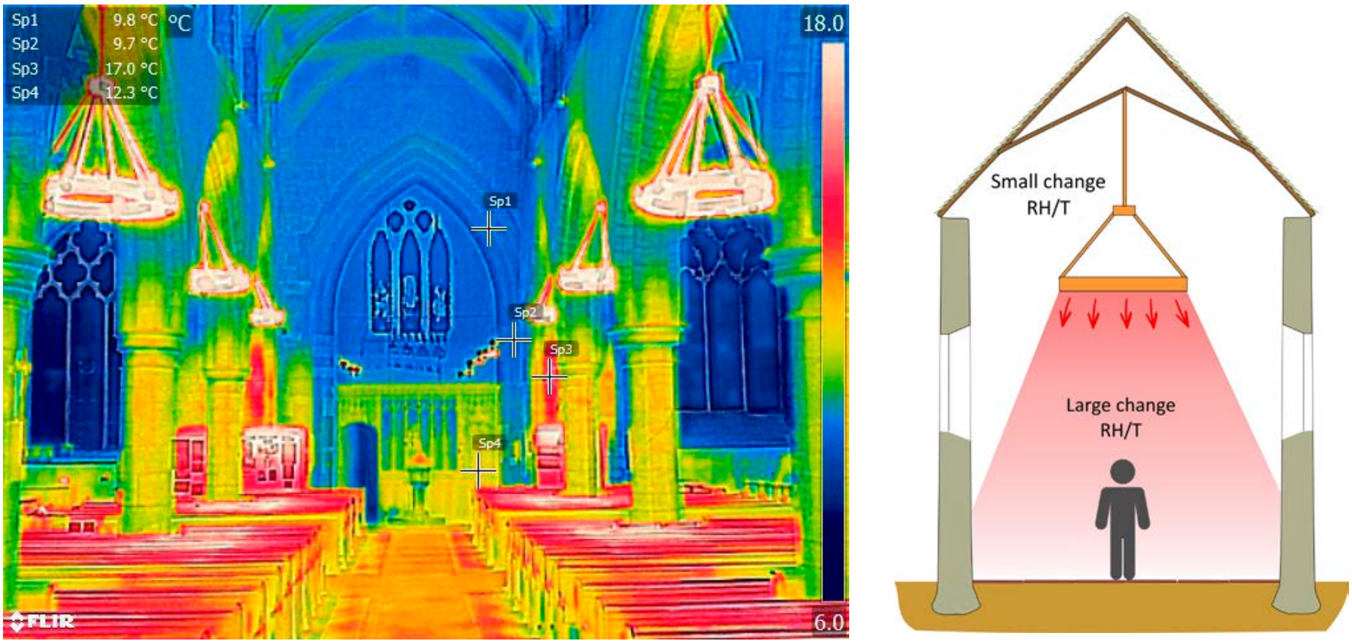


Figure 38: Thermal image showing radiant heating using chandeliers (left) and heat transfer associated with heating chandeliers, showing limited change in conditions outside of the beam radius (right).
© Tobit Curteis Associates

In many historic buildings, local radiant heating systems can be used alongside background convective heating. The limited air warming provided by the convective heating reduces the overall chill – with less potential impact on sensitive fabric and contents than conventional space heating alone – while local radiant units provide comfort heating for users.

Heating zoning

The various areas of a building will have different heat loss characteristics. Because areas may be used for a variety of activities at different times, they will also have diverse heating needs. To provide efficient heating, systems may need to be designed with different criteria for individual areas.

Building compartmentation can allow heating to be used very effectively if there are separate controls for each zone, or individually controlled heaters. For example, in a domestic house we can heat rooms to different levels at various times of the day depending on occupancy and activity. However, even without a physical partition, it is possible to achieve various levels of heating by using different types of heaters and heat loss control measures. Radiant heating can be localised, whereas convective heating is often more widespread. For example, in a church where radiant pew heating or overhead radiant chandelier heating is used, only units in the occupied areas need to be switched on to provide thermal comfort. By contrast, if a hot water convective system is used, the whole space may need to be heated for the comfort of a small group in one part of the building.

Conservation heating

Unstable relative humidity can damage historic fabric or contents that are sensitive to changing relative humidity. In response, in the 1970s, the National Trust with Dr Bill Bordass developed 'conservation heating': an approach that manages relative humidity using space heating controlled by a humidistat rather than a thermostat.

With conservation heating, space heating is turned on and off to keep relative humidity within a predetermined band (the band in which material damage is minimal). When the relative humidity increases above the set level, heating is turned on and the increase in temperature will depress the relative humidity. Conversely, when the relative humidity falls below the set level, heating is turned off to allow the relative humidity to increase. Most conservation heating systems have low and high temperature overrides to prevent freezing and overheating. Success depends on the location of the humidistats and the heaters, which must be positioned to encourage widespread heat distribution and gradual rather than sudden changes in temperature and humidity.

Conservation heating operates irrespective of the ambient temperature. Thus, it is very likely to be on in the summer, when the relative humidity is high, and off in the winter when it is low. This means that, in some cases, a building can be uncomfortably cold/hot for users during the winter/summer months.

In buildings where the primary concern is conserving the fabric and contents, but the comfort of users is also necessary for specific events, a combination of humidity-led conservation heating and ordinary thermostat heating can sometimes be used. This will provide conditions that are conducive to conserving the fabric and contents on a day-to-day basis, but allows for periodic thermal uplifts during events. Such systems need to be carefully designed and managed, and fragile fabric and contents should be monitored closely. However, they can offer an effective compromise between comfort and conservation.

It should be noted that the term 'conservation heating' is often misapplied to gentle background heating, which is not intended to stabilise relative humidity.

4.3 Artificial controls: Ventilation

Ventilation is often recommended in historic buildings to modify the internal environment and to maintain good indoor air quality. There are statutory minimum ventilation requirements for human occupation and certain combustion appliances.

Like heating, the effects of ventilation are sometimes difficult to anticipate, so it is important to understand how it works and what it can achieve. The term ‘ventilation’ is generally used to describe two separate functions – air exchange and air movement – each with different effects.

Air exchange

Air exchange occurs when one body of air is exchanged with another (typically, when external air is exchanged with internal air). If the external air has a lower moisture content than the internal air, then the internal air will become drier. The reverse is also true: ventilation with moist external air will increase the water vapour content within a building. When the weather is hot, external air may feel drier because it is warmer and has a lower relative humidity than internal air, but it may, in fact, contain a large amount of water vapour. When this warm moisture-rich air enters a building and touches a cold surface, the temperature falls and the relative humidity increases; in extreme cases, condensation can occur. This is common when buildings are ventilated in the spring and external air warmed by spring sunshine enters a building that has cooled over the winter months. The same pattern sometimes accounts for the apparent ‘sweating’ of flagstone floors in spring and early summer, and for water droplets that collect and drip off cold copper water pipes. It can, however, occur throughout the year.

Figure 39: Condensation on a marble wall monument caused by ingress of warm spring air into a church where the fabric had been chilled over winter. © Tobit Curteis Associates

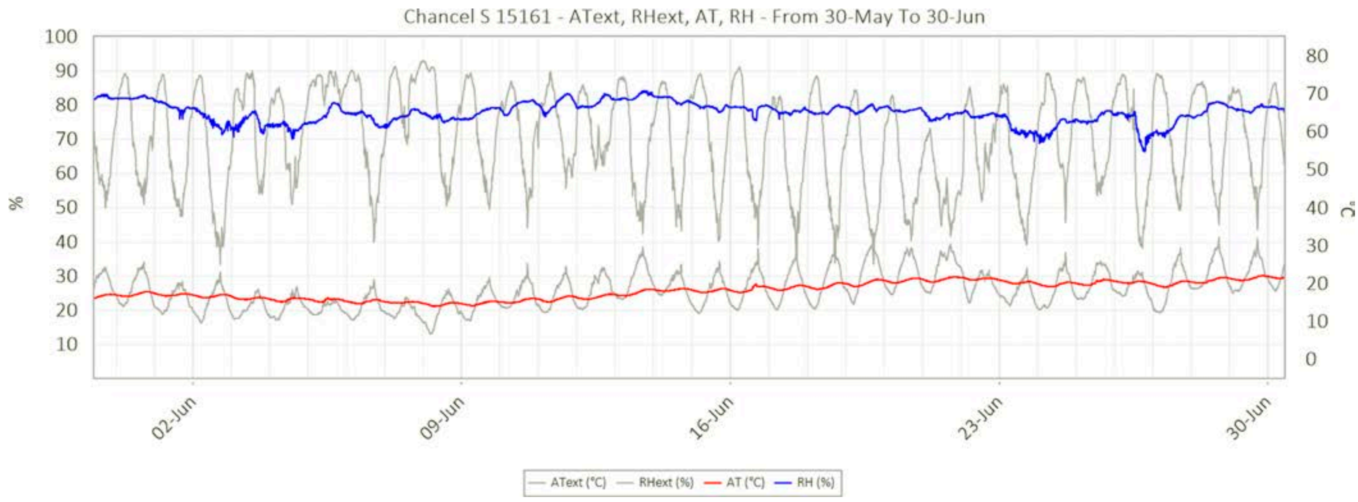


Figure 40: Chart showing internal (red and blue) and external environmental conditions (grey) in the early summer. While the external values fluctuate on a diurnal basis by more than 10°C and 40% RH, internal values fluctuate by less than 2°C and 5% RH. Ingress of external air in these conditions would destabilise the internal environment. © Tobit Curteis Associates

Even if it does not cause condensation, ventilation with external air (which has unstable relative humidity) will generally destabilise internal environmental conditions. This may harm sensitive materials, such as timber, painted surfaces or salt-contaminated masonry.

External ventilation can be used safely if there is a good understanding of the external and internal conditions, and the ventilation process itself can be controlled. For example, if the aim is to reduce the internal relative humidity on a day when the internal and external temperatures are similar and external relative humidity is low, then opening doors and windows will allow this to happen.

Ventilation with external air in response to a specific event (showering, boiling water or a large gathering of people in wet coats, for example) can be effective in reducing temporary periods of excessive relative humidity; indeed, it may be a statutory requirement in some situations. In those circumstances, it relies on the fact that the external air has a lower moisture content than the internal air.

Ventilation can be automated as part of conservation environmental controls to import external air only when its moisture content is lower than that of internal air. The process can be automated using electronic sensors and fans (sometimes known as 'conservation ventilation'), but this system is costly and complex, and only appropriate in very limited circumstances.

A similar approach is known as ‘borrowed air’ ventilation, in which dry air in one part of a building is used to ventilate an adjacent area where there is an elevated moisture level. A typical example would be ventilating a damp crypt in a cathedral with dry air from the nave. The advantage is that the nave air has, in effect, been conditioned by the building envelope and so the only mechanical control is the air transport fan.

Uncontrolled external ventilation may be beneficial in some situations. For example, the uncontrolled ventilation of roof spaces via the existing roof covering is generally beneficial if the roof structure is in good condition because it aids evaporation of condensation that has formed on the underside of the cold roof covering. It is, therefore, important that proposed insulation materials, the design and existing condition of the structure, and ventilation routes are considered together. See also Historic England’s research reports on ventilation.

Temporary uncontrolled external ventilation can be useful in some scenarios, for example in the initial stages of drying following a flood, when the instability of the introduced outside air is less damaging than the effect of the floodwater on the internal fabric. However, there will come a point during the drying process when the risks associated with the unstable and possibly high humidity external conditions outweigh the risks to the drying internal fabric. The level of ventilation will then need to be controlled.

Air movement

Often, when ventilation is suggested, what is really needed is air movement. This can prevent a build-up of moist air in a part of the room where the building fabric is slightly damp or cold, such as a corner at the base of an external wall. Air movement distributes any increased water vapour content in the air in this part of the room throughout the larger mass of air in the room, thereby minimising its effect. Opening a window is a simple way of creating air movement or introducing ‘fresh air’, but it is often done without considering the effects of allowing in external air. If air movement is the only requirement, then using mechanical fans generally provides a more predictable result (hence their use in libraries and archives). Convective heating also causes air movement which, if designed correctly, can be used to avoid the build-up of stagnant and humid air.

Air movement also increases evaporation and is, therefore, an efficient way to dry out wet surfaces. However, if that air movement is achieved by introducing warm moist air into a cold space (through an open window, for example), any increased evaporation may be cancelled out by the higher water vapour content of the incoming air and the potential to cause condensation.

Ventilation is just as complex as heating when it comes to the safe control of environmental conditions in sensitive buildings, where fabric and contents are concerned. It needs to be planned with the same level of care as would be applied to a new heating system.

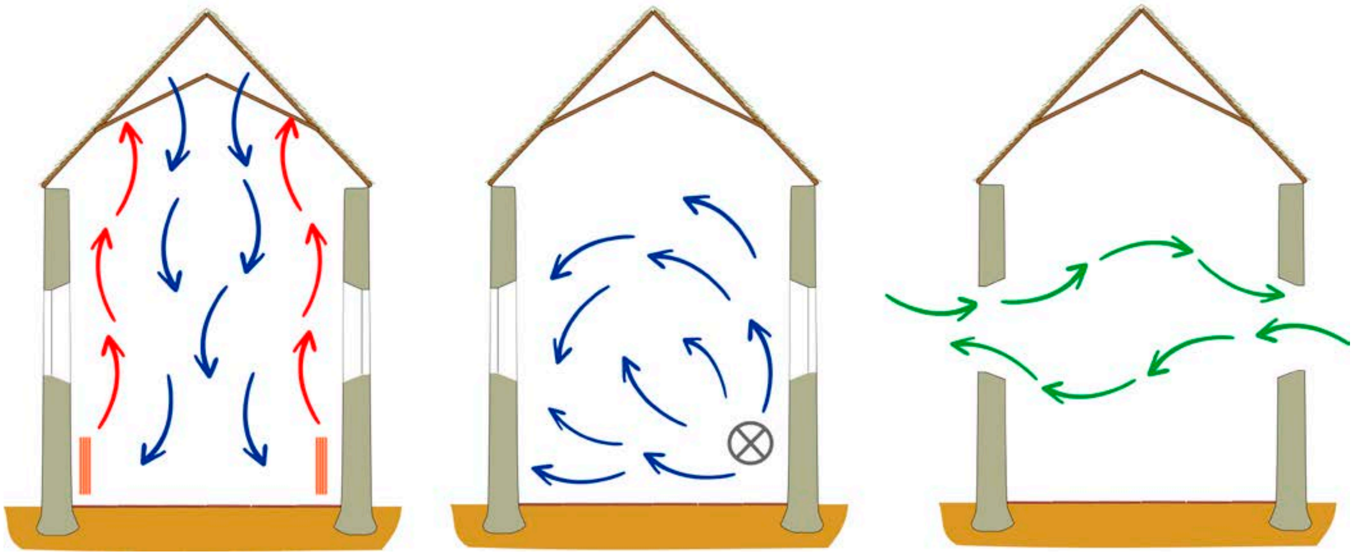


Figure 41: Three examples of air movement. On the left, air movement is generated as a result of convective heating causing warm air to rise which then cools at height and descends. No air from other spaces is introduced and so the water vapour content of the air remains largely static. In the centre is an example of mechanical fan air movement mixing air throughout the room but also without introducing uncontrolled air from elsewhere. In the right-hand image, air movement is generated by opening windows which, while successfully moving the air within the room also introduces uncontrolled external air which may have either a positive or negative effect on the internal microclimate. © Tobit Curteis Associates

4.4 Artificial controls: Comfort cooling

Comfort cooling limits the maximum temperature in a space. Used in isolation, comfort cooling is likely to drive up the relative humidity, in the same way that heating will drive it down. Therefore, to be both safe and effective in an environmentally sensitive space, comfort cooling generally needs to be used as part of an integrated air conditioning system that includes humidification and dehumidification, as well as temperature and air filtration control.

4.5 Artificial controls: Humidification and dehumidification

Relative humidity can be managed by changing the volume of water in the air (the absolute humidity) using mechanical humidification and dehumidification. Humidification involves introducing water vapour into the internal air. In some circumstances, for example in a museum storeroom, this can be useful to avoid the air being too dry for vulnerable collections made of organic materials (such as parchment, ivory or leather) and causing them to distort or crack. But remember that any water vapour introduced into the building this way does not simply disappear. Some will be lost through air leakage to other spaces, including to the exterior, while some will penetrate into 'hidden' spaces, such as behind panelling or into floor spaces, where it may condense on cold surfaces. For traditional buildings, construction materials are often hygroscopic (they absorb moisture from the air), so much of the water vapour will penetrate into these porous materials and may condense. Therefore, when considering humidification in a historic building, the ultimate destination of the introduced water needs to be understood, especially if the fabric and contents are sensitive.

Dehumidification is used to reduce the water vapour content of the air to produce conditions conducive to a particular need, be it the comfort of building users or the conservation of sensitive collections. With highly sensitive collections, such as those in museum storerooms, dehumidification can be useful. However, in many buildings, the process is employed to reduce elevated levels of water in the air caused by building defects. In other words, it is used to disguise the symptoms of high humidity rather than to address the underlying causes. It is often only a temporary solution and can sometimes be damaging. This is because dehumidification will increase the evaporation of water from wet building fabric, which will, in turn, increase levels of salt activity and other forms of deterioration.

In extreme and temporary situations, such as after a flood, dehumidification can be an effective tool to reduce very high moisture levels. Its use needs to be controlled so that the rate of drying is slow and progressive. Rapid dehumidification in these circumstances can cause the surface of a wall to dry, but not the core. This may cause delayed outbreaks of moisture activity – often after repair and redecoration have taken place.

Dehumidifiers are complex mechanical systems, many of which require high energy input and a significant level of care and regular maintenance. Many systems are installed with the intention of running them 24 hours a day. Poorly maintained portable dehumidifiers may overflow and cause yet more damage. Dehumidifiers also produce considerable heat, and it is important to understand where the heat is discharged to avoid secondary damage. While dehumidification is appropriate in some circumstances, it is essential that its purpose is clearly defined, and that the way in which the system works is understood and well managed.

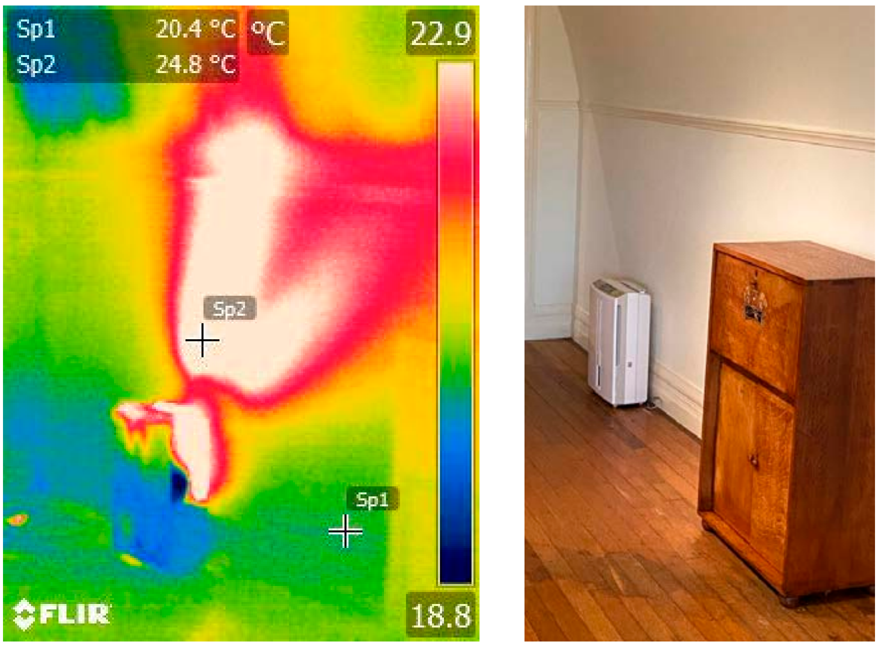


Figure 42: Mechanical units can have unexpected effects. Heat output from dehumidifiers may be beneficial, but can also cause damage if located next to a sensitive artefact or piece of furniture. Thermal image (left) shows the spread of the heat output from the dehumidifier in this example (right, room in normal light). © Tobit Curteis Associates

Although humidification and dehumidification are generally mechanical processes, there are passive approaches that can be considered in specific circumstances. For example, sorbent gels can be used to moderate relative humidity in display cases. These gels absorb and desorb moisture from the air and so maintain the relative humidity at a certain level, thus moderating fluctuations. The amount of gel required will depend on the stability of the ambient environment (outside the case). For example, in a stable environment such as a museum, volumes of gel may be modest, but in an unstable or high humidity environment, far higher amounts may be required.

A similar principle operates at room scale, where porous structures and materials that absorb and desorb moisture are present or can be (re)introduced. For example, a room with lime-plastered walls and a limewash or distemper finish will be able to absorb and desorb moisture, thus moderating relative humidity fluctuations and producing more stable environmental conditions. By contrast, a cement render or a lime plaster painted with a standard modern emulsion paint will be far less porous and will not buffer the humidity. This will, in turn, make conditions within the room more unstable. Soft furnishings, carpets, timber floorboards and timber panelling all provide a moisture-buffering effect.

4.6 Artificial controls: Air conditioning

Air conditioning systems can combine heating, cooling, humidification, dehumidification, air filtration and ventilation to provide air appropriate for a particular space. In broad terms, there are two main types of air conditioning system:

- Centralised system, with conditioning plant in a single location and ductwork to supply and extract conditioned air to and from the building interior
- Localised system, with air conditioning plant in each room

With both these systems, a low relative humidity can be achieved by using dehumidification alone, or in combination with increased temperature (except with localised direct expansion (DX) cooling systems, which remove heat from a space through evaporation and condensation of a refrigerant). Conditioned air is often partially recirculated through the system so that energy used to condition the original air mass is not lost. However, in an occupied space, the recirculated air will carry an increasing carbon dioxide load (this is often controlled to ensure good air quality) and will, therefore, be mixed with replacement air, often from the exterior, which will itself need to be conditioned.

Air conditioning mechanical plant is expensive. In addition, such systems often use considerable energy (depending on whether steam or gas humidification is used) and require careful management, servicing and maintenance, which adds to the cost. The plant is generally large, and installing it in a historic building can be complicated and visually intrusive because of the need to accommodate extensive internal infrastructure, including pipework and ducting. Furthermore, the refrigerants used in some systems can harm the environment (see Government guidance on air conditioning inspections).

Air conditioning systems can set specific relative humidity and temperature parameters and force the indoor environment to achieve them, irrespective of the building envelope. Trying to hold relative humidity to a tight band causes continuous very rapid fluctuations. These can be very harmful to the building fabric and contents; salt damage, for example, is worst when relative humidity changes quickly, and constant low levels of expansion and contraction can cause failure in organic materials.

For these reasons, introducing full air conditioning is rarely appropriate in a historic building. In the limited instances where air conditioning is the most suitable management system in a historic building – such as in archives and museum storage facilities, where a precise level of control is essential for the artefacts – significant care has to be taken with both the system's design and operation to minimise the risk of damage.

For the effective long-term conservation of a historic building and its contents, it is much better to design or modify the building envelope to produce the highest level of passive buffering and use the mechanical system only to 'top up' the level of control. Not only is this far more energy efficient, but also when the mechanical system fails – as is almost inevitable at some point – the deterioration of the environmental conditions will be slower and more limited. It will have a less harmful effect on fabric and contents, and will allow short-term emergency control measures to be put in place. If a building is reliant on a mechanical system alone, failure can cause sudden and severe changes, which may result in irreversible damage to sensitive fabric and contents. Therefore, where a high level of mechanical control is essential, it is important that the system is resilient and has back-up facilities included in the design.

The Historic England website provides further information on historic heating and ventilation equipment.

5. Environmental performance for conservation and historic buildings projects

When considering the environmental risks to a historic building where a project is being developed, it is important to clarify whether the aim of that project is to repair and conserve the fabric, re-establishing the original environmental conditions, or to upgrade and change the building to provide different environmental conditions that support its contemporary use.

5.1 Historic building repair and conservation

Repair and conservation projects aim to rectify defects and enable the building to function effectively. While such projects may involve enhancing some elements of the building envelope (for example, installing larger and better designed rainwater goods to cope with current or future weather patterns), they are not generally focused on changing the form of the building, the way it is used or the comfort of users. Nevertheless, it is important to understand the building's environmental performance and the underlying causes of failure if defects are to be addressed effectively. Lack of understanding of building performance, poor design of architectural features or components, or poor repair and conservation measures may not only fail to solve the original problem but also may cause significant damage to building fabric and contents.

Figure 43: Repairs being undertaken on a Historic England building to allow its re-use and ensure its long-term conservation.
© Historic England Archive

5.2 Building improvements and change of use

Many historic building projects involve changing the use of the building from its original purpose. For example, historic houses are converted for modern living or commercial use, historic buildings have modern museums installed, parish churches require increased heating and facilities such as kitchenettes and lavatories, and industrial buildings are adapted for domestic use. Many such projects also involve changing the building's environmental performance to make it more suitable and comfortable for these new 21st-century uses. Even if a building is not being converted or adapted to a new use, it may be desirable to make changes to improve its energy efficiency (see Historic England's webpage on Energy Efficiency and Retrofit in Historic Buildings).

In an historic building project, the first step should be to understand how the building envelope would have performed originally (how well it buffered external environmental conditions), and how its environmental performance characteristics have changed or deteriorated. Designs can then be developed to address defective performance, before evaluating the potential impact of changes to the building envelope, such as installing insulation or mechanical controls, including heating, ventilation and light control.

While many adaptations may be simple in a modern building, in a historic building they can present risks and may cause severe and costly long-term deterioration if not well thought through. Typical examples include: space heating for thermal comfort, which can accelerate salt damage or timber movement; ventilation, which introduces unstable air and may cause damage to sensitive contents; insulation, which can lead to condensation and insect attack in walls and roofs; and changes to flooring, which may reduce evaporation and drive water into porous historic walls. All these scenarios are well researched and problems can, therefore, be pre-empted. Well-designed investigations can identify the risks at an early stage and so allow the design team to resolve any issues.

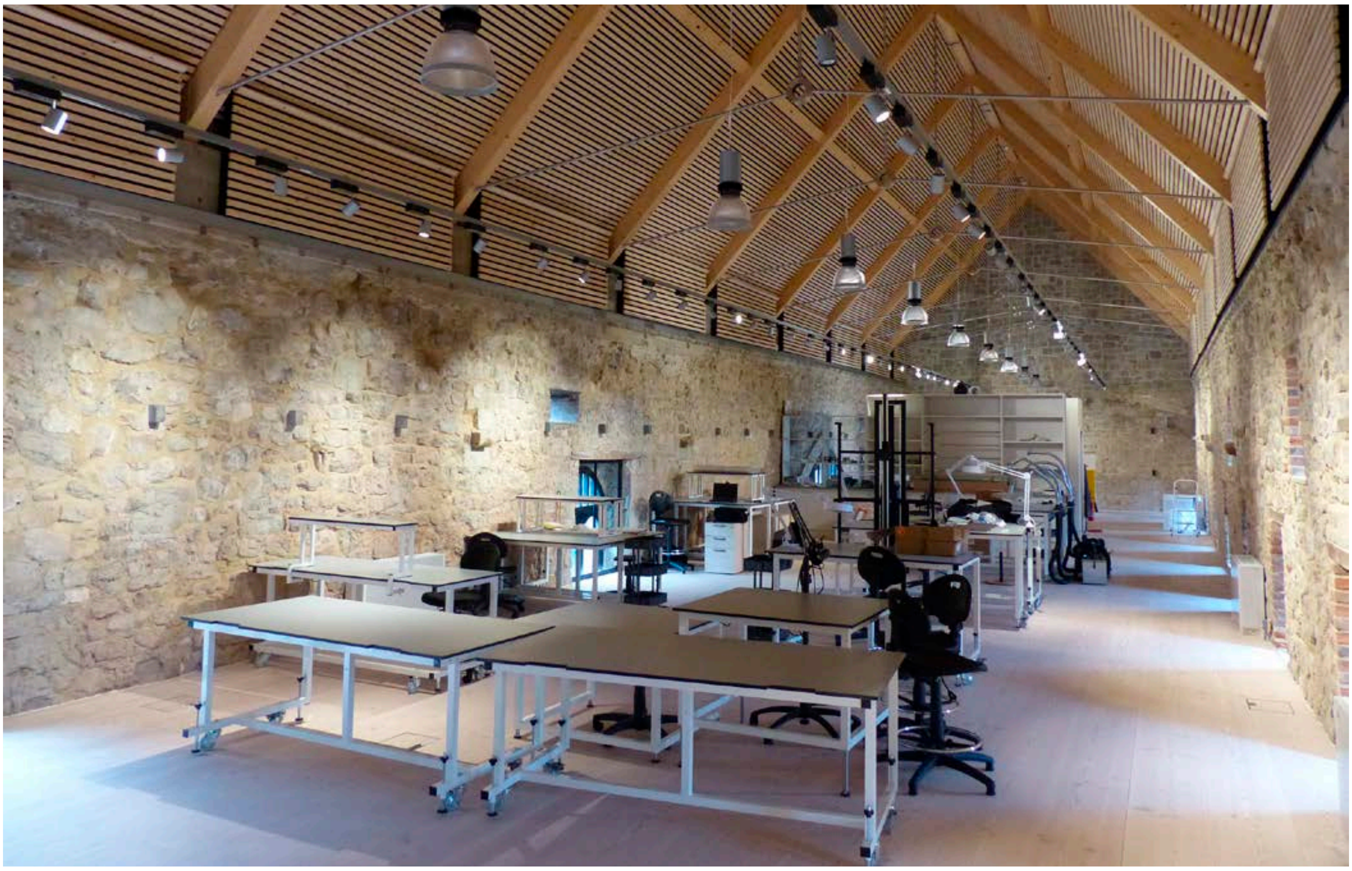


Figure 44: The medieval barn at Knole in Kent, which was repaired and refurbished by the National Trust to become their principal painting conservation studio, provides an example of carefully planned building adaptation using building environmental performance assessments.
© Tobit Curteis Associates by kind permission of the National Trust

6. Building environmental performance assessment

6.1 What is a building environmental performance assessment?

A building environmental performance assessment (BEPA) is the process by which the environmental performance of a building is evaluated. Its aim is to determine if and why the environmental performance is defective, and to allow successful repairs or changes to be made without adversely affecting the historic building fabric or contents. A BEPA conducted at the outset of a project should provide all the basic information to make decisions about environmental deterioration and control and system upgrades. It is a type of investigative Building Performance Evaluation (BPE).

In its simplest form, a BEPA involves a physical examination of the building envelope and rainwater disposal system. It seeks to understand the routine use of the building by the occupants and considers the existing services. In more complex cases, a BEPA can also include environmental monitoring, moisture sampling and materials analysis. It should be a practical, proportionate and cost-effective tool, used to support the conservation, repair and/or development of the building.

A BEPA generally aims to understand three different aspects of a building's environmental performance:

- The original environmental performance of the building
- The building's current changed performance and how this affects its condition and usability
- How the building's environmental performance can be improved to support the conservation of the historic fabric and contents/collection, or, for development projects, how changes can be made to improve the usability of the building while controlling conservation and environmental risks

For all three, the building performance triangle (building envelope, people and services) should be considered.

6.2 Understanding the environmental performance of a building

The first step in understanding the environmental performance of a building is to assess how the building envelope and rainwater disposal system remove rainfall and groundwater from the building structure. This is generally carried out by a visual assessment of the building, examining its design and the condition of the fabric. In some cases, condition reports will have been carried out by others (for example, with Church of England churches, there should be a quinquennial inspection report undertaken by the church architect). A review of published hydrology and groundwater conditions can be useful, when available, and in some cases a full drainage survey or rainwater goods capacity calculations will be necessary.

The next step is to examine the performance of the building envelope in terms of providing buffering between internal and external environments. The design, materials and physical condition of the building fabric will have an influence on this, as well as the way in which the building is used. A visual assessment will be the starting point, but spot readings using thermal imaging and humidity, temperature and liquid moisture sensors, as well as identifying materials, can be useful in refining an understanding of the building. Assessing the design and use of any mechanical control systems will provide additional information on the existing conditions within the building. It is also important to understand how the building is used: for example, occupancy patterns, visitor numbers and type and frequency of events.

In most cases, a simple BEPA produces sufficient information to develop a project. However, in particularly sensitive or complex cases, more detailed investigations are necessary, including opening-up, materials analysis and long-term environmental monitoring. The decision to embark on investigations of this type is best made once the initial BEPA is complete.

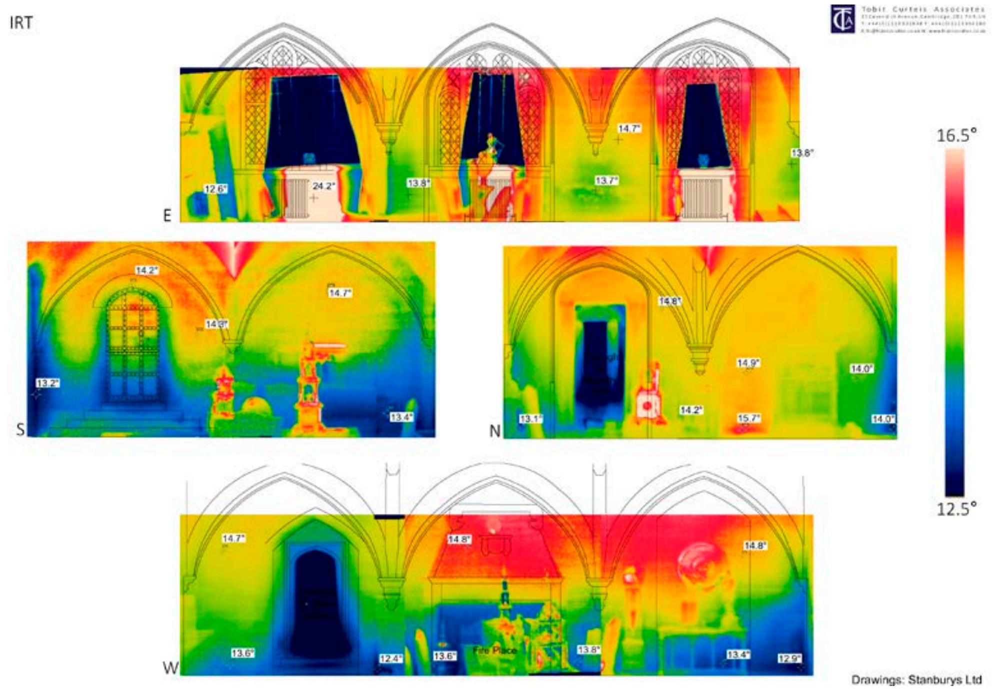


Figure 45: Moisture mapping using thermal imaging. Cold temperature does not always mean a high moisture content. A good understanding of the building's history (including repair and other modifications over time), and cross-reference with a condition recording of the building fabric and other surveying techniques are essential to interpret thermal images correctly. © Tobit Curteis Associates by kind permission of the National Trust

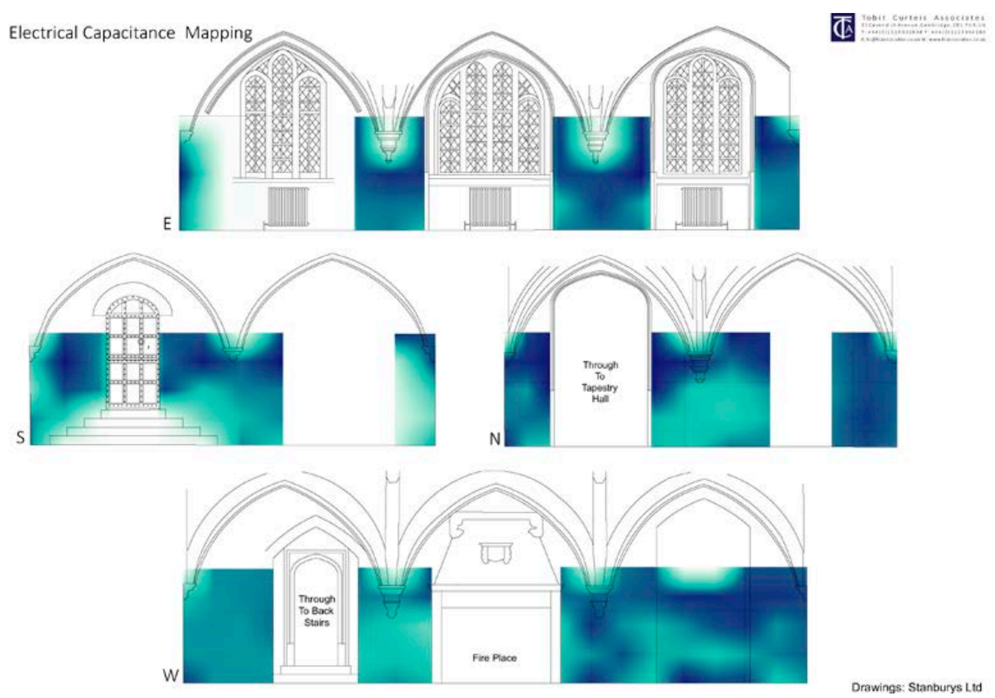


Figure 46: Moisture mapping using electrical capacitance surveying. © Tobit Curteis Associates by kind permission of the National Trust

6.3 Conservation, repair and development guidance

Having identified the causes of deterioration to the building fabric or contents/collection associated with environmental factors, the BEPA should provide advice on approaches to repair and conservation that will address the defects without transferring the risk to other areas. In most instances, this will be overall design guidance rather than technical specification (the latter should be provided by the project architect or engineer).

In many cases, a BEPA will have been undertaken to identify the causes of deterioration of specific areas of the building fabric, particular monuments or parts of the contents. In such cases, the BEPA should provide clear guidance on approaches to controlling the underlying causes of environmental deterioration and give recommendations for conservation treatment. For the conservation of artefacts and monuments, a technical specification will need to be prepared by a specialist conservator.

For development projects, the BEPA should provide advice on how the stated aims of the development can be achieved without creating environmental conditions that will harm the historic fabric or contents. This information can then be used by the project architect when preparing designs and specifications.

6.4 Thermal improvements: Defining needs and risks

Both repair and development projects often have a key aim of improving thermal comfort for people using the building. The BEPA will need to address the conservation risks as well as the optimal design for improving comfort. A first step in this process is to clearly define the needs of the building fabric, contents/collection and building users. It is important not to prejudge the situation and jump to solutions before fully understanding the problem. A useful approach is to ask the five 'W' questions (who/what/when/where/which):

- **Who** are the target users? Young children and the elderly generally require a greater level of thermal comfort than young people and adults. There may, however, be many user types in the building at the same time, all of whom will perceive thermal comfort differently. The thermal improvements solution will have to address all of their needs

- **What** activities will the target users be engaged in? People who live in domestic properties will require different conditions to those who briefly visit a historic building (who typically enter from the exterior wearing outdoor clothing, and then move around)

- **When** and for how long will thermal comfort be necessary? Visitors who are viewing a building or collection are often in a particular area for a short period of time, unlike people who are attending a seated event or living or working in a building. In many buildings, the thermal comfort requirements will vary considerably over the course of the day, week or month, depending on the type of event and when it takes place. Likewise, occupants of domestic houses will use different parts of the building at different times of the day and so have varying needs for thermal comfort

- **Where** in the building will the people be? Many historic buildings host different activities in different areas. Heat loss and heat gain measures, including type of system, compartmentation, distribution, zoning and timing, should be considered in each area

- **Which** areas of the building (and contents) are at risk from environmental changes that will arise from the project, and what measures are necessary to avoid or control that risk?

It is important to remember that heating and other services should be used to control the building environment for the care of the building fabric and contents, as well as to improve comfort and usability.

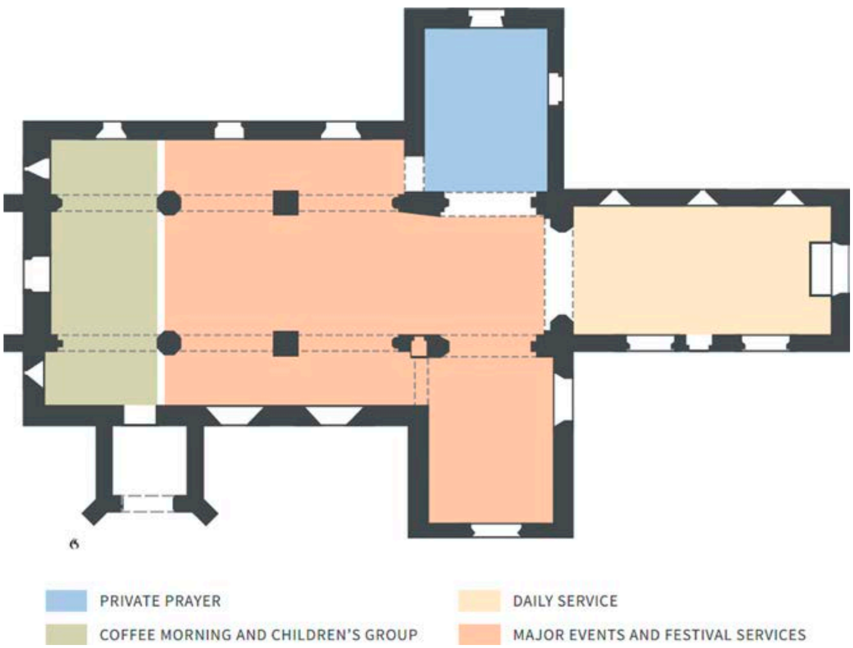


Figure 47: Example of a marked-up diagram showing how to do the 'Five Ws' exercise. Different areas of the building may be used at different times and for different activities. By establishing how the building is used, warming needs will become apparent and heating systems can be designed accordingly. © Historic England Archive

Running through the five 'W' questions will help inform a robust methodology for heating and other passive and active controls. It is useful to mark building plans and room data sheets with the different activities and periods of use, so that environmental performance problems and needs can be better defined.

6.5 Professional advice

In straightforward cases, an informed and experienced conservation architect or surveyor can carry out a basic BEPA. Indeed, much of the assessment is regarded as a general condition assessment. In complex and sensitive cases, more detailed investigations by a building performance advisor may be necessary.

Procuring competent professional advice in this area is not straightforward. It is an emerging field that covers a range of disciplines, and as yet there is no formalised training route or accreditation. An investigator should have experience of architectural conservation and building environments, and an understanding of building conservation projects, so that information gathered can be structured to provide practical design support in the early stages of the project. The exact skill set required will vary depending on the nature of the project. A building environmental performance expert may have a background in architecture, surveying, conservation, energy assessment, or mechanical and electrical services engineering. Importantly, they will need to be familiar with how all aspects of the building performance triangle interact. When carrying out a BEPA, the advisor will work alongside subject experts to help identify, understand and repair building failures, or design effective environmental controls (with a chartered building services engineer), for example. Increasingly, they will need to have expertise in energy and carbon assessment.

There is a wide range of practitioners who claim to provide BEPAs (or surveys that are said to provide similar information). A potential client should always obtain references from other clients and examples of previous work when assessing the suitability of an investigator for a particular project.

In general, building environmental performance advisors should be able to work with and question specialists in related conservation design and construction fields. They should have experience and expertise in the following areas:

- Relevant periods of building construction, including traditional materials and techniques
- Historic building deterioration and conservation
- Historic collections materials, deterioration and conservation
- Environmental performance of historic buildings
- Historic and modern building services systems employed for historic buildings, museums and collections
- Survey and information/data-gathering techniques, including environmental monitoring, thermal imaging, liquid moisture surveying and materials analysis
- Museum and collections conservation management and environmental control
- Project structure and design processes

A BEPA is often conflated or confused with specific investigative techniques on which a specialist may draw, such as environmental monitoring or thermal imaging. These are particular tools that may be used as part of a detailed BEPA. While these and other techniques can be useful in the right context, in isolation or in the hands of an inexpert investigator, they may lead to false conclusions, and hence incorrect and costly interventions.

6.6 Instructing a building environmental performance advisor

When instructing a building environmental performance advisor, it is important to define the areas of concern rather than the particular questions or investigation techniques. For example, a useful instruction would be: 'My client has a damp and cold building that they want to use for public meetings and concerts. They also want to make the building more thermally efficient. They are worried about how this might affect the historic fabric and want to understand the deterioration issues and how these can be controlled.' The investigator can then work with other stakeholders to define specific questions and methods of investigation. From this, a brief can be formed, and costs provided.

A poor instruction would be: 'Our client has a damp building and has asked us to procure environmental monitoring in the six locations listed below.' The best outcome would be that a professional investigator would ask to discuss the underlying situation and map out the actual requirements of the survey. The worst outcome would be that a less professional or less knowledgeable investigator might simply do as instructed and provide quantities of uninterpreted data, which would absorb funds and serve no practical use.

6.7 When to carry out a building environmental performance assessment

To be most useful, the BEPA should be carried out at a very early stage of the project, when the basic aims and design are still being developed (RIBA stage 1–2). A good BEPA should provide insight into the risks and vulnerabilities of a building and the limitations of certain interventions, as well as ways in which the design could work around them. If the environmental performance is considered only after the design is developed, issues may arise that will preclude certain elements of the project and require costly and time-consuming changes.

Investigative work in building conservation projects is not the same as academic research, although in some cases it can feed into wider studies. It should focus on a specific understanding of the issues in a particular building, with the aim of providing information that has a practical and cost-effective outcome.

6.8 Structure of a building environmental performance assessment

A formal BEPA undertaken by a professional and experienced investigator can take place in up to five phases, depending on the needs of the project:

1. **Preliminary assessment (commonly undertaken in RIBA stages 1–2)**
   The initial study is intended to define the issues involved and refine specific environmental questions. It includes an assessment of the building envelope and rainwater disposal system. A review of past building condition information should be carried out, so that the physical history of the building and the proposed changes

can be understood and discussed in relation to the project aims. At this stage, spot measurement techniques, including thermal imaging and electrical capacitance, resistance or microwave moisture surveys, might be used. The output should be a detailed illustrated report, characterising the environmental issues and the suggested approaches for control and improvement.

For many projects, this preliminary assessment will provide sufficient information and no further investigation will be necessary. In complex cases, more detailed studies may be required, and recommendations and costs for these should be included in the report.

2. **Detailed investigations and environmental monitoring (commonly undertaken in RIBA stages 2–3**)
   Where more detailed investigations are required, these should address specific environmental deterioration or control issues that require a greater level of understanding or longer-term performance data than can be gained in a preliminary assessment. This may involve environmental monitoring, combined with thermal imaging and other instrumental surveys or materials analysis.

   Most diagnostic environmental monitoring surveys will be relatively detailed and will require a minimum of 12 months of data. In this way, seasonal variations both for the building envelope and for services such as heating can be understood.

3. **Project design input (commonly undertaken in RIBA stages 2–4)**
   Depending on the sensitivity and complexity of the project, it may be useful for the environmental building performance advisor to have direct input into the project design. This may include advising on the type of repair and control measures and suggesting long-term environmental and conservation management measures. For sensitive buildings and collections, this may also involve specifying target environmental conditions and developing approaches to both passive and mechanical control.

   In some projects, it may also be necessary to get advice on protecting environmentally sensitive building elements during building work, using temporary mechanical services such as space heating or dehumidification, for example. Any such measures should be designed and installed in close collaboration with the design team and in particular with the conservation advisor, architect and building services engineer (not to be confused with the building services technician).

4. **Project monitoring (undertaken in RIBA stages 5–6)**
   For projects where sensitive structures or collections are involved (for example, buildings with extensive wall paintings), environmental monitoring may be necessary during the building repair or development process to avoid damage. For example, if

space heating is decommissioned during a winter project, this may leave sensitive fabric at risk of condensation. The level of reporting detail required is generally less than for the diagnostic stage. However, inspections need to be carried out regularly during the works to identify deteriorating conditions swiftly.

In projects where mechanical services are involved, it is important for there to be a testing period after commissioning. This will involve the investigator, building services technician and building services engineer. It will comprise a set of tests to evaluate not only if the mechanical systems are working correctly, but also if they are achieving the required environmental conditions in the building.

5. **Post-completion assessment (undertaken in RIBA stage 7)**
After completing a large and complex project, it is important to assess the efficacy of the intervention. This generally involves 12 to 24 months of environmental monitoring and building use assessment. During this time, control systems can be fine-tuned. A greater understanding of the post-project building performance, environmental deterioration and control measures can be developed, thereby improving knowledge for future interventions on the building and elsewhere.

Throughout the BEPA, it is important that the information generated is fed back to the design team and building managers. It can then be used for the effective protection and management of the building and contents. Where possible, the information should be made accessible to other similar projects to increase the understanding of how BEPAs can be employed to improve project outcomes.

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8. Glossary

Absolute humidity is the actual number of molecules of water in air, expressed in terms of the ratio of the mass of water vapour to the volume of air (grammes of water per cubic metre of air, g/m3).

Air conditioning is the artificial treatment of air to adjust its temperature, humidity, cleanliness, air quality and circulation. It typically uses chilled water, or the evaporation of liquefied gas, to both chill the air and remove water vapour by condensation.

Buffering is the attenuating effect of building materials on atmospheric fluctuations (temperature, relative humidity, air pressure, radiation and so forth), originating outside the building (the external local climate) or inside the building (for example, from heating, lighting, air conditioning and use or occupancy of individual rooms).

Building envelope is the term used for the weathertight skin that separates the interior environment of a building from its external environment. It comprises the roof, walls, windows, doors, floors and foundations, as well as systems for controlling and disposing of water (including rainwater goods, roof coverings, damp-proof courses and drains).

Condensation is the process of forming a liquid from its vapour. When moist air is cooled below its dew point, water vapour condenses and forms a film of liquid water or a cloud of mist. Water vapour can condense on surfaces (superficial condensation) or inside pores or on the internal interfaces between materials (interstitial condensation).

Conduction is the transfer of thermal energy by direct contact between molecules, from one part of a substance to another and to another substance in physical contact with it.

Convection is the transfer of thermal energy in a liquid or gas by a combination of fluid circulation and conduction. The driving force for natural air convection is buoyancy: portions of the air in contact with the source of heat become hotter, expand, become less dense and rise. Their place is taken up by colder portions (producing a convection current).

Convective heating is a system that warms the air by convection. It includes hot water central heating, electric convective heaters (both passive and fan-assisted), under pew convective heaters and hot air blower systems.

Dehumidification is the process of reducing the moisture content of air. It is achieved either by desiccation (exposing the moist air to a special material able to effectively absorb water vapour) or by refrigeration (passing moist air over a cold surface – usually a refrigerating coil – so that the water vapour condenses).

Dew point temperature is the temperature at which moist air is cooled sufficiently for condensation to take place. Dew point temperature increases as the amount of moisture in the air increases, because warmer air can hold more moisture. If at any time the temperature of a surface falls below the dew point temperature of the air, the air coming into contact with the surface will deposit the water it can no longer hold.

Environmental monitoring is the simultaneous recording and processing of data from selective environmental parameters, usually with the aid of specialist equipment such as dataloggers. It is carried out at carefully selected sites and for as long a period as is necessary to capture all the important cycles, trends or permutations of a building environment. In conservation practice, this usually means for at least one year (and preferably two), to cover all the usual seasonal variations.

Permeable refers to the ability of a material to transmit fluids (especially water or gases), notably through pores.

Radiant heating is a heating system that transmits energy directly to the surface of a person or object. The category includes electric pew back heaters, wall-mounted panel heaters, overhead electrical radiant units (including IR and electric bar heaters) and underfloor heating (which is also typically 50 per cent convective).

Radiation is the transfer of thermal energy as electromagnetic waves (that is, by the propagation of IR energy).

Relative humidity refers to the ratio of vapour pressure of water in the air to the vapour pressure of water in saturated air at the same temperature. In other words, the percentage of saturation at a given temperature. Air at 50 per cent relative humidity is holding half of the number of water molecules it potentially could hold at that temperature. As the temperature increases, the air can support more water vapour, so air with a relative humidity of 50 per cent at 25˚C will be holding far more moisture (that is, have a much higher absolute humidity) than air of 50 per cent relative humidity at 15˚C.

Salt is a compound resulting from the replacement of a hydrogen atom or atoms in an acid by a positively charged atom such as a metal ion. Salts are typically neutral, ionic and crystalline at ordinary temperatures.

Saturation is the point at which a volume of air at a given temperature holds the maximum amount of water vapour possible (see Dew point, Relative humidity).

Ventilation is the management of air exchange and air movement in a building, by natural or mechanical means. It is ostensibly used to reduce humidity, replace stale air and dilute or evacuate gases, dust and particulates, and to provide ‘fresh air’ for the occupants.

Contact Historic England

East of England
Brooklands
24 Brooklands Avenue
Cambridge CB2 8BU

Tel: 01223 582749
Email: eastofengland@HistoricEngland.org.uk

Fort Cumberland
Fort Cumberland Road
Eastney
Portsmouth PO4 9LD

Tel: 023 9285 6704
Email: fort.cumberland@HistoricEngland.org.uk

London and South East
4th Floor
Cannon Bridge House
25 Dowgate Hill
London EC4R 2YA

Tel: 020 7973 3700
Email: londonseast@HistoricEngland.org.uk

Midlands
The Foundry 82 Granville Street,
Birmingham B1 2LH,

Tel: 0121 625 6888
Email: midlands@HistoricEngland.org.uk

North East and Yorkshire
Bessie Surtees House
41-44 Sandhill
Newcastle Upon Tyne NE1 3JF

Tel: 0191 403 1635
Email: northeast@HistoricEngland.org.uk

37 Tanner Row
York YO1 6WP

Tel: 01904 601948
Email: yorkshire@HistoricEngland.org.uk

North West
3rd Floor, Canada House
3 Chepstow Street
Manchester M1 5FW

Tel: 0161 242 1416
Email: northwest@HistoricEngland.org.uk

South West
Fermentation North (1st Floor)
Finzels Reach
Hawkins Lane
Bristol BS1 6JQ

Tel: 0117 975 1308
Email: southwest@HistoricEngland.org.uk

Swindon
The Engine House
Fire Fly Avenue
Swindon SN2 2EH

Tel: 01793 445050
Email: swindon@HistoricEngland.org.uk

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