Moisture in buildings: an integrated approach to risk assessment and guidance

Neil May and Chris Sanders

bsi.

Contents

List of figures

Preface

It is recognized that moisture can damage the structure and internal environment of buildings. British and European Standards support the relevant legislation, regulations and statutory guidance in this field (such as Approved Documents in England and Wales). They are sometimes directly referenced in certification processes and in guidance documents.

Until recently, most standards for buildings have been primarily concerned with the design and construction of new buildings. Less attention has been paid to the increasingly important fields of retrofit and the renovation of existing buildings, especially older, solid-wall buildings, where issues of moisture movement and risk are of a different nature from those found in new cavity construction.

Historically, types of moisture have been divided into discrete categories such as driven rain, flooding and condensation. In reality, however, these types often overlap and interact.

There are also new challenges arising from the changing ways in which buildings are being constructed, retrofitted and lived in, particularly regarding attempts to create low-energy buildings with increasing amounts of insulation and airtightness.

Problems can also arise from lack of data and research on moisture issues in buildings, and the inherent complexity of interactions between climate, building fabric, services and occupant behaviour.

This paper has been prepared by the Sustainable Traditional Building Alliance (STBA), with the support of the former Department of Energy and Climate Change (now the Department for Business, Energy and Industrial Strategy) and is published by the British Standards Institution (BSI). It offers a new framework for the development of future moisture standards, and guidance and practice that addresses the challenges of moisture risk. It suggests an integrated and safe approach to moisture risks in buildings for the future. It has been created to stimulate and assist discussion in revising existing standards and guidance such as BS 5250:2011, *Code of practice for control of condensation in buildings*.

It should be reiterated that this paper is only a framework for the future development of standards and guidance, and not a standard or guidance per se. As such, it is not endorsed by BSI and should not displace any existing standards. The framework suggested needs testing, both theoretically and in practice, so that workable and successful formal standards and construction processes can evolve.

The general approach of this paper has been endorsed by academic experts and mainstream practitioners and is backed by considerable research both in the UK and in Europe. As such, it stands as a clear statement of current understanding of moisture risk in buildings: the science, causes and practical approach which should be taken to manage the risk.

Part funded by BEIS.

1. Introduction: changing context and understanding

Inappropriate[1] moisture levels in buildings are considered to be a significant cause of the majority[2] of all building failures, including some building-related occupant health problems.[3] Evidence from research, building owners, occupants, and industry[4] seem to indicate that such failures and problems may be changing and increasing in some areas due to factors such as increased airtightness and insulation, fuel poverty, overcrowding and changing use of buildings.[5] However many factors and their possible interactions are still uncertain. In particular, there is as yet insufficient knowledge of the complex inter-relationship between increased energy efficiency, airtightness, indoor air quality and human health and wellbeing, and the measures set out in this report will not be sufficient to allay concerns in these areas. The measures in this document relate solely to the control of moisture — a real enough problem by itself.

The understanding of moisture movement and moisture risk in buildings has developed considerably in the past few years, although there are still many gaps and uncertainties in this knowledge. Not only have the mechanisms of moisture movement been explored more fully, but the types of buildings and applications being studied have widened (in particular existing retrofitted buildings). At the same time there is a growing acknowledgement of the key role of moisture in the health of occupants as well as in the health of building fabric. Furthermore, the standards to which buildings are constructed and retrofitted are changing, to a large extent as a result of changing energy standards in buildings. The air permeability of buildings is being reduced and traditional walls are being insulated. Building use is also changing, with more sedentary lifestyles and greater moisture production from appliances such as showers and washing machines. Predicted changes due to climate change over the next century, i.e. milder, more humid winters and larger volumes of driving rain, will also tend to increase moisture problems where they occur.

In view of changing conditions and greater understanding, it is apparent that the current approach to moisture issues in standards, regulations and certification is inadequate and requires substantial review and revision. The current approach is based predominantly upon the idea of a building as composed of discrete building elements in perfect conditions, not affected by their interactions with other building elements (fabric and services) or by their context or use. In reality, however, most building elements interact in multiple and sometimes complex ways with one another, occupants and the external environment. Building materials are also affected by changes to their condition over time. The failure of the current approach to deal effectively with this reality has led to significant moisture risks. A new approach is therefore required.

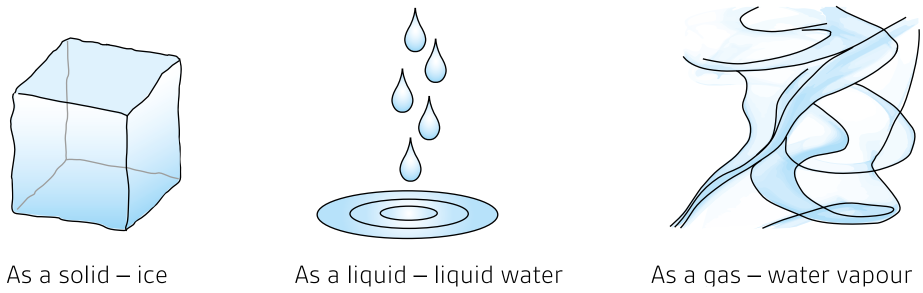
1. What constitutes inappropriate moisture levels is a complex and uncertain issue, which is highly dependent on context. However there is an established connection between certain moisture levels (particularly high levels of moisture as vapour and liquid) and undesirable outcomes such as freeze-thaw damage, surface and interstitial condensation, mould formation, insect infestation and dust mite epidemics. These, in turn, can lead to fabric decay and occupant health problems. See footnotes 2 and 3.
2. Research indicates that 80% of building failure is related to moisture (Kumaraperumal et al., 2006). Interstitial condensation has been identified as increasingly responsible for structural decay and as a result has been recognized in the Building Regulations since 2004 (Kumaraperumal et al., 2006). Also see *WHO Guidelines for Indoor Air Quality: Dampness and Mould* (WHO, 2009): 'Moisture has become a major cause of building damage: it has been estimated (Bomberg and Brown, 1993) that 75–80% of all the problems with building envelopes are caused to a certain extent by moisture'. The Swedish Centre for Moisture (a collaboration of industry, government and academia) makes the claim on its website that 70–80% of all building problems are caused by moisture. See http://www.fuktcentrum.lth.se/english/vision/.
3. (BRE, 2010). The *WHO Guidelines for Indoor Air Quality: Dampness and Mould* (WHO, 2009) make a clear connection between dampness in buildings and a range of respiratory and other problems and that this affects a considerable proportion of buildings: 'A review of studies in several European countries, Canada and the United States in 2004 indicated that at least 20% of buildings had one or more signs of dampness' (Institute of Medicine, 2004). Several studies conducted in the United States estimated the prevalence of dampness or mould in houses to be approximately 50% (Mudarri and Fisk, 2007).
4. See, for example, reports in Inside Housing, http://www.insidehousing.co.uk/repairs/rising-damp/7001375.article?sm=7001375 and http://www.insidehousing.co.uk/home/analysis/breaking-the-mould/7005664.article?sm=7005664, which refer to several reports of increasing moisture related problems in housing, both from fuel poverty and from retrofit of houses. In the recent past there have been very sharp and large rises in many cases. See also recent research by Exeter University (Sharpe, 2015). However, the English Housing Survey 2014 shows a considerable decline in damp problems from 12.8% of all dwellings in 1996 to 4.3% in 2012, the majority of this decline being in water penetration from outside and rising damp. Decline in condensation and mould was much less and is now the main element of damp in housing according to the survey. On the other hand, the recent UK Home Health and Safety Rating Survey figures indicate much higher levels of high risk of damp and mould. Furthermore, detailed longitudinal studies are required as well as investigation into methods and criteria.
5. The *WHO Guidelines for Indoor Air Quality: Dampness and Mould* (WHO, 2009, p.3) lists poorly implemented energy conservation, urbanization (particularly poor housing and inequality), climate change, and the quality and globalization of materials and designs as 'widely acknowledged global trends [which] contribute to the conditions associated with increased exposure to dampness and mould'.

2. Key factors in a robust moisture management approach

The key factors in a new approach to moisture risk in buildings are:

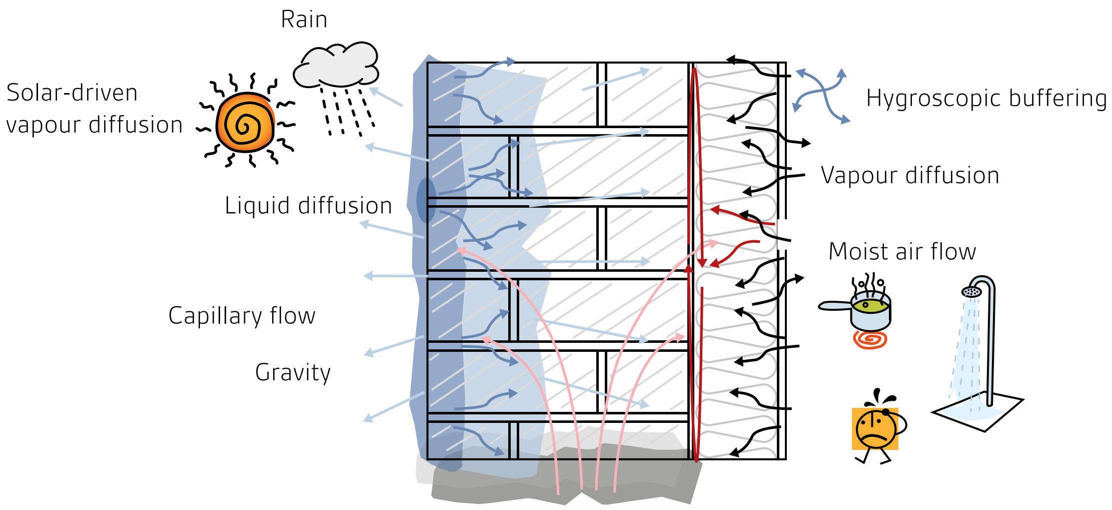
1. Moisture risk in buildings must be related not only to fabric failure but also to occupant health.
2. Moisture risk relates to all states of water as a gas, liquid and solid, and in all locations. For example, interstitial water, surface condensation, relative humidity (RH), the absorption of liquid water, and freeze-thaw effects are conditions that interact and should be considered together, not separately as they often are in standards and regulations. For example, condensation risk is currently treated separately from driven rain risk or flooding.

Figure 1 – States of water



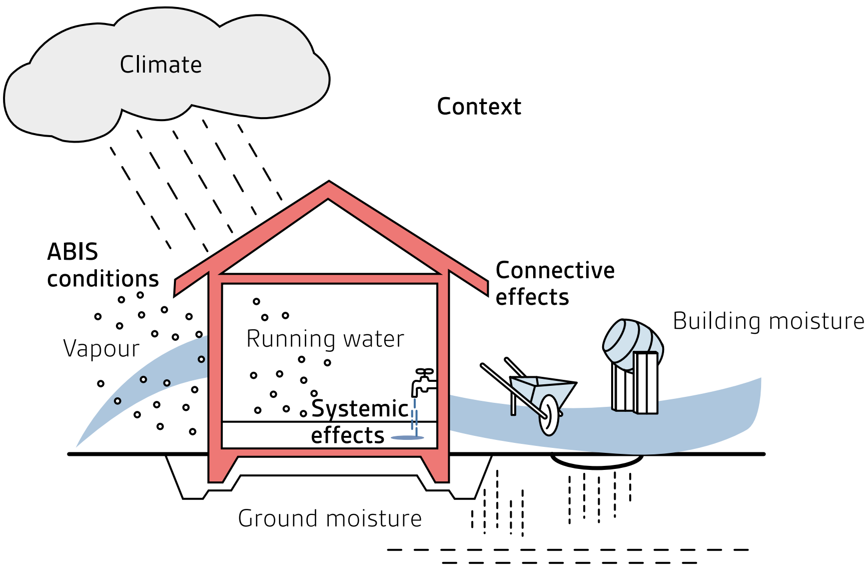
3. Similarly, consideration of moisture risk must take into account mechanisms by which moisture is spread. These include vapour diffusion, liquid flow through material pores, capillary flow, hygroscopic buffering and air movement. Temperature and vapour pressure gradients through materials, due to heat input from solar gain or the occupancy of the building, as well as gravity in certain situations, all affect moisture movement. The interactions between these mechanisms must be considered as part of an integrated dynamic process.

Figure 2 – An example of some of the moisture interactions that can occur together or separately in one situation (internal wall insulation of a solid wall)



4. Moisture problems occur mainly at the junctions between elements and the interfaces between materials. Any approach to moisture risk which does not take this into account is inadequate. These effects are called *connective effects* in this document.
5. Moisture problems also occur at a whole building level, particularly in regard to indoor air quality, but also in relation to fabric condition. This has always been so, but is now far more significant because of the increasing airtightness in buildings. These effects are called *systemic effects* in this document.
6. Moisture risks from systemic effects arise not only from the building fabric conditions but also from planned and unplanned moisture production, heating and ventilation in a building. Any moisture risk assessment and strategy must take these factors into account.
7. Solutions to moisture problems must take into account 'as built' and 'in service' conditions (here called *ABIS conditions*). These are conditions which exist (in existing buildings) or which are likely to exist (in new buildings). The assessment of buildings or building elements under 'as designed' or 'theoretical' conditions (here called *ADT conditions*) can only be a partial risk assessment. ABIS conditions should therefore be the main factor in moisture risk assessment and guidance.
8. Understanding the context of a building is essential for understanding moisture risk and measures to reduce it. Context here means not only the geographical location, orientation and local conditions of shelter, but also the condition and form of the building, its material composition and construction type, and its past and future use.

Figure 3 – Different factors to consider in moisture risk assessment



9. Moisture risk is a human as well as a technical issue. An effective process of moisture risk assessment and design must take into account occupant behaviour and the human interactions between those involved in the design and construction process.
10. Moisture risk is one of many factors that must be considered during the design of a building. Sometimes there will be conflicts between moisture safety and other health concerns, e.g. the presence of Volatile Organic Compounds (VOCs) or radon, and between aims such as energy-efficiency, security, acoustic insulation, and cost. Sometimes there may be no practical solution which meets all concerns and aims (this can be particularly likely in retrofit). In such situations it is essential that compromises are reached which are acceptable on the broadest basis, do not constitute undue risk to the occupant or the building and include the implementation of measures to manage the accepted risk as well as possible.

11. There is considerable uncertainty in regard to many aspects of moisture risk, including moisture risk criteria (for humans and certain fabric elements), material and weather data, interactions between building elements, people and context, moisture mechanisms and physics.[6] Moisture risk assessment and guidance must deal with this uncertainty.

12. Increasingly, greater energy efficiency and comfort are required from buildings. As a result buildings are changing radically as insulation and airtightness are increased. These new conditions require new skills, technologies, understanding, design and use. Moisture risk in airtight buildings is of a different nature to the risk in leaky buildings and creates systemic and connective effects which were previously less common, or unknown. We need to deal with this new situation not only by acknowledging uncertainty, but by building learning and moisture awareness into the guidance and regulation of all aspects of buildings, not only in standards and regulations specifically related to moisture.

3. Current standards and regulations for moisture risk assessment and guidance in buildings

3.1 Regulations and standards

There are a large number of regulations, standards, guidance documents and sources of information covering issues surrounding moisture risk in buildings. These can usefully be divided into three categories (A–C), which form a hierarchy.

A. Regulations and standards which specify the methods needed to minimize moisture risks in new-build and retrofit

The four sets of Building Regulations in the UK[7] contain requirements that the building fabric and the health of the occupants should not be affected by moisture from the ground (including flooding), wind-driven precipitation and surface or interstitial condensation. It is significant that these three requirements, and the subsequent guidance on how to meet them, are dealt with separately. There is no recognition of the fact that moisture from a number of sources may enter a building and interact, causing problems not directly dealt with by the separate areas of regulation and guidance.

Approved Document C (DCLG, 2013) is the published guidance document for ways of meeting Regulation C2, Resistance to moisture. English regulations and the equivalent Scottish, Irish and Welsh regulations describe detailed measures that can be taken to combat moisture from the ground and driving rain. Surface condensation and mould growth are simply covered by reference to a fall-back U-value and use of robust construction details. The issue of interstitial condensation is covered by reference to BS 5250:2002.

Approved Document F (DCLG, 2010), and the equivalent sections of the other UK countries' regulations, includes design guidance for the provision of minimum ventilation for the people inside buildings, and for reducing the risks of surface mould growth. However the guidance given is very general, and is aimed primarily at new buildings and not retrofit, which presents a more complex situation. The criteria for mould growth consider only conditions that are typical for internal surfaces. The applicability of these criteria to other surfaces and conditions (such as those that occur interstitially) has not been assessed yet. Approved Document F gives design guidance for four principal ventilation strategies, from natural through to continuous mechanical with heat recovery. Other ventilation strategies available on the marketplace, which in some situations may be better suited to surface mould control, are not explicitly covered by the Approved Documents.

BS 5250:2002 has been superseded by BS 5250:2011. However, the technical content has not changed significantly. This contains discussion of the principles of moisture movement and condensation in buildings and a discussion of

6. (Pollack, 2013).

7. England: Approved Document C, http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partc/documentc

Scotland: Scottish Domestic Technical Handbook,
http://www.gov.scot/Topics/Built-Environment/Building/Building-standards/techbooks/techhandbooks/th2015dom-complete

Wales: Approved Document C, http://gov.wales/topics/planning/buildingregs/approved-documents/part-c-moisture/?lang=en

Northern Ireland: Northern Ireland Building Regulations Technical Booklet C,
http://www.buildingcontrol-ni.com/assets/pdf/TechnicalBookletC2012.pdf

the different types of floors, walls and roofs, providing prescriptive advice and, where relevant, recommendations for the use of calculations of condensation risk to provide further guidance. However, in spite of the discussion of wider moisture issues, the sections on building elements are concerned only with plane elements, and not connective or systemic effects. Furthermore, the guidance given in these sections on building elements does not, on the whole, account for ABIS effects such as building faults and in-service degradation. The calculation procedure specified is the simplified method in BS EN ISO 13788. BS 5250:2011 only briefly mentions the advanced calculation methods in BS EN 15026. BS 5250:2011 is currently being revised to include more detailed recommendations for calculation techniques to use in different circumstances.

The Building Research Establishment (BRE) Document BR 262 (BRE, 2002) provides very comprehensive guidance on the types of problems, including those related to moisture, which may occur when thermal insulation is added to buildings. It was last revised in 2002, so needs revision and updating in the light of new understanding and best practice in several aspects (for example in internal wall insulation).

B. Calculation methodologies which can be used to assess the performance of elements and buildings

There are two calculations which can be used to assess the risks of moisture problems and develop remedies.

BS EN ISO 13788 specifies the methodologies for calculating a) the risk of surface condensation and mould growth and b) a simplified calculation of 'interstitial condensation'. The method is commonly known as the 'Glaser method', after its originator.

The Glaser method makes a number of important assumptions:

- The analysis is purely 1D. 2D or 3D effects are ignored.
- Moisture transport is by vapour diffusion alone.
- There is no storage of moisture within components.
- The transport properties of the materials are not affected by their moisture content.
- The internal and external conditions are constant for a month.
- 12 calculations using the monthly mean conditions are carried out and the accumulation and evaporation of any condensate calculated over a year.

These limitations are clearly stated in the scope of the standard with the conclusion that 'Consequently the method is applicable only where the effects of these phenomena can be considered to be negligible'.

All the phenomena excluded from the scope of BS EN ISO 13788 contribute to the performance of many structures, especially traditional masonry walls, both before and after insulation. They also contribute to the 'in-service conditions' of all buildings. The moisture transport properties of stone and the thermal conductivity of insulation are strongly dependent on moisture content. Liquid water moves through porous materials, such as sandstone and wood, under moisture concentration gradients, with transport coefficients which are very strongly dependent on moisture content. While air movement through solid stone walls is not likely to be important, air leakage from the interior to locations behind wall lining systems, such as lath and plaster, may transport much more moisture into the system than all other processes combined. All the materials in traditional walling are hygroscopic and take up moisture from the surrounding air, depending on the ambient RH.

BS EN ISO 13788 does not take into account the diurnal variation of internal and external climate, solar radiation and longwave radiation loss on the outside of buildings, and, very importantly, does not allow for the impact of wind-driven rain (WDR) on the outside. To remedy these deficiencies, a further standard was developed to cover 'full' modelling of the hygrothermal performance of structures.

BS EN 15026 specifies a system of equations to allow the calculation of non-steady heat and moisture flows through a structure made up of a number of different materials with multiple transport properties. The scope of the standard states:

> *This standard specifies the equations to be used in a simulation method for calculating the non-steady transfer of heat and moisture through building structures.*
>
> *It also provides a benchmark example intended to be used for validating a simulation method claiming conformity with this standard, together with the allowed tolerances.*
>
> *The equations in this standard take account of the following storage and one-dimensional transport phenomena:*
>
> - *heat storage in dry building materials and absorbed water;*
> - *heat transport by moisture-dependent thermal conduction;*
> - *latent heat transfer by vapour diffusion;*
> - *moisture storage by vapour sorption and capillary forces;*
> - *moisture transport by vapour diffusion;*
> - *moisture transport by liquid transport (surface diffusion and capillary flow).*
>
> *The equations described in this standard account for the following climatic variables:*
>
> - *internal and external temperature;*
> - *internal and external humidity;*
> - *solar and longwave radiation;*
> - *precipitation (normal and driving rain);*
> - *wind speed and direction.*
>
> *The hygrothermal equations described in this standard shall not be applied in cases where:*
>
> - *convection takes place through holes and cracks;*
> - *two-dimensional effects play an important part (e.g. rising damp, conditions around thermal bridges, effect of gravitational forces);*
> - *hydraulic, osmotic, electrophoretic forces are present;*
> - *daily mean temperatures in the component exceed 50 °C.*

The assessment methods specified in BS EN 15026:2007 are implemented in a number of commercially available software packages, but the most widely used is WUFI (an acronym of the German for transient heat and moisture: *Wärme und Feuchte instationär*).

Theoretically, BS EN 15026 covers most known material properties, climate issues and moisture mechanisms and as such is appropriate for all constructions, particularly where there is significant moisture storage or where the outer surface may absorb driving rain. However it does not cover the following:

- Airflow. This means it is less relevant to assessments of structures in which moisture movement is dominated by airflows, e.g. pitched roofs. Airflow may also be a significant factor when there is unintended air leakage into any building element.
- 2D issues (i.e. reveals, junctions). As many of the most significant issues require 2D modelling, calculations according to BS EN 15026 cannot be said to cover all or even the most important moisture risks.
- ABIS conditions or building faults in construction internally or externally where unintended moisture ingress occurs (this applies to both new and existing buildings).
- Assessment of the effect of hygroscopic materials on indoor RH (which can affect both the moisture condition of fabric elsewhere, as well as human health and comfort).[8]

8. This is also called 'moisture buffering'. The term expresses the way materials absorb and desorb moisture at different relative humidities in order to achieve their equilibrium moisture content. In this way they can also remove humidity from the air and reduce RH. They can smooth out peaks and troughs of RH which can be very important in preventing RH from crossing mould formation thresholds, as well as providing a more comfortable and stable indoor atmosphere. Certain materials, such as natural fibres and unfired clay materials, have much greater hygroscopic qualities than others.

There is no clear protocol for the use of BS EN 15026, which means that different users of programmes may use different parameters and assumptions and produce widely varying results.

It should however be noted that there are non-standardized models available which incorporate airflow, 2D issues and ABIS conditions such as the software DELPHIN, WUFI and WUFI 2D, utilizing the method set down in ASHRAE 160 (ASHRAE, 2009). These issues are currently under review for the next revision to EN 15026. The use of non-standardized modelling can be very helpful in identifying moisture risk, as suggested in this standard, but not fully determining it. The future standardization of these processes is to be welcomed.

The minimum internal surface temperature, which determines the risk of condensation or mould growth at2D or 3D junctions (commonly known as thermal bridges), can be calculated using the methods specified in BS EN ISO 10211 and BR 497 (BRE, 2016).

C. Sources of the material properties and climate data necessary to run the calculation techniques

The material properties needed for the BS EN ISO 13788 model, and some of those needed for the BS EN 15026 model, can be measured with the standardized methods summarized as follows.

BS EN ISO 12572 specifies the measurement of the water vapour resistivity of a material or the resistance of a product, which is one of the two parameters needed for the BS EN ISO 13788 calculation methods. The standard can be used to derive the variation of resistivity with imposed humidity, a key parameter in the BS EN 15026 method.

BS EN ISO 15148 specifies the measurement of the rate at which water is absorbed into a material, when the surface is in contact with liquid water. This determines the degree to which driving rain is absorbed and is a key parameter in the BS EN 15026 method.

BS EN ISO 12571 determines the equilibrium moisture content of hygroscopic materials as a function of the ambient RH and is a key parameter in the BS EN 15026 method.

BS EN ISO 10456 contains tabulated values of the density, thermal conductivity, specific heat, and water vapour resistance factor at low and high imposed humidities for a wide range of materials used in construction. These properties are all essential to BS EN 15026 methodology.

It is important to note that many existing buildings, especially pre-1945 buildings, contain materials which currently do not, or cannot, have standardized qualities. This is partly due to the variable nature of natural materials such as stone, clay and timber, and partly due to the more localized, small scale and sometimes handmade nature of production. Particular care is required therefore in the assessment of the material qualities of old buildings. Even within a single building there may be very different qualities even for similar materials (such as brick, stone, mortar, timber). This uncertainty is one reason why assessment must not be over-reliant on modelling, but must prioritize the principles in Section 4 of this document.

3.2 Guidance

Standards for moisture risk assessment and guidance have previously relied upon an elemental approach using prescriptive advice based upon experience, or standardized modelling (mainly BS EN 13788). Within moisture standards such as BS 5250, and documents such as BR 262 as well as Accredited Construction Details, there are also lists of relevant principles, which, taken as a whole, cover nearly all the key factors listed above. There are therefore three primary ways in which moisture risk assessment is made in the standards:

- Prescriptive guidance: based on experience in commonly used applications where there is good evidence of success over many years. Much of BS 5250 is of this nature (for example in the section on ventilated roofs). Accredited Details are another type of prescriptive guidance for some connective effects. BR 262 also contains useful guidance for moisture risks due to thermal insulation with prescriptive advice (although some of this guidance is out of date and needs revising).

- Modelling: where there is uncertainty in regard to experience, but sufficient certainty of data and parameters. Standards ISO 13788 (steady state, only considering water vapour) or BS EN 15026 (dynamic, all water states, but only 1D and not including air movement or ABIS effects); also for some connective effects the standard EN 10211.[9]
- Principles-based assessment: where there is uncertainty in regard to experience, and data and/or parameters. Principles are well explained in BS 5250, BR 262 and in Accredited Details, but are not formalized or integrated into the process of design, which is still primarily based upon a building elements approach.[10] Principles-based assessment is not the same as prescriptive guidance, as it requires understanding and judgement by the person assessing the building element as well as an acknowledgement of the limits of guidance and the need for ongoing care.

There are several sources of guidance on the principles underlying moisture problems in buildings, modelling and assessment methods and so-called robust details. However the problem lies in communicating them to and getting them accepted and implemented by an industry which has both very different priorities and a low level of on-site expertise and quality control. Public policy has concentrated on reducing ventilation and increasing insulation levels in housing and other buildings, to save energy and reduce the cost of heating. There has been no corresponding awareness of the associated increased risks to the health of the occupants and damage to the building fabric caused by moisture.[11]

3.3 Consequences for certifications, insurance, training, site practice, etc.

The lack of integration of moisture issues in the different standards as well as the incompleteness and inherent uncertainty of the modelling standards have significant consequences for building design, construction, repair and use. Systems of testing, certification and insurance based on standards (which although voluntary have been widely adopted) have to a large extent determined actual design and construction, as well as product development and availability (and product exclusion), building repair and maintenance and building management and use. The effects of this are considerable, particularly in the areas of least certainty and understanding such as the retrofit of existing buildings. It is essential that standards are integrated, errors and gaps are minimized and that uncertainty and complexity of interactions are addressed in a new approach to moisture risk and design.

4. Limitations of knowledge

In addition to the limitations of the current standards it is important to understand the limitations of knowledge in regard to moisture risk and design in buildings. These limitations can be categorized under the following headings:

(a) Material properties and weather data

(b) Building physics

(c) Human behaviour

(d) Interactions

(e) Designer and contractor understanding

It should be noted that not all of these limitations are equally problematic. Some, such as weather data, could be made available through the Met Office relatively quickly. Others, such as the properties of traditional materials, require extensive programmes of research and testing. The interactions of moisture (not to mention other,

9. It should also be noted that there are many non-standardized modelling approaches which do incorporate connective and ABIS effects. However they are not subject to standards at present.

10. In regard to driven rain assessment the standard BS 8104 is one of the few examples of a process which takes geographical context fully into account through orientation, topographical features and shelter (although it is using out-of-date weather data). It also looks at the building shell as a whole, and not as a sum of its different elements. However, it only deals with driven rain impact and context is only one principle; as such BS 8104 can be part of a wider principles-based approach, but not in any sense a complete approach.

11. See for example the conclusion (paras 79–81) of the final report by UCL and Leeds Metropolitan, published by DCLG in 2011 (Oreszczyn et al., 2005) which, in paragraph 80, states that although some of the robust details examined are adequate and accurate, 'The findings of the fieldwork suggest that the house construction industry is not able to produce, with any degree of consistency, construction that is well designed and achieves the performance required of robust construction. The failure is not a question of one or two developers and their subcontractors making errors but a failure at the systems level, involving the whole industry including developer, designer, constructor, regulator and materials & component suppliers.' The reasons given for failure are to do with knowledge, approach, training, and variability of buildings from the 'book details'.

non-moisture related agents) with human health are so complex that high levels of uncertainty will remain in this area for many years. A new framework for moisture risk assessment and guidance should therefore embed a learning and feedback process in design, construction and use, so that regulations and standards can be improved as knowledge increases in different areas and at different speeds.

(a) Material property and weather data

- Building materials of existing buildings: there is a significant lack of data relating to the hygrothermal qualities of existing buildings. This lack of data, as well as inherent uncertainty, increases in natural and locally made materials and particularly in handmade products. Some materials also change their qualities over time and under different conditions.
- Existing building construction, particularly in pre-1919 solid wall buildings is very variable. The types of masonry, mortars and plasters and the amounts of voids can vary considerably.
- Weather data: neither regional nor site-specific data is available freely. Weather variations over small distances can be very significant to driven rain impact.
- There is very little data about building performance (energy use, internal RH) and building element performance of existing buildings.

(b) Building physics

- Moisture movement within materials is still subject to considerable uncertainty, not only because of the lack of material data, but because the physics of moisture storage and movement in porous materials itself is highly complex and is still a developing science.
- The understanding of airflows in buildings is highly complex and cannot easily be modelled; also the magnitude of the airflows, which determines the moisture transport, is highly variable from case to case as it is dependent on adventitious cracks and gaps in the fabric.

(c) Human behaviour

- There is very little research on how people react to moisture risks (i.e. how people ventilate their buildings when there is high RH, or how they deal with maintenance of leaking gutters or windows) and particularly to changing environments (for example the behavioural changes that can occur when an existing building is retrofitted). This means that projections about moisture risk and behavioural responses are largely based on assumptions not on real evidence.

(d) Interactions

- The physical interactions between different moisture conditions internally and externally with the form, materials and ventilation of buildings are complex and currently cannot be modelled.
- The interactions between human behaviour, human health, moulds, mites, bacteria and moisture in buildings are also highly complex and dependent on multiple contextual factors including the age, health and culture of the occupants, the level of occupation, the location of the building, its condition etc.

(e) Design and contractor understanding

- There is very little understanding of moisture physics, moisture safe design, or issues around moisture in construction in the industry due to the low profile of this issue and the assumption that moisture risk is adequately covered by current standards.
- Generally there is very little feedback to designers and contractors from actual projects as to delivered building performance of any kind, but particularly in regards to moisture risks and effects. This is partly due to the lack of understanding in occupants as to the causes of moulds, fabric decay etc., and partly due to the fact that many moisture problems take many years to manifest themselves.

5. A new approach

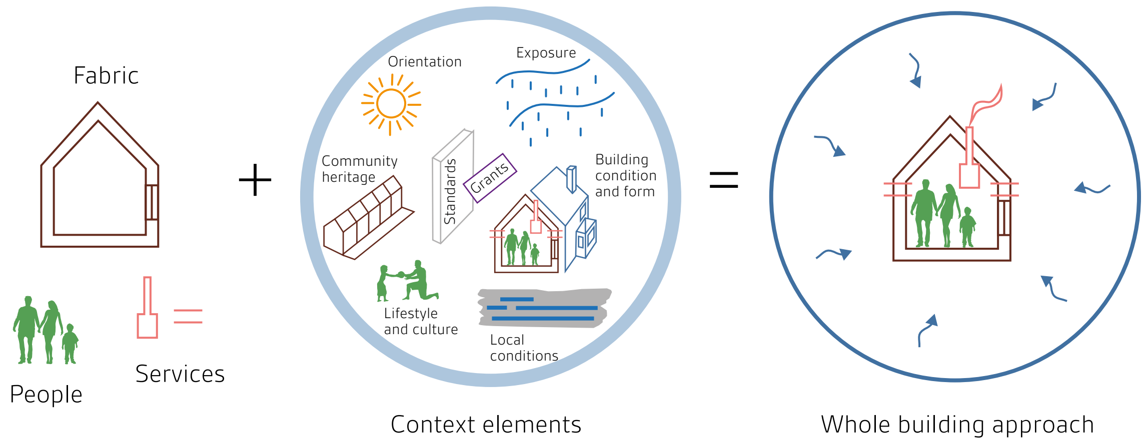
As shown in Section 3, current standards fail to address the key factors outlined in Section 2 and require substantial revision. However the limitations of knowledge identified in Section 4 mean that it is not possible to move to a new set of standards at the present time. It may never be possible to eliminate considerable uncertainty and risk in this area. A new approach is required which deals with the complexity and uncertainty in a low-risk way.

This white paper proposes that the way forward is to take a principles-based, whole-building approach to tackling moisture risk, using a joined-up process. The whole-building approach is based upon principles with support from prescriptive guidance and modelling where these are appropriate and useful.

- *The whole-building approach*. The whole-building approach takes into account the interactions between fabric, services and occupants in the context of the building or buildings under consideration.

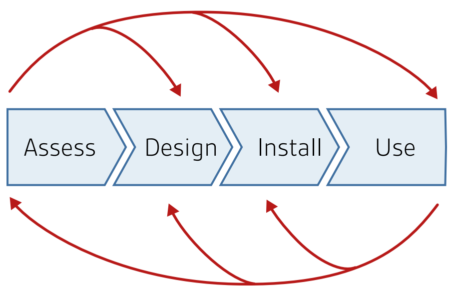
  Note that context here refers not only to the geographical place, but also to the history and future of the building, the condition and building form, and the lifestyle and culture of the occupants. The whole-building approach meets the requirements of the first eight key factors in Section 2, provided that the principles in Section 6 are followed.

Figure 4 – The whole-building approach



- *The joined-up process*. The joined-up process integrates assessment (planning), design, building and use in a way that ensures communication, feedback and learning.

Figure 5 – The joined-up process

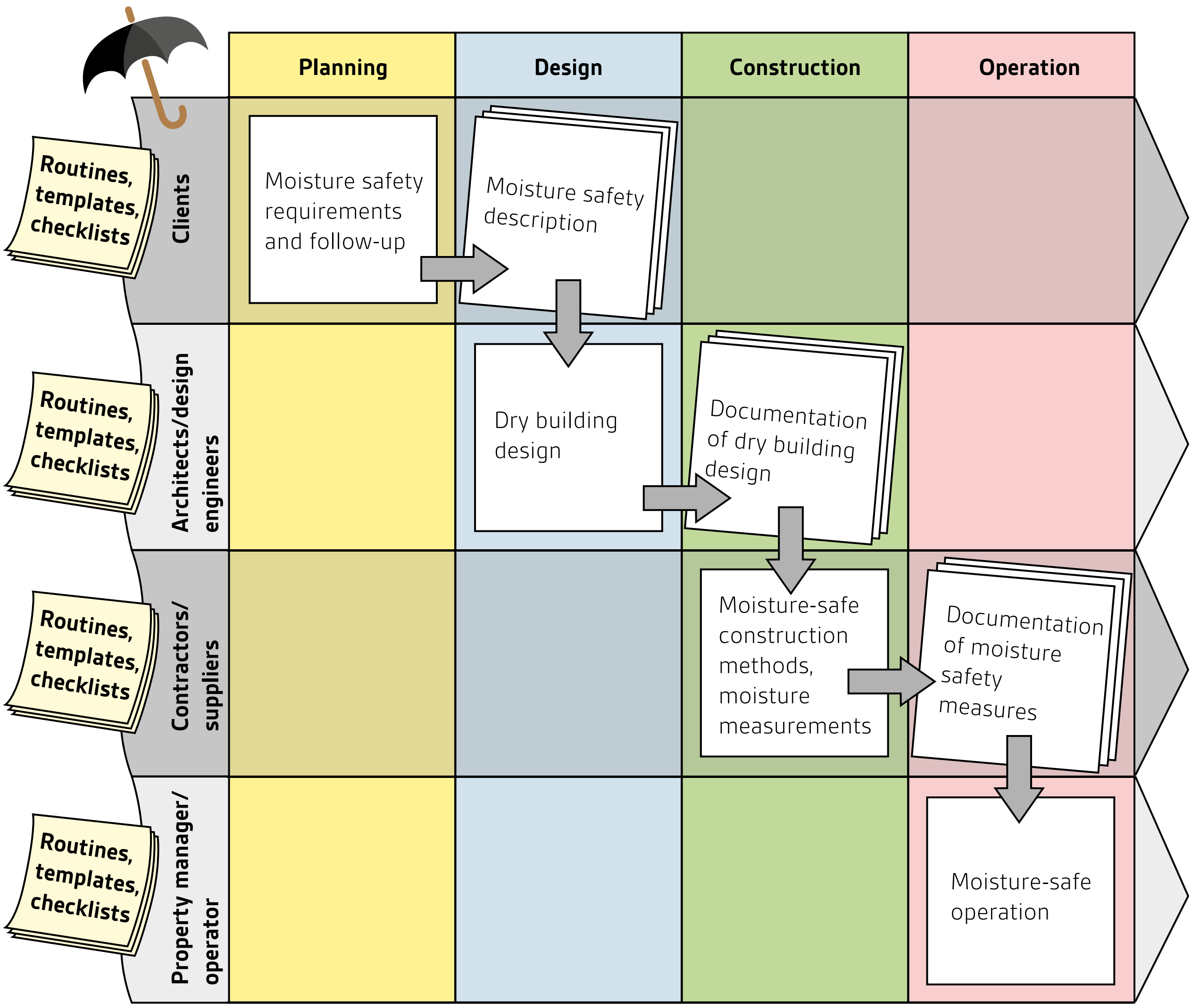


As noted in Section 2, key factor 9, moisture risk and guidance is as much a human as a technical issue. Moisture risk assessment, aims and strategy need to be balanced against other key design aims, and be part of an ongoing discussion and feedback process throughout a building project (key factor 10). Uncertainty (key factor 11) must be actively managed through caution, learning and feedback. Establishing the correct process for moisture risk assessment, design and management is therefore essential. This needs to be integrated into all parts of the assessment, design, construction, use and maintenance of the building, with feedback from each part of the process.

The integration of moisture risk process into the planning, design, construction and operation of a new building under the Swedish ByggaF method[12] is shown in Figure 6. The diagram here is specifically for a commercial building but can be used or adapted for other types of buildings including renovation of existing buildings.

The ByggaF method suggests that there is a formalized process ensuring that moisture risk assessment and strategy is carried through into moisture safe design, construction and operation. It is suggested that a Moisture Safety Expert is a key member for this and of the Planning/Assessment and Design team, whose work continues throughout the process until handover. The expert can be a trained architect, designer, technician, surveyor or engineer and not necessarily an additional member of the existing design team. In addition a Moisture Safety Officer should be a key member of the construction team, liaising with the Moisture Safety Expert and dealing with both the planned

Figure 6 – A schematic description of the ByggaF method



12. See the following documents. For a full list contact the authors of this white paper.
(Mjörnell et al., 2007, Mjörnell and Arfvidsson, 2008, Mjörnell et al., 2012, Mjörnell, 2014).

construction process as well as unforeseen design and construction issues on site. For this reason, both of these team members need to understand the principles of moisture safety, how to deal effectively with them and how to integrate them into other aims of the project (such as energy efficiency, security, acoustic insulation). This situation will be even more critical in renovation or non-standard buildings where unforeseen situations can occur more frequently.

It is suggested that a similar process and similar roles should be adopted for building projects in the UK. This will substantially reduce moisture risk in all building projects as well as improving the quality of buildings generally. On small projects (such as single building new-build, renovation or extensions) this role may be taken by a designer, an external consultant or by a trained contractor.

Responsibility and liability for overall moisture safety on a project should be clearly allocated to a single individual or company; this will always be the Moisture Safety Expert where such a role is involved. In other cases the trained contractor, designer or consultant in charge of moisture safety will take on this responsibility.

The requirement for experts or contractors trained in moisture safety will not be necessary for works on buildings where no alteration to overall moisture risk or performance can occur, or in applications where prescriptive guidance is considered sufficient for all moisture risks including ABIS, connective and systemic effects as described in this new assessment framework. In such cases, however, responsibility for moisture safety must still be allocated to a single individual or company.

For this joined-up process and whole-building approach to function, the principles of a whole-building approach to moisture risk and moisture safety must be fully understood by the Moisture Safety Expert and Officer, or other responsible person or company. It must be embedded in the design and construction processes. The principles should be at least partially understood by all others involved in the construction and by the owners and occupants of the building. The proper communication of why moisture risk occurs and how to manage it is the responsibility of the Moisture Safety Expert and Officer or other trained responsible person or company, but is also a task for government and support agencies in the education of the public and industry generally. The principles of the approach are the subject of the next section.

6. The principles of a whole-building approach to moisture

A whole-building approach as explained in Section 5 must integrate fabric, services and people and place them in context while also dealing with uncertainty. In regard to moisture risk this approach can be broken down into four principles.

The key principles are:

1. Understand the **context** of the building and the building project and ensure **compatibility** of the design with this context.
2. Ensure **coherence** in approach and detailing.
3. Build in **capacity** in the design and construction phase for mistakes, uncertainties and future challenges.
4. Ensure that **caution** is taken in the use, maintenance and after care phase where there are ongoing requirements of care and uncertainty of outcomes.

The joined-up process deals with the need for integration between stages in a building project, allows for conflicting priorities and values to be resolved or managed and ensures learning and feedback.

The different aspects of each of the principles are explained below, including practical measures that need to be taken to address the issues raised by each aspect.

6.1 Context and compatibility

General principle

It is essential to understand the context of a building project and then ensure that the project is compatible with this context. Context refers not only to location and surroundings but to the planned use of a building, the available skills and supply chain, and any financial constraints. In this document the issue of skills, supply chain and finance are covered only briefly under the heading of capacity, as context is primarily being considered in terms of design.

In relation to the repair, renovation or retrofit of existing buildings, the context is to some extent wider than in new-builds as it includes all new-build contexts and also the existing building itself, its form, construction and condition.

New-build and retrofit contexts can vary over time and for this reason sufficient capacity and caution should also be exercised to ensure future changes to context do not introduce new major moisture risks at a later stage.

It should be noted that moisture risk assessment and measures have to be set in the context of other aims of the building project, such as providing energy efficiency, cost effectiveness, beauty, heritage and comfort. Even though health is a major reason for moisture measures, there may be conflicts between measures for moisture protection and other measures for the control of toxins (such as radon or traffic pollution, for example). Any moisture strategy, therefore, has to be integrated into these other aims and a holistic and whole-building approach adopted in a joined-up process.

Geographical context: location, orientation, local exposure

Primary principles

The understanding and assessment of location, orientation and local conditions are essential to understanding moisture risks from driven rain, flooding, wind and solar effects.

Practical measures

The site should be located on the driving rain map in BR 262 or Approved Document C to determine the overall exposure. In critical cases, the detailed driving rain maps and the assessment methodology in BS 8104 should be used to allow for local variations in topography, sheltering and orientation; visits to site should be made particularly in adverse conditions. Flood risk may be significant in some locations; this can be determined from the Environment Agency and its equivalents.

In particular, designers of buildings in Driving Rain Index (DRI) Areas 3 or 4 or with local high exposure need to consider the impact of the geographical environment in terms of design, construction and maintenance. Detailing around openings, junctions and at ground level must be appropriate and robust. Roof design in particular needs to be appropriate to location (see BRE Building Elements Series, *Roofs and Roofing: Performance, diagnosis, maintenance, repair and the avoidance of defects*, BR 302, BRE 2000), as do measures at openings and in terms of rainwater goods and drainage. Solid wall building retrofits in all areas, but particularly in exposed areas, need to minimize the disruption of the equilibrium between the wetting and drying of the walls due to external rain and wind, and the effects of solar driven moisture in walls and solar drying. Solar driven 'reverse' condensation can be more severe in the least exposed areas.

Modelling to BS EN 15026, where material and weather data are available, can assist in understanding the effects of location, orientation and local exposure. Just as importantly, a knowledge of building performance, vernacular design and the monitoring of existing buildings and new projects can assist in identifying risks and appropriate strategies.

Form

Primary principles

The shape of a building, its height and whether it is single or dual aspect are all important considerations for moisture risk (single aspect buildings are nearly always more difficult to ventilate correctly). Complex building forms (in all aspects including external walls, roofs and floors, windows, abutments and all junctions) are often more difficult to detail for weathering, insulation, airtightness or ventilation. This can increase moisture risk in many ways.

Practical measures

In new-build design and in alterations and extensions to existing buildings it is essential to adhere to a form which is compatible with the geographical context and also with the available skills of contractors and users. Complexity in new and existing buildings should be approached with full detailing coherence. Generally, simplicity of form alleviates moisture risk.

Materials and construction method

Primary principles

The building materials and construction method have a considerable effect on moisture safety in a number of ways. In retrofit, this is a given context for new work. In new-build it is part of the design process. Certain materials and construction methods will be more or less appropriate in different contexts (geographical, form, use, condition).

Practical measures

In any area the materials and construction methods used in traditional buildings evolve to be compatible with the local climate; these can provide guidance for design and construction practice in both new buildings as well as existing and, in particular, traditional buildings.

In work on existing buildings, an understanding of the materials and construction methods is essential prior to new work being undertaken. Correct assessment of the hygrothermal qualities of walls, floors and roofs is necessary. It is not always apparent from the surface what the actual make-up of a traditional wall may be, so a proper and, if necessary, invasive survey of materials and construction form is essential prior to any work being specified. Testing of materials or expert assessment may be required. For an understanding of traditional materials and construction and the consequences of this, see work by Historic England (*www.historicengland.org.uk/advice*), Historic Environment Scotland (*www.historicenvironment.scot*), the Society for the Protection of Ancient Buildings (*www.spab.org.uk/advice*) and the Sustainable Traditional Buildings Alliance (*www.stbauk.org*).

Modern existing buildings can also hold surprises, so an understanding of original construction techniques and materials, as well as past interventions, is necessary for all existing building risk assessment and design.

An understanding of the durability of materials and construction methods under different moisture conditions is essential. Of particular importance is an understanding of the difference between moisture open and moisture closed buildings, materials and systems. This issue is dealt with separately in the following section on coherence due to its importance. In undertaking new work on existing buildings compatibility of new materials with the existing materials is essential.

Condition

Primary principles

The condition of the fabric and services is an essential part of any moisture risk assessment of an existing building. Buildings in good condition are, on the whole, much more able to deal with interventions and abnormal events (such as freak flooding) than buildings already under stress or not in equilibrium (i.e. buildings in good condition have more capacity). Understanding the building condition and moisture performance of a building and, importantly, what constitutes good or poor conditions and the consequences of these, is essential prior to altering a building.

In new buildings it is important to understand the likely condition of the materials and structure (and particularly the junctions) over the lifetime of the building.

Practical measures

In existing buildings first fully assess the fabric and services condition and performance. Poor fabric condition in walls, roofs or floors should be addressed prior to new work being undertaken. In particular where a building is not in equilibrium due to poor weathering, poor drying (internally or externally) or trapped moisture, these issues should be addressed and equilibrium restored. In particular, roof and wall detailing, mortars and pointing should be addressed, as should ground levels, rainwater goods and drainage. Internally adequate ventilation should be maintained or installed, both in the fabric (i.e. under suspended floors and in vented roofs) and in the building generally.

In new buildings assess the durability of key elements and connections. Reduce vulnerable connections and increase durability wherever possible. This may mean simplifying or changing design or specification. For example, mastic joints should be avoided in critical positions such as around external openings and where access is difficult, particularly in areas of high exposure. In regard to services, ensuring that ventilation systems are robust and easy to maintain is important.

Use and occupancy type

Primary principles

Designers should understand not only their buildings but how the building users interact with the building and the likely future use of the building.

Practical measures

High occupancy and high water usage (particularly when bathing, washing clothes and cooking) can considerably increase moisture risk and push balanced systems into imbalance in some situations. Sufficient capacity of systems and buildings to cope with high or unusual occupancy or use is therefore an important consideration where this is likely to occur.[13] Furthermore, it is essential that controls of heating and ventilation systems are adaptable to changed conditions and are usable by occupants or managers.

6.2 Coherence

General principle

Having understood the context of a project and made sure that the general project aims and criteria are compatible with this context, the next stage is to ensure that there is coherence in detailing and in the process of design, construction and use. Coherence is an essential concept in the assessment and mitigation of moisture risk.

Coherence of moisture approach in materials and systems

Primary principles

There are two fundamentally different approaches possible to moisture control in regard to the fabric of buildings: moisture closed and moisture open approaches.

A moisture closed approach, which is used in many modern buildings, attempts to eliminate moisture risk in the fabric (particularly external walls, floors and roofs) by excluding moisture as a vapour or liquid by the installation of impermeable materials and systems.

A moisture open approach allows both moisture ingress and egress through the many hygrothermal mechanisms as listed in key factor 3. The moisture carrying capacity and decay mechanisms of the building materials and systems as well as the use of the building will determine how much moisture ingress is acceptable without detrimental effects to fabric or occupants. A moisture open approach is found in most traditional buildings, which use naturally moisture open materials. The approach can also be used in new buildings. Correctly designed, a moisture open approach can have greater capacity to deal with construction moisture and ongoing building faults as it allows for some moisture ingress and has physical mechanisms for drying. This is not to say however that moisture open approaches of any type are always safer or better than moisture closed approaches. This depends on context.

13. Obviously building use can change over the long term. This is referring to possible or likely changes in the short and medium term. For example sheltered housing for elderly people, social housing for families, or large detached executive homes have different levels of moisture risk from high occupancy and moisture generation.

While the terms 'moisture open' and 'moisture closed' broadly characterize two significantly different approaches, they are not by any means a complete description of possible approaches to moisture. For example it might be possible to have a capillary closed but vapour open approach, which is indeed common in both new and existing buildings, and also in some parts of traditional buildings. There are also commonly existing buildings that incorporate more than one approach without difficulty, particularly where buildings are not airtight or well-insulated. However any attempt to further refine the terminology here risks introducing unnecessary complexity and confusion. The point of making the distinction between moisture open and moisture closed approaches is to flag the need for awareness of the radically different fabric moisture control strategies, and the importance of a coherent approach in designing and carrying out new work.

Practical measures

Moisture problems often arise where there is a clash of approach to moisture management in the terms laid out above. This can occur in new or existing buildings, so a coherence of approach is important in all cases, with particular attention on interfaces between different building methods (for example where new meets old). Difficulties can occur in retrofit in particular if moisture closed approaches are used on moisture open fabric. Certain conditions which are in equilibrium in existing buildings may become problematic when these buildings are repaired or retrofitted, due to changed moisture movement (through, for example, moisture closed mortar or plasters, increased airtightness, vapour barriers or increased insulation). In order to ascertain the level of risk a proper assessment of the building context must be undertaken.

A moisture closed approach can be adequate in a moisture open traditional building if there is a low contextual risk or a complete coherence of systems (i.e. a moisture open fabric is entirely enclosed in moisture closed materials and systems, including at damp course level), but only when there is minimal residual moisture from in-service conditions and where there are no vulnerable materials such as timber. This approach is not recommended unless there is expert design (including assessment) and high quality application. It does not meet the principle of capacity and caution.

The principle of maintaining the original designed moisture performance of existing buildings is a good starting point for repair and new work, although consequent fabric interventions and change of use should also be borne in mind. Any deviation from original designed performance principles has to take into account ongoing moisture movement, residual moisture issues, and both connective and systemic effects.

Thermal coherence

Primary principles

The insulated envelope should, as far as possible, be made uniform over the surface of the building to minimize locally depressed internal surface temperatures that can promote surface mould. There will, inevitably, be higher heat flows and lower temperatures at junctions and openings; the effects of these can be minimized by effective design and detailing.

Practical measures

Ensure insulation levels (i.e. U-values) are equal or similar, as far as possible, around the whole building element, in order to minimize contrasts and creation of possible thermal bridging problems.

Ensure thermal bridging at junctions (roofs, floors, walls, windows and door reveals), lintels and in the frame of buildings is minimized. Use calculations complying with BS EN 10211 and BR 497 where necessary to see if there is likely to be condensation as a result of thermal bridging. Follow Accredited Construction Details where these directly relate to the application and context.

Ensure that convective bypass is eliminated by detailing to prevent air infiltration through and behind insulation layers and party wall cavities.

Airtightness

Primary principles

Undesigned air infiltration is a major route for energy loss in houses. However, ventilation is necessary for good indoor air quality, including the reduction of high internal humidity. Good design of ventilation systems and detailing of the building can achieve an effective balance between these potentially conflicting aims. Air leakage from the interior into the fabric can be the dominant mechanism for transporting water vapour into regions where it can cause problems. This can be minimized by detailing an airtight layer on the warm side of the building envelope.

Practical measures

Ensure that the airtightness strategy is consistent for the whole building and that airtightness measures are fully linked. In new-build there should, as far as possible, be a continuous air barrier (not necessarily a vapour barrier) on the warm side of the building envelope. In design and construction drawings the clear identification of the air barrier is essential, both to ensure that a continuous air barrier is technically possible (if there are areas where fabric elements cut across the air barrier, then this means the barrier is not possible and the design should be altered), and to highlight its importance to site managers and contractors. Where details are complex, 3D modelling and careful site supervision are essential.

In retrofit a completely coherent, airtight layer may not be possible and so a strategy must be defined which minimizes airflow into those parts of the external fabric where airtightness measures are possible without increasing airflow into any areas where such measures are difficult or impossible. A retrofit airtightness strategy must also ensure that moisture is not trapped in areas where there is residual moisture. In such situations a vapour open air barrier (not only membranes but also plasters and renders) may be useful.

Weathering/waterproofing

Primary principles

Some degree of damage due to weathering of buildings is inevitable, but can be minimized by attention to detailing, especially taking into account the materials present. The principles of deflection, draining, drying and decay resistance are useful[14] in a coherent approach which addresses the whole building.

A distinction must be made between moisture open and moisture closed approaches, particularly in regard to capillarity. A coherent approach is essential in this regard, and different approaches must be avoided where possible. If mixed approaches are unavoidable then the detailing of junctions will require additional care.

Practical measures

A whole-house strategy for rain and drains minimizes risk. This means a strategy which fully takes into account the context of the building and then details the rain deflection, drying and drainage accordingly. This can be either a moisture open or a moisture closed approach. The detail must then deal with all materials and junctions in a coherent way. It is important in masonry construction that the mortar (and pointing) is compatible with the brick or stonework. The application of capillary closed pointing onto capillary open brickwork or stonework can cause significant freeze-thaw damage to masonry and in some cases lead to water penetration into the building.

Weathering is often concentrated in areas affected by run-off from above or severe wind pressures on corners or ridges. The building should be designed and detailed to minimize local effects and to protect more vulnerable materials and areas. Vernacular building design specific to an area is often a good indication of what is functional, and should be a starting point for designing buildings and renovations.

Water resistant flooring and other surfaces should be provided in areas where there is likely to be spillage of water, such as bathrooms, kitchens and utility rooms. However, this provision must be integrated with other moisture control systems in a building to ensure that surfaces do not trap moisture and cause problems in other parts of the structure.

14. (CMHC Building Technology, 1999)

Ventilation, heating and fabric coherence

Primary principles

A coherent approach is required because many moisture problems in fabric and indoor air quality are highly influenced by ventilation and heating. Ventilation and heating are not the main subject of this document but are an essential component of any moisture strategy.

Practical measures

Efficient, robust and usable ventilation and heating systems, appropriate to the building context (including condition and use) will significantly reduce moisture risk not only to the health of occupants but to fabric as well, as reduced levels of excess humidity (due to effective ventilation and heating) reduce stress on fabric. In particular, in retrofit of buildings, ventilation and heating can be effective in reducing moisture risks where thermal coherence is unachievable or where rain penetration or damp is unavoidable. All fabric retrofits should have a heating and a ventilation strategy. Internal wall insulation in particular should not be attempted without a ventilation plan which is appropriate to the particular building and which is properly designed and installed.

6.3 Capacity

General principle

Where there is uncertainty about the moisture performance of a building, capacity should be built into the processes of assessment, construction and use. Capacity should take into account not only current but future uncertainties, such as potential building use and occupancy patterns as well as the effects of increased driven rain or wind because of possible climate change.

Capacity in design

Primary principles

Do not over-optimize. Building design that pushes the capacity of a building to deal with moisture to the limit is likely to fail. Ensure that design for moisture risk is not overwhelmed by energy strategies to increase performance. Particularly in retrofit, but also sometimes in new-build, a balance needs to be struck between energy reduction and moisture safety.

Practical measures

Design for the most severe internal and external conditions likely to be experienced by the building. Consider this both generally and where particular conditions, such as exposure, building form, condition or materials raise the risk level, and design accordingly. For example in areas of high driven rain consider increasing rainwater capacity, increasing roof overhangs, removing vulnerable junctions in the design, extra attention to detail at openings, etc. Where the qualities of certain fabric materials are unknown (such as the porosity of a brick wall), design for the worst type. Where there are risks internally due to unknown moisture levels and air permeability ensure capacity for full ventilation design and installation.

Always ensure buildability in design, particularly in airtightness detailing, which can look simple on a 2D drawing but is impossible or very difficult in real 3D.

If calculations used to assess the performance of a building suggest that it will ‘just pass’, reconsider the design. Allow for maximum occupancy in a similar way. Finally allow for the differences that might occur between a building as designed and as built and occupied, and try to minimize these differences by good design and use of appropriate materials.

Capacity in process: skills, supply chain and budget

Primary principles

It is important that any design for a new building or for the repair or retrofit of an existing building takes into account the availability of contractor skills, types of product and budget necessary for the project being designed. Skills, product knowledge and budget should be in excess of the projected minimum, as even the best projects will encounter unexpected issues and require further resourcing. Sufficient capacity is essential to avoid real and long-term moisture risks.

Practical measures

A thorough understanding of the buildability of designs, of the required skill set, of the availability of adequate products for a particular application, and the cost of all these factors is essential in ensuring a successful approach to a project that does not fall apart during construction process or in use due to expensive or difficult maintenance requirements. Extra capacity should be added wherever possible, but particularly if any of these factors is difficult or uncertain.

6.4 Caution

General principle

The many uncertainties, complexities and unknowns in regard to moisture risks, both at the point of design and over the life of the building, necessitate caution in design and construction and ongoing watchfulness in use in order to mitigate possible problems. In particular many serious moisture problems may be hidden from view for some time prior to their effects being felt (for example when there is moisture build-up in the middle of walls, behind linings or in joist or rafter ends; or in slowly accumulating levels of mould or dust mites). Because of the many complex interactions in walls and the difficulty in understanding fully their consequences, in addition to building in additional capacity, measures of caution should also be built into construction and particularly user information and maintenance programmes.

Completion of a building project should not be considered to occur at practical completion of works, but when the building is in equilibrium (after the input of new materials and systems) and when it has been shown to be operating safely for the long term. In some situations this will mean that completion is after two years, but in others with less certainty and higher risks, this may be considerably longer.

Usability

Primary principle

Usability of services (particularly ventilation and heating) is essential. The context of the user should be prioritized in the specification of services.

Practical measures

The joined-up process in Section 5 must include a proper understanding of building use. Where there is a known building owner or occupant, they should be included in the joined-up process at all stages. Feedback at different stages and after completion will help to ensure the building is used effectively and that ongoing problems are resolved. A good and clear handover process and simple, accurate and readable instructions (or web-based information including videos) should all be made priorities.

Maintenance

Primary principles

Both services (particularly ventilation and heating) and fabric (particularly rainwater goods and drains) must be easy to maintain.

Practical measures

Handover of buildings must include clear and informative maintenance manuals or web-based information. If possible, maintenance programmes should be established, and where owners or occupiers cannot maintain their fabric and services themselves, options for external assistance and contracts should be provided. Automated reminders about maintenance may be advisable.

Monitoring

Primary principles

Where there is uncertainty about the moisture safety of a measure or part of the building, allow for simple checks and testing to be undertaken with clear instructions on to how to assess or feedback information.

Practical measures

Handover of buildings should include instructions on what to check and how to check it. Ongoing involvement of the main designer or contractor will, in many cases, be necessary and desirable for all parties. Where invasive monitoring or external checks are advisable, access should be provided for in the design and construction of the building (for example, the lifting of a floorboard to examine joist ends could be easily planned for, as could the provision of a ladder to check rainwater goods). Monitoring of services operation, particularly ventilation, is as important as fabric monitoring. Thermographic imaging and air pressure testing can be useful and cheap methods of looking at overall building performance, if undertaken correctly.

Clear indications about what is acceptable and what is a moisture risk or problem should be devised both for designers and for contractors and occupants, with further information as to what to do or who to contact for more information.

Feedback

Primary principles

Ensure that knowledge of problems and concerns as well as success and comfort is communicated back to all parts of the supply chain including procurers, designers, contractors and product suppliers. In this way future designs can be improved and risks reduced.

Practical measures

Include the owners and occupiers wherever possible in the joined-up process of planning, design, and construction/installation. It should be considered that the project does not finish at practical completion, but only when the building is performing as designed. This will inevitably mean that actual completion will be some time, perhaps years, after practical completion, and will require an ongoing relationship with building owners/occupants. This engagement can be minimal and largely web-based. The more completely the whole-building approach and joined-up process are followed, the more likely that the building will be moisture safe and the client contented, and the less need for feedback and remedial actions.

6.5 Summary table

Below is a summary table of the principles discussed. It is suggested that both training modules and checklists can be developed from the table.

The relevance of different principles varies according to the type of work, the location, building use, condition etc. New buildings of simple form, in unexposed locations, with normal usage will require less attention to certain principles than many other types of work. But all buildings require some attention to the details as part of this new approach to moisture risk.

Principle	Sub-principle
Compatibility with context	Geography
	Form
	Materials and construction method
	Condition
	Use
Coherence	Coherence of moisture approach
	Thermal coherence
	Airtightness
	Weathering/waterproofing
	Ventilation, heating and insulation
Capacity	Design
	Process
Caution	Usability
	Maintenance
	Monitoring
	Feedback

7. The role of prescriptive guidance and modelling

The principles of the whole-building approach, along with a joined-up process, are the key elements of a robust moisture risk assessment. Within this framework the role of prescriptive guidance and modelling is as follows:

1. Prescriptive guidance

   (a) For building elements: in floors and roofs in new-build, and some renovation projects, prescriptive guidance (as given, for example, in BS 5250 and BR 262) is sufficient for the design process (and sometimes for the installation process) provided that connective, systemic and ABIS effects are taken into account in addition to the prescriptive guidance.

   (b) For accredited details: for standard common details, some accredited details can be extremely helpful in design. However the current accredited details need to be revised in the light of current best research prior to their use as standard details.

2. Standardized and non-standardized modelling

   (a) The use of standardized modelling utilizing either BS EN 13788 or BS EN 15026 is acceptable for the assessment of building elements within the conditions laid down by the standards, under ADT conditions. However, results from such modelling should not be used as proof of moisture safety, except in limited cases for individual building elements, and never for a whole building. In the whole-building approach the connective and systemic effects as well as the ABIS conditions must be considered.

   (b) The use of non-standardized modelling of airflow, 2D effects and ABIS effects (for example by using the ASHRAE 160 standard) can be helpful in considering connective effects and ABIS conditions. Particular care must be taken that such models are used with full training and knowledge of inputs and outputs.

   (c) Modelling of all types (standardized and non-standardized) should always be considered as a tool for exploring possible risk, not for determining risk.

The following table indicates, for a range of structure types, where prescriptive guidance may be adequate and where standardized calculations will be useful for assessing the moisture risk of building elements under ADT conditions.

This table must not be used except in conjunction with a whole-building approach (and the whole-building principles in this document) as well as a joined-up process of implementation. It is only relevant currently, and mainly to new-build rather than existing buildings.

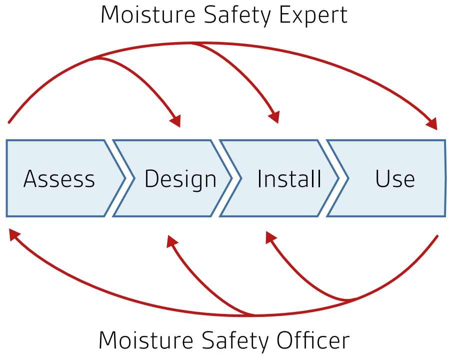
Ground floors	ADT assessment method
Ground bearing floor with membrane	Prescriptive guidance
Suspended concrete floor	BS EN ISO 13788
Suspended timber floor	BS EN ISO 13788
Walls	**Calculation method**
Solid masonry wall – External insulation	Prescriptive guidance
Solid masonry wall – internal insulation	BS EN 15026
Masonry wall with cavity – external insulation	Prescriptive guidance
Masonry wall with cavity – insulation within the cavity	Prescriptive guidance
Masonry wall with cavity – internal insulation	BS EN ISO 13788
Masonry wall of concrete with insulating formwork (ICF)	Prescriptive guidance
Framed wall – external insulation	Prescriptive guidance
Framed wall – insulation between framing members	BS EN ISO 13788
Framed wall – internal insulation	BS EN ISO 13788
Framed wall – thermal insulation between and across framing members	BS EN ISO 13788
Cladding system – composite insulated panels	BS EN ISO 13788
Cladding system – built in situ	BS EN ISO 13788
Cladding system – rainscreen cladding	Prescriptive guidance
Structural insulated panel system (SIPS)	BS EN ISO 13788
Roof	**Calculation method**
Cold pitched roof	Prescriptive guidance
Warm pitched roof with high resistance (HR) underlay	Prescriptive guidance
Hybrid pitched roof	Prescriptive guidance
Cold flat roof – dense structure	BS EN 15026
Cold flat roof – framed structure	Prescriptive guidance
Cold flat roof – metal deck	BS EN ISO 13788
Warm flat roof	Prescriptive guidance
Inverted flat roof	Prescriptive guidance
Site-assembled sheet metal roof	BS EN ISO 13788
Pre-formed (composite) insulated roof panel	BS EN ISO 13788
Structural insulated panel system (SIPS)	BS EN ISO 13788

8. How to undertake moisture risk assessment and design

1. Establish overall approach

- Joined-up process with feedback at every stage: appoint fully trained and qualified Moisture Safety Expert to the design team and Moisture Safety Officer from within the construction team. On single building works including extensions and one-off retrofits, a trained designer, contractor or consultant may be sufficient for both roles. Ensure clear allocation of responsibility/liability.

Figure 7 – The role of Moisture Safety personnel in a joined-up process



- Whole-building approach integrating fabric, services and people with context: ensure all key members of planning, design and construction teams understand and use the whole-building approach.

Figure 8 – Whole-building approach: People, services and fabric within context

2. Assessment/planning

- Use the principles in Section 6 to assess context and ensure compatibility. Choose primary materials, method and form to be compatible with geography, use, and future use.

3. Detailed design
   - Build up design from building elements and services in whole-building approach.
   - Use prescriptive guidance and modelling where necessary to determine best building elements.
   - Use accredited details (where available and correct)[15] for connective effects where they also meet the principles in Section 6.
   - Use principles to check and ensure coherence between all elements at interfaces and in regard to systemic effects.
   - Use additional modelling or assessment to check connective, systemic and particularly ABIS effects where principles indicate risk. This modelling (currently non-standardized)[16] is only a guide to risk, not proof of safety. Principles should still be applied to modelling results.
   - Use principles to ensure capacity and caution. These are particularly important where there is a high level of uncertainty.
4. Installation
   - Use joined-up process to ensure communication and feedback at all times.
   - Use principles to ensure capacity and caution in construction and where there are uncertainties.
5. Use and maintenance
   - Use joined-up process to ensure communication and feedback at all times.
   - Use principles to ensure caution in use and where there are uncertainties.

Summary table of the main principles and guidance required in each stage

Joined-up process	Primary whole-building principles	Other guidance
Assess	Context	–
Design	Coherence/capacity/caution	Prescriptive and modelling
Install	Capacity/caution	–
Use	Caution	–

9. Consequences for standards, regulations, testing, certification processes and training

The consequences of this new approach to moisture risk for standards, certification and training are considerable. It marks a move away from prescription to process and from 'ticking boxes' to learning. In regard to insurance and liability it means not trying to remove risk altogether but trying to manage risk through processes. This is necessary because the reality is that moisture risk cannot be eliminated in buildings; it increases as we place greater demands of energy efficiency and comfort, as well as increased burdens of internal moisture generation, upon buildings. The methodology proposed in this white paper addresses the challenges faced by this changing situation, as well as many challenges already present but less visible in buildings in the past.

Consequences for standards

- All standards must address the key factors outlined in Section 2 in an integrated and robust way. In particular the approach of BS 5250 must be revised to that indicated in this document. If an elemental approach is to be continued it must include ABIS effects as well as connective and systemic effects and be seen as a subset of a whole-building approach and joined-up process.

15. Currently there are no accredited details for retrofit and those for new-build require revision.
16. Such modelling includes use of 2D WUFI modelling and use of the ASHRAE 160 standard where 1% of driven rain is inserted into the modelling to indicate a building fault or residual moisture.

- Modelling must account for ABIS effects. The use of BS EN 13788 must be restricted to conditions suited to its use. Protocols must be developed for the common use of BS EN 15026. All modelling must be used as evidence of concerns, not as proof of safety, and be seen as a subset of a whole-building approach and joined-up process.
- All standards must acknowledge clearly areas of uncertainty and conflict with other standards.
- Standards must take into account the level of knowledge, skills and actual performance of the sector, and be specific about the level of training required for those using standards.
- Where there is uncertainty, methodologies must be based upon principles and ongoing learning.

Consequences for regulations

- One of the problems of Building Regulations and Approved Documents is that they separate issues such as Resistance to Moisture (Part C2) from Energy (Part L), Fire (Part B), Access and Use (Part M) and even Ventilation (part F). There needs to be guidance on the integration of these issues, particularly in the renovation of existing buildings. There also needs to be constant awareness of the conflicts that may arise between different regulations, and clear identification of these conflicts and how to resolve them. In some cases they will not be resolvable (as per key factor 10) so a method for compromise must be worked out.
- A greater consideration of retrofit must be incorporated into building regulations, as many of the existing standards, data, testing and construction approaches should only be used for new-build.
- As there is both conflict and uncertainty in regard to moisture risk in many regulations, it is suggested that, just as standards must move to incorporate principles and ongoing learning, so must regulation. This learning will require simple methods for monitoring and reporting of results (feedback). This feedback should be to a central hub as well as to local compliance bodies, so that learning is enhanced also at a research and policy level.

Consequences for certification

- Certification of systems and products must adapt to the new approach in standards and regulation. This will require upskilling of certification bodies, and the development of new methods of assessment based not only upon building element testing, but integration with the rest of the building in line with the whole-building approach and principles.
- Where there is uncertainty, suppliers of systems for certification will be expected to allow monitoring and assessment of whole-building effects as well as elemental effects. This will drive a whole-building approach into the supply chain.
- Certification of individuals and organizations for competency in moisture understanding will be needed. The role of Moisture Safety Expert and Moisture Safety Officer will require formalization, as will those checking applications and monitoring long-term effects.

Consequences for training and procurement

- The whole-building approach and joined-up process cannot work without considerable upskilling of all parts of the supply chain (assessors/planners, designers, contractors, suppliers) as well as users, insurers, compliance bodies and government. In particular, Moisture Safety Experts and Moisture Safety Officers require training. Such training is not currently available and will need to be developed in stages as knowledge and feedback increases. The requirement for qualified experts and site practitioners, in schemes set up by the Swedish Moisture Centre, is now integrated into planning consents and building regulations in parts of Sweden and is a model which should be considered. Only if there is an approval system which is enforced and for which there are rewards (such as access to tenders, reduced building regulations requirements) will this succeed in the market.

References

ASHRAE (2009) Standard 160-2009, *Criteria for Moisture-Control Design Analysis in Buildings*

Bomberg, M T, Brown, W C (1993) Building envelope: heat, air and moisture interactions, *Journal of Thermal Insulation and Building Envelopes*, vol. 16, p. 306

BRE (2000) BR 302, W H Harrison, *Roofs and roofing: performance, diagnosis, maintenance, repair and the avoidance of defects*

BRE (2002) BR 262, *Thermal insulation: avoiding risks*

BRE (2010) Roys, M, Davidson, M, Nicol, S, Ormandy, D and Ambrose, P. *The real cost of poor housing: (FB 23)*

BRE (2016) BR 497, *Conventions for calculating linear thermal transmittance and temperature factors*

BS 5250:2002, *Code of practice for control of condensation in buildings*

BS 5250:2011, *Code of practice for control of condensation in buildings*

BS 8104, *Code of practice for assessing exposure of walls to wind-driven rain*

BS EN ISO 10211, *Thermal bridges in building construction. Heat flows and surface temperatures. Detailed calculations*

BS EN ISO 10456, *Building materials and products. Hygrothermal properties. Tabulated design values and procedures for determining declared and design thermal values*

BS EN ISO 12571, *Hygrothermal performance of building materials and products. Determination of hygroscopic sorption properties*

BS EN ISO 12572, *Hygrothermal performance of building materials and products. Determination of water vapour transmission properties*

BS EN ISO 13788, *Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation*

BS EN 15026, *Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation*

BS EN ISO 15148, *Hygrothermal performance of building materials and products. Determination of water absorption coefficient by partial immersion*

CMHC (1999) *Wood Frame Envelopes*

DCLG (2013) Approved Document C, *Site preparation and resistance to contaminants and moisture*

DCLG (2010) Approved Document F, *Ventilation*

English Heritage (2014) *Practical Building Conservation - Building Environment, Ashgate*

Historic Scotland (2015) Technical Paper 15, *Assessing risks in insulation retrofits using hygrothermal software tools: Heat and moisture transport in internally insulated stone walls*

Institute of Medicine (US 2004) *Damp indoor spaces and health*, Washington, DC: National Academies Press

Kumaraperumal, A et al. (2006) *Prediction of fabric moisture contents in a historic building using CFD and heat, air and moisture transfer modelling compared with full-scale measurements*, Yokohama: the 4th International Symposium of Computational Wind Engineering (CWE 2006)

Mjörnell, K. et al., (2007) *A Method for Including Moisture Safety in the Building Process, Performance of the Exterior Envelopes of Whole Buildings*, Clearwater Beach, USA: X International Conference

Mjörnell, K, Arfvidsson, J (2008) *ByggaF, A Method for Including Moisture Safety in the Building Process – Experience from Pilot Projects*, Copenhagen: Nordic Building Physics Symposium; Proceedings of the 8th Symposium on Building Physics in the Nordic Countries, vol. 3, pp. 1181–1188

Mjörnell, K, Arfvidsson, J, Sikander, E (2012) A Method for Including Moisture Safety in the Building Process, *Indoor and Built Environment*, vol. 21, pp. 583–594

Mjörnell, K (2014) *Industry Standard ByggaF*, Lund: proceedings of NSB2014

Mudarri, D, Fisk, W J (2007) Public health and economic impact of dampness and mold, *Indoor Air*, vol. 17, Issue 3, pp. 226–235

ODPM (2004) *The Egan review – Skills for sustainable communities*, p.5

ODPM (2005) Oreszczyn et al., *Condensation risk – impact of improvements to Part L and robust details on Part C*

Pollack, G (2013) *The Fourth Phase of Water*, Ebner and Sons

Sharpe, R A et al. (2015) Higher energy efficient homes are associated with increased risk of doctor diagnosed asthma in a UK subpopulation, *Environment International* 75, pp. 234–244

STBA (2012) *Responsible Retrofit of Traditional Buildings*

WHO (2009) *WHO Guidelines for Indoor Air Quality: Dampness and Mould*, 3.2, p. 3, 34

England: Approved Document C
http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partc/documentc

Scotland: Scottish Domestic Handbook
http://www.gov.scot/Topics/Built-Environment/Building/Building-standards/techbooks/techhandbooks/th2015dom-complete

Wales: Approved Document C
http://gov.wales/topics/planning/buildingregs/approved-documents/part-c-moisture/?lang=en

Northern Ireland: Northern Ireland Technical Booklet C
http://www.buildingcontrol-ni.com/assets/pdf/TechnicalBookletC2012.pdf

BSI is grateful for the help of the following people in the development of the white paper series.

Authors

Chris Sanders, BSc MSc

After graduating in physics and meteorology, Chris worked for the Building Research Establishment (BRE) in Scotland for 30 years, initially condensation problems in houses and their roofs. He produced guidance documents giving advice on avoiding thermal bridging in housing and other buildings. Chris is Convenor of the CEN and ISO Working Groups developing European and International Standards on moisture and was, until recently, chairman of BSI committee B/540/2 responsible for BS 5250, *Code of practice for condensation in buildings*, which forms an integral part of the Building Regulations. Upon joining Glasgow Caledonian University in 2003, Chris was Director of the Centre for Research on Indoor Climate and Health, a multidisciplinary team which carried out research and consultancy work in all aspects of energy use, moisture problems and the internal environment of houses. Chris retired from Glasgow Caledonian University at the end of September 2013, but still carries out a large amount of consultancy work in the fields of thermal insulation, thermal bridging and moisture modelling.

Neil May, Director, Sustainable Traditional Buildings Alliance

Neil was a historian, anthropologist and film maker before becoming a building labourer in 1989. In 1992 he set up his own building company specialising in ecological and conservation building. In 1999 he set up Natural Building Technologies which he ran until 2014. Neil was a founder Director of the Good Homes Alliance and the Alliance for Sustainable Building Products. Neil was also formerly a founding director of the Passivhaus Trust.

Currently Neil works part time at the Institute for Environmental Design and Engineering at UCL, where he runs the UK Centre for Moisture in Buildings as well as working on health, energy and wellbeing, the Housing Crisis and unintended consequences. He also works part time as a director of the Sustainable Traditional Buildings Alliance running projects with central and local government.