THE WINDOW IN CONTEXT

THE INTERPLAY BETWEEN BUILDING COMPONENTS

TIM PADFIELD

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Abstract. The ventilation requirement for a house is a compromise between the need to keep the indoor relative humidity down and the need to minimise energy consumption. The first requirement is itself a short circuited train of reasoning about how to prevent condensation in the structure, with consequent mould growth. The second requirement was until recently defined in terms of permitted energy loss through the envelope but is now more liberally defined as the permitted energy used to keep the occupants physically comfortable.

Mould growth in the occupied part of the house is only indirectly a consequence of high indoor relative humidity - it is usually a consequence of uneven wall temperature. Mould growth in the hidden parts of the structure is often a consequence of air leakage from the inhabited part, often amplified by extreme temperature gradients within the structure. Designing a structure that is robust enough to be badly built and intermittently maintained is just as important to the life cycle costs as is the energy consumption from day to day.

Trends in building design have been towards complicated, light structures, optimised through the use of computer models but not always performing as expected when released into the care of the occupants. In particular the intricate detailing and the tendency to use non water absorbent materials brings a considerable risk of condensation in the northern European climate, with subsequent mould growth. Air barriers have not provided the expected security from condensation within the outer envelope of buildings.

There are some rather fundamental holes in our knowledge of the dynamics of biological growth and our knowledge of the movement of water to the potential sites of biological growth. In particular the ecology of microorganisms has been relatively neglected in favour of experiments based on sterile media inoculated with purified organisms in a constant environment. The influence of air flow and air exchange on growth has been neglected.

The movement of water in hygroscopic materials is not understood, to judge by the failure of the many models to account convincingly for water and dissolved salt movements in porous materials and their difficulty in dealing with lateral irregularities in real walls. There is continued reliance on the mathematical analogy between heat and material transport through porous materials, even though the movement of water molecules through the mesh of different sized pores is unlikely to be a purely diffusive phenomenon.

The erratic ventilation caused by undisciplined use of windows is a considerable further inconvenience for these modellers. It is perhaps easier to believe that one has control when all the windows are sealed shut and a computer controlled ventilation system is installed, but experience does not always support this conviction. It is also true that mechanical air conditioning is capable of very accurate control in enough instances to justify its installation, even in countries such as Denmark, where it should not be necessary.

There is an increasing interest in the properties of water absorbent, porous materials, which, combined with permeable membranes to retard vapour flow, promise to allow a measure of dehumidification and air purification by gas movement through the entire wall, rather than through pre-ordained channels such as ducts and windows.

These material investigations, together with physiological studies of people's tolerance to draughts and uneven temperature indoors, promise to re-activate the discussion on the use of traditional ventilation through windows as a perfectly reasonable way to control the indoor climate without unreasonable waste of energy.

1. Introduction

This article is an attempt to bring together information from the fields of microbiology, ecology, physics and the historic development of houses. When the various threads are interwoven there emerge interactions and synergies that are surprising, and open up avenues of exploration in building technology that are not yet in the mainstream of academic endeavour.

I start with a review of the biology of organisms that damage houses and the people who live in them. The next section deals with the various materials used to build and decorate houses and how the use of non-absorbent building materials increases the risk of water damage. Finally I put forward some ideas on how we should be developing building materials and designs to simplify the making of a healthy indoor environment and to make buildings which can survive a measure of neglect.

2. Microorganisms

This first section reviews what we know about the climatic conditions and material properties that favour growth of microorganisms in buildings. The discussion centres on fungi. Bacteria generally require a very high relative humidity (RH) to thrive. Algae require a high RH and also light. They are therefore not often found in hidden parts of a building. Lichens also require light and seem to be confined to the outside of buildings. It seems to be the fungi which cause the most damage to buildings and their occupants. The chemicals and spores emitted by fungi are held responsible for much respiratory illness and fungi are also thought to be the main food of dust mites, whose excrement is one of the main causes of asthma.

High relative humidity is the factor most often cited as facilitating mould growth, but a survey of the literature reveals a more complicated, and by no means fully understood, interplay of environmental influences.

2.1. **Water activity as the measure of water availability.** W.J.Scott [Scott 1957] is generally credited with introducing the idea that the limit for biological growth of an organism is mainly determined by two variables: temperature and water activity. As often happens, his introduction of water activity (which is identical with relative humidity) as a defining variable has been accepted more wholeheartedly than he himself intended.

Scott describes the connection between the concentration of water in a dilute solution of a salt or a soluble organic molecule, with the vapour pressure of water above the solution. The solute, that is the dissolved material, interacts with water in a way that increases the overall intermolecular forces and thus makes the water molecules more difficult for an organism to take in. This increased intermolecular force also manifests itself in a decreased tendency for water to escape into the vapour phase. The *relative* diminution of the vapour pressure is thus a measure of the organism's difficulty in obtaining water. The relative humidity is defined as the partial pressure of water vapour divided by the saturation partial vapour pressure of water, that is the water vapour pressure over a free water surface in an unventilated container. The RH is often quoted as a percentage, to give it a convenient numerical value. The degree to which the actual RH is lower than 100% can

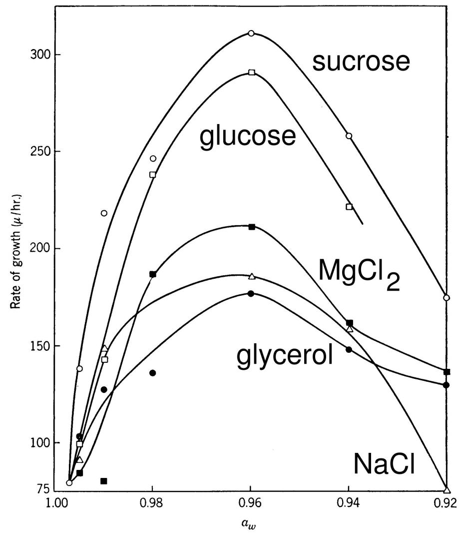

FIGURE 1. The growth of *Aspergillus amstelodami* stops in sodium chloride solution at a water activity of 0.92 (92% RH), while growth continues in solutions containing glucose, sucrose, glycerol and magnesium chloride. Water activity diminishes to the right. Note also the slow growth at very high water activity. (adapted from Scott 1957 p.116).

be regarded as a measure of the difficulty any organism has in getting water into its cells.

It has long been assumed that organisms cannot directly control the movement of water molecules through their cell walls. If the cell is short of water, and is therefore in danger of collapse through lack of internal pressure, referred to as turgor, it synthesises hygroscopic chemicals, such as glycerol, mannitol and various sugars. These reduce the activity of water within the cell, so that water diffuses into the cell from the surrounding liquid, or, in principle, from the surrounding humid air. The hygroscopic entity can also be an ion, which can be transferred in through the cell's active transport mechanism, a process which needs energy. When, later, the ambient water activity rises, the cell metabolises the now excessive hygroscopic molecules to re-establish equilibrium. This process is known as osmotic regulation of the cell fluid. A good description can be found in [Finkelstein 1987].

2.2. **Limits to the validity of water activity as a controller of biological growth.** Scott was not dogmatic about the overriding importance of water activity. He notes that yeasts, which are related to the fungi, grow in liquid with water activity as low as 0.62 (62% RH) but have not been reported to grow on solids at this low water activity. He also noted that the limit for growth was affected by the nature of the solute. Figure 1 shows the limited ability of an *Aspergillus* species to grow in sodium chloride solution.

On the other hand there are organisms that require a high concentration sodium chloride solution to thrive. The commonly observed pink discoloration of the whitewashed walls of damp churches is caused by organisms

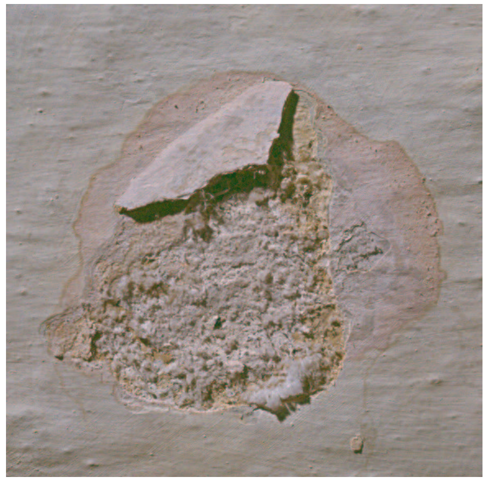

FIGURE 2. Pink discolouration of biological origin, probably a halobacterium, arround an efflorescence of salt on the inner side of the wall of Gierslev Church, Sealand, Denmark. The picture is about 15 cm across. Photo by Roberto Fortuna.

that thrive in a salty environment (figure 2). Enzyme activity in the cell is strongly influenced by the nature of the solute that the cell secretes to maintain its osmotic balance with its surroundings. The nature of the soluble components of the substrate therefore has a powerful influence on the viability of organisms stressed by low water availability. A common mechanism used by many organisms to survive freezing, which is a form of water stress characterised by a rapid increase in ion concentrations in unfrozen residual liquid, is to increase the concentration of glycerol, mannitol and sugars in their cell fluid. Glycerol can even be imported from the surroundings. In this way the organism can attain the same water activity as the extra-cellular fluid, but with a completely different chemistry.

Felix Franks [Franks 1982], a noted authority on water, was also sceptical of the indiscriminating acceptance of water activity as the limiting factor for organic growth. He points out that any system showing hysteresis in water absorption and desorption, as do all organic polymers and many silicates, cannot have a defined water activity, because water activity is a variable of state, meaning that it is independent of how that state is approached. Franks points out that foods (and I will add building materials) also have a solid hygroscopic component, while the equations used to define water activity are based on homogeneous binary solutions with a non-volatile solute. A cellulose molecule in damp wood can scarcely be considered as a homogeneous aqueous solution.

2.3. **Water activity in porous media.** Water activity in a homogeneous solution is defined in terms of the vapour pressure of water above it. In the world of soil science a different tradition has established itself where the difficulty a plant has in taking up water is described as a suction pressure. Athough these two concepts turn out to be equivalent and interconvertible, the use of parallel systems of units in related disciplines has caused considerable confusion and misunderstanding. The matter is discussed by Passioura [1982]. For the moment we need just note that the availability of water to organisms in porous media is controlled both by solute concentration, as described in the previous section and by the retention of water in fine capillaries where the water column is under such high tensile stress from the surface tension of the curved capillary surfaces that its availability to the organism is reduced. Water adsorbed on surfaces is also included in the capillary component.

In the botanical literature the reduction of water activity caused by the addition of soluble substances is referred to as the osmotic potential. The plant cell can increase its own solute concentration until water enters the cell by osmosis. The difficulty of extracting water against the surface tension acting in the meniscus formed in small capillaries is called the matric potential. These two forces combine to hold water back from the living cell. In the botanical and soil science literature the water activity is called the suction pressure. A relative humidity of 85%, in building physics terminology, is equivalent to a water activity of 0.85 in microbiologists jargon and a suction pressure of minus 22 megapascal in soil science speak.

Finally, there is the vapour phase to consider. Here the water activity is exactly expressed by the relative humidity. One characteristic of water in the air is that it is very dilute, compared with water of equivalent activity in a solution, or in the capillary pores of a solid. The water concentration in a saturated potassium nitrate solution, as is commonly found in the masonry of the cellars of older buildings, will be approximately 900g/l. The water vapour in air at equilibrium with this solution (95% RH) is, at 20°C, 0.016 kg/m3 = 0.016 g/l. The difference in concentration is dramatic. One might suspect that kinetic, rather than equilibrium thermodynamic considerations, would limit the usefulness of water vapour to the stressed organism.

It is really only building scientists who have to consider all three phases: the aqueous liquid and the water vapour within the unsaturated porous solid. The liquid phase can stress the organisms ability to get water out of by containing a lot of solute, the solid phase can retain water by holding it in very fine capillaries where surface tension holds the liquid under strong tensile stress which the cell can only overcome by making solutes to lower its internal water activity. Finally the water in the vapour phase defies capture by being very dilute. Furthermore it contains no solutes, which means that the cell has no chance of capturing solutes from it to use to absorb water vapour. The cell must therefore manufacture its own activity reducing solutes if water vapour is the only water source available to it.

On the other hand, the solutes may be toxic, so that the organism cannot use them. In an unsaturated porous material the solute may also accumulate at the points where the organism absorbs the water, leading to a low water activity at that point and increasing resistance to further water absorption.

The unique problem that building science has, that soil science does not have, is that the water vapour is diffusing through a wall, often independently of liquid movement. Soil scientists regard percolating water as the main distributor of water, with the pore vapour phase always passively at equilibrium with the pore water.

A central question therefore is how much does a high relative humidity in the pore volume encourage mould growth in the absence of an accessible liquid phase containing dissolved salts.

According to Adan's [1994] (p.61) very comprehensive survey of the mycological literature 'Unambiguous data on the effects of the amount of water at the same RH on fungal growth have not been found in the literature.' Adan presumably means concentration, when he writes 'amount'.

Adan also observes (p 101) that the conidia (spore bearing growth) of *Penicillium chrysogenum* show liquid drops as the RH is raised in a high pressure scanning electron microscope, suggesting that the fungus itself can exude deliquescent substances to absorb water directly from the air. Such processes are well known in the animal world. Dust mites, for example, exude potassium chloride and then re-absorb the liquid formed at high RH.

2.4. **Ventilation.** A variable that has been consistently ignored in biological research is the air speed over the organism. The reason probably lies in the experimental difficulty of holding a circulating air system sufficiently sterile and constant in water activity. Most researchers culture their spores in small enclosures whose water activity is controlled by saturated or unsaturated salt solutions. The air is not stirred. Evidence for the possible influence of air movement comes indirectly. Kristian Fog Nielsen [Nielsen 2001] refers to cultures on building materials in a climate chamber with moving air. He complains that the growth was uneven, probably because of uneven air velocity over the culture dishes.

For millenia, the standard household advice has been to ventilate houses to inhibit mould growth. Unfortunately ventilation affects so many interdependent variables in the microclimate that this good advice cannot be interpreted scientifically. Ventilation will even out the temperature, and therefore the local relative humidity. Ventilation will dry out obscure corners which have moisture in the walls from other sources than the room air.

One might suspect that ventilation might have a powerful influence on the growth of organisms in the real world. It very often happens (about half the time in fact) that the porous substrate that the organism is growing on has a higher water activity than the air above it. The organism will relatively easily hold its equilibrium with the pore solution but its aerial parts will be bathed in a medium of lower water activity. Fungal mycelium is fairly impermeable, but not entirely. Even more frequently, one can imagine a situation where the wall is nearly always at a higher water activity than the indoor air. This happens when there is rising damp, or driving rain on the outside of the wall. The wall will then be evaporating water into the air for long periods.

A closely related matter is air exchange rate. Microorganisms emit a vast range of signal chemicals which inhibit the growth of other organisms, even of the emitting organism itself. Forsyth [1955] noted that that Wheat Rust fungus spores do not germinate in closed flasks because of an inhibitory volatile substance, which he identified as trimethylethylene. A damp, sealed roof or wall construction should be a poison gas battlefield of some intensity.

2.5. **The influence of the substrate.** From the earliest investigations there have been parallel studies using both agar and real industrial materials as growth media. Scott mentions the greater range of permissible water activity for yeast growth in a homogeneous medium compared with a 'real world' substrate. Grant and coworkers [Grant 1989] measured the limiting water activity for growth of three *Cladosporium* species on various substrates. The limits on agar were 0.81 to 0.85. Corresponding values for industrial substrates varied from 0.9 to 1.0. The influence of added nutrient on bare and emulsion painted wood based paper was also considerable: carboxymethylcellulose added as a readily accessible carbon source reduced the limiting water activity by 0.05 (5% RH) units in several cases but often there was no difference at all.

Nielsen and co-workers [2000] measured the growth of seven microorganisms on 27 building materials over a 7 month period. They observed no growth at 70% RH, only slight growth on wood and wood products at 80%. At 90% RH many materials were attacked, but not gypsum board. Their visual tests were supplemented by other tests which revealed the existence of mycelium, visually indistinguishable from the fibres of the substrate.

There are some microorganisms that need an unusual environment, a high water activity is not enough. The already mentioned pink discoloration around the salt efflorescence in Gierslev Church, Sealand, is an unidentified halophile organism, maybe a halobacterium, which can grow at around 0.75 water activity.

The nutritional requirements of microorganisms are often so special that many have never been grown in the laboratory. A relevant case is the growth of *Penicillium* on oak timber within the organ case in Køge Church, south of Copenhagen. The Conservation Department of the National Museum made a climate record for about a year, during which the relative humidity within the organ case was hardly ever above 65%. Only some oak timbers were attacked, immediately adjacent pieces being entirely unaffected. The biologists at the Technological Institute were unable to culture the organism to identify the species. There are several *Penicillium* species that can survive at quite low relative humidity. Wolfgang Krumbein, of the University of Oldenburg, who is a specialist on microbiological growth on inorganic substrates, reports many failures in culturing bacteria found on the surfaces of buildings.

One often hears that modern wood is more susceptible to rot than old wood, because it is cut with the sap in the cells. I show an embarrassing example from Gierslev Church where we (The Conservation Department of the National Museum) conserved and re-mounted the 16th century altar picture (figure 3). We removed the painting from its place directly in front of the porous stone altar, which rested directly on the earth and was visibly wet when we removed the painting. It was replaced in a ventilated mount, shown from the back in figure 4, and screened from the air immediately around the stone altar. On our next visit a year later the oak planks of the

FIGURE 3. The altar of Gierslev Church, Sealand, Denmark. Note the sixteenth century painting in front of the altar. Photo by Roberto Fortuna.

FIGURE 4. The back of the new frame supporting the old picture, at the time of installation. The new timber was attacked by mould within one year, though the original oak planks were unaffected.

picture were unaltered but there was mould growth on the modern timber of the frame!

The observation that mould does not grow where it should, according to the measured relative humidity, has been understandably ignored by microbiologists: it is not the obvious way to a brilliant career. Examples are therefore anecdotal rather than carefully documented.

One of the often cited examples of survival through (careful) neglect is Skoklosters, near Uppsala. This historic house museum is not warmed, nor inhabited, in winter, except for a small office in the basement. The seventeenth century interior decoration is generally in good condition. According to curator Bengt Kylsberg there is ice on the wallpaper throughout the winter,which evaporates without melting in the spring. Mould growth and corrosion have only been observed on some weapons in the armoury which had incautiously been entrusted to a conservator for treatment. One can suspect that the refreshing mixture smeared onto the weapons contained humectants, such as glycerol, which gave microorganisms the means to reduce their water activity, and maybe also a nutrient source.

There is one unconsidered source of nutrient which is particularly prevalent in the roofs of modern buildings. This is the breakdown products of building materials. Bogaard and Whitmore [2002] studied the astonishingly rapid breakdown of paper under cyclic change of relative humidity between 25% and 75%. The small molecules released by this mechanical-chemical process can provide nourishment for microorganisms. In a sealed roof construction the local relative humidity can swing violently with the changing temperature of the roof skin, caused by radiant heating from sunlight. Apart from the expected daily cycle from maybe 5%RH in bright sunlight to 100% on a clear night, there are also fluctuation caused by clouds passing over.

The continuous, slow breakdown of wood products is attested by the volatile compounds given off over centuries, including acetic acid, which can be metabolised by moulds.

2.6. **The combined influence of temperature and water activity.** The frequently cited paper by Ayerst [Ayerst 1969] contains data exclusively from cellulose film or agar, encapsulated in test tube reaction flasks. His paper is, however, useful for the detailed graphs of the response of microorganisms to combinations of temperature and water activity.

The lowest water activity that can support mould growth is 0.7 at 35°C, among the candidates investigated by Ayerst (figure 5). At the normal temperature of damp corners in inhabited houses, say 12°C, the limiting water activity is much higher: about 0.9. The most frequently wet area in houses in cold climates is the inside of the outermost component in the wall during the winter. This is also the coldest part, so the much higher limit for growth at temperatures below 5°C means that such places must in practice contain liquid water before growth will occur. On the other hand a few organisms are reported to grow at 60% relative humidity: the fungus *Xeromyces bisporus* and the yeast *Saccharomyces rouxii* [Brock 1974].

There is good evidence from observation of old buildings that have been unheated for centuries that mould growth is supressed when the period of high relative humidity coincides with the cold period. I have already mentioned Skoklosters, near Uppsala, (figure 6) a time-capsule of seventeenth century art and equipment. The interior is in impressively good condition, in accordance with general experience that furniture, in particular, endures better in unheated houses.

Krus [2001] has collected the data for germination and growth of several mould species as a function of time and temperature. He then drew in a 'worst case' curve designating the lower limit of temperature and RH for mould growth. His limiting curves are shown in figure 8.

It is evident from this section that the temperature dependence of the limiting RH is of great importance in buildings. Mould in the corner of a warmed room requires a much lower RH than mould growth towards the outer skin of a well insulated building. We shall see later that the outer parts of buildings tend to dry out quite quickly in spring, before the temperature

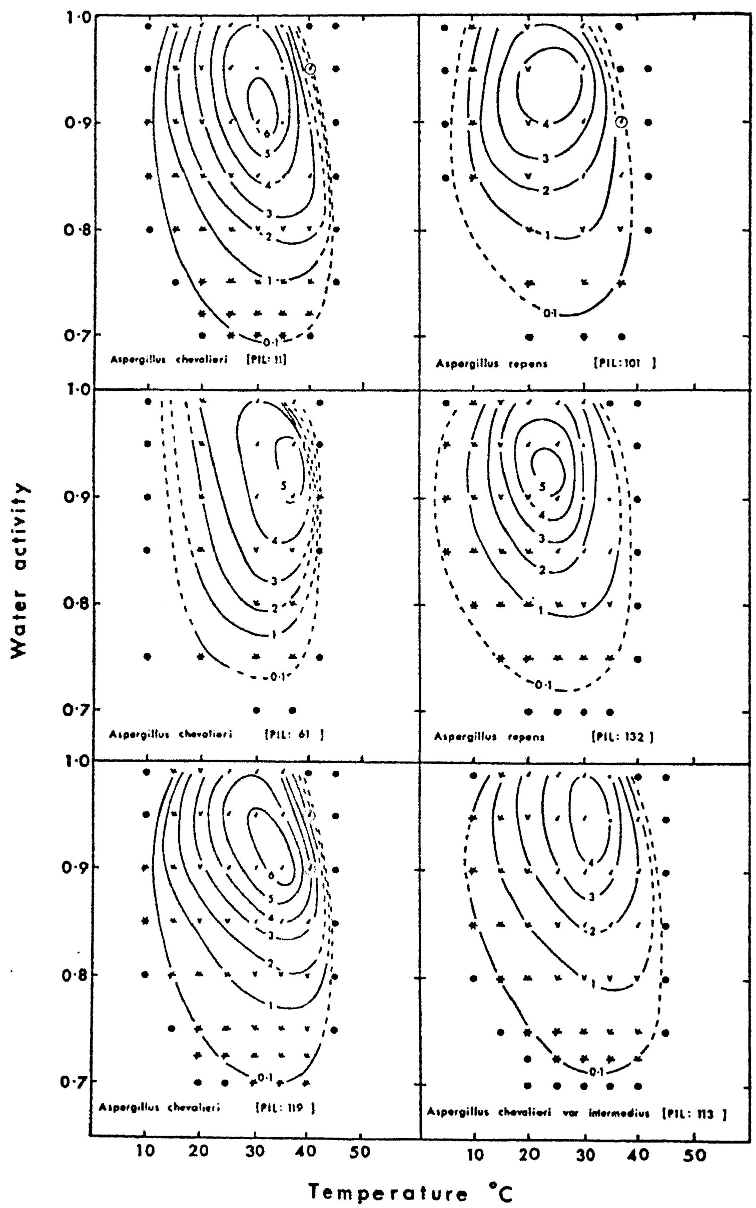

FIGURE 5. Germination time (left) and growth rate of *Aspergillus chevalieri* as a function of both water activity and temperature (from Ayerst 1969).

has risen significantly. The most humid period indoors is, however, in the relative warmth of early autumn.

2.7. **Time of wetness.** It takes some time for the dry spore to germinate. Grant [1989] calculated the fraction of time over a certain RH in out of the way corners of dwellings, based on the RH and the surface temperature. This measurement however, does not indicate how long the RH was consistently over a certain RH. Adan [1994] p.167 mentions an experiment by Pasanen

Figure 6. Skoklosters House, near Uppsala in Sweden. The interior is largely unchanged since the seventeenth century.

Figure 7. An interior view of Skoklosters House. The furnishing is generally in good condition. The house is unheated all the year and dark, except when visitors are shown round in groups.

[1992] which indicates that intermittent wetting is enough to cause mould growth on wallpaper.

Adan measured the response of mould to alternating high and low RH. The result for painted gypsum plaster is shown in figure 9. The periods of low RH were long enough to ensure that there is no residual effect from water evaporating into the boundary layer from the substrate. On the other hand the water content of the substrate will always be higher than the equilibrium value for the low environmental RH. Adan considers this matter in some detail. The reader is referred to the original thesis, which is a substantial contribution to the subject of mould growth on porous materials.

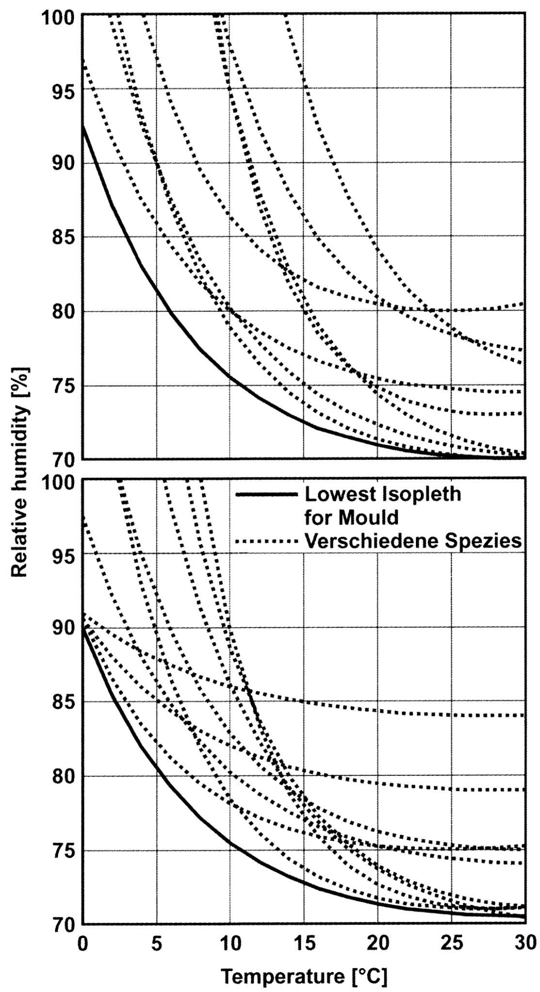

FIGURE 8. Limiting temperature and relative humidity for germination (top) and growth of common house moulds. From Krus 2001.

One must conclude from Adan's results that a low RH following a period of luxuriant growth at high RH will discomfort, but not kill the organism.

2.8. **Competition between species.** Agarossi and co-workers [Agarossi 1989] give an account of attempts to combat biological growth in Etruscan tombs at Cerveteri, north of Rome. A series of biocides designed to target particular groups of organisms: algae, actinomycetes and bacteria, were used in turn. Each disturbed the ecological balance, causing abundant growth of organisms that were opportunistically enjoying the absence of others that had previously held them in check. My dentist tells of patients who have not heeded the warning on their asthma inhalers, to rinse the mouth after inhaling. The medicine kills bacteria in the mouth, giving perfect growth conditions for fungi, which attack the gums.

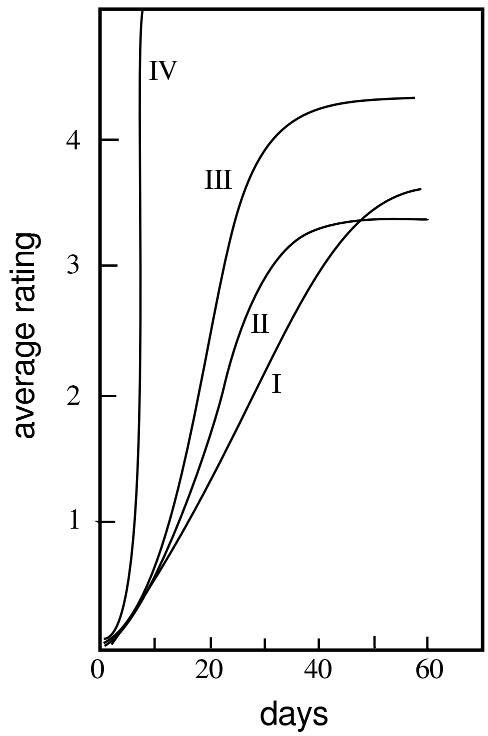

FIGURE 9. Mould growth during repeated alternating periods of high and low RH. The Y axis unit is the logistic growth rate, described in detail in Adan [1994] page 178. The substrate was gypsum coated with acrylic emulsion paint. The mould was *Penicillium chrysogenum*. The high RH exposure for all curves was 6 hours at 97%RH followed by 6 hours at a lower RH: I = 10%, II = 33%, III = 58%, IV = 87%. Redrawn from [Adan 1994]

An impressive example of limited growth in apparently ideal conditions is the Copenhagen Museum of Modern Glass Art, opened in 2001 in the cisterns that once supplied the city with water (figure 10). There is a constant thin layer of water on the floor and the underground site provides a rather constant temperature. The abundant fuzz of mould on the statues and their plinths testifies to good growing conditions, but the structure itself, with stuccoed pillars supporting the roof, is not visibly contaminated. Many authors note that 97% RH, rather than saturation, is the optimal water activity for fungal growth, but do not write that saturation prevents growth. A more likely explanation is that a thriving bacterial biota is preventing the fungi from establishing themselves.

The infrequency of mould where the relative humidity is constantly high is also demonstrated by caves and underground military structures. Figure 11 shows the interior of Garderhøj Fort, Near Lyngby, north of Copenhagen, built in 1886-1892. The iron fittings are corroding briskly, but there is very little visible mould growth. Maybe the competition from strongly growing bacteria is an effective deterrent. This is hardly a useful way to

FIGURE 10. Mould growing on the plinths and on the sandstone statues in the cisterns under Søndermarken, Frederiksberg. There is always 1 cm of water on the floor, so the relative humidity is always close to 100%, yet there is no obvious growth on the pillars supporting the roof of the underground structure.

protect an ordinary house from mould growth, but it does suggest the possibility of arranging deliberate biological protection of buildings. Indeed the Fraunhofer-Institut für Bauphysik is setting out to investigate the possibility of biological control of biological growth on building materials.

2.9. **Other influences.** The pH is known to influence the growth of organisms, which themselves alter the pH of their surroundings. The most dramatic example is the Dry Rot fungus, *Serpula lachrimans*, which needs the alkalinity of building mortar or calcareous stone to neutralise the oxalic acid which it secretes. Fungi generally prefer neutral to acid conditions but there are several that flourish in alcaline environments, so pH tends to influence the balance of species rather than the degree of infestation.

Light is essential to algae and lichens, which are therefore not found within building structures. Fungi are killed by ultra-violet radiation, but there are also reports of increased fungal activity in near ultraviolet radiation [Adan 1994].

Oxygen is nearly always sufficiently abundant in buildings. Among the physical variables, surface roughness is reported to have a surprisingly weak influence.

FIGURE 11. Garderhøj Fort, from 1892, is constantly close to 100% RH but is relatively free of visible mould growth.

2.10. **Unexplored, or unconvincingly documented, effects.** The most astonishing hole in the literature is the lack of information on the effect of air movement and air exchange. Air movement is universally recommended for inhibiting mould growth, but has never, as far as my reading goes, been investigated with scientific rigour. The scientific argument for the irrelevance of air movement is that the organism is always in passive equilibrium with the surrounding air, which is in equilibrium with the solid surface of the substrate.

The fungal hypha is in contact with the capillary liquid in the plaster at only a few places. The fungal hypha has a robust outer skin of chitin or chitin-cellulose complex. This is fairly impermeable to water. The water uptake of the organism must therefore be concentrated in some specialised areas of the mycelium. Nevertheless, in a high wind even the chitin protected aerial hyphae will lose water, which will force the limited area of water absorbing tissue to work harder, which means that it will have to synthesise more hygroscopic molecules, to provide a stronger driving force for diffusion of water into the organism.

Passiora [1982] (p 13) reviews the literature on water uptake through plant roots in soil. It is more difficult for plants to extract water and nutrients from soil than from homogeneous solution. One explanation is the accumulation of solutes at the root surface, causing a local increase in osmotic pressure. One would expect a similar problem for fungal hyphae extracting water from a salt laden wall to compensate for loss to the dryer air of the room.

Another factor reducing root efficiency, which should also apply to fungal mycelium, is the incomplete contact between the root and the pockets of capillary water between the soil particles.

The general acceptance of water activity as the limiting factor for germination and growth is a self-reinforcing assertion: there are no studies of the effect of water concentration at constant activity. Furthermore the discussion of water activity is confused by circular arguments. Theoretically, one can deduce that the thermodynamic definition of water activity is, ideally, identical with the ratio of actual vapour pressure to saturation vapour pressure, that is the relative humidity. In practice, mycologists define the water activity by imposing a defined relative humidity. The water activity is not measured directly. The whole concept of osmotic equilibrium depends on liquid equilibria across a semi-permeable membrane. When one side of the semi-permeable cell wall is bathed in air with a given partial water vapour pressure, but no solute, the situation is far from that which the theoreticians have so elegantly explained. One can draw an analogy with the over-familiar use of pH in quite dry conditions. The pH is, when rigorously defined, the log of the hydrogen ion concentration in moles per litre of aqueous solution. There are no hydrogen ions in the air, whatever the water vapour concentration.

In general, there is an understandable tendency to take the insights from simplified, usually homogeneous systems, and apply them indiscriminately to multiphase systems, fixing deviations from the in-vitro results with empirical correction factors, practical but without fundamental significance.

The final hole in the body of research results is the lack of investigation of why organisms do not grow in places where they would be expected, such as adjacent to places where there is abundant growth but an apparently identical microclimate. In Denmark we have Medieval churches which are regularly over 80% RH (figure 12). The massive walls are known to buffer the local relative humidity [Padfield and Eshøj 1993], so the time the wall surfaces and the boundary layer of air that encloses the fungal mycelium are continuously over 80%RH is quite long.

It must be acknowledged, however, that we nearly always find fungal hyphae during microscopic studies of fragments of wall plaster from the interior of churches, though to the naked eye there is no sign of fungal growth. The suspicion of widespread infestation that is not visible to the naked eye is reinforced by the curious behaviour of the 15th century wall painting (figure 13) on the vaults of Gerlev Church in Sealand, Denmark. The paintings turn grey in winter, and brighten up again in the summer, probably because of seasonal variation in the fungal metabolism.

2.11. **The risk of experimental error.** There is some controversy over whether condensation is necessary to start fungal growth, or merely a high water activity, in the region 0.8 to 0.98. One matter that is seldom adequately described in the papers cited in this review is the accuracy of the experimental control of water activity. Anyone who has made experiments where high RH is required will appreciate that it is extremely difficult to avoid intermittent condensation. At a nominal 97% RH, condensation may occur when the specimen under observation is just one degree cooler than

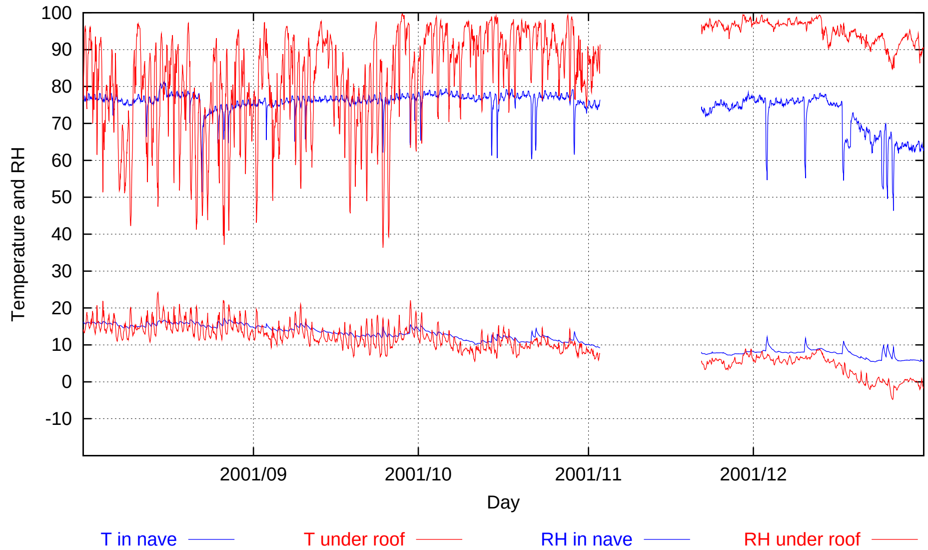

FIGURE 12. The relative humidity measured under the roof of Rørby Church, Sealand, Denmark. For the first months the new roof tiles had no mortar between them to reduce ventilation, so the RH was very unstable. Later, the roof was made more airtight and at the same time the church heating was started. The relative humidity then rose to a steady high value, fed by water vapour from the church below diffusing through the brick vaults. These two microclimate patterns, and intermediate states, are characteristic for many churches and probably have been so for several hundred years, yet the church roof timbers are generally in good condition. Data from Poul Klenz Larsen, The National Museum of Denmark.

the controlling salt solution, or other RH-controlled air stream. Such a temperature difference can arise simply by uneven light irradiating the apparatus. I write that condensation 'may' occur, because a short period at low temperature will not cause condensation onto a spore support that is hygroscopic - it will buffer the RH for a time. Several researchers, however, have used spores attached to carefully cleaned glass microscope slides, which have negligible ability to buffer the climate. Although the early researchers report calibrating their systems with thermocouple psychrometers, they do not report the stability of their experimental arrangements, which often ran for several weeks.

Assertions that condensation is necessary for mould growth in the real world, as contrasted with the world of agar gels, cannot be lightly disregarded. Intermittent condensation into porous walls is very difficult to detect. Indeed it is difficult to define what 'condensation' means in a porous material, where there is a smooth transition from the hygroscopic region, up to 99% RH and the capillary condensation region, which leads to the state of total saturation.

FIGURE 13. The fifteenth century painting on the vault of Gerlev Church, Sealand, Denmark. The background turns grey and then white again on an annual cycle, probably from the annual pigmentation cycle of a fungus.

2.12. **Models for biological growth in buildings.** In spite of the evidence for many factors influencing the growth of microorganisms there is a clear tendency to isolate relative humidity as the major influence. The German building standard states that 80% RH is the upper limit for safe conditions. Innumerable secondary sources give values between 65% and 80% as the limit for biological growth in buildings. There has been an efflorescence of computer models to predict the local relative humidity in hidden parts of wall and roof structures, and thus define the risk of mould growth in any building design. The programs are invariably validated by the people who write them. I have not read a comparison of various programs, using the same starting data. This is surely because the programs are so difficult to use. The source code is sometimes secret, or so convoluted and sparsely documented that it still breaks the fundamental rule of scientific writing: that an experiment should be repeatable from the written account. The authors may say that the fundamental algorithms are published, but that does not guarantee correct programming. There is a powerful case for introducing into building physics the concept of open source programming, where programmers collaborate to refine programs. One could also urge the adoption of the even more modern concept of 'extreme programming', where

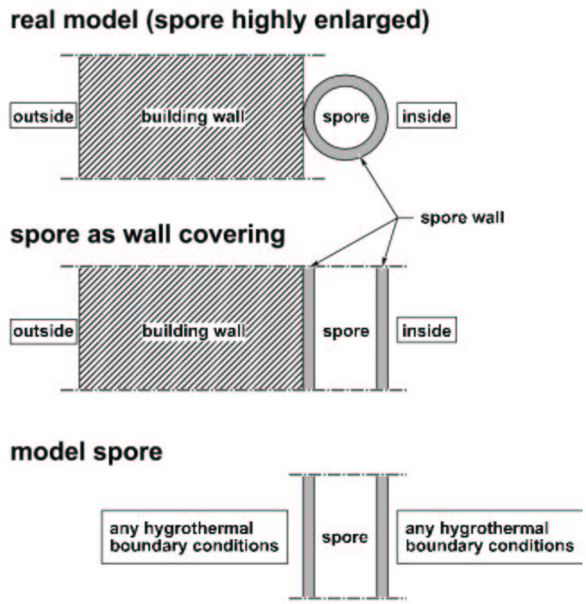

FIGURE 14. The adaptation of the WUFI program for predicting heat and moisture movement in walls to spore germination and growth. The spore is expanded to a wall element, 10 mm thick.

one first writes the routines that test the accuracy of each module in the program, before writing that module.

There is a lack of modularity in the pioneering programs. By modularity I mean dividing the code into discrete bits which each do a limited part of the whole task. The early programs also had to be written with ingenious algorithms to save memory and processing cycles. They have proved difficult to adapt to new information and new priorities. This is is amusingly illustrated by one of the top HAM (heat and moisture) programs: WUFI. Krus [2001], and the team from the Fraunhofer-Institut für Bauphysik in Holzkirchen, have introduced mould spore germination rates into WUFI. To do this they have to make a second run of the program with the spore enlarged to the dimensions of a calculable wall element. This adaptation of a well established program to unforeseen tasks will be seen again in the discussion about the influence of the wall on the interior climate - another effect that the early programmers didn't take account of. The linear programming style of most of the early programs is now surely hampering their rational development but it takes courage, determination and funding to start again, incorporating a decade of development in building physics, microbiology and programming.

The bioWUFI team have taken a different approach from Adan to rapidly varying RH in the inner components of walls. They use the permeability of the spore wall, and the water storage necessary to bring the spore up to active growth. In other words they treat the spore as a typical, lifeless component of the building until it reaches a water content that permits active hyphal growth to start. The diffusion coefficient for water through the spore

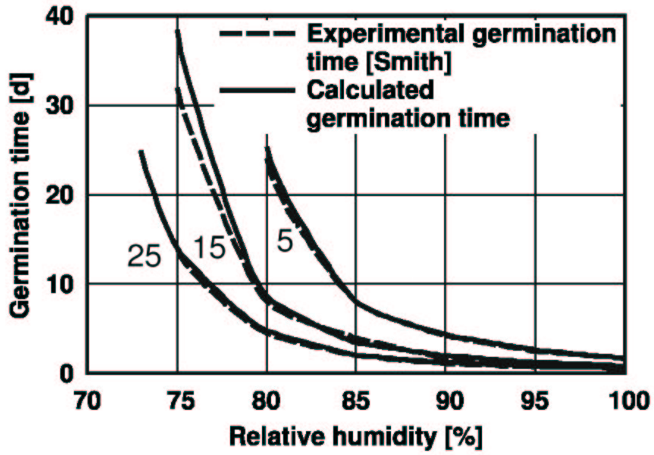

FIGURE 15. The germination rate of mould spores as a function of RH, time and temperature. From Krus[2001].

wall increases rapidly with increasing water content. For calculation purposes the spore is expanded to a 10 mm thick, parallel sided wall component. The sorption curve of the spore is taken from the literature. The predicted germination time as a function of RH is shown in figure 15. At 97% RH the germination time is about a day, perhaps less, so these results are consistent with Adan's reporting of nearly instantaneous water absorption, as seen under environmental scanning electron microscopy at 97%RH. The biologically enhanced WUFI program, however, is able to integrate the influence of moderate RH and time to predict the likely start of mould growth.

The development of this biological addition to WUFI is thoroughly documented in Sedlbauer's ph.d thesis [2001].

Finnish and English researchers have also been active in developing models for the combined effect on mould growth of RH and temperature in a fluctuating environment [Clarke][Hukka 1999], with comparable results.

One characteristic of nearly all the computer models is that they assume that water vapour diffuses according to Fick's law, which is an example of a general type of physical law where the rate of the process is proportional to the potential driving it. Fick's law states that heat flow is proportional to the temperature gradient across the test specimen. The equation describing the transfer of heat by molecules vibrating against one another has been borrowed to describe the wanderings of water molecules in porous materials. This has also been modelled as a random blundering about, a so-called stochastic, or Monte Carlo model, which gives the same result as Fick's law predicts, but in reality there are powerful chemical forces holding water to the surfaces of clay particles and the entry of water molecules into the wood structure alters the pore size.

Padfield [1999] made a very simple experiment with a dynamically changing water vapour potential in a system at constant temperature. The movement of water vapour through a clay mortar was modelled according to the simple Fickian rules. It proved impossible to match theory to reality. There was a phase difference between the real and the modelled process that could

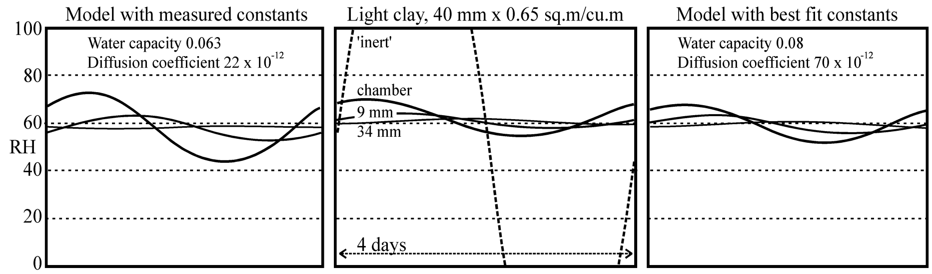

Figure 16. The centre graph is the measured relative humidity at the surface (chamber) and at two depths in a clay plaster specimen exposed to a sinusoidally varying water vapour flux in a sealed chamber. The dotted curve is the RH expected with an impermeable, non-absorbent specimen. The chamber relative humidity is strongly buffered by absorption within the specimen. On the left is the 'Fickian' model, using statically measured constants for diffusion and sorption. On the right is a modelled result where the constants have been adjusted to fit reality. It proved impossible to get both amplitude and phase in the model result to fit the experimental result. From Padfield [1999].

not be removed, even by replacing the measured measured values for water sorption and permeability to give a best fit (figure 16). A phase shift has also been observed in a more recent, unpublished experiment, using an entirely independent model program [Peuhkuri 2002].

Generally, computer modelling of the building envelope has been a spur to thinking about the materials and the design of wall and roofs, but it is premature to use the programs as design tools in the architect's studio. As I will show in a later section, the programs are a long way from being able to deal with the intricate forms of real architecture, spiced with typical construction defects. The real usefulness of the programs is to explore general ideas about constructing fault tolerant buildings that won't rot if one neglects their maintenance for a year or two.

2.13. **Summary of the biological input to discussions of the mould growth potential of building envelope design.** Mould growth depends on an RH between 65% and 100% but is slow below 80%. Mould growth in building components is negligible below 5°C and reaches an optimum for many species around 30°C. There is a very strong influence of temperature on the limiting RH for growth, which approaches saturation at 5°C and has its minimum value at the optimum temperature for growth. The nature of the substrate is surprisingly unimportant: roughness and porosity have little influence. Good nutritional value reduces the RH limit for mould growth somewhat, up to 10% in selected examples. The influence of containment and air flow over the hyphae is unknown. The influence of hygroscopic salt solutions is unknown.

3. Trends in building and ventilation techniques that are relevant to the mould resistance of buildings

3.1. **Airtightness for energy efficiency.** Airtightness is a mantra of modern building physics. If the building leaks it loses energy. One could cynically add that if the building leaks it is impossible to model its behaviour. Bad workmanship is notoriously difficult to treat mathematically. The dominant wisdom is that the building should be airtight, and then ventilated in a supervised manner, by computer in large buildings. There have long been attempts to extend computer control to ever smaller units of habitation, the so-called 'intelligent house', but there is a growing resistance to such abstract control of peoples' everyday life. The technologist's ideal of total airtightness with all ventilation air channelled through a heat exchanger is considered by Svendsen and co-workers [Rose 2002]. Their test house did not meet the efficiency target for heat exchange but there is no doubt that a carefully built demonstration house can give impressive energy economy.

3.2. **Airtightness for moisture protection.** Airtightness is a mantra of modern building physics. If the room walls are not airtight, human-generated moisture will penetrate the structure and condense somewhere on its way to the generally cooler outside skin of the building. The danger is greater nowadays because efficient insulation gives a colder skin, even below ambient temperature on a clear night. Another trend in building methods which increases the risk is the use of prefabricated units, joined on site. The units can be made very airtight because they are made in factories where quality control is easily enforced. Joining them together on site is another matter, because of variation in the weather and more difficult supervision. The resulting structural inhomogeneity channels air through the few cracks between units. Condensation is concentrated in a few places. The resulting locally abundant water will then move according to gravity, which, like leaks, is very difficult to model realistically. I give a case history later.

Air movement through cracks would not be so serious if the crack were lined with water absorbent material, which could absorb and disperse the passing water molecules, then release the absorbed water in a warmer period, or simply transmit it sideways so that the water is distributed over a wider area of wall, from which it can evaporate. An example of such a wall is air dried clay. The high water sorption of the clay gives considerable protection against discrete leaks, though it cannot cope with constant diffusion of indoor air through the entire wall. Modern buildings tend to use non absorbent materials such as paint, polyethylene, dense concrete, glass and steel. Furthermore, constructional details are quite complicated, so water can pool in unexpected places and remain there quite a long time without evaporating, because the air is streaming through somewhere else.

3.3. **Airtightness and the indoor climate.** Airtightness is a mantra of modern building physics but we are rapidly approaching a situation where the outdoor air is cleaner than that indoors, even in big cities. A vast array of volatile chemicals evaporate from building materials, furnishing and decorative finishes. The airtight, non-absorbent building does nothing to hinder this environmental insult. Modern people spend most of their

Figure 17. The National Gallery of Canada in Ottawa, designed with meticulous attention to the continuity of the air barrier.

time indoors, so the threat to health is quite serious. The pollutants are at present ventilated to the outside, together with the human generated moisture. The ventilation requirement is usually given in air changes per hour, about 0.5. The ventilation requirement is normally set by the need to reduce the water vapour concentration, which is always above the outdoor concentration. The air exchange rate thus established gives us plenty of oxygen and adequate removal of carbon dioxide, except in very crowded places. The air exchange requirement for ventilating toxic chemicals is not definable, because it depends on each individual object in the house. The much discussed sick building syndrome has proved extremely difficult to define in scientific terms, in spite of a torrent of publications. The modern human animal, with his/her demand for comfort and happiness, has proved to be a difficult experimental subject, leading to conflicting research results. Instead of a summarising a collection of references, I refer the reader to the many publications from the International Centre for Indoor Environment and Energy [International Centre].

Two discussions which are particularly relevant here are the controversy over the discomfort caused by low RH (under 30%) and the irritation caused by draughts. Both low RH in winter and draughts are used as arguments against using windows for ventilation. Both pre-humidifying and pre-warming of air can better be done in a heat and moisture exchanger with distribution through pipes to each room. However, new findings suggest that modern office folk are not such tender creatures as microclimate researchers once thought.

3.4. **Examples of damage caused by non-absorbent materials combined with imperfect construction.** It is not difficult to find examples of buildings which suffer condensation in spite of a carefully specified air barrier. The National Gallery of Art in Ottawa, Canada, (figure 17) suffers from condensation in the skylights which moves several floors down to drip from the ceiling of the ground floor (figure 18). This building is not just

FIGURE 18. The bucket (arrowed) catches dripping condensation from the skylight. The National Gallery of Art, Ottawa

chosen as a random example - it was meticulously designed to have an air barrier to hold back air humidified to 50% RH for the sake of the pictures.

Large buildings are predominantly made of non absorbent and airtight materials, both as interior finish: plastic paint, and as exterior finish: glass, concrete. The roof is typically flat and built as a sealed sandwich with airtight materials enclosing a porous, water-inert insulation, which, in Denmark, is usually mineral fibre. There is one dominating characteristic of these buildings: they do not interact with water vapour. This is often presented as an advantage but is in reality a disadvantage. There are always air leaks around the manufactured panels. Air is therefore concentrated into channels. If the air flow is moderate it will not much influence the thermal gradient through the construction, so condensation will occur in cold weather. If the flow is very fast, the heat transferred by the air will prevent condensation, but this situation seldom arises, and would in any case indicate an unacceptable energy loss. One characteristic of this condensation is that it is abundant in the few places where it occurs. Here, the condensation will be heavy enough to drip down. Construction details are nowadays sufficiently intricate that it is often difficult to trace the path from the water stain visible indoors back to the source. The stain is therefore attributed to a leak and the roof is repaired, without preventing the stain re-appearing after condensation during the next cold spell.

Much effort is put into designing a comprehensive air barrier, and much supervisory effort is used on site, also after disaster has struck. Figure 20 shows the inside ceiling insulation being ripped out of a museum store in Maryland, USA. Although the whole roof was rebuilt (figure 21) the failure was limited to half of the long passage. Inconsistent quality control was the immediate cause of failure, though the design was risky.

Figure 22 shows a ribbon of ice forming from condensation on the inside of a window frame in the same building. This also was traced to a break in the installation of the air barrier. It is a very good example of the amount of water that can be generated overnight by a small break in an otherwise

FIGURE 19. The north east facing facade of the IBM building in Lundtofte, near Copenhagen, photographed on a cool evening. There is condensation on alternate levels of the glass facade, which shows as dark patches, in contrast to the clear reflection of the sky in the unaffected glass. An apparently homogeneous facade has systematically uneven hygrothermal characteristics.

impermeable construction. Even adjusting the fans to impose a slight vacuum within the building did not entirely stop the leakage of water vapour. This is because the incoming air also sticks to easy paths through the envelope, so that the humid inside air can still diffuse to the cold outer skin of the wall. The wall was concrete slabs with internal insulation of expanded polystyrene, then a polyethylene membrane and painted gypsum board on the room side.

My point is that specifying an air barrier as the main defence against condensation within the wall or roof structure is a dangerous practice, though it appears to be conservative. If the building is also deliberately humidified, as in a museum, a hospital, an electronics factory or even in an ordinary office, failure of the defence against condensation is sure.

A building made of water absorbent materials but with the same frequency of cracks through to the outer skin, will defend itself against condensation because the flowing air will lose water vapour continuously to the immediately surrounding material, which will in turn allow it to diffuse sideways to dry material which is not directly in the path of air flowing from the interior of the building. I don't know of many measurements of these processes, because absorbent walls are typically made of unfired earth or straw bales, which have only recently caught the attention of building physicists, though clay is still the world's most widespread building material. I can

FIGURE 20. Ceiling insulation being stripped from a museum store in Maryland, USA, because of condensation on the roof above. Condensation only occurred on the half of the long 'street' that was badly sealed.

FIGURE 21. Polystyrene insulation being put on the roof of the street shown in the previous figure.

only use my own experience of historic house museums where solid brick walls, without insulation, do not seem to suffer condensation.

3.5. **The effect of the annual climatic cycle on the microclimate within the building envelope.** An extreme, and instructive, example of condensation caused by a combination of modern demands for comfort, fire resistance and energy efficiency was the indoor precipitation in the Arts and

FIGURE 22. Ice accumulating from water vapour leaking through a gap in the air barrier of the museum store in Maryland.

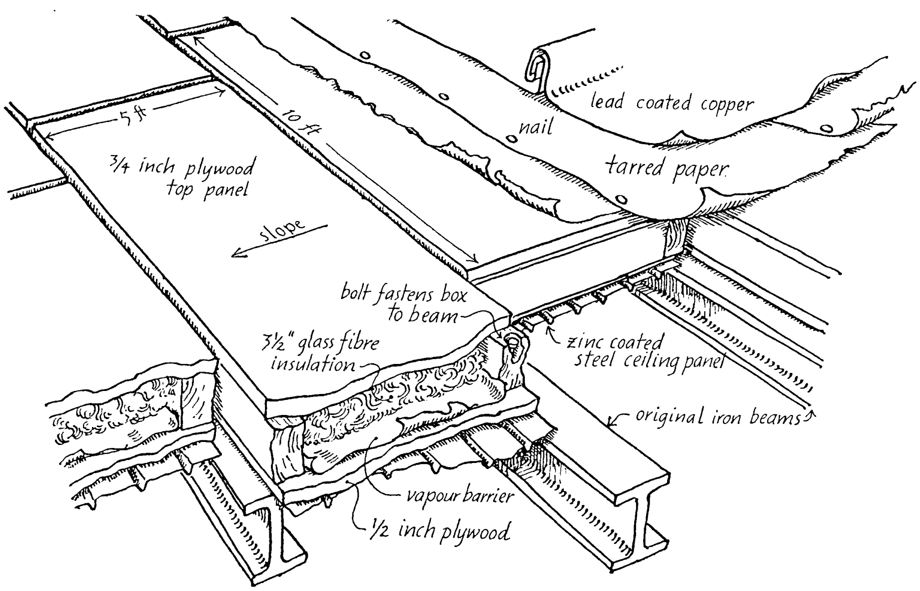

FIGURE 23. The design of the roof of the Arts and Industries Museum in Washington DC.

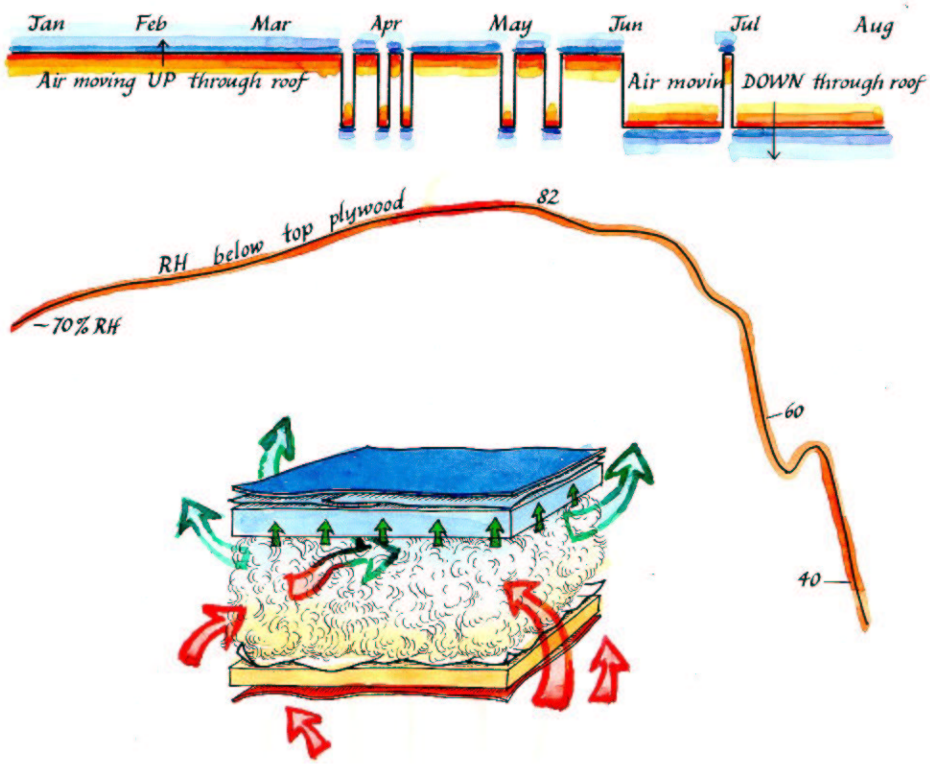

FIGURE 24. Moisture accumulated in the upper plywood layer during the winter, from air flowing between the prefabricated roof casettes. The trace at the top is the direction of air flow through the roof, driven by the stack effect, over a period from winter into summer. Below this is the RH measured just below the upper plywood. Notice the very sharp fall in RH in early summer.

Industries Building of the Smithsonian Institution in Washington DC, which sent the engineers scurrying about the roof looking for leaks [Padfield 1999]. Figure 23 shows the roof construction of pre-fabricated boxes, each with its own air barrier. Air from the heated and humidified interior (this is a museum, so the interior is humidified for the benefit of the exhibits) penetrated the structure through the joints between the boxes. The condensed water invaded the boxes from above, bypassing the air barrier. During the early summer the sun warmed the top of the roof, distilling water onto the vapour barrier on the now cooler, interior side. After a while the water drops coalesced and cascaded into the interior through joints in the ceiling. It was very dramatic, but short lived. As the graph in figure 24 shows the roof dried out within a week or two and the process stopped, until the next spring sunshine. The condensation was also limited to the morning hours, as shown in figure 25. If the air barrier had had even a thin layer of absorbent material over it, the condensation would never have reached the interior of the building and would have disappeared entirely over a few weeks.

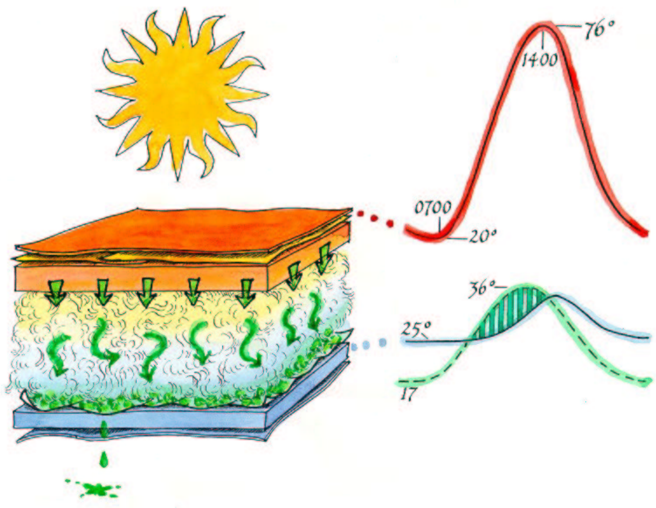

FIGURE 25. Episodes of acute condensation are caused by bright spring sunshine warming the upper plywood and distilling water vapour onto the polyester air barrier which covers the lower plywood. The morning period of condensation is shown by the crossing curves of the air barrier temperature and the dew point of the air directly above it (the curve that starts lowest). The dew accumulates until the drops coalesce and cascade down the slope and into the room below through gaps in the ceiling. These dramatic events are limited to a few days in early summer. After that the roof dries out until the next winter recharges the water content of the upper plywood.

FIGURE 26. Mycelium of *Penicillium* around crystals of ammonium dihydrogen phosphate. The fire retardant salt had been added to the plywood used for the roof deck. The picture is about 1.5 mm across.

FIGURE 27. The Renwick Gallery in Washington DC. Note the bold modelling of the 19th century facade, with stone details on a massive brick building.

Another piquant detail was the abundant fungal growth on the plywood roof deck (figure 26). The mycelium embraced nutritious crystals of ammonium dihydrogen phosphate, a fire retardant chemical which had recrystallised separately from the biocidal borax salt.

I describe this building in some detail because it shows how difficult it is to model the behaviour of buildings. The magnitude of the air flow through the roof due to the stack effect would be very difficult to predict. The way in which the water vapour moved up through the cracks between the casettes but moved down through the casette construction would be difficult to believe without the evidence from the sensors. The mould growth fostered by the separation of the fireproofing salts was another hard-to-predict phenomenon. The water absorbent plywood played a vital role in the disaster, but a water absorbent coating to the air barrier would maybe have prevented the disaster altogether.

Another example shows the combined effects of a short seasonal event with variation in the thermal gradient through the complicated facade of an old building.

The Renwick Gallery in Washington DC is shown in figure 27. In spite of its massive appearance, the new stone decoration is a skin, separated from the brick core by an air gap (figure 28) bridged by stainless steel pins. This intricate and expensive reconstruction technique was designed to prevent soluble salts from migrating into the new stone, which is actually coloured concrete.

A perspective cross section through the rebuilt facade is shown in figure 29. Moist air from the interior diffuses through the solid brick wall and enters the air gap. The air gap is at a varying distance from the boldly modelled surface of the building. Consequently, the temperature of the air gap varies,

FIGURE 28. The 1 inch (2.5 cm) gap established between the bick structure and the new stone (actually coloured concrete) decorative elements. Sensors were placed in this gap and at other places in three sections through the building.

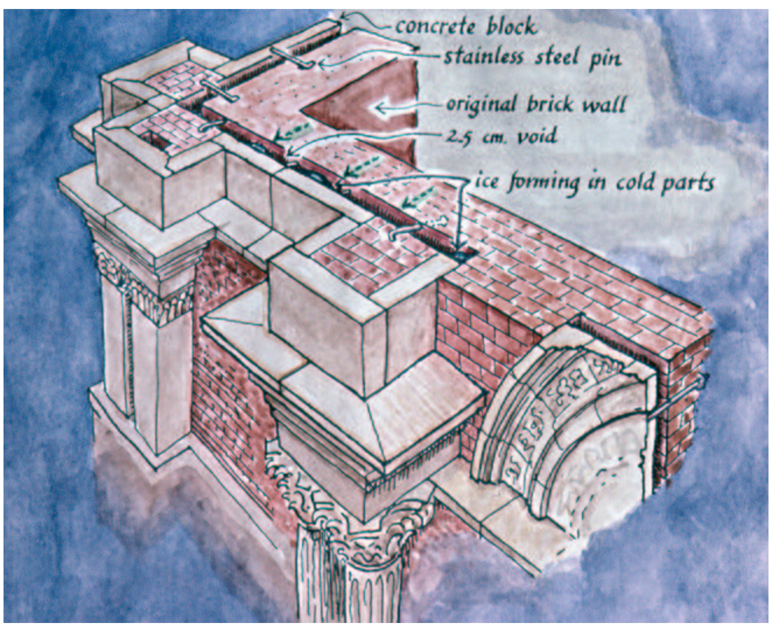

FIGURE 29. During the winter, moist air diffuses from the interior into the gap, which is in many places covered on the outer side with impermeable concrete blocks. The temperature of the gap is uneven, because of the bold sculpting of the facade, so vapour moves laterally to accumulate as ice in the cooler parts.

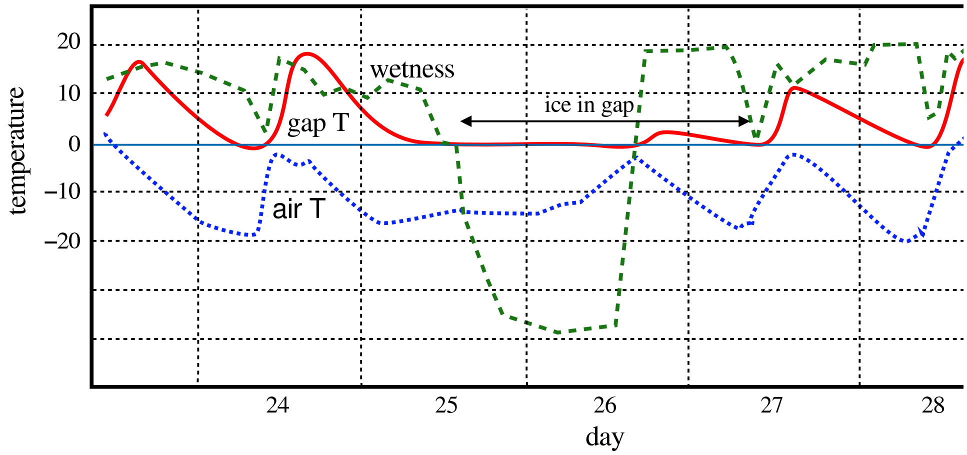

FIGURE 30. A sequence from the climate record showing a period of freezing followed by a long period of thawing, indicating considerable accumulation of ice where the wetness sensor was placed. The wetness sensor measured the surface electrical conductivity of the stone and so gave a 'dry' reading when frozen. Evidence for ice persisting after the wetness sensor has recovered its wetness comes from the slow rise in temperature of the gap at this measuring site

allowing lateral moisture movement. Instruments embedded in the building show that ice forms in the gap in such quantity that it takes several hours to melt (figure 30). The concentration of water in particular places is here vastly increased by accumulation of ice, which prevents immediate drainage through the cavity. In this building also there was a short period of about two weeks in spring where a daily distillation of water across the gap could be seen in the instrumental record. At other times of year the data logger gave a very boring account of the good behaviour of a dry wall.

These examples show that there is scope for protecting buildings against the occasional coincidence of natural forces that spell disaster: what the geologists call 'punctuated equilibrium'. The design can then function normally on the edge of stability, if the designer also builds in a buffer against these climatic extremes.

4. A rational strategy for improving the performance of dwellings

There are trends in building physics, and in experimental structures, that are threatening the dominance of the strategy of total control of every parameter, which has so clearly failed to produce consistently healthy buildings.

4.1. **Is the vapour barrier really necessary?** I have presented abundant evidence that the air barrier does not always work in practice. The next question is whether it is necessary or useful. Simonsen and co-workers [2000B] have shown that a house with a porous wall can certainly survive the Finnish winter. They replace the absolute vapour barrier with the concept of a vapour resistance ratio. The interior surface of the outer wall should be between three and five times as impermeable to water vapour as the outer surface of the wall. The water vapour leaking from the interior will then diffuse through the outer surface fast enough that the outer parts of the structure do not get wet enough to rot.

In another paper in the same symposium [Simonsen 2000] Simonsen points out that porous interior walls will pass useful quantities of carbon dioxide and volatile organic compounds through the wall.

The establishment of a suitable ratio of permeabilities is a good first step towards a rational choice of building standards for resistance to condensation and mould growth, but a limit to the absolute values of permeability would be even more useful, because it would allow quantification of the possibility of venting water vapour, carbon dioxide and other unwanted gases, through the whole area of the house wall instead of through channels poked through the walls, with fan blades spinning within them. One of the important arguments for relaxing the demand for absolute impermeability is that the house can 'breathe'. This is a somewhat sentimental description of a real process: the absorption and transport of water vapour through the entire fabric of the building.

A different approach is presented by a group of researchers in Dresden [Häupl 2000]. They have looked at the possibility of insulating historic buildings on the inside, so that the facade is not disfigured. They have demonstrated that calcium silicate porous insulation laid directly against the interior walls does not rot, even though there is occasional condensation on the wall side of the insulation. The insulation wicks the moisture back to the room side where it evaporates again into the room air. The risk of condensation is difficult to predict, or to prevent, because old buildings often have thick interior decoration in oil paint, of very high vapour resistance.

4.2. **The case for the entirely porous wall.** These two subtle approaches to relaxing the rules for vapour barriers on the warm side of the insulation, the room side in northern Europe, hint at the vast unexplored possibilities of building materials that are both porous, insulating and water absorbent. The only representative of this class in common use is cellular concrete (gasbeton) but such materials are not new. Figure 31 shows a row of houses in a village in central Devon, England, where many houses are built in 'cob', an earthen matrix filled with angular stones. It is an unusual form of earth construction which has arisen because of the nature of the local bedrock: a schistose rock which weathers readily into small angular fragments that cannot easily be used for conventional stone building. The vapour transmitting, and vapour buffering properties of this material are, sadly, no longer realized in these buildings, because both the interior and exterior surfaces are commonly covered with plastic paint of vastly less permeability than the material between.

If we combine the information we have on the RH and temperature dependence of mould growth and the sorption data for materials, we can see that in the high RH region, over 80%, where mould growth accelerates, sorption of water by materials also increases steeply. An absorbent material needs much water to increase its equilibrium RH from 80% to 90%, so absorbent

FIGURE 31. Houses in a village in central Devon, England. They are built in 'cob', a form of earth building with angular rock fragments embedded in an earthen matrix. The bottom metre or two of the wall is usually of stone. Both sides of the walls would originally have been limewashed but they are now usually covered with an impermeable plastic paint. The walls are up to a metre thick, because the technique is not at all refined. This great mass of wall gives a high thermal inertia which compensates to some extent for the lack of insulating value of the earth.

materials are peculiarly well suited to reduce the risk of mould growth. A non-absorbent wall will see wild swings from condensation to dryness, but the short periods of total saturation will encourage mould growth much more than the periods of low RH will inhibit it. The results of Adan [1994] are very important to this discussion.

One practical advantage of the use of massive, homogeneous walls of absorbent materials is that they are very forgiving of faults and neglect. If water accumulates, for any reason, at a particular point, it will rapidly disperse into the surrounding material. Earth walls are therefore surprisingly water and neglect resistant. It is both sad and instructive to see the long, gentle decline in the rural earth buildings of south west England, a notably rainy region of the world. Figure 32 illustrates the local saying about building maintenance: 'A cob building needs a good hat and good boots'.

Building physics has for some time extended its interest to such vernacular techniques. One notable centre for research is the University of Grenoble. In Denmark's Technical University there has long been a slender thread of research in the properties of alternative building materials such as organic insulation, lightweight clay bricks and recently a remarkable fibre reinforced lime bound material from France called Canosmose. An anecdote about this research illustrates that there is still some way to go in integrating unusual materials into the curriculum of building science studies.

A group of students from the Technical University of Denmark chose to study the physical properties of 'Canosmose' a mixture of chopped hemp

Figure 32. A slowly disintegrating earth building in central Devon. The tin roof and the stone base to the wall ensure surprising durability even against driving rain, frequent fog and an unheated interior.

stalks (Cannabis sativa) with calcium hydroxide binder and a small portion of a top-secret dark powder. The students made a cylinder of the material, which is designed to fill the walls of timber frame constructions. They then measured the water uptake in the normal manner by dunking one end of the cylinder in water and weighing it at intervals to reveal the expected quadratic relation between water uptake and time. But it didn't suck. The students in their final presentation were very embarrassed at their failure to get results, attributing the problem to all sorts of technical errors, like failing to reset the clock or letting the water leak out of the container. The possibility they didn't ever consider was that this water vapour absorbent, porous material could also be water repellent. A possible explanation is that the lime formed calcium soaps with organic compounds in the hemp fragments but that is just speculation. We should simply be aware that there are interesting materials outside the mainstream of the building suppliers catalogues.

There are arguments against the homogeneous wall that provides in one material the total requirement for bearing the structure, insulating, and protecting against condensation. It will surely be thicker than the minimum hi-technology membrane that is now fashionable. An argument put forward by the manager of a gasbeton (cellular concrete) factory in Denmark was that it was a difficult material to plaster and Danes prefer a yellow brick facade anyway.

One must not deny the importance of tradition, but it is also important to evaluate materials for their intrinsic properties, outside the confines of traditional thinking, both aesthetic and scientific.

5. The relevance of this discussion to the window project

Like the devastating introduction of artificial ultramarine blue to the far eastern painters in the late nineteenth century, the development of glass that can insulate as well as an opaque wall has led to a proliferation of glass wall architecture in office building. It has variously been described as cigar box architecture, membrane architecture and worse. But styles change and we should have our material data sheets ready for the next architectural revolution.

One result of the glass facade style is that the outer skin of these buildings is impermeable. The danger of condensation in a cold climate is well understood and two approaches are used to minimise the chance of trouble. An air barrier is installed, or the air space behind the outer skin is ventilated, so that outdoor air, with its relatively low water content (though normally high RH) is brought into the building and warmed slightly so that there is no danger of condensation on the inner surface of the outer layer of glass. This air circulation can be forced but is also designed to run through natural convection. My point is that the first alternative: preventing indoor air from reaching the outer glass by fitting a barrier layer, is very difficult to achieve. The second method seems to have a good record so far, but we must wait for reports of how well the natural circulation systems work.

The tendency to regard the window exclusively as a source of light and a psychological connection to the outside world is convenient for the designer, because designing openable windows to remain airtight for many years is a formidable challenge. It is really a chemical problem: Polyvinylchloride (PVC) is the material of choice for making intricate sealing strips with profiles which include bends and furrows and changes of stiffness. Soft PVC is, however, not durable. It is also regarded as an environmental hazard - outgassing toxic plasticisers.

If houses could be designed to work well with windows that are opened when it is convenient for the occupier one could minimise energy loss and unpleasant draughts. For example, a bedroom with water absorbent and carbon dioxide permeable walls will hold a good microclimate throughout one night with windows closed. The windows can be opened for a short period during the day to regenerate the buffer capacity of the wall. This is also the time when the ambient temperature is highest, so the energy loss is less than if the windows were slightly open all night to ventilate away moisture and carbon dioxide.

There is a good case for returning, for ordinary dwellings at least, to simpler, more massive structures, made of water absorbing and permeable materials and with windows that provide adequate ventilation when the inhabitants want it. When the windows are shut, the porous walls take the load of water vapour, carbon dioxide, and worse gases. The computer is used for its proper purpose of playing games rather than controlling ventilators.

Until the late 1990's, building physicists were passive observers of the interaction between the indoor climate and the room surfaces and furniture. It is encouraging to see an outburst of interest in actively modifying the materials and structures of buildings to generate a more subtle indoor comfort,

FIGURE 33. An earth house in Stenlille, Sealand, Denmark. The walls are made with a version of the cob technique, modified to resist earthquakes. The roof is fireproofed with clay laid on poles. The small windows are fragments of glass set directly into the earth walls, without frames. The large window illuminates an indoor garden with underground heating from air pumped from the apex of the house by a solar powered fan. Underfloor heating is provided by a downdraught burning wood stove invented by Ianto Evans. Flemming Abrahamson was the architect. Oh! One other thing: the arrow points to small holes in the wall caused by whitewashing at the wrong time of year. Corn seeds in the fibre reinforcing the earth sprouted in the moisture from the whitewashing process and broke through the surface.

where the parameters which we do not consciously sense, RH and carbon dioxide concentration, are held at moderate levels by the building itself.

Building physicists have much to offer to, and maybe to learn from, the alternative ecological enthusiasts who mix their clay with water from holy springs then tramp the mud to the accompaniment of lyrics from the high school songbook before smacking the dough up on the slowly rising wall of their new house. Practical work brings new insight and surprises. I finish this article with a picture (figure 33) of a clay house of advanced design that was recently built by Flemming Abrahamson and Ianto Evans in Stenlille, south west of Roskilde in Denmark.

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7. References

Scott, W.J. 1957. Water relations of food spoilage microorganisms. Advances in Food Research, 7, pp 83 - 127.

Franks, F 1982. Water activity as a measure of biological viability and quality control, Cereal foods world27 pp 403 - 407.

Nielsen, K. Fog, 2001. Mould growth on building materials Secondary metabolites, mycotoxins and biomarkers. ph.d thesis, Technical University of Denmark, Biocentrum.

Grant, C., Hunter, C.A., Flannigan, B. Bravery, A.F. 1989. The moisture requirements of moulds isolated from domestic dwellings, International Biodeterioration 25, pp 259 - 284.

Ayerst, G. 1969. The effects of moisture and temperature on growth and spore germination in some fungi, J. Stored Products Res. 5 pp 127-141.

Agarossi, G.; Ferrari, R.; Monte, M.; Gugliandolo, C.; and Maugeri, M. Changes in the microbial system in an Etruscan tomb after biocidal treatments. In book. VIth International Congress on deterioration and conservation of stone. Supplement = VIe Congrès International sur l'altération et la conservation de la pierre. Torun, 12-14.09.1988, (1989), pp. 82-91.

Brock, T.D. 1974, Biology of microorganisms. ISBN 0-13-076992-4

Finkelstein A. 1987 Water movement through lipid bilayers, pores, and plasma membranes, Theory and reality. Wiley, N.Y.ISBN 0-471-84787-9

Adan, O.C.G 1994 On the fungal defacement of interior finishes. ph.d thesis, Technical University of Eindhoven.

Passioura,J.B. 1982. Water in the soil-plant-atmosphere continuum. In: Person,A and Zimmerman, M.H.(eds.) Encyclopedia of plant physiology, vol 12B, Springer ISBN 3-540-10906-4

Padfield, T. and Eshøj, B 1993. 'The use of porous building materials to provide a stable relative humidity', Preprints of the ICOM-CC Conference, Washington DC, 1993, pp 605-9.

Krus M., Sedlbauer K., Zillig W., Künzel H. M., 2001. A new model for mould prediction and its application on a test roof. II International Scientific Conference on The Current Problems of building physics in the rural building, Cracow, Poland, Nov 2001.

Rubel, G.O. 1997. A non-intrusive method for the measurement of water vapour sorption by bacterial spores. Journal Journal of applied microbiology. 1997 v 83 n 2 p243.

Sedlbauer, K. 2001. Vorhersage von Schimmelpilzbildung auf und in BauteilenBauingenieur- und Vermessungswesen, Stuttgart University.

Clarke, J. A., Johnstone, C. M., Kelly, N.J., McLean, R. C., Nakhi, A. E. (no date) Development of a simulation tool for mould growth in buildings. http://www.hvac.okstate.edu/pdfs/bs97/papers/P189.PDF

Hukka, A. and Viitanen H., (1999), A mathematical model of mold growth on wooden material, Wood Science and Technology, v33(6) pp.475-485.

Rose, J., Svendsen, S. 2002 Single-family houses that meet the future energy demands. 6th Symposium, Building Physics in the Nordic Countries 1 pp 269-276. ISBN 82-91412-02-2.
http://www.bygg.ntnu.no/batek/buildphys/ (not functional at the time of writing)

Padfield, T. 1999. The role of absorbent building materials in moderating changes of relative humidity' , Ph.d. thesis, Department of Structural Engineering and Materials, Technical University of Denmark,Report R-54 1999. ISBN 87-7740-256-1.
www.natmus.dk/cons/tp/phd/phd-indx.htm

International Centre for Indoor Environment and Energy:
http://www.ie.dtu.dk/

Nielsen, K. F., Nielsen, P. A. and Holm, G. 2000. Growth of moulds on buiding materials under different humidities. Healthy Buildings 2000, 3 pp 283 - 288

Simonson, C. J. and Salonvaara, M. H. 2000 Mass transfer between indoor air and a porous building envelope. Healthy Buildings 2000, p 117 - 122, 123-129

Simonson, C. J. and Ojanen, T., 2000B. Moisture performance of building envelopes with no plastic vapour retarder in cold climates. Healthy Buildings 2000, 3 477 - 483.

Häupl, P., Fechner, H., Grunewald, J. and Petzold, H., 2000. The thermal improvement of a wooden frame work house by measn of a capillary active inside insulation. Healthy Buildings 2000, 3 269-275

Peuhkuri, R. 2002. A ph.d to be published by the Department of Civil Engineering, Technical University of Denmark.

Bogaard, J. and Whitmore, P. M. Exploration of the role of humidity fluctuations in the deterioration of paper. 2002. in Works of art on paper, books, documents and photographs, techniques and conservation. Baltimore conference of the International Institute for Conservation, pp 11-15. ISBN 0 9500525 7 4.

Forsyth, F. R., The nature of the inhibiting substance emitted by germinating urediospores of *Puccinia graminis var. tritici.* Canadian J. of Botany 33 pp 363-373.

Conservation Department, The National Museum of Denmark, Brede, DK-2800 Kgs.Lyngby, Denmark.

E-mail address: tim@padfield.dk