ENGLISH HERITAGE
PRACTICAL BUILDING CONSERVATION

BUILDING ENVIRONMENT

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To the memory of John Ashurst (1937–2008), an inspiration and friend to all the editors, whose encouragement and support was a great motivation for this new series of Practical Building Conservation.

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Series Editors: Bill Martin and Chris Wood

Volume Editors: Robyn Pender, Brian Ridout, Tobit Curteis

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THE PRACTICAL BUILDING CONSERVATION SERIES

This series of *Practical Building Conservation* technical handbooks supersedes the original five volumes written by John and Nicola Ashurst, and published in 1988.

The series is aimed primarily at those who look after historic buildings, or who work on them. The ten volumes should be useful to architects, surveyors, engineers, conservators, contractors and conservation officers, but also of interest to owners, curators, students and researchers.

The contents reflect the work of the Building Conservation and Research Team, their colleagues at English Heritage, and their consultants and researchers, who together have many decades of accumulated experience in dealing with deteriorating building materials and systems of all types. The aim has been to provide practical advice by advocating a common approach of firstly understanding the material or building element and why it is deteriorating, and then dealing with the causes. The books do not include detailed specifications for remedial work, neither do they include a comprehensive coverage of each subject. They concentrate on those aspects which are significant in conservation terms, and reflect the requests for information received by English Heritage.

Building conservation draws on evidence and lessons from the past to help understand the building, its deterioration and potential remedies; this encourages a cautious approach. New techniques, materials and treatments often seem promising, but can prove disappointing and sometimes disastrous. It takes many years before there is sufficient experience of their use to be able to promote them confidently. Nonetheless, understanding increases with experience and building conservation is a progressive discipline, to which these books aim to contribute.

The volumes also establish continual care and maintenance as an integral part of any conservation programme. Maintenance of all buildings, even of those that have deteriorated, must be a priority; it is a means of maximising preservation and minimising costs.

Most of the examples shown in the books are from England: however, English Heritage maintains good relations with conservation bodies around the world, and even where materials and techniques differ, the approach is usually consistent. We therefore hope the series will have a wider appeal.

Dr Simon Thurley

Chief Executive, English Heritage

ABOUT THIS BOOK

Any book that tries to deal with the vast topic of 'the building environment' must necessarily cover a great deal of ground, from the weather, the physics of heat and moisture, and the basics of architecture and engineering, to the building's use and the maintenance and repair of complex materials and systems. *Building Environment* is the product of the many years spent observing buildings by the volume editors and their contributors: buildings of all kinds, modern as well as traditional in construction, in all uses and under all conditions. It presents a comprehensive overview of building performance, and aims to equip anyone responsible for a building's care with sufficient knowledge to be able to recognise fundamental problems, and to either confidently deal with those that are straightforward themselves or successfully delegate those that are more difficult to specialists.

Many patterns of deterioration appear repeatedly, and familiarity with these patterns makes it possible to recognise and even predict common causes of problems, such as the inevitable blocked gutters and drains. Even so, every building environment is essentially unique, and the underlying causes may not always be as they first seemed. We therefore aim to steer readers away from 'symptoms-led' thinking: the same patterns of deterioration can arise from many different problems, and it is important to always approach the situation with an open mind. This is why the book is structured to present a coherent and logical picture of first what the building environment is, then how it works, how it fails, and finally how problems can best be remediated.

After a short **Introduction**, the **Building Science** chapter describes the physical processes that explain the many links between the building and its environment. **Interactions with the Environment** shows how these links affect the way building envelopes are designed to work, and the impact of their surroundings. The role played by the building occupants – particularly when trying to adjust the interior conditions – is covered in **Controlling the Interior Environment**. **Deterioration & Damage** looks first at the environmental degradation of individual building materials, before proceeding to consider how the envelope as a whole can fail. **Assessing the Building Environment** covers the actions needed to understand how a particular building is functioning and how it is failing, including specialist investigations such as environmental monitoring. A short chapter discussing approaches to **Diagnosis** is followed by **Care & Repair**, which introduces the various maintenance and remedial works designed to address environmental problems. Finally, the **Special Topics** at the end of the book address three important issues associated with the building environment: human health; disasters such as floods and fires; and reducing energy use and carbon emissions.

At times the conclusions we have drawn will be familiar to most readers, at others they may be at variance with accepted wisdom; but we have taken the decision to contest familiar notions which we have good reason to believe to be wrong. Too many problems can be traced back to the repetition of misconceived ideas about how building environments operate.

The audience for this volume of *Practical Building Conservation* is certain to be diverse: not only architects and surveyors with many years of experience dealing with historic buildings, but also students, building managers and homeowners who wish to keep their houses in the best possible condition. For this reason a good deal of introductory material is included; we hope that this will prove helpful even to experienced readers when they need to explain to their clients and colleagues exactly how building envelopes work.

USING THESE BOOKS

For accessibility and ease of use, the information given in the text has not been footnoted, and rather than references, short lists of further reading are given at the end of the appropriate chapters. References to other sections within the text are given in **bold**, and references to other publications in ***bold italics***.

Links to other books in the ***Practical Building Conservation*** series are indicated throughout the text by the relevant volume symbol, showing that more information on the topic will be found in that volume.

• Conservation Basics	➲BASICS
• Concrete	➲CONCRETE
• Earth, Brick & Terracotta	➲EARTH & BRICK
• Glass & Glazing	➲GLASS
• Metals	➲METALS
• Mortars, Renders & Plasters	➲MORTARS
• Roofing	➲ROOFING
• Stone	➲STONE
• Timber	➲TIMBER

Although every attempt has been made to explain terms as they first occur in the text, a glossary has also been included, and this can be found just before the index.

INTRODUCTION

INFLUENCES ON THE BUILDING

THE EXTERIOR ENVIRONMENT

The primary influence on a building is always the environment to which it is exposed. This is typically very complex, since it includes not only the weather, but perhaps also pollution, runoff patterns, the water table, ground movements and many other factors of this type. Every building environment will depend to some extent on the local terrain, and crucially on the way the surrounding land is being used.

The exterior environment has no predefined geographical limit, but extends out as far as any factor that might be affecting the building condition. In some circumstances this could be quite considerable distances: for example, winds can carry sea salts far inland, which means that an assessor trying to understand a problem related to chlorides may be forced to take the maritime environment into account, even though the structure may be some way from the coast.

The building itself will alter the exterior environment in its near vicinity, such as windiness or runoff. To try to understand patterns of complex environmental problems (for example, storm damage, pollution, flooding or traffic vibration), the position, construction and even the materials of the building will need to be taken into account.

As a result, the exterior environment of every building will always be unique.

COMPONENTS OF THE EXTERIOR ENVIRONMENT

AIR QUALITY

The air may contain gases and particulates – ‘pollutants’ – able to interact adversely with building materials. Pollutants can be in the form of particles, droplets of liquid or gases, and may be ‘primary pollutants’ emitted directly into the air by some process such as volcanic eruption or combustion; or ‘secondary pollutants’, which will form when two or more primary pollutants interact.

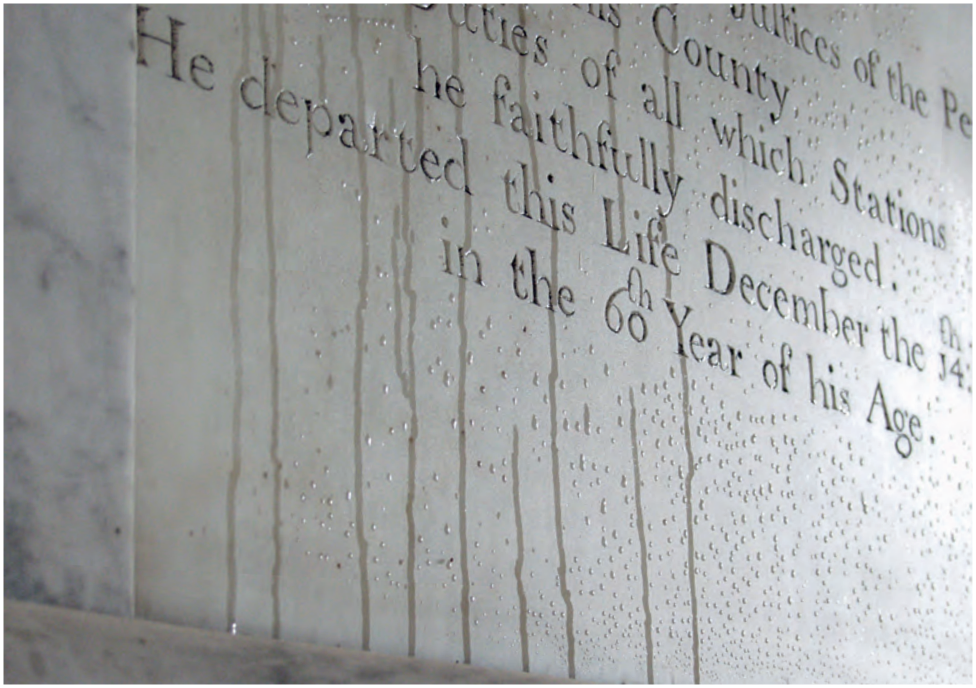
WEATHER

‘Weather’ is the term used to describe the state of the local atmosphere: that is, hot or cold, wet or dry, calm or stormy, clear or cloudy (‘climate’ is the term used for the average atmospheric conditions over longer periods of time).

The components of the weather that have the most impact on buildings include rain and snow, the temperature and humidity of the air, the direction, strength and gustiness of the wind, and the patterns of sunlight. These all will vary locally and according to exposure, and may well have different impacts on different parts of the building.

Condensation on surfaces

Condensation on cold surfaces may collect to form liquid water. If the surface is of sufficiently low permeability (glass or metal, for example, or as here, polished marble), the water may run down the surface.



CONDENSATION & EVAPORATION

In almost every collision a molecule of water vapour makes, whether with another water molecule, or some other molecule in the air, or a surface, it will lose a little of its energy, until eventually it may be left with too little energy to break away again the next time it collides. A molecule which can no longer break away is said to have 'condensed'.

The more water molecules there are in the air, the more likely they are to collide, losing so much energy that they are forced to condense. If the vapour pressure of air near a surface is very high, eventually the surface may be covered in a film of liquid water: that is, by 'condensation'.

The colder the surface, the more energy the vapour molecules will lose each time they collide with it, so condensation is more likely on a cool surface. How cold the surface would have to be to cause a film of condensation depends on the air's absolute humidity and temperature (that is, on the vapour pressure). The vapour pressure can be used to calculate a 'dew-point temperature' [DPT]; if a surface exposed to air at that vapour pressure drops below this temperature, then water will begin to condense onto it.

Condensation is not a permanent state. A condensed water molecule will absorb heat energy from the surface and from the air, and occasionally from vapour molecules colliding with it. Eventually it may gain enough energy to break free of the surface once more: that is, to 'evaporate'. Heating a surface will cause some of the water molecules condensed upon it to evaporate again.

SATURATION & RELATIVE HUMIDITY

Returning for a moment to the image of an imaginary box of air, it is easy to see that if more water molecules are added to the box, eventually there will come a point where the number of water molecules condensing exactly equals the number of molecules evaporating: beyond this point, adding more water molecules to the air will simply cause the same number of molecules to condense out. The vapour pressure therefore remains steady, and the air is said to be 'saturated': that is, it is holding as much moisture as it possibly could at that temperature.

If the number of water molecules in the imaginary box were kept constant, but the air was heated, each molecule would have more energy to lose before it would be forced to condense: in other words, hotter air can hold more water molecules.

If there is a source of liquid water in a sealed container, the air in the container will take up water molecules by evaporation until the air is saturated. This can take some time, depending on the size of the container and the surface area of the source (the greater the surface area, the faster the evaporation).

Free air is rarely saturated, but instead will be holding only a fraction of the water molecules it could potentially hold. The actual extent of saturation is usually expressed as a percentage, and is called the 'relative humidity' [RH] (relative to saturation, in other words). By definition, the RH of saturated air is 100 %, so air at 50 % RH is holding half of the number of water molecules it potentially could hold at that temperature. Air with an RH of 50 % at 25°C will be holding much more moisture (that is, it will have a much higher AH) than air of 50 % RH at 15°C.

Condensation in voids

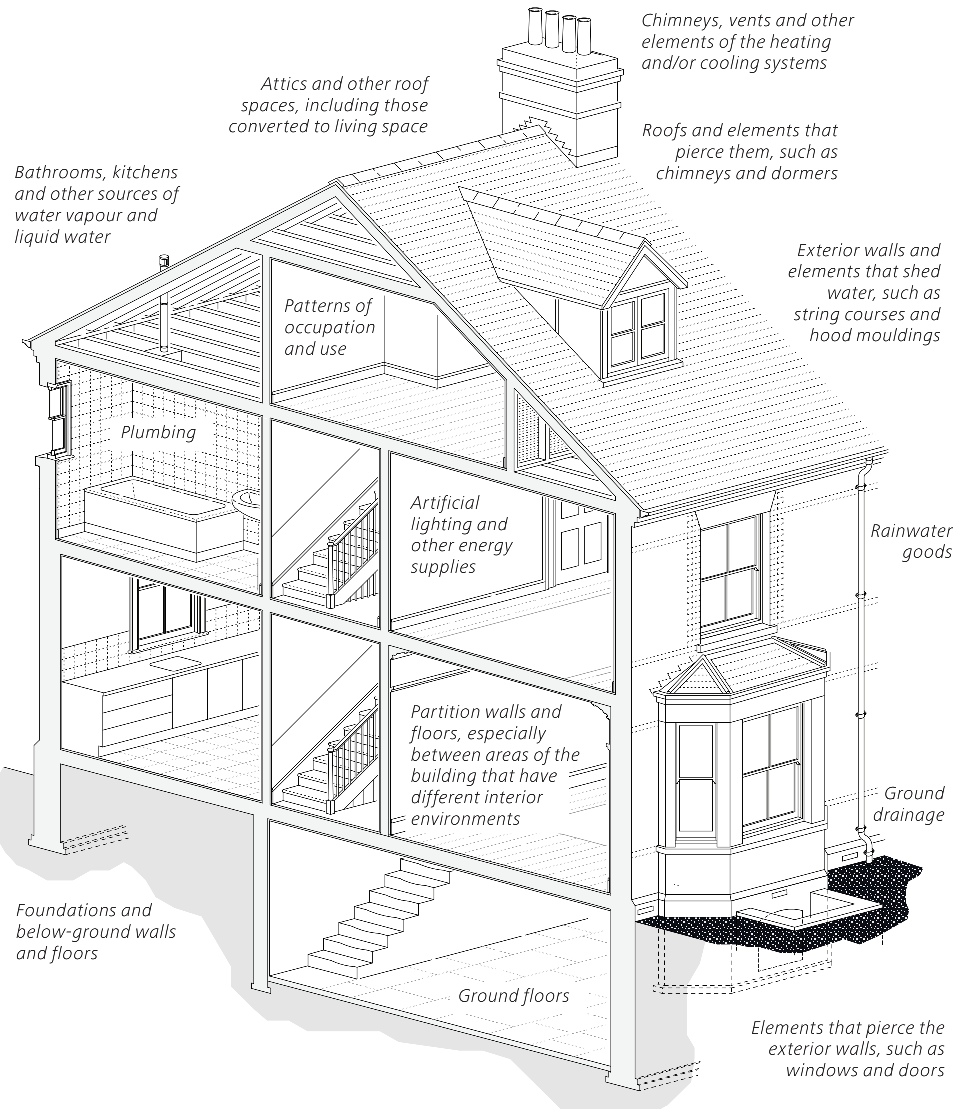
Because so very few water molecules are needed to saturate air, if the air in a void or hollow exposed to some sink of liquid water is allowed to equilibrate, its relative humidity will reach 100 % no matter how small that sink of moisture may be. In a closed container even a single drop of water will be ample to cause the air within to saturate: the condensation in these bottles shows that each is at 100 % RH, regardless of the quantity of liquid water present.

For this reason, measuring the relative humidity in a void in a wall can only show that the wall is dry or that it has some moisture within it: it cannot indicate how much moisture is actually present.

FUNCTIONS OF THE BUILDING ENVELOPE

To determine how a building envelope might be operating, a clear picture must be developed of the purpose and action of each of its components, of how they work together as a whole, and of how the ensemble interacts with the exterior and interior environments. Even apparently decorative elements often have functional purposes, which must be understood if repairs and alterations are not to endanger the operation of the envelope.

IMPORTANT ELEMENTS OF THE BUILDING ENVELOPE



The building envelope

Every building envelope is unique. It will be composed of elements deliberately intended to serve a weatherproofing function (such as the roof and exterior walls), elements intended to control interior conditions (such as the fireplaces and other heating systems), and elements which are primarily intended to serve other purposes, but which will still have a strong impact on the interior environmental conditions (such as interior partitions and plumbing). Even apparently minor elements such as wallpapers can have a significant effect on the envelope's condition and behaviour.

KEEPING THE BUILDING DRY

In any climate that is not extremely arid, the fundamental demand on any building envelope is that it should be able to handle water. This function is critical to the way the building envelope is detailed and constructed.

Water meets the envelope in many forms, and from many sources, of which rainfall and groundwater are the most important. Almost all the familiar detailing of buildings stems from the need to move water from these sources safely away from the fabric, and especially to keep it from penetrating to the interior.

Water can be taken up by the building fabric in different ways: absorbed as a vapour, drawn up as a liquid into the pores or through fine cracks, joints and interfaces between building elements, condensed from the air onto cold surfaces, or by a combination of any or all of these (see **Building Science**). It can then travel through the structure, driven a little by gravity and very much by the ambient conditions, especially those causing evaporation. As it moves, it will transfer heat, and it can often transport contaminants as well.

The phase in which water is found (liquid, vapour or ice) is critical to its behaviour, and will also affect building materials in different ways. Phases may be very localised, since they will depend on so many factors: not only the temperature, but also (amongst others) the flow of air across the surface, the chemical and physical nature of the material, and the nature and concentration of any contaminants.

DEALING WITH RAINWATER

Like light falling on glass, rainwater meeting the envelope can be deflected from it, absorbed and held by it, or transmitted through it, and the ways in which the building does this are a marker of how successful it is at fulfilling this primary role:

- *Deflection*
  Good envelopes deflect as much rainwater as possible, by using features such as drips and overhangs. Water may be collected and channelled away in gutters and drains.
- *Absorption*
  Traditional building materials such as brick, stone and lime mortar are permeable, and can absorb rainwater in surface pores, from which it can later evaporate.
- *Transmission*
  Modern rainscreen building systems allow a degree of transmission, with penetrating water being collected in internal drainage systems, but in both modern and traditional systems transmission of rainwater right through the envelope is a sign of failure.

How rainwater interacts with the envelope depends on other environmental factors as well, most notably windiness, air temperature and solar radiation. The risk of failure, and therefore the need for good detailing, increases with exposure to all these factors.

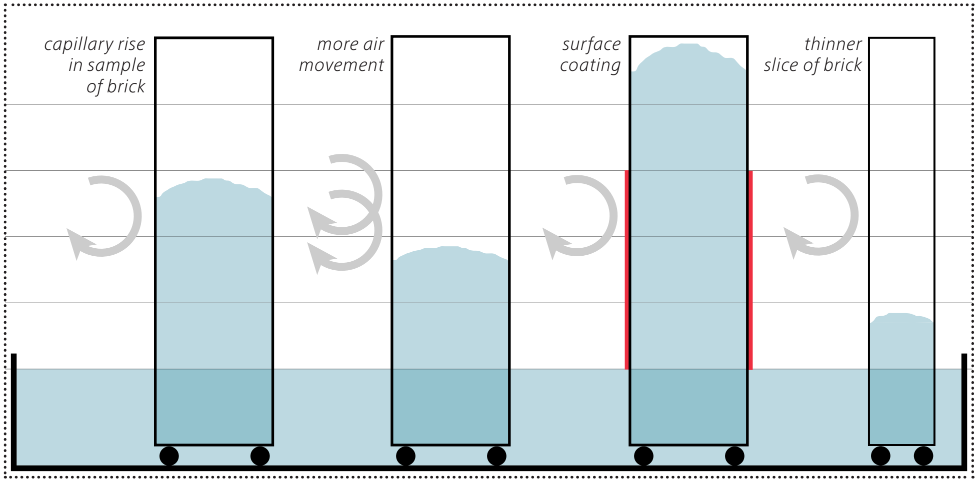
Ground drains may also be used to slow or stop runoff across sloped open ground. Most are based on the 'French' drain, which American engineer Henry French developed for agricultural land. These were originally simple sloped trenches filled with gravel, set across hillsides to catch the water as it ran down; later they incorporated perforated pipes and geotextile linings to stop them silting up too quickly.

The drains around building perimeters, intended to collect and dispose of both surface runoff towards the building and rainwater from the downpipes, are usually modified French drains that direct the collected water towards a discharge point (commonly a private soakaway or a public sewer). In England, there has been a fashion for backfilling perimeter drains with coarse gravel rather than capping with clay, especially if the drainage was installed specifically to deal with moisture problems. This, however, is counter-productive, since the gravel lets water run in easily, but prevents it evaporating; it also makes maintenance difficult (see **Deterioration & Damage** and **Care & Repair**).

Protection from Capillary Rise

If a wall made of permeable materials has water at its base, it will rise up the wall to the point where the rate at which water is being removed by evaporation equals the rate at which it is being drawn up through the material. This process is governed by the permeability of the wall and the speed of evaporation, which means it is affected by the ambient conditions (the temperature, humidity, and especially the air movement), the porosity of the materials and the structure of the wall (the thickness and nature of the joints between materials being particularly important).

Although some theoretical models have suggested that in a thick homogeneous wall water could rise several metres, real buildings present a very different picture. In a brick wall with lime-mortar joints, for example, moisture almost never rises higher than one or two courses, except where the wall has been given an impermeable coating such as a cement render, which prevents evaporation. Even in the laboratory, it has proved almost impossible to make realistic walls with significant rising damp.



Capillary rise

If a sample of permeable material is exposed to a continuous source of moisture at its base, water will rise up to the point where the rate of uptake equals the rate of evaporation.

Increasing the rate of evaporation (for example, by increasing the airflow across the sample) reduces the maximum height of capillary rise, whilst partially coating the sample to reduce the evaporation will make the water rise higher. Capillary rise will also be lower in a thin wall, where the greater surface area-to-volume ratio makes evaporation more effective.

Rising damp?

The pattern of damage over the length of this run of brick masonry demonstrates why 'rising damp' – capillary rise from the water table – is unlikely to be a cause of serious moisture problems.

The classic pattern of decay and salt staining that is often attributed to rising damp is visible only on the exposed section of wall to the right, where it is clear that the true cause is water percolating down from the top of the wall. To the left, where the top of the masonry is protected, only the very base shows any sign of moisture damage, as would be expected where the source of moisture is the water table.

Serious problems from groundwater seem to have begun when sewers and mains water supplies were introduced in the mid-19th century; this was when the term 'rising damp' was invented and damp-proof coursing introduced. Leaking pipes are a much more serious source of persistent water than the water table, and the problems seem to have been exacerbated when cement renders were introduced (these prevent evaporation and so drive moisture further up the wall). Often the render will have been applied in response to a moisture problem, and thus have made the situation worse rather than better. Impermeable finishes may also make it difficult to locate the true source of the water.

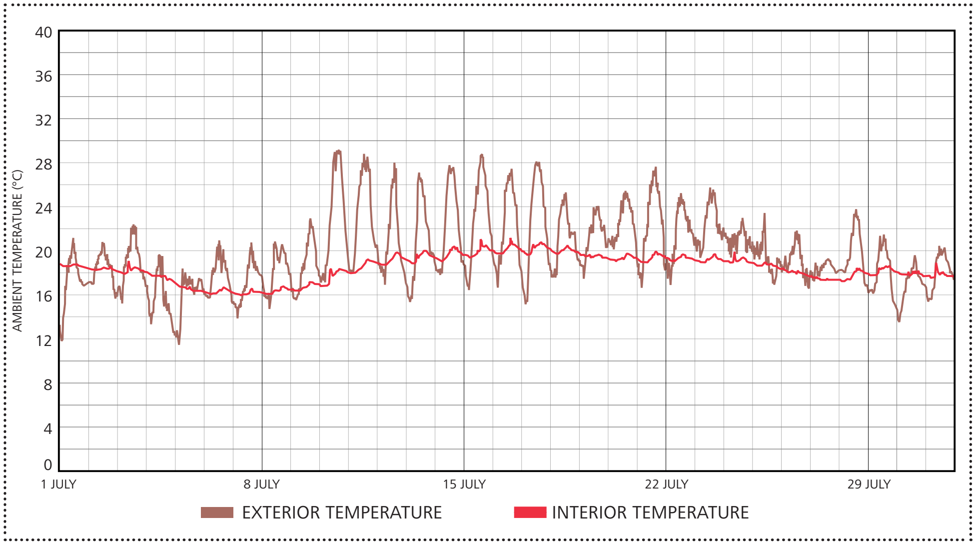
One reason for the resistance of real walls to moisture rising from the base is their inherent inhomogeneity, and particularly the many interfaces between the different materials; every joint between mortar and brick will hinder the passage of water through the wall. Fundamentally, however, capillary rise is limited by evaporation, and this is far more effective in a real wall than is assumed in most theoretical models. The model most often used to calculate potential capillary rise assumes the wall to be like a bundle of fine long straws, each having a single entrance and exit. This is a reasonable analogy for water uptake in a tree, but not for building materials, where the pore structure is multi-directional and branching, with many links to surface pores through which moisture can evaporate. In practice, moisture problems from groundwater tend to occur when the wall has an impermeable finish such as a cement render that prevents the water from evaporating.

Interestingly, there is no evidence of any technology to prevent rising groundwater until the late Victorian period. The first 'damp-proof course' was a system of interlocking vitrified stoneware tiles laid through the depth of the wall a little way above ground level to deal with infiltration from poor early sewers, which tended to back up and flood cellars. This was developed and christened in 1859 by John Taylor; other builders used bituminous materials, but slate quickly became the popular choice. By the late 1870s damp-proof coursing had been incorporated into English building legislation, and although sewers and water supply systems are now much less problematic, it is still required for new build. For existing buildings, alternatives such as injected damp-proofing are sometimes used, although there is little or no evidence that these are effective (see **Deterioration & Damage**). The original cause of the problem appears to have been forgotten, and 'rising damp' has become a catch-all phrase for all moisture problems in walls, even when the water is percolating down from above.

Although the water table will not in fact be a source of problems for most types of construction, water-sensitive materials such as timber and cob will still need to be protected from ground moisture. The traditional approach has been to construct walls made primarily of these materials onto a masonry plinth made of stone or brick.

Traditional buildings usually provide good thermal buffering, since both the materials and the construction have a great deal of thermal mass. Metal and glass were used sparingly, and serious thermal bridges were therefore uncommon. Radiative transfer into massive walls and floors was reduced with wall and floor coverings of timber or fabric (panelling, tapestries and carpets).

By contrast, materials with low thermal inertias are critical to modern architecture. In response, engineers have been forced to develop sophisticated ways of increasing thermal mass, such as thermal breaks, multilayered insulation systems for walls and IGUs [Insulated Glazing Units] to replace single sheets of glass in windows and curtain walls. Glass may also be covered with plastic filters to reduce radiative uptake.



Thermal buffering

Like many medieval churches, St Botolph's, at Hardham in Sussex, has massive masonry walls. These have an extremely high thermal inertia and are therefore excellent temperature buffers. During the day, their external surfaces are warmed by the sun and the air; this heat transfers through the wall slowly, so that by evening – when the exterior conditions have begun to cool – the interior will still be warming. If the building is not heated, maximum interior temperatures will be reached well after the hottest part of the day, and although the interior will always be cooler than the exterior maxima, it will also stay warmer than the coldest exterior conditions. In other words, the interior temperatures will be both more stable and less extreme than the exterior.

In a building of this type, thermal buffering is enhanced by the small amount of surface area taken up by windows and other components of low thermal inertia.

If such a building is heated or cooled, buffering will reduce the amount of energy that must be used to achieve the desired temperatures.

BUFFERING THE EXTERIOR HUMIDITY

The primary mechanism for humidity buffering is air exchange: buildings that are very 'leaky' tend to have internal relative humidities that closely follow those of the exterior air. The secondary mechanism is permeable materials absorbing and releasing water vapour in response to changing relative humidities. If the interior vapour pressure is constant, the fabric and the interior air will be at equilibrium, but if the vapour pressure of the air changes, then hygroscopic materials such as brick, stone, lime plaster and especially timber will respond by either taking up or giving up moisture until a new equilibrium is reached.

Every permeable building material will have its own characteristic hygroscopicity, taking up moisture from the air in a way that depends on (amongst other factors) the structure of its pore system and the presence of contaminants such as salts. Moisture absorption and desorption depends on the ambient conditions: for example, plotting a hygroscopic material's moisture content against changing ambient relative humidity generates a characteristic curve, showing the 'equilibrium relative humidity' of the material.

Some degree of existing moisture is important to the material's buffering capacity, since very dry materials absorb moisture much less effectively (just as a sponge will not absorb water when dry, but becomes very absorbent indeed once slightly wetted: the reasons for this are discussed in **Building Science**). It has been shown experimentally that an oven-dried lime plaster will absorb very little water vapour from the air, but after several months or years of exposure, even plaster in perfect condition will be holding some moisture in its pores, and will therefore be an excellent buffer. Materials such as timber will usually be holding significant amounts of moisture (as much as 15 % by weight for wood in good condition), and this acts as a sink of water when, say, a temperature increase causes the ambient relative humidity to drop. It also helps the wood to take up water vapour when the humidity rises again (that is, when the temperature drops, or wetter air enters the building).

The envelope will also have its own characteristic 'hygric mass': the way it buffers humidity will depend not only on the permeability of single materials, but on the behaviour of complex groups of materials. Discontinuities, interfaces, joints, surface finishes and coatings may all have a significant impact. For example, moisture-resistant coatings such as vinyl paints will hinder evaporation much more than they hinder moisture uptake, so painted plaster may steadily become wetter (see **Building Science**).

The average absolute humidity in the interior will be steadier, but typically slightly higher, than the exterior.

All parts of the building can contribute to the humidity buffering, including the interior and the contents such as timber furniture. The floor is one of the largest surfaces for moisture exchange; traditional solid floors, which do not incorporate damp-proof membranes but are bedded directly onto the earth or onto a permeable lime-based mortar, can account for more than half the moisture content of the fabric. So long as there is plentiful air movement and air exchange this does not damage the building, and indeed it prevents groundwater being driven up the walls.

Freeze-thaw damage

Freeze-thaw damage can occur in any wet permeable material exposed to low temperatures, but is most commonly seen in masonry. Problems may be exacerbated by the use of cement-based mortars, which trap water. The pattern of deterioration reflects not only exposure, but also the variation in the quality of the bricks or stones, since it is the weaker units that will fail. So many factors can be at work that freeze-thaw is often hard to unequivocally pinpoint as a reason for deterioration.

Indirect Damage

Many of the problems indirectly caused by temperature involve its effect on moisture. For example, cooling may lead to condensation, and wet permeable materials may break down under freezing conditions, especially if subjected to repeated cycles of freezing and thawing.

Although the precise mechanism for freeze-thaw damage is not well understood, it may be related to the bursting of water pipes in cold weather. In this case at least, it is not actually the force exerted on the walls of the pipe by the expansion of the water as it freezes that does the damage: the pipe is much too strong, and instead forces the ice crystals to grow along the pipe. This compresses the air trapped ahead of the ice front, so air pressure will build up until eventually it is sufficient to split the pipe apart at the joints. Hot-water pipes are more prone to failure than cold-water pipes, since the cold-water system often includes toilet cisterns which act as expansion valves.

Roofs that are periodically covered in thick snow face other problems. If the ceilings are not insulated and the attic space above is not very well ventilated to the exterior, the roof covering may heat up, causing the snow to slide off, which can be a risk to building elements below. The meltwater may refreeze at the eaves, causing ice dams that endanger not only the eaves and gutters, but passers-by as well.

IMPACT OF SUNLIGHT

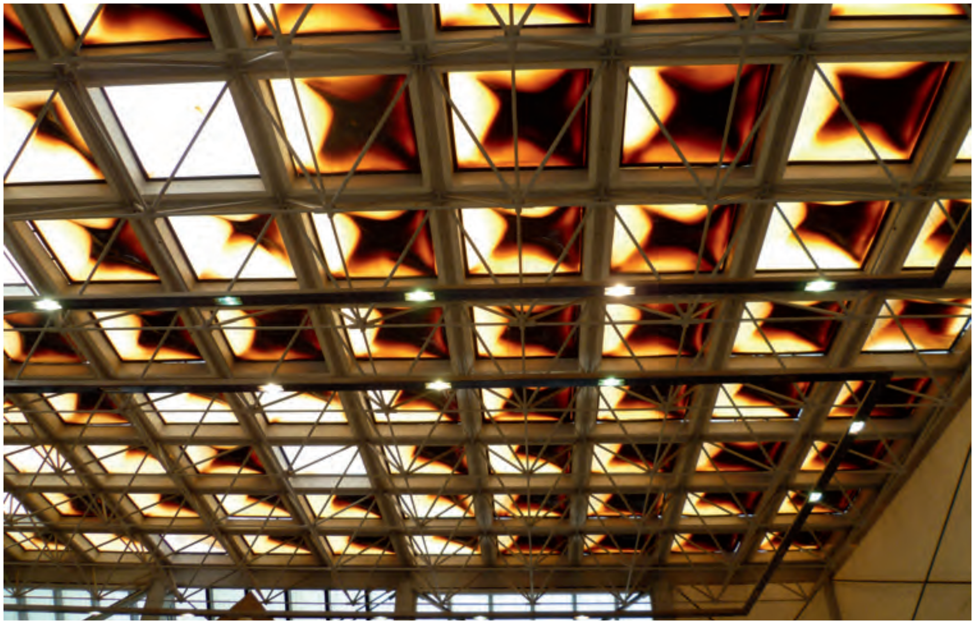
As with temperature, sunlight can cause damage both directly and indirectly, although in this case the direct damage is usually confined to superficial changes, and it is the indirect damage – chiefly localised heating – that is able to cause the most severe problems for most building envelopes. Since exposure depends on the building and its surroundings, this can change quite dramatically through the day and the year.

Direct Damage

Although the ultraviolet component of sunlight can break down organic materials in building components, this is usually superficial. It is of most importance for decorative surfaces such as wall paintings or wallpapers that incorporate dye pigments, where the appearance can be dramatically altered by fading. Exposed timberwork will change colour, but this will not affect its strength to any significant degree. Sunlight can also break down glues and sealants such as putties and silicones, which can be a serious issue for some modern curtain-wall construction, but the degree of damage will depend on the exposure. ➲GLASS

Indirect Damage

Solar heating can cause materials to expand and contract, and can also act as a catalyst for chemical reactions. Solar heating can cause very high vapour pressures in surface pores and inside hollow-wall construction, and this can force moisture through the wall. Sunlight exposure is also a critical factor governing the growth of plants and microorganisms in and around the building.



Sunlight damage

Many plastics are very susceptible to damage from ultraviolet light.

In this railway station roof, the transluscent panels have severely discoloured. Even newer replacement panels (such as that at top left) are beginning to show signs of the same deterioration.

Taking readings of environmental conditions with a hand-held meter

Hand-held electronic meters are now available at little cost; most will measure relative humidity and temperature, and may calculate absolute humidity and dew point. More sophisticated models may have interchangeable probes, allowing the surveyor to take readings of other environmental parameters such as air movement or pollution.

Although hand-held meters will only give spot measurements, and the readings for a single day should never be given too much weight in interpretation, they can still be a handy way to examine the overall behaviour of the building envelope, and can be used to help plan more exact investigations.

Water problems will not always be due to a problem with the building envelope, or to condensation: leaks in plumbing and heating pipes, or even in fire-protection systems, are common sources of problems.

Most assessors find it useful to map superficial decay onto elevations. Relative moisture and salt levels in walls can also be roughly mapped using resistance or capacitance moisture meters, and although the results will not be accurate, the resulting patterns may help to narrow down a hidden source of moisture. It is possible to take spot measurements of temperature and humidity, usually with hand-held meters. Although the information this gives should be approached with caution, it can be a way of making general comparisons, especially when looking at the potential effects of heating: comparisons between different internal spaces, for example; or between the exterior and interior.

Each room will need to be assessed separately, as well as considered in terms of impact on the envelope as a whole. Windows and doors must be checked not only for signs of leaking and other similar problems, but to see whether they are operating correctly.

If the likely source of moisture-related damage is still not clear, it may be necessary to look at the exterior once again, double-checking details that could be causing problems, such as the pointing, the joints between building elements (for example, around windows), and the flashings and seals.

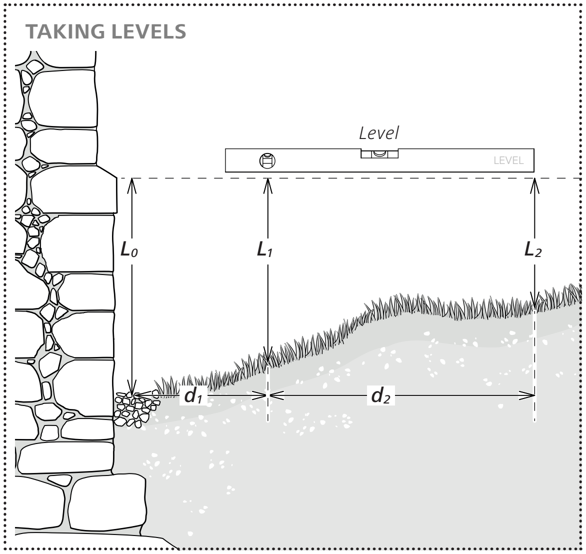
Recent changes to the fabric (for example, the addition of carpets or tiles, or of impermeable paints or wallpapers, or the installation of a new heating system) can be a critical factor, so these must be identified. Changes in the way the building is being used are equally important, as are any alterations that have been made to the environmental management. All evidence of building services, both old and new, will need to be recorded, and the building users questioned to construct a picture of the ways the current services (such as heating) are actually being used.

MAKING DETAILED MEASUREMENTS

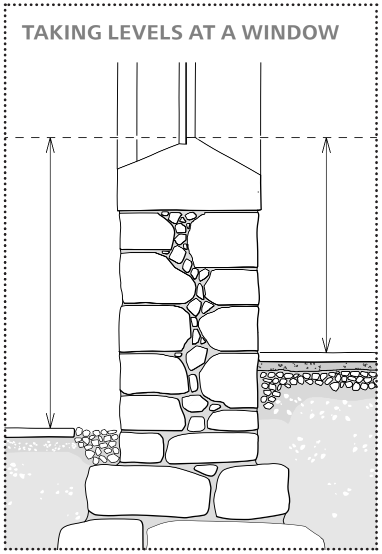
Almost every aspect of the building environment has the potential to merit closer investigation and measurement as part of a building performance survey, from the slope of the surrounding ground to the structural soundness of the building elements.

CHARACTERISING THE GROUND SLOPE

If it is suspected that the ground levels are causing runoff problems, or there are subtle issues between interior and exterior ground levels, this can be checked very easily with simple tools (string, a metre rule and a level), though it does require that the surveyor has some assistance. Alternatively, professional surveying equipment can be used.



TAKING LEVELS



TAKING LEVELS AT A WINDOW

Determining relative ground levels

Top: Interior floor levels, the difference in the interior and exterior ground levels, and the slope of the ground around the building, can all be determined to sufficient accuracy for most purposes using the simplest of tools: two straight sticks or metre rulers, a tape measure, string and a builder's level, or a line level.

Bottom left: Measurements are taken relative to one point, usually inside the building, with the measurement team working outwards from there; each reading becomes the baseline for the next measurement. The results are marked onto a building plan.

Bottom right: To connect the internal and external measurements, it is usually easiest to note the height of the same window sill on the interior and exterior.

Selecting the Correct Sensors & Probes

Data is only as good as the sensors gathering it, so it is important to understand their accuracy and repeatability. Readings taken for investigating the building environment rarely need to be as accurate as (for example) readings taken for process control in factories. Repeatability of measurements taken by a single sensor, or between different sensors around the building, is much more important than accuracy.

All electronic sensors must be supplied with power, but the way in which this is provided varies. Hardwired probes generally draw their power directly from the datalogger, but radio telemetry probes are generally powered by batteries (like stand-alone loggers, these require periodic renewal; but because battery life can be transmitted along with the data, warnings can be provided to the logger when battery power is low).

Some probes – hot-wire air velocity sensors, for example – require more power than can be provided by batteries. They must therefore be supplied with electricity either directly from the mains, or from solar panels (or some other alternative source).

It is convenient to group probes into 'clusters': this not only makes installation easier, but means that the readings from the sensors are as comparable as possible.

Here, each cluster includes a thermistor reading surface temperature, and a combined relative humidity and temperature [RH&T] probe. All probes are protected from the drying and cooling effects of air movement by screens (a block of green foam in the case of the thermistors, and filters or a Stevenson screen in the case of the RH & T probes). This ensures accurate and repeatable readings.

Most monitoring begins with equipment to measure temperature and relative humidity, often together with surface temperatures. Monitoring exterior and interior microclimates is also standard, as this more than any other comparison reveals how the building envelope is working. The weather station is a particularly useful tool, combining in a single unit the measurement of exterior temperature and relative humidity, rainfall intensity, sunlight, and wind.

Structural monitoring can also be incorporated in a programme of environmental monitoring to check whether or not apparent weaknesses reflect serious problems, and whether or not these are affected by environmental parameters such as temperature or wind. This can mean monitoring ground motion, structural frame response, component response, and creep or settlement.

COMMON ELECTRONIC SENSORS USED TO MONITOR THE ENVIRONMENT

PARAMETER	TYPE OF MEASUREMENT	SENSORS	COMMENTS
AIR TEMPERATURE	Direct	Thermometers Thermocouples Thermistors Resistance sensors	Thermocouples are not reliable when used to measure temperatures close to the ambient air temperature
SURFACE TEMPERATURE	Attached sensors	Thermistors Resistance sensors	Accuracy depends on method of attachment
	Remote sensors	Infrared thermometers Infrared thermography	Readings depend on surface emissivity as well as temperature
AMBIENT HUMIDITY	Direct	Capacitance sensors Dew-point sensors	Need regular recalibration
LIGHT	Direct	Photodetector	Can measure different wavebands
	Indirect	Photodetector	Can measure different wavebands
AIR MOVEMENT	Pattern and speed of flow	Smoke tests Particle velocimetry	Air movement is very variable, so spot measurements can be particularly deceptive
	Speed of flow	Cup anemometers Hot-wire anemometers Ultrasound	The presence of probes can cause turbulence and affect the reading; this is a great problem at low speeds
AIR EXCHANGE	Indirect	Tracer gas	On-off measurement: therefore, conditions under which to monitor must be chosen carefully
	Direct	Door or window opening	Closure of window or door completes circuit May need quite complicated processing to extract both numbers of opening and closing events, and the duration of each separate event
MOISTURE CONTENT	Indirect	Resistance sensors Embedded capacitance sensors Embedded microwave-capacitance sensors	Best systems based on measuring dielectric change, but currently no totally satisfactory method, since sensor must be inserted in a drilled hole, and this changes the characteristics of the material
WATER EVENT	Direct	Strip with a simple printed electronic circuit; presence of liquid water completes circuit	Can be used to detect surface condensation or, for example, blockages in gutters Can be used to trigger an alarm
HEAT LOSS	Indirect	U-value reading with flux meter	U-value is a measurement of conductive heat loss only
AIR POLLUTION	Direct	Air pumped through analytical device	Sensor can be chosen to detect a range of pollutants, or to monitor a single pollutant to a greater accuracy

COMMON OBSERVED SYMPTOMS OF ENVIRONMENTAL PROBLEMS

AREAS OF ‘DAMP’

DESCRIPTION	POSSIBLE CAUSES	ACTIONS TO SUPPORT DIAGNOSIS
MOIST PATCHES HIGH ON WALL		
	Source of liquid water; common causes include: • blocked rainwater goods • chimneys with rainwater penetration • impermeable renders trapping moisture May be hygroscopic salts; sources include: • deposition of combustion products in flue • trapped organic material in flue • building use • internal pollutants (such as sulphate deposits from heating)	Look for decay of embedded timbers (such as joists and lintels) Map distribution of damage, and compare to possible building flaws Look for possible sources of hygroscopic salts If source is unclear, take samples from wall to determine moisture content and distribution, and salt content (look for hygroscopic salts)
CONDENSATION ON IMPERMEABLE SURFACES		
	Visible water beading on impermeable surfaces such as glass or metal under certain conditions; wall feels cold and damp to touch; may be damaged finishes or signs of moisture problems (such as decay for timber affected by runoff) May be liquid water problem, with condensation as apparent or real side-effect Unusually thin masonry walls, chilled by wind Liquid moisture problems from other sources, including blocked rainwater goods or drains May well be exacerbated where problems have led to wrong interventions (for example, a cement render)	Under what conditions does water-beading appear? May be necessary to monitor environmental conditions, including surface temperature, and to understand how the heating system is being run Map distribution of damage, and compare to possible building flaws Assess quality of pointing and render, checking especially for fine cracks that could wick in moisture
CONDENSATION INSIDE SECONDARY GLAZING		
	Significant condensation on the inside of the glass, occurring regularly; runoff staining below the window; decay of timber cill and horizontal members of windows, or corrosion of horizontal members and joints of metal windows High interior humidity (coupled with cold glass) Insufficient ventilation to exterior, especially where wall has moisture problems	Under what conditions does condensation occur? May be necessary to monitor environmental conditions Look for liquid moisture problems in surrounding wall
CONDENSATION INSIDE INSULATED GLAZING UNIT (‘DOUBLE’ OR ‘TRIPLE’ GLAZING)		
	Failed seals (these have a limited lifespan) Sometimes cracked glass	Seals can be tested by placing a cup containing dry ice against the glass; if the seals have failed, this will provoke condensation If glass has cracked, look for source: • impact • glazing unit fits too tightly in frame, so that thermal movement causes failure

COMMON OBSERVED SYMPTOMS OF ENVIRONMENTAL PROBLEMS

NON-VISUAL SYMPTOMS

POSSIBLE CAUSES	ACTIONS TO SUPPORT DIAGNOSIS
MUSTY OR DAMP SMELL	
Timber decay Mould growth Most common in areas with limited air circulation	Is the smell present all the time, or only after the room has been shut up? Look for sources of water: most commonly liquid water leaks, but condensation can also be a problem (such as condensation behind impermeable insulation or membranes)
SPACE FEELS 'STUFFY'	
Insufficient air exchange and/or air movement Sources of ventilation such as windows, chimneys sealed up Central air-conditioning system with inadequate filtering or ventilation	Is it a problem at most times, or only in certain conditions or times of the year? Is it a problem in all rooms, or only in certain rooms? Check airflow and air exchange, especially around doors, windows, chimneys
SPACE FEELS DRAUGHTY	
Air leakage through windows, doors or chimneys Open-plan interior: no ability to isolate spaces Poor control systems: heating causing air currents, or pulling in colder air; heating using blowers or localised radiators; air conditioning blowing air too strongly Large areas of glass (thermal bridging)	Is it a problem at most times, or only in certain conditions or times of the day or year? Is it a problem in all rooms, or only in certain rooms? Check condition of windows, doors and so on Check airflow and air exchange, especially around doors, windows, chimneys Check for hidden major air leaks through fabric
SPACE FEELS TOO COLD	
Radiant heat loss to thermal bridges or materials that readily absorb heat from the body, such as: • large areas of glass • thick masonry walls • cold floors Inadequate heating, or heating/cooling system that is badly controlled	Is it a problem at most times, or only in certain conditions or times of the year? What activities are happening in the room? How are occupants dressed? What is the heating system? How is it controlled?
SPACE FEELS TOO HOT	
Solar gain, especially through large areas of glazing Inadequate ventilation Extensive heating system and insulation Inadequate cooling, or heating or cooling that is badly controlled	Is it a problem at most times, or only in certain conditions or times of the year? What activities are happening in the room? How are occupants dressed? Check air temperature, ventilation and air exchange What is the heating/cooling system? How is it controlled? How is the building insulated?
SPACE FEELS HUMID	
Condensation problems Insufficient air exchange and/or air movement Incorrect heating system, or control of heating system Building use involves a great deal of moisture Moisture-resistant materials have been used, such as AVCLs, water-resistant insulation, or impermeable wallpapers or paints	Are there any building flaws letting in liquid moisture? Is it a problem at most times, or only in certain conditions or times of the year? Is it a problem in all rooms, or only in some parts of the building? Check airflow and air exchange, especially around doors, windows, chimneys Monitor to determine vapour content of air, and identify sources of vapour

Dealing with Moisture from the Ground

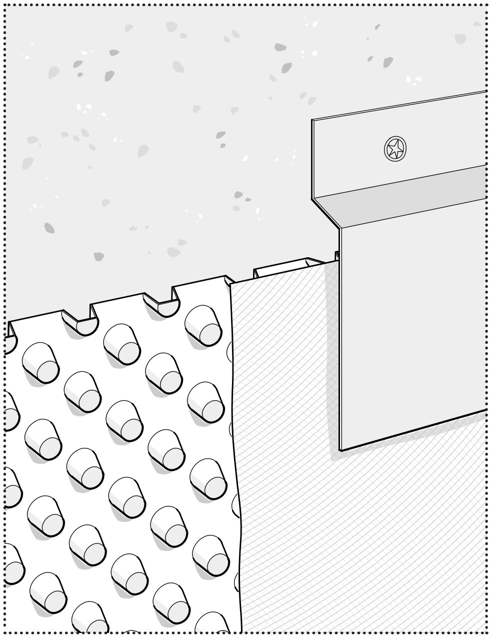
In masonry walls that have not been rendered with cement or given some other waterproof finish, groundwater is unlikely to affect more than the first course or two of masonry, but cellars, underfloor voids, and the walls of buildings where the earth has been allowed to build up against the exterior, may be very wet on the interior.

Preventing Lateral Penetration

If there is a problem that cannot be managed by maintenance or repair of the existing drains, or by installing land drains uphill from the building, there are two principal approaches: to add a waterproofing layer on the buried section of the wall, or take back the earth to create a ventilated trench. Both require excavation near the footings, and so will probably need advice from a structural engineer as well as a drainage expert. If the building is listed or the surroundings of historic importance, digging may require statutory consent, and possibly archaeological supervision.

Excavation

Historically, the ground outside basements or cellars in use was sometimes dug away to match the interior ground level, forming well areas or perimeter passageways. This approach allows the walls to dry out and stay dry, but excavation around an existing building is a costly and invasive exercise that may have both structural and archaeological implications, and could change the character of the building. It is only possible where excavation would not endanger the structure, and where it does not impinge on building or landscape significance. Excavations should generally incorporate a land drain as a fail-safe.



To separate an exterior wall from the ground abutting it, and thereby prevent lateral penetration of water, one approach is to use a geodrain. This must be capped at the top to ensure that water flowing down the walls travels over the geodrain, rather than behind it.

Waterproofing

Waterproofing coatings and metal flashings are not likely to have long lifespans when buried and exposed to quantities of water and salts from the ground, and so a modern geodrain (a plastic barrier with integral drainage channels) may be a better choice. This will need to connect at the bottom to the drain, and be flashed at the top to prevent water washing down the walls from entering. It will need to be replaced when it begins to fail.

Barriers such as geodrains do entail some risk. There is likely to be some leaking through and especially under the barrier, and if water does get in to the wall, it will be able to dry only towards the interior.

Damp Proofing

Damp proofing, which was first introduced in the second half of the 19th century to prevent damage from faulty sewers, is now an automatic inclusion in new construction. A damp-proof course [DPC] is a layer of some waterproof material such as sheet lead, slate, bituminous felt or plastic carried through the entire thickness of the wall just above the ground, to cut off water rising from the footings. This may be bedded into the joint between two courses of masonry, or set on the top of the plinth supporting a timber frame or an earthen wall, or some other moisture-sensitive form of construction. A damp-proof membrane [DPM] is usually a thick sheet of polythene, which may be used in various ways: for example, to protect church monuments positioned against exterior walls, or to isolate a concrete floor slab.

Injected 'damp-proofing' systems are not recommended for building conservation: not only is there no evidence that they work, but the risk from the associated cement renders and the damage from drilling multiple holes into the wall through which large quantities of liquid are introduced make them unacceptable (see **Deterioration & Damage: Problems Due to Alterations & Interventions**).

It is very rare that a DPC or DPM will be found to be a desirable option for controlling water: it risks moving the moisture problem elsewhere. To protect a building with its footing immersed in water, the damp proofing would need to form an unbroken barrier across the floor and through the walls, and an internal perimeter drain would need to be installed together with a pump to take the water it collects back to the exterior. Retrofitting damp-proof coursing into a building which was never designed to incorporate one is extremely invasive: to protect timber cill beams resting on damp masonry plinths from decay the frame would have to be jacked up section by section to insert the DPC; masonry walls would need to be cut through section-by-section using special saws, or long drills and chisels. It is difficult to imagine any situations where such invasive works would be justifiable.

Drying Wet Fabric

It is rarely necessary to install any special systems to dry walls recovering from moisture problems, except perhaps where the source of the water was widespread and prolonged: a flood or fire, for example (see the **Special Topic**: **Dealing with Disasters**).

Drying proceeds in two stages, and it is only the first – Stage I, where there are liquid flow paths from the centre of the material to the surface – that is able to remove substantial quantities of moisture from bulk material (see **Building Science**). Where possible, it is desirable to prolong Stage I drying so that more moisture is removed from the walls, so it is usually best not to accelerate the process to any great degree: slight airflow and good air exchange can often be helpful, but strong heating and too-powerful fans can easily dry the surface pores, moving the process into Stage II drying (which is very slow). Rapid drying also increases the risk of material damage.

Certainly drying should not be accelerated until all leaks have been dealt with: if the moisture sources have not been removed, drying will never be effective, whatever the mechanism. Trying to dry fabric wetted continually by a high water table, for example, would simply pull more water through the wall, exacerbating deterioration and raising the humidity within the room.

Proprietary treatments for drying 'damp walls', such as electro-osmosis, are generally unnecessary, and may prove counter-productive.

Managing Birds

Whether birds cause serious problems depends both on the habits of the species, and on where the perches, nests or roosts are located on the building. Since many different birds depend on buildings for nest sites, it may be necessary to balance nature conservation and building conservation. Information about the conservation status and the control of different bird species can be obtained from the Royal Society for the Protection of Birds.

Many different approaches to bird deterrence have been tried, including flying hawks, scarers and audible repellents, but these do have certain drawbacks, not least that their action is not species-specific. Culling is often proposed for controlling pigeon populations, but it is never effective unless the population is very small and isolated; otherwise, birds in neighbouring areas will simply move in.

Laws Protecting Birds

All wild birds, together with their nests and eggs, are protected by the Wildlife & Countryside Act 1981. It is an offence to damage or destroy an active nest, or to prevent the parent birds having access to it. In the case of birds that are listed on Schedule 1 of the Act, such as the barn owl, it is an offence even to disturb the birds when they are near or at the nest.

In England, General Licences are issued by the Government to allow 'authorised persons' (the owner or tenant of the land or property, or someone acting with the owner's permission) to kill or capture certain species of birds, including feral pigeons. General Licenses allow people to carry out activities that affect protected species without the need to apply for a personal licence. They are only used for activities that carry a low risk for the conservation or welfare of the protected species, and where a personal licence would be routinely issued. If a building manager plans to act under the authority of a General Licence, they must be satisfied that they are eligible to do so and must act within the provisions of the relevant General Licence: the conditions of the licence must be checked carefully to ensure that the situation is covered, and to comply with these conditions. If the planned work cannot be carried out under the provisions of a General Licence, a specific or individual licence must be sought from Defra. Details of general licences can be found at *www.naturalengland.org.uk/ourwork/regulation/wildlife/licences/generallicences.aspx#a*

Legislation can change rapidly according to the conservation status of the bird, so it is important that the latest advice is sought from the relevant government department before any action is taken. The website of the Royal Society for the Protection of Birds [RSPB] also has excellent and detailed advice (*www.rspb.org.uk*).

All bird nests are protected by law: it is illegal to intentionally disturb or destroy the active nest of any wild bird. Nestlings must be allowed to fledge before any action is taken to block access or remove nests. If nests are found during roofing works, eggs and nestlings should not be disturbed, and Natural England should be consulted.

Endangered species should be allowed to nest wherever there is no direct conflict. If the roof must be sealed off to prevent damage, nest boxes can be positioned under the eaves for threatened birds such as starlings, sparrows and swifts; these can be cleaned after the breeding season to limit the number of parasites. Shelves can also be fitted below the nests to catch droppings.

If nests must be removed, it will be necessary to ensure that they are no longer in use (for larger buildings and commercial properties, it is wise to seek advice from an independent specialist organisation such as the Pigeon Control Advisory Service).

Preventing Perching

Feral pigeons and other troublesome birds will perch on buildings to overlook regular food sources. If perching is a problem, the most important step is to try to remove the source of food (for example, preventing people feeding pigeons in the area).

Preventing Roosting & Nesting

Birds such as pigeons need to be prevented from entering areas where they may roost or nest in numbers, such as courtyards, balconies and windows, or around statuary or pipe work. Roosting sites may also be popular with other more desirable birds; but fortunately pigeons are large, so it is often possible to exclude them and not the smaller songbirds.

The problem will have to be dealt with in the winter, ideally between October and February when birds should have finished nesting. Any holes or gaps giving access to the roof or some other sensitive area of the building will need to be cleaned out and sealed, which should be done mid-morning to minimise the risk of trapping any roosting birds. If there is any doubt as to whether all birds have left, a fine wire mesh can be fixed over the entrance, and checked at intervals to ensure that no birds are trapped; permanent repairs can be made when it is certain that no birds remain.

The access to the site will then need to be repaired, or blocked off with netting or the correct wire or nylon mesh. Monofilament mesh, for example, comes in a range of sizes: 19 mm for birds as small as sparrows, 28 mm for starlings and larger birds, 50 mm for pigeons, and 75 mm for gulls. If well installed, netting can be relatively inconspicuous, and does not noticeably reduce light levels in the building. However, it does tend to trap windblown leaves and rubbish, so maintenance is an important issue.

Netting and mesh

Netting can provide some protection from birds for elaborate features on the building façade, but it is not necessarily unobtrusive.

COMMON INDOOR AIR CONTAMINANTS

PRINCIPAL SOURCE		CONTAMINANTS
BUILDING & FURNISHING MATERIALS	Fabric Underlying ground	Dust, glass fibres, asbestos fibres, radon
	Paints and glues, including those in laminated wood Cleansers, disinfectants and solvents	Volatile organic compounds [VOCs] such as formaldehyde Heavy metals such as lead
	Off-gassing (such as the softeners and solvents released by many industrial plastics)	Toxins of various types and degrees of seriousness (such as cyanide from some types of rubber-based sealants)
	Treatments such as biocides	Biotoxins
MICRO-ORGANISMS	Furniture	Dust mites
	Damp materials Stagnant water	Fungi spores, mould spores, bacteria
BUILDING USE	Heaters burning carbon-based fuels Diesel-powered generators Combustion engines (for example, cars)	Carbon monoxide; particulates
	Furniture Occupants	Carbon dioxide; dust
	Photocopiers Electric motors Electrostatic air cleaners	Ozone

The storage tanks of air-conditioning systems, which are often found on the rooftops of commercial buildings, can support the growth of microorganisms such as *Legionella* bacteria.

HEALTH HAZARDS IN BUILDINGS

An assessment of health hazards in a building may be desired for one of two basic reasons:

- works are being proposed that could expose the workers or other building users to hazardous materials (such as asbestos, lead or bird droppings)
- building users are reporting health problems that could be associated with the building or its contents (such as respiratory problems).

Although health problems reported by occupants can arise from any combination of contaminants, the underlying causes are often linked to environmental issues such as inappropriate temperatures and humidities, or insufficient intake of outdoor air.

In cities particularly, commercial buildings are often airtight and use central air plants deliberately designed to limit air exchange with the exterior. This makes it easier and cheaper to condition the building air, and reduces the need to precondition incoming air to bring it to the right temperature or to filter it to remove pollutants, but its unfortunate side-effects cannot be denied. In poor air-conditioning systems, the building air is run through the ceiling and underfloor spaces, which are usually very dirty; even ducts and filters may only rarely be cleaned.

ASSESSING HEALTH HAZARDS

Assessments of hazards during building works in the UK are covered by the Health and Safety Executive. The latest regulations and practice recommendations should always be consulted and followed (*www.hse.gov.uk*).

It is harder to assess health problems associated with use of the building, because potential causes are many, and active factors are challenging to isolate. Not only all information about symptoms, but the nature of the building itself, will need to be taken into account. For example, if the building was constructed in the 20th century, or has major 20th-century renovations, asbestos may be a risk.

An assessment survey should be made to investigate all possible causes of discomfort, including the lighting and heating, the fabric and furnishings, and the air plant. Forced ventilation should be checked to determine the mix of outdoor and indoor air, the air distribution, and the nature and state of the ducting and the filtration systems. All possible issues, from mould growth to ozone-generating equipment or sources of standing water, will need to be mapped and compared to patterns of occupancy and illness.

In some cases it will prove necessary to call in experts to analyse samples of the air and from building surfaces, or to monitor pollutants, or to study airflow. Further information about general environmental monitoring can be found in **Assessing the Environment: Specialist Investigations**.

ALTERATIONS TO THE BUILDING ENVELOPE

Aside from the many passive and managerial actions that can be taken to reduce the risk of disaster, there are a number of interventions on the building envelope that prevent or reduce damage from flood and fire, and less common disasters such as lightning strikes and earthquakes.

FLOOD-PROTECTION ALTERATIONS

Floodproofing can take many forms, including meticulous maintenance of plumbing and other internal sources of water. For ground floods, where the sources are coastal flooding, riverine flooding or flash flooding, the options are trying to divert the water away from the building, or to stop it at or preferably before it reached the envelope. For buildings prone to repeated ground flooding, it may also be wise to limit damage by internal rearrangements.

IMPROVING RESISTANCE TO GROUND FLOODS

Measures to prevent or limit the damage from ground floods vary widely in cost, effectiveness and invasiveness; no single solution is right for every building, and indeed most would only be considered for buildings at significant risk. Modifications fall into three groups:

- works to the surroundings to make flooding less likely
- works to the building to stop floodwaters entering
- works to the building to restrict the amount of damage if floodwaters do enter.

Factors to be considered when weighing up the cost of intervention against the likely benefit include the types of flooding that are likely to be encountered (both sources and duration), how often such floods may occur, how much warning is likely to be received, and of course the exposure of the building. For example, a basement flat in a city may be at sufficient risk from flash runoff floods, water-main bursts or blocked sewers to make it worthwhile to install some form of permanent low barrier at the base of the door.

Making Flooding Less Likely

Most district flood prevention work is the province of the Environment Agency and associated government organisations, but there are a number of actions that can be taken if the building owners have access to the surrounding ground, and there are no insurmountable issues related to historic landscapes or gardens, or buried archaeology. The most important are:

- to ensure that any existing land and building drainage is in good condition, or install improved drainage systems
- to re-landscape to redirect surface water away from the building, and to replace impermeable surfaces with materials that allow the water to soak into the ground.

Preventing Water Entering the Building

Floodwater can enter the building through:

- floors and exterior walls (especially through cracks and joints)
- windows and doors
- other apertures in the envelope, such as vents, air bricks, pipe ducts, and gaps around piping and cabling
- partition walls from neighbouring properties
- back-flowing plumbing systems and sewers.

The first step is therefore to find some way of permanently or temporarily sealing any flaws or apertures. Permanent actions include repairing faulty pointing, replacing cracked cement renders, and sealing gaps around piping and cabling that passes through the exterior walls. For apertures that have important uses, such as doors and drainage holes, sealing methods will need to be demountable. This stops them acting if the flood arrives without warning, so it may be necessary to consider hybrid systems if the risk of flash flooding is very high.

There are a number of systems designed to be applied to the building perimeter to stop floodwaters entering. Most will only hold the water back for a short time, but this may be long enough to prevent damage from flash floods, or (for floods of longer duration) to allow the building contents to be moved or otherwise made safe. Structural engineers do generally advise, however, that no more than one metre or so of floodwater should be held back at the building envelope, since the pressure exerted on the exterior walls by more water than this could cause structural damage.

Buildings may have little protection against runoff floods, which can result from burst water mains and sewers, as well as from heavy rainfall.

Over the past two centuries, the amount of energy consumed to make and operate buildings has increased tremendously. The Industrial Revolution relied upon the exploitation of fossil fuels, starting with coal. Lower energy costs made energy-intensive materials like glass and steel easier and cheaper to make, and as a result new architectural systems began to replace traditional forms of construction. At the same time, developments in mechanised transport made centralised processing and production feasible, and soon led to larger and more sprawling cities. Habits and expectations of individuals and organisations also changed, while building operation became more energy-dependent (see **Controlling the Interior Environment**, in the main text of this volume).

Energy Use & Carbon Emissions

To reduce emissions, the options are to save energy, reduce electricity use and switch to low-carbon energy supplies.

When burnt, the carbon and hydrogen in fossil fuels combine with oxygen to produce heat, carbon dioxide and water. The quantity of carbon dioxide released in relation to the amount of energy produced (expressed as kilograms of CO_2 per kilowatt-hour [$kgCO_2$/kWh]) depends on the fuel source, and the efficiency of the system used to convert it to heat or electricity. The percentage of emissions attributable to using electricity is very high, because on average UK thermal power stations deliver roughly a third of the energy contained in the fuel as electricity at the point of use. In the UK between 2005 and 2010, a typical carbon factor (the emission rate per unit of energy at the point of use) for electricity was 0.53 $kgCO_2$/kWh, while that for gas was 0.185 $kgCO_2$/kWh. UK government policy is to reduce the carbon content of national electricity generation, but this will take time to happen.

Regardless of its carbon content, saving electricity is important because of its relatively high energy cost. After accounting for generation and distribution losses, thermal power stations in the UK deliver only about a third of the energy contained in the fuel as electricity at the point of use (as a comparison, the efficiency of an ‘A-rated’ gas, LPG or oil-fired boiler is around 90 %).

THE IMPACT OF THE ENERGY SUPPLY

The choice of energy supply for a building will have many effects at the national level:

- *Avoided requirements*
  Power from local renewable generation (solar, wind or water power) may be intermittent, which means that central supplies may be called upon from time to time. This has implications for the national supply in terms of capacity, management and efficiency, as well as on carbon factors.
- *Reduced requirements*
  The benefits of improved efficiency at the local or community level (for example, using electricity in heat pumps, or fossil fuels in Combined Heat and Power [CHP] systems) may not be entirely straightforward. Energy use can increase if a CHP is not available, or a heat pump is inefficient at the time the electricity grid is under stress because of a cold winter spell.
- *Lower-carbon fuels*
  Burning gas produces less carbon per kWh than burning either oil or coal, but the associated methane leaks from production and distribution need to be properly taken into account.
- *Biofuels*
  Biofuels must be sustainably produced, so a high proportion of the carbon released when they are burnt can be sequestered by the growth of new crops. Unfortunately, some biofuels require high inputs of fossil fuels to produce, and others may be provided unsustainably.

ENERGY & CARBON IN THE BUILT ENVIRONMENT

Given a particular site and context, the three most important influences on a building's energy use in operation are:

Fabric

The principal factor to be considered is how effective the building envelope is in providing a suitable indoor environment passively (including buffering of heat, humidity, and solar gain; providing natural ventilation and lighting via daylight).

Equipment

The equipment is the actual user of energy. This includes both the fixed building services (principally heating, cooling, ventilation, hot water, and lighting), and the other energy-consuming equipment (for example, the computers and appliances used for business, cooking, or entertainment).

People

Factors to consider include how the occupants maintain their buildings; the standards they consider appropriate for the internal environment; the technical services and equipment they bring in; and how they occupy the spaces.

These factors are highly interdependent: for example, the effectiveness of a building envelope will critically depend on how well it is maintained, and the control, maintenance and operation of the technical systems will affect fabric, people and the amount of energy used. The complex system of fabric, equipment and people must be looked at holistically if the use of energy in the building is to be understood and reduced.

Measuring Thermal Performance

To fully understand how the building envelope is performing, measurement will sometimes be needed. A variety of techniques and equipment can be used; few are technically challenging, though all demand some expert interpretation. Expertise may also be needed to judge which factors are critical: for example, draughts can be a major source of discomfort, and therefore put greater occupant demands on the conditioning systems, but they do not necessarily originate from air leaks; many are triggered or exacerbated by local heating or cooling (cold air returning over the floor to replenish the hot air rising from a radiator or convector, or downdraughts from tall, cold window surfaces).

Measurements can be made at three levels: basic (typically spot checks made with relatively easy-to-use equipment); intermediate (requiring more time or preparation, or more elaborate equipment); or advanced (often needing specialist equipment and expertise, and possibly disruptive and time-consuming). Only rarely will the answer to the questions being asked be so critical as to require advanced assessment.

The table below summarises some of the main methods used to measure air infiltration, heat transfer and radiant heat exchange when assessing the thermal performance of the envelope for an energy assessment; more details of measurement and monitoring can be found in the main text (**Assessing the Building Environment**).

MEASUREMENT TECHNIQUES

GENERAL COMMENTS	BASIC	INTERMEDIATE	ADVANCED
AIR INFILTRATION			
Occurs not just through doors and windows, but via holes and cracks, where window and door frames meet the walls, between floorboards and often behind skirtings	Hand-held smoke sticks or chemical smoke puffers; note that there may be constraints on using these in some historic interiors Dry ice	Fan pressure testing can quantify the infiltration rate and allow targets for improvement to be set; specialists can usually make tests within a few hours, even on large buildings Pressure testing is also valuable in the course of alteration work, to establish quality standards and to identify any remaining sources of leakage	Tracer gases or smoke tests to find rates and routes of air circulation (latter will require smoke detectors to be switched off, and neighbours and fire authorities to be alerted) All smoke generators leave deposits on surfaces, and so smoke tests may not be possible in sensitive historic interiors
HEAT TRANSFER THROUGH THE FABRIC			
Tests here can be useful, but are only practicable in cold weather, typically November to February U-values are not constant, but will vary with moisture, wind and solar radiation	Checks of the thermal envelope can be made with an infrared camera, which can draw attention to areas of excessive heat loss Interpretation is challenging and needs care, especially when looking at glass and metal	Heat-flux sensors attached to the surface of the fabric at typical points, to monitor heat movement; to calculate U-values, exterior and interior temperatures must also be measured Will usually take several weeks for readings to become steady enough for an assessment of thermal transfer	Co-heating tests, which measure the energy used to keep a building at typically 25°C, are best suited for research, as the process takes several weeks (during which the building cannot be occupied) Cannot be used if the building fabric or contents are sensitive
RADIANT HEAT EXCHANGE			
The loss or gain of radiant energy from occupants can be difficult to measure accurately, because not all the surfaces in a room will be at the same temperature	Empirical (sensation of heat loss)	Infrared cameras	Black-globe thermometer to measure the 'mean radiant temperature' at a particular point, and readings used to determine the 'operative temperature' (weighted average of air temperature and mean radiant temperature, with allowance for air movement)

The review of the energy use and equipment should include:

- annual energy consumption, by fuel and preferably by end-use
- a summary of how the building is managed and maintained, and of how the services and equipment are operated and controlled (both centrally and locally)
- an assessment of each item of energy-consuming equipment: what is there, its size and condition, its appropriateness to the building and the building's uses, and how it is being operated
- a summary of how committed the building occupants and managers are to reducing energy use
- a summary of any opportunities for making improvements, and of possible risks and constraints.

Determining how and where energy is being used will not only make it clear what actions would be likely to reduce consumption most effectively, but could also draw the attention of occupants to wasteful practices and habits, obtain their detailed feedback, and trigger simple and effective behavioural improvements.

Limitations on thermal imaging

Imaging glass is particularly difficult: glass is opaque to infrared, and it is also highly reflective. It is perilously easy to over-interpret thermal images of façades: here, the same windows imaged twice in quick succession on the same camera show a wide variation in 'surface temperature' readings, due almost entirely to reflectivity.

Inaccuracies must be minimised as far as possible by controlling how and when the image is taken, by processing the images with care, and finally by interpreting the results in the light of a good understanding of how building systems behave.

CHECKLIST: INCREASING THE THERMAL RESISTANCE OF WALLS

ACTION	GENERAL COMMENTS	OTHER CONSIDERATIONS
SIMPLE ACTIONS		
REPAIR (INCLUDING REPOINTING & REPAIRS TO PERMEABLE RENDERS)	Appropriate repairs will improve airtightness and water penetration (a dry wall will transfer much less heat); the materials volumes in this series give information about the repair of walls of various types	The correct intervention depends on the materials and construction of the wall; but permeable materials such as lime mortars and renders should always be used Consider replacement of impermeable renders and mortars where practicable
INTERMEDIATE ACTIONS		
RENDERING	Applying a permeable render can benefit both solid and cavity walls Renders will cut air infiltration and water penetration Dry walls have much more thermal resistance	Use only permeable materials such as lime-based mortars; additives such as hemp can increase insulating capacity Rendering will alter the appearance of the building Many older buildings were rendered in the past, so there may be a precedent in historic records
PLASTERING	Applying a permeable plaster can benefit both solid and cavity walls	Use only permeable materials such as lime-based mortars Additives such as hemp can increase insulating capacity
INTERIOR HANGINGS OR PANELLING	Lining the interior with thinnish sheets of permeable material, battened off the wall, will improve thermal response and reduce radiant heat loss	There will be an impact on appearance, and some reduction in the usable area of the room; panelling may be difficult to detail around original features such as decorative cornices It is wise to design panelling to be easily openable to check the condition of the wall behind

External wall insulation will have a serious impact on a building's appearance, though if a façade is in poor condition it may sometimes be possible to incorporate the measure into a sensitive programme of improvement or restoration.

External insulation carries a high technical risk, and so must be meticulously well designed and installed. The loss of water-shedding details such as drip mouldings can lead to water ingress, and leaks may occur at eaves and cills, and around pipework (note the water stain at the corner of the window here). This is of great concern since the insulation will also reduce evaporation from the wall, and may hide signs of water problems until they are very well established.

CHECKLIST: INCREASING THE THERMAL RESISTANCE OF WALLS

ACTION	GENERAL COMMENTS	OTHER CONSIDERATIONS
CHALLENGING ACTIONS		
INSULATION	Demands careful design, correct choice of materials, good detailing and extremely high standards of workmanship Methods and materials will vary according to type of wall, and whether it is being insulated externally, internally or by filling a cavity Great care must be taken to eliminate all possible moisture sources from the wall before works begin Internal and external wall insulation will hide the condition of the wall beneath, so it is wise to consider installing time-of-wetness sensors or other moisture monitoring to reveal problems should they occur	
	INTERNAL WALL INSULATION	
	Permeable, hygroscopic insulation would normally be preferable Thickness may need to be limited to reduce condensation risk Significantly reduces interior floor space, which can be problematic in small rooms Installation requires the occupants to vacate the building Tends to cause problems of thermal bridging	To limit thermal bridging, partial insulation may be necessary to upper floors, partitions and party walls where these meet the insulated wall Internal services, including electrical wiring and heating pipework, may need to be rerouted
	EXTERNAL WALL INSULATION	
	Where space is available, exterior wall insulation can safely be made much thicker than interior wall insulation Advantage can be taken of the thermal mass of the wall to help buffer temperature fluctuations and reduce risks of summer overheating if night ventilation is adequate Can be installed while the building remains in occupation Presents fewer problems with thermal bridges than internal wall insulation Insulation must be protected from the weather by a render, or some other protection such as cladding, or hanging tiles or slates	Carries a significant risk of inducing or exacerbating liquid-moisture problems External pipes, gutters and other services will usually need to be removed and altered before replacement Detailing (especially around openings, and at cornices and eaves) must be meticulous, since any water entering from leaks or condensation will be trapped behind the insulation; problems may go unnoticed until they become very serious
	CAVITY WALL INSULATION	
	Increases the thermal resistance of the wall, but does not affect its appearance Least risky in dry, sheltered areas; caution is needed in sites prone to driving rain Loose fill materials should be used rather than foam to give some potential for extraction (which is still extremely difficult) Cavity walls can also be insulated internally or externally	Carries a significant risk of inducing liquid-moisture problems If the cavities open into the roof space, they must be closed Borescope investigations should be made to locate moisture sources, and thermal and moisture bridges; these must be dealt with before insulation Not suitable for cavity walls bonded with bricks Always use reputable contractors, and obtain appropriate insurance-backed warranties
	INSULATION OF FRAMED CONSTRUCTION	
	Sometimes possible when cladding or interior finishes are removed for maintenance Options are similar to those for insulating roofs at rafter level	If insulation is entirely within the framing, the frames will act as thermal bridges; it is therefore best to combine insulation between the framing with a complete skin of render or insulation (preferably on the exterior)

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