6

CASE STUDIES IN HUMIDITY BUFFERING BY POROUS WALLS

Humidity buffering in the real world

The purpose of the experimental part of this thesis has been to give some quantitative support to the concept of using interior walls as buffers for the interior climate, particularly in museums and archives. In this chapter I describe some case histories where the principle of using porous materials as a buffer has been applied in real life. In some of these examples buffering has not been the intent of the builder.

Humidity buffering by the walls of Fanefjord Church

Figure 6.1 Fanefjord Church, Møn, Denmark, from the south west. Photo: Poul Klenz Larsen

There are few buildings which are porous right through. Stables and churches are just about the only buildings which have a porous inner surface to the outer walls. They are limewashed and many of the churches are also decorated with ancient paintings. It is the challenge of preserving these paintings that has provided the opportunity to study their microclimate in some detail.

The first example is Fanefjord Church on the Danish island of Møn (23). The walls are made of brick, with lime plaster inside and outside. The ceiling is brick vaults.

The climate inside and outside the church is shown in figure 6.2. The inside RH is lower than that outside, as expected, because the church is heated. The diagram also has a line showing the expected inside RH, calculated from the water content of the outside air, operated on by the inside temperature

The observed RH is higher than it should be and is remarkably stable at about 45%. There must be some source of water which humidifies the church, so that the interior water vapour concentration is higher than that outside.

Churches are simpler to study than houses, because there is very little man made moisture added to the inner climate. It would be easy to explain the phenomenon as water from the ground ascending into the floor and up the walls but there is no quantitative evidence for this.

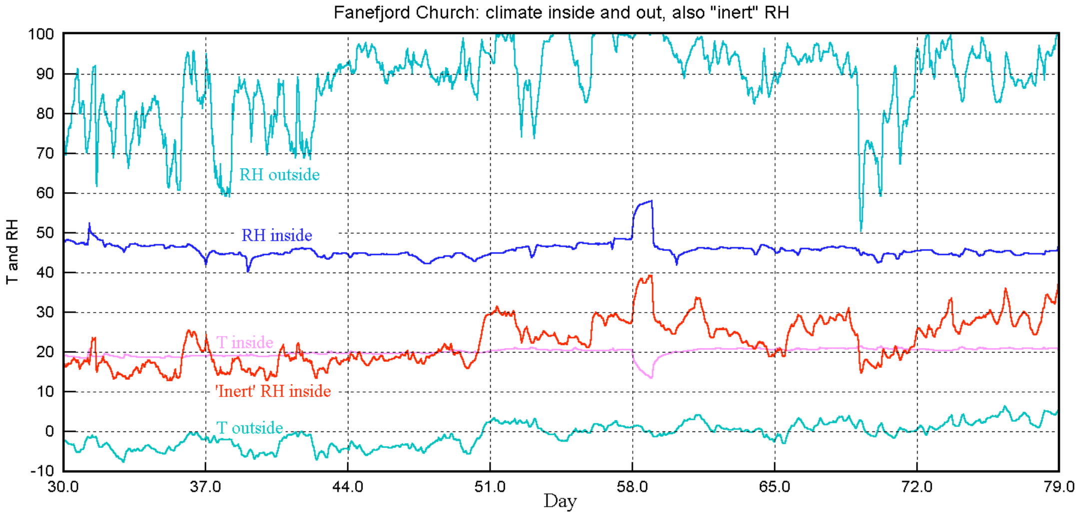

Figure 6.2 The climate inside Fanefjord Church. The red line marked 'Inert' RH is calculated from the water content of the outside air raised to the inside temperature. The measured RH is much higher. This humidification is attributed to movement of water inwards through the wall, so that the RH across the wall tends to equality, rather than the vapour pressure, as orthodox theory would suggest. Climate data from Poul Klenz Larsen.

The observed buffering cannot be explained by buffering by the wall in the moderate RH region of the sorption curve. This can only provide buffering for about a day. A model prediction of the performance of a brick church is shown in the next diagram.

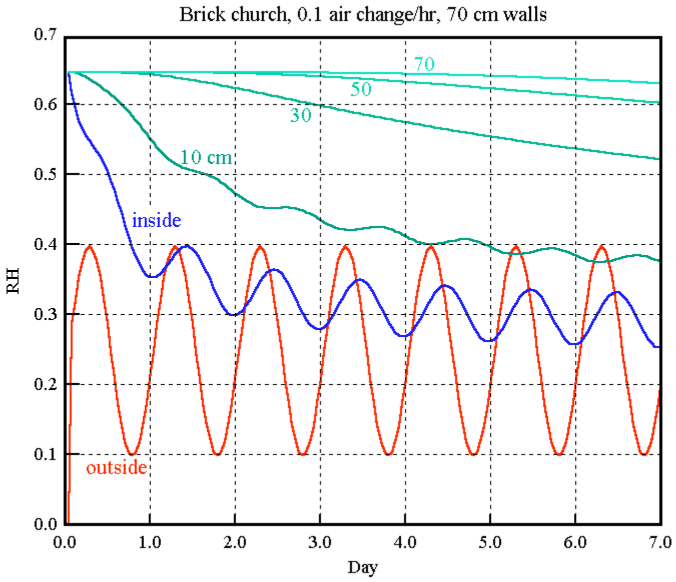

Figure 6.3 A computer model of a brick building with 0.1 air changes per hour, as measured in Fanefjord Church. The model simulates the onset of the heating season by using a very low outside RH of air at the same temperature as the church interior.

The computer model predicts that the interior RH will only be buffered by the walls over a period of about a day, with the long term adjustment to the average prevailing RH substantially complete after about a week. The observed buffering must be caused by another mechanism altogether.

Gundsømagle Church

The same pattern of climate occurs in Gundsømagle church in Zealand, Denmark (figure 6.4). This church is built mainly of lime tufa, which has a very open, porous structure and is reputed to hold water and give damp interiors. The wall is covered on both sides by lime mortar and limewash.

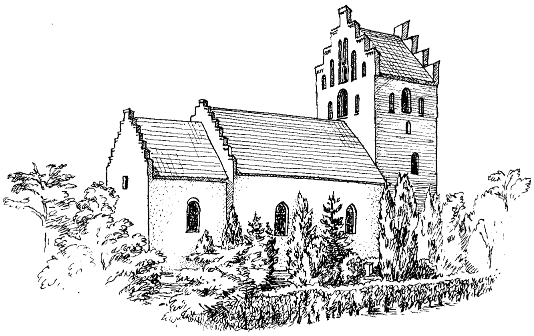

Figure 6.4 Gundsømagle Church, north of Roskilde, Denmark. The choir and nave are built of lime tufa.

The indoor climate in winter has a much higher RH than would be expected by calculating the RH of outside air raised to the inside temperature. The graph for a seven week period in autumn is shown in figure 6.5.

The pattern is the same as in Fanefjord: when the church is heated in winter the RH falls from the high summer humidity but remains moderate and surprisingly stable.

The climatic stability of Gundsømagle church was investigated in a two year campaign by Eshøj and Padfield (24,25,26).

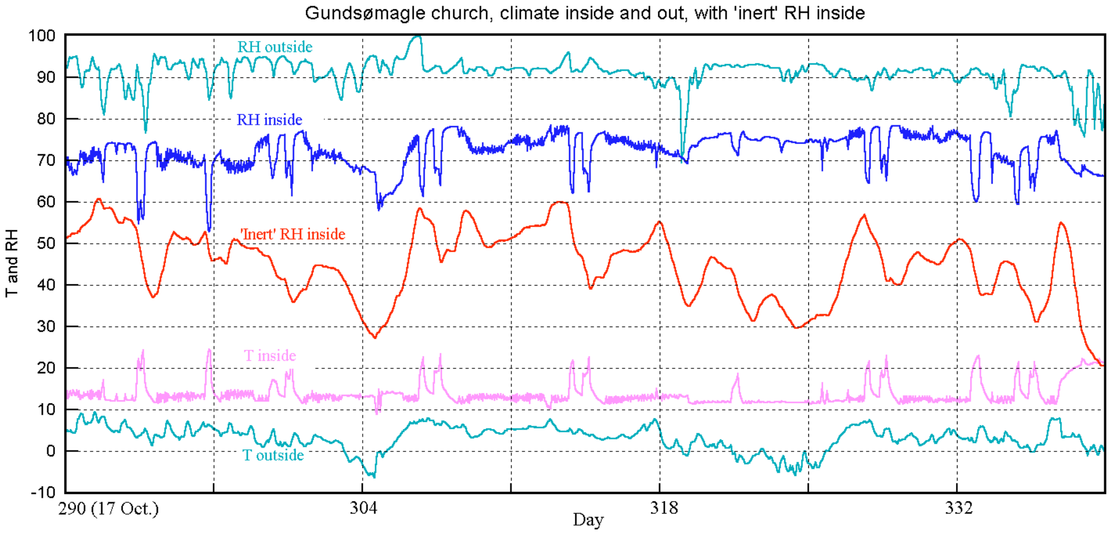

Figure 6.5 The microclimate in Gundsømagle Church, Zealand, Denmark. The curve in the middle shows the theoretical course of the RH in the church if the only source of moisture were the outside air. The curve is smoothed to take account of an air exchange rate of about 0.1 per hour.

The results are summarised here because they show the ability of supposedly relatively unabsorbent materials to contribute a very significant stability to the indoor climate. The mechanism for this stabilisation is, however, not established beyond doubt.

The influence of the walls on the microclimate in Gundsømagle Church

The reason for measuring the climate in the church was the conservator's concern about damage to the very delicate (in both the æsthetic and the material sense) wall painting, from the 12th century. A small corner of this painting is visible in figure 6.6. which also shows some temporary 20th century additions to the wall decoration.

The white box hanging from a string and resting very delicately indeed against the painting, is measuring the surface temperature of the wall and the RH and temperature of the room air. It can do both because the boundary layer, that is the transitional layer of air between wall and room, is only about 20 mm thick. The round device is a shallow acrylic cup, 200 mm in diameter, with its opening against the wall. A silicone membrane is stretched slightly around the perimeter to give an elastic seal against the irregular plaster surface. The temperature and relative humidity are measured inside the container.

With this arrangement in place we waited patiently for the few short periods which would reveal how the building behaves climatically. Such critical periods are often caused by unusual behaviour by the weather, or by people.

Figure 6.6 Measuring devices resting against the north wall of the choir of Gundsømagle church. The white box measures surface temperature and room temperature and RH. The circular cup measures temperature and RH in the enclosed space within 10 mm of the wall, and also measures the surface temperature.

Our opportunity came: for one week the heating was left on. It was a long sermon, or a mistake, but the physics is the same.

The series of pictures that follows builds up the interpretation of the climate step by step. The first picture shows just the measured climate in the church and outside.

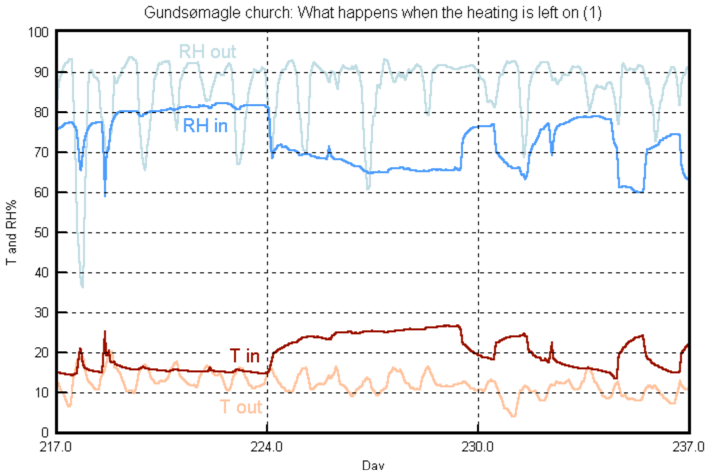

Figure 6.7 The climate during a three week period. In the middle week the heating was left on. Notice how the inside RH varies in the opposite sense to the temperature, as expected for the RH in a mass of air subjected to a varying temperature.

The next graph adds the theoretical RH calculated from the water content of the outside air and the temperature of the inside air.

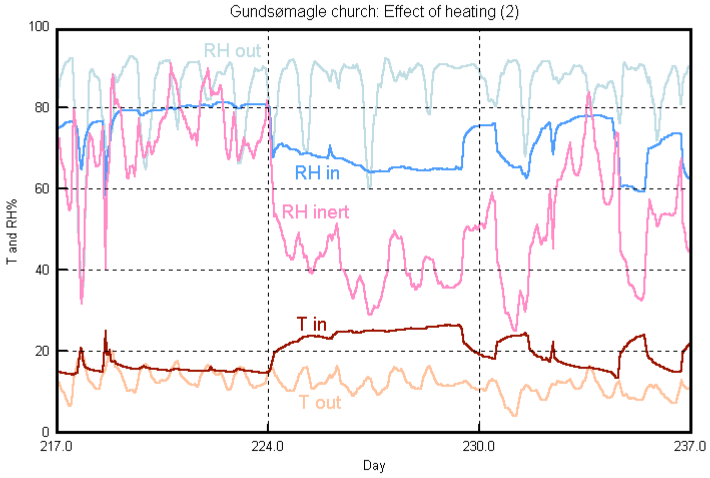

Figure 6.8 The new curve is the imaginary course of the RH calculated with the water vapour content of the outside air raised to the inside temperature. The calculated RH drop caused by heating is twice the measured drop.

There must be a source of water in the church to keep the RH considerably higher than that achieved by warming up air from outside to the inside temperature.

One possibility is that the walls release water vapour. When the RH falls because of the sudden rise in temperature, the wall should release water into the air to compensate. The wall will only release water vapour until the RH *at its surface* is again in equilibrium with its water content. In the next diagram the RH at the wall surface is calculated. This is obtained by taking the temperature and RH of the air in the church and calculating the water vapour content. This water vapour content and the wall temperature are then used to calculate a wall surface RH.

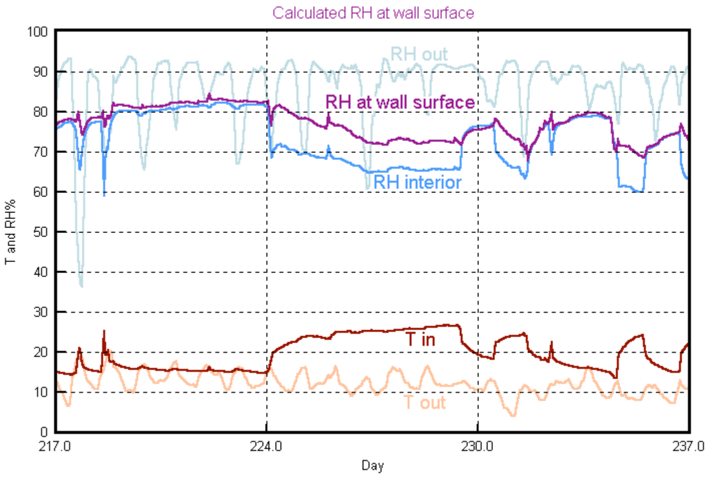

Figure 6.9 The RH calculated for the wall surface is added. This cannot be measured because the boundary layer is thin compared with the bulk of a RH sensor, which would also disturb access to the wall at the point of measurement.

Notice that there is no sudden jump in RH at the wall surface when the heating period starts. The RH gently descends, partly because the water reserves in the surface layer of the wall are released into the air but also because the temperature is slowly increasing throughout the period of warming.

The wall appears therefore to be buffering the RH perfectly *at the wall surface*. The remaining drop in RH in the church is due to the temperature difference between wall and room air, which is quite high because of the lack of insulation and also because of the suddenness of the heating, so that the thermal inertia of the thick wall keeps it relatively cool.

The hypothesis that it is the wall that is the RH buffer for the church climate is reinforced by data from the cup sealed against the wall.

The sensor within the cup, though close to the wall, is outside the boundary layer of cool air and yet cooler than the church air, because of the insulating value of the acrylic plate and the still air within the cup. The RH does therefore drop as the temperature rises but then remains steady, as one would expect, because there is no loss of water from the enclosure. When the heating is turned down the RH in the cup bounces back immediately.

The case for humidity buffering by the wall is reinforced by a separate experiment in which the same cup was placed against the floor. The RH in the cup did indeed rise, but at a rate so slow that the floor could not function as the main source of water.

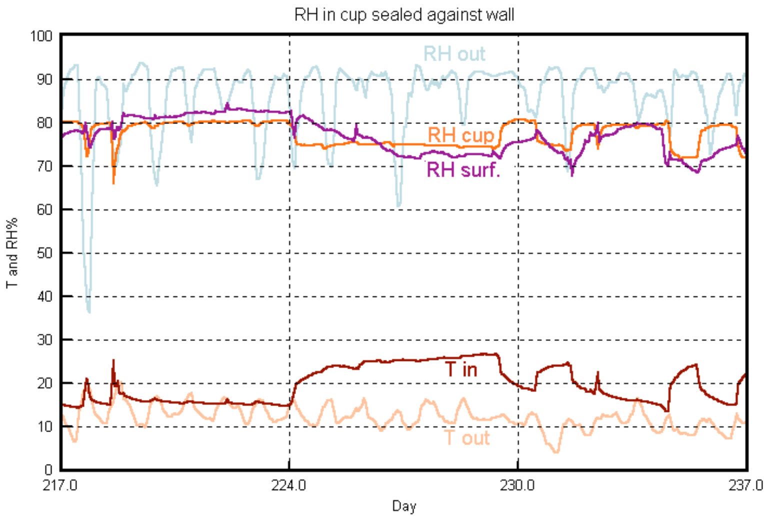

Figure 6.10 The RH within the cup sealed against the wall is shown in this diagram. In the stagnant air within the cup the RH is buffered perfectly by the wall. The small step down during the heating period is caused by the position of the RH sensor within the boundary layer.

The final graph in this series, figure 6.11, shows the climate over a longer period. The climate in the sealed cup is compared with the climate in the church. On about day 260 and again at day 285 the church was aired. The climate in the cup does show the influence of this influx of dry air, but not nearly as much as the room air.

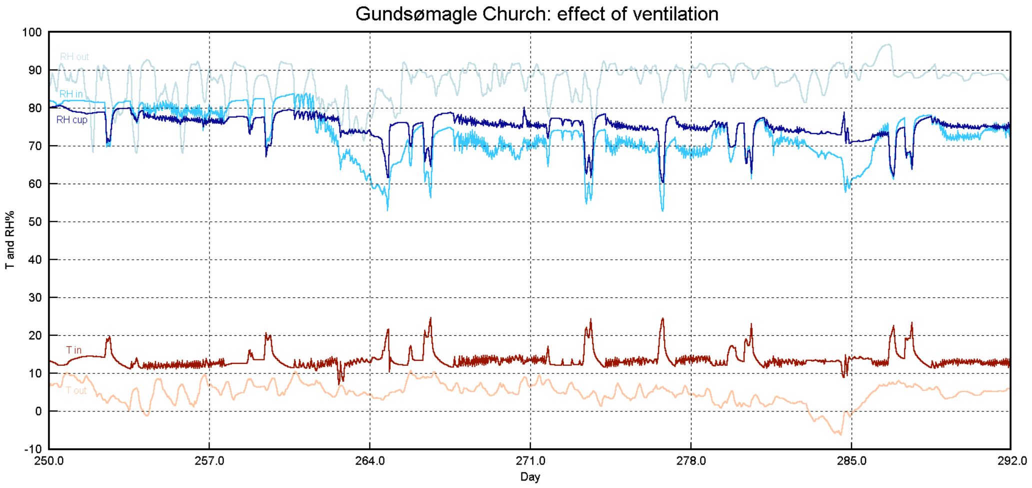

Figure 6.11 A longer extract from the climate record, showing two periods, around days 260 and 285, when the church was ventilated. The RH in the cup, the upper bold line, responds a little to the ventilation but much less than the air in the church. The church RH does not fully recover from the ventilation beginning on day 260. Recovery after day 285 is aided by a period of high outside RH.

How the church climate is controlled by the walls

The experimental evidence suggests strongly that the porous wall buffers the church air very effectively. This is surprising because the materials involved: lime plaster, brick and porous limestone, have very little buffering capacity at the moderate RH within the church. The surface area and the thickness available is large, because these materials are very porous. Even so, the rapid recovery after ventilation shown in figure 6.11 suggests considerable water reserves. An explanation of the phenomenon must also account for the continuous excess water content in the air within the church, compared with that outside.

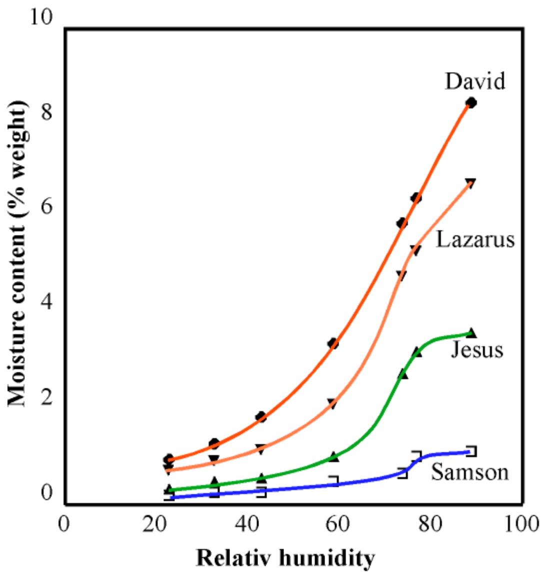

Figure 6.12 The sorption isotherm of lime mortars from Fanefjord Church (23). The samples are taken near the figures painted on the vault.

The three steepest curves are for mortars with close to 1 mol/kg soluble salts. The lowest curve is for a relatively pure mortar with about 0.15 mol/kg.

One possible mechanism is provided by the hygroscopicity contributed by the salt content of normally non-absorbent materials. But there is another mechanism that does not depend on contamination of the bricks. At high RH the moisture content of clean brick reaches less than 10g/kg. Brick is however easily wetted and the capillary water content is about 150 g/kg, depending very much on porosity. Fog, dew or rain will wet the outside of the wall to this condition. The water will now move by capillarity inwards to a point where the temperature is higher. The vapour pressure at this point will be higher than that outdoors. Further inward movement of liquid involves smaller pores where the RH over the meniscus is lower, so the vapour pressure will fall again. In addition the capillary movement will be slower through the finer pores.

At some point within the wall the capillary movement of water becomes insignificant in comparison with the vapour diffusion. At this point, according to Poul Klenz Larsen, the vapour pressure is still higher than that outside and higher than that in the interior of the church, so further movement of water to the interior is down the vapour pressure gradient all the way.

My way of looking at the matter starts off in the same way, with a reservoir of capillary water towards the outside of the wall, with a fairly definite boundary where vapour diffusion takes over. The vapour diffusion, however, follows the relative humidity gradient into the interior of the church.

Both theories give the same result so the only way to decide the matter, or to reveal a completely different mechanism, is to make an experimental wall or bore holes in an existing wall and measure temperature and RH through the section.

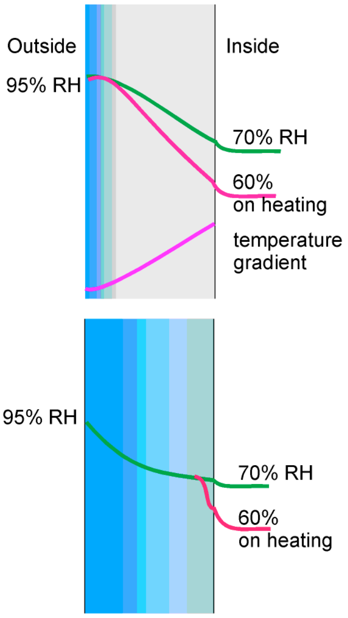

Figure 6.13 Two models for RH buffering by church walls during brief periods of heating.

In the top diagram a reservoir of capillary water just within the outside surface of the wall feeds vapour into a linear vapour pressure gradient through the scarcely absorbent pores of the wall.

In the bottom diagram a more absorbent wall has buffer capacity right through to the inside. The gradient is more unpredictable, depending on the history of the weather. Only the inner surface responds to episodes of heating. This model fits the data from Gundsømagle church, except that the measured properties of the materials do not provide enough hygroscopicity. Soluble salts within the wall do, however, increase the buffer capacity.

The observed response to heating of the church interior can be explained in this way: at a steady state one would expect that the RH gradient would fall in a linear manner through the wall. The greater part of the thickness of the wall, which will be below 90% RH, will contain very little water compared to the outside layer. It will function as a nearly inert, porous medium which allows steady diffusion of water vapour from the reservoir in the outside surface layers. The linear gradient is established by water vapour passing into the church under the influence of the lower RH caused by heating the outside air that leaks in. When the church is suddenly heated further for a service the air falls in RH, thus steepening the gradient through the wall. The establishment of a new equilibrium is quite rapid in a porous wall with low buffer capacity.

On the other hand one could imagine a situation in which the wall has an enhanced buffer capacity, due to small quantities of water soluble ions such as nitrate, chloride, magnesium and calcium. These will generate a liquid at moderate RH which gives the wall substance a much steeper sorption curve. Another source of buffer capacity is the organic polymers which are a product of the rich fungal and bacterial life in the walls of churches.

Such a wall will have a less uniform RH through it, because the water capacity ensures a slower movement of water, controlled by the history of the weather. Such a wall has a buffer capacity at the inner surface. The moisture stress imposed by sudden heating will be taken up by the inner surface layers of the wall.

The two models are shown in figure 6.13. A combined model could be constructed in which the water reservoir at the outside functions as a slow supplier of water, accounting for the higher than expected RH in the church air through the year. The relatively brief episodes of warming for services would extract water from the limited but definite buffer capacity of the interior surface of the wall, which would then be re-supplied from the capillary reservoir towards the outside.

The observed microclimate is compatible with this model, which does not invoke water vapour movement by diffusion driven by vapour pressure difference, though it does not exclude it as a competing process. Vapour pressure driven movement alone will give a high humidity near the outer surface of the wall but can only explain the high RH indoors by invoking a region of the wall at 100% RH and at a higher temperature than outside. This mechanism should give a much higher RH within the cup against the wall than is observed.

Experimental confirmation of the conflictng ideas put forward in this chapter would involve considerable effort in putting sensors within the wall and would require removing a statistically reliable number of specimens of material from the old walls. It would also require firm control over the operation of the building, particularly the heating and the ventilation.

The first mechanism proposed, that for the nearly unabsorbent wall, is an extension of the isothermal experiment reported in chapter 4, figure 4.35: cellular concrete with gypsum plaster over its surface. This figure is interpreted as showing that the cellular concrete contains capillary water. This means that it is at equilibrium with a very high RH. The gypsum plaster coating it cannot share this moisture because it has a coarser capillary structure. A steep linear RH gradient develops within the gypsum, which functions as a porous retarder of vapour movement, with almost no sorptive capacity at all. The gradient remains stable as the reservoir of water in the cellular concrete shrinks, because the RH at the surface of this reservoir is close to 100% over a very wide range of water content. This gives a very stable inside RH, so long as the vapour flux leaking from the church through openings in the building is constant.

The church as a whole seems to function as a heat driven pump: water moves inwards through the wall to give a higher interior water content, which leaks out through cracks in the building. The balance between these two processes gives the observed moderately high RH within the building.

The climate behind pictures mounted against the outer walls of the Chapel of Ledreborg, Denmark

The experiment with the cup mounted against the wall in Gundsømagle church can be criticised as unrealistic, because the diameter of the cup was small compared with the thickness of the wall. This section describes the climate in a much wider, but not much deeper enclosure.

The chapel of Ledreborg, the country seat of the Holstein-Ledreborg family, a few kilometres south of Roskilde in Denmark, is a remarkable contrast to the pastel simplicity of the Lutheran churches described above. It is an exuberant baroque construction, and consecrated to the Catholic faith. The microclimate is also more lively, partly because of the greater area of window and the lack of protection for the entrance door. Another important factor contributing to the more variable climate is the complete lack of absorbent surfaces in the interior.

Figure 6.14 Ledreborg House, near Roskilde, Denmark. The chapel is at the right (west) end of the main house. Photo from Ledreborg brochure.

There are, however, hidden absorbent surfaces. The oil paintings that cover much of the interior are set in shallow recesses in the outer walls. These recesses have just lime plaster covering the brick wall. The brick is coated on the outside with a cement render, from early in this century.

Conservators are generally rather anxious about the welfare of pictures that hang on the outer walls of houses. This anxiety proved reasonable, in this particular building. When the conservator took down one painting for repair a baroque addition to the original architecture was revealed: a well grown fruiting body of the dry rot fungus, *Serpula lachrimans,* clinging to the back of the canvas.

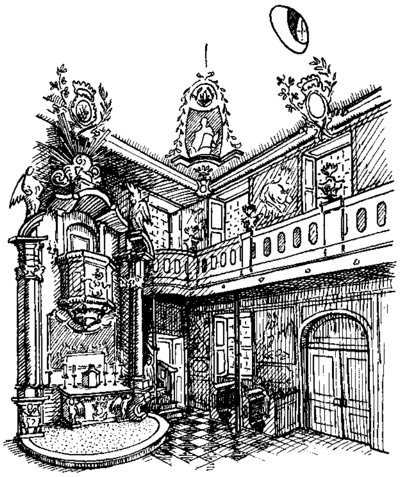

Figure 6.15 The interior of the chapel of Ledreborg house.

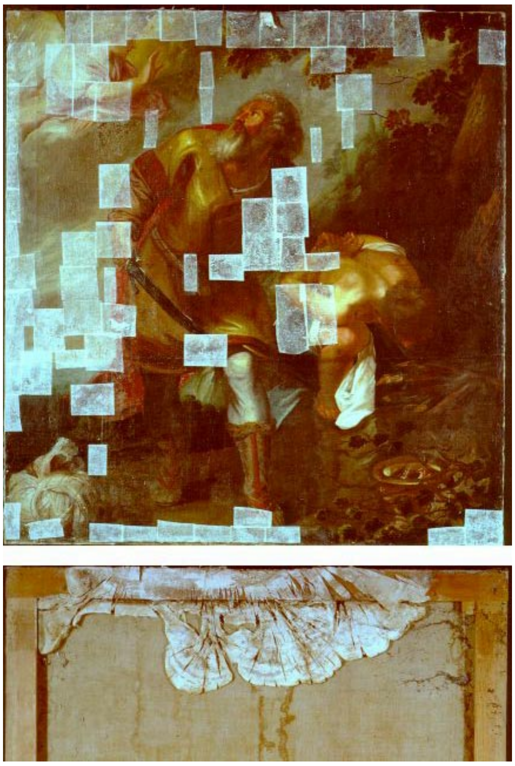

Figure 6.16 An 18th C. oil painting by Isaac Isaacsz. The white squares are temporary repairs. Below is a portion of the back of the picture showing the dried remains of the fruiting body of the Dry Rot fungus.

The National Museum had, at that time, a student, Annabel Robinson, who was interested in microclimatic matters relevant to the conservation of art.

We decided to investigate the microclimate behind the pictures with full scientific rigour (27).

The climate measurements

While the damaged canvas was in intensive care in the National Museum's workshop we put in the vacant niche two paintings, one designed to imitate the original, the other with a polyester film stretched over the back of the frame, to exclude water vapour coming from the direction of the wall.

The two pictures were set side by side in the recess, as shown in figure 6.17. Temperature and humidity sensors were placed in front of these pictures and in the air

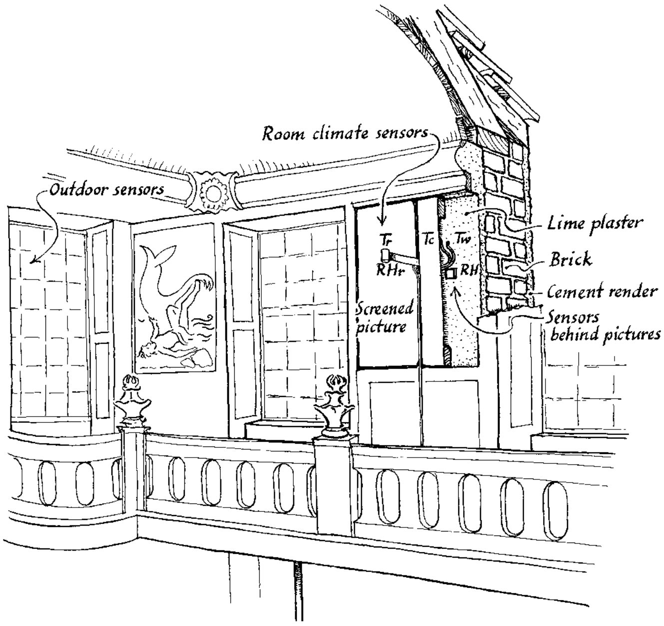

Figure 6.17 The wall structure, showing the placing of sensors to investigate the microclimate behind the painting. The sensor assembly behind the test pictures consisted of a RH sensor and thermocouple within a radiant heat shield in the middle of the space (about 40 mm) and two springy thermocouples, one touching the back of the canvas, the other touching the surface of the wall.

space between the canvas and the wall. The outside climate was measured in a shaded spot on the flat roof of the west wing, just outside the chapel.

The microclimate around the pictures

The climate measurements are summarised in three graphs. Figure 6.18 shows the outside (dotted) and inside temperature and relative humidity (RH) for a 15 week period

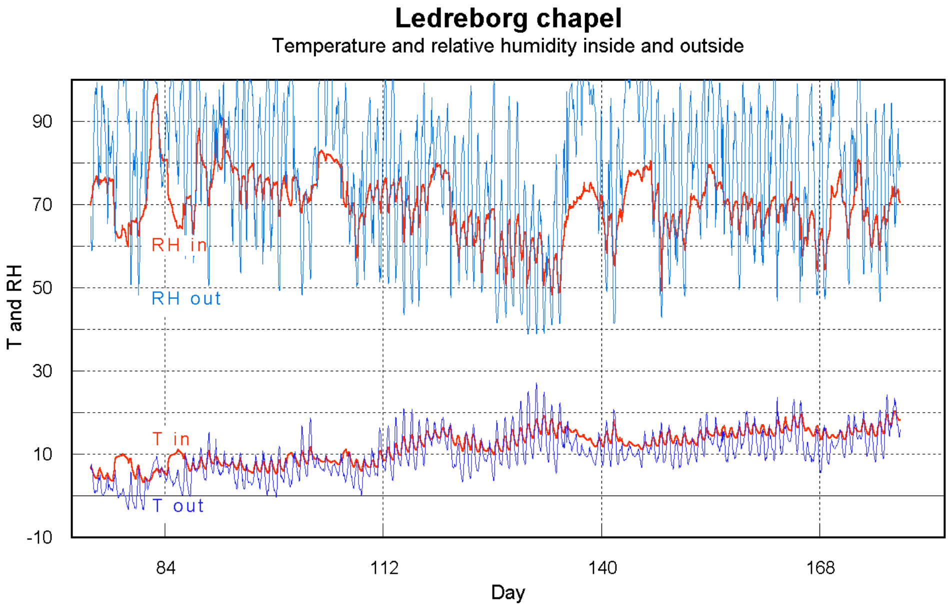

Figure 6.18 Temperature and relative humidity inside the chapel and outside. The chapel was only heated on two brief occasions at the beginning of the period.

starting on the 14th. March 1994. The inside relative humidity is generally a moderated version of the outside RH. The daily cycles of RH are caused mainly by the daily temperature cycle acting upon room air that is rapidly exchanging with outside air. The outer door has no lobby, the door at the balcony level is poorly fitting and the windows are not particularly airtight. The room is high and open, encouraging convective air exchange (the "stack effect").

The temperature and humidity cycling is only moderately damped out by the room. The abundant wood panelling is a fairly good thermal insulator, reducing the stabilising influence of the thermal inertia of the wall. The paint on the wood prevents moisture movement which would stabilise the relative humidity.

Figure 6.19 shows the microclimate around the paintings. The upper curves show the RH in the room (dotted) and at the back of each of the two experimental paintings. Both the polyester-protected canvas (the line rising from 30% RH) and the unprotected canvas (bold line) had been stored for several weeks in a room at about 40%RH. The unprotected canvas came rapidly to equilibrium close to the running average of the RH in the chapel, while the protected canvas came slowly to equilibrium with its new surroundings over a period of about two months. At the end of the measuring period the two RH traces have converged. The RH behind both canvases is more stable than that in the room.

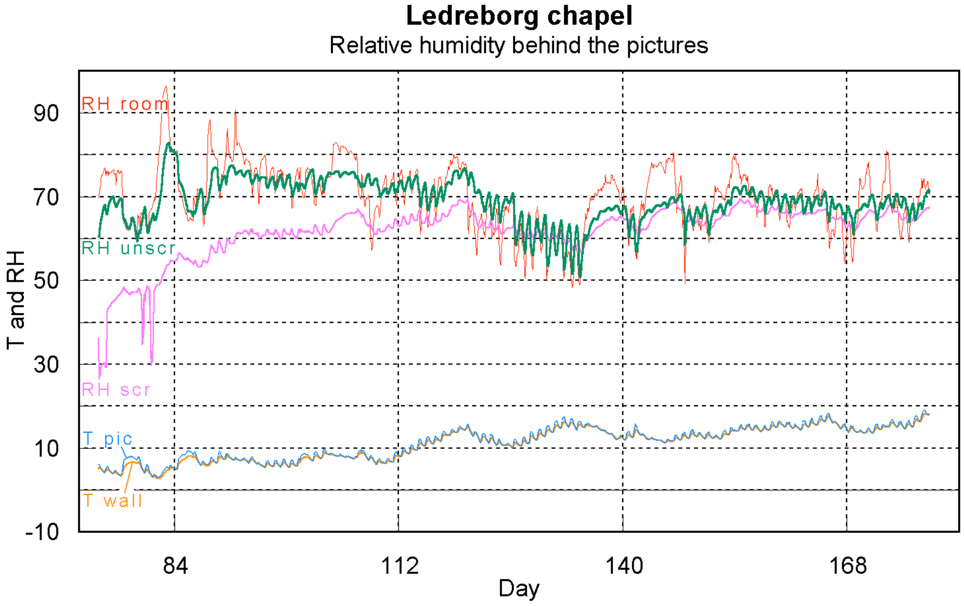

Figure 6.19 The microclimate behind the two test pictures. The protected picture comes much more slowly from the 40% RH of the painting workshop to the high RH of Ledreborg. After a few weeks, however, both paintings have much the same RH behind the canvas, within the accuracy of measurement of the sensors.

A detailed study of figures 6.18 and 6.19, together with a close up of a shorter period, shown in figure 6.20, suggests that the canvas of the polyester protected picture is stabilising the RH of the air trapped behind it but that the wall is actively stabilising the RH behind the unprotected picture, and therefore behind all the other pictures in the room.

The lowest line in figure 6.20 is the temperature difference between the pictures and the wall surface (the two pictures have identical thermal environments). Notice that the RH behind the unprotected canvas (the top curve) is cycling up and down with minimum values that coincide with maximum values of the temperature difference between the picture and the wall (the picture surface is warmer than the wall surface). At first glance this could be attributed to air exchange with the room, because the RH in the room goes up and down in the same pattern. However, a closer look at figure 6.19 shows that the relationship between RH in the room and behind the painting is not easily explained by this theory. Around day 130 the RH behind the picture is varying more than that in the room but the peaks in room RH on days 105, 137 and 145, when the temperature was rather stable, do not penetrate behind the canvas.

These observations can be explained by assuming that the wall is controlling the RH to a constant value *at the wall surface*. This air then convects away from the wall to the back surface of the painting, keeping the exact water content it acquired when it came to equilibrium with the wall surface. Because the picture canvas is at a higher temperature than the wall, the air warms up and therefore drops in relative humidity.

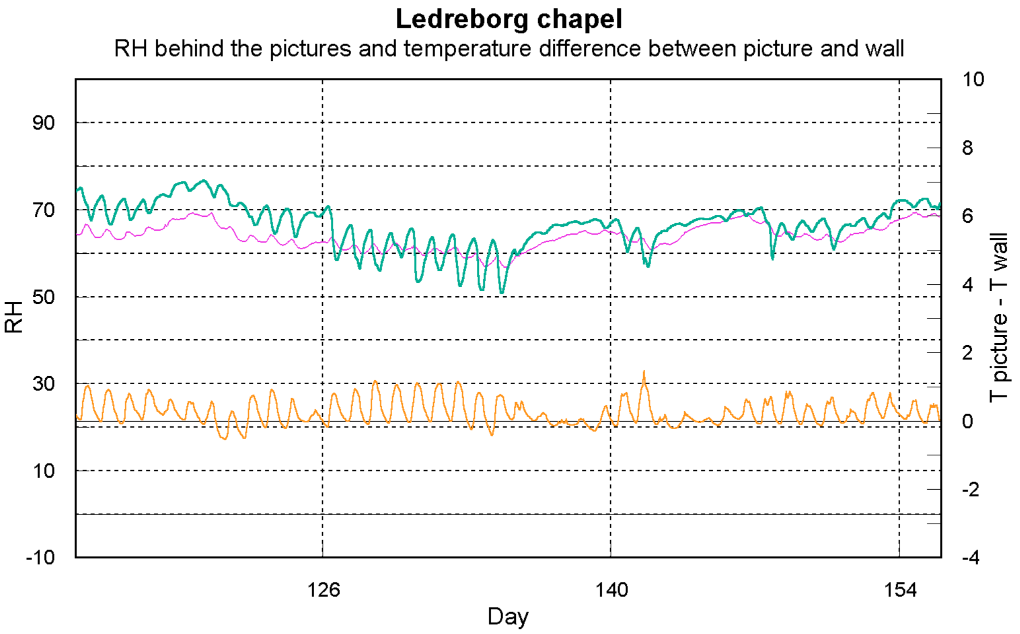

Figure 6.20 Relative humidity in the space between the picture canvas and the wall. Notice just after day 121, for example, that the RH cycles are in opposite phase. This is the evidence for buffering by the wall behind the unscreened picture. The screened picture has small RH peaks that approximately coincide with temperature peaks at the canvas. This RH pattern is characteristic of a closed container filled with abundant buffer, in this case the canvas. The unscreened RH has larger RH peaks when the temperature difference is at a minimum. This can be attributed to buffering of RH by the wall ***at the wall temperature****. This buffered air warms up to the canvas temperature with consequent fall in RH.*

This explanation may seem very indirect and speculative but it is supported by a consideration of what happens at the back of the protected painting. Here the wall plays no part in the moisture transfer, because of the impermeable polyester sheet which separates the wall from the air space behind the picture. The air trapped behind this picture exchanges water vapour only with the canvas of the picture itself, so the RH at the back of the screened picture is much more constant. There is just a slight increase of RH as the temperature rises, which is a known property of cellulosic fibres in a confined, nearly airtight space.

The opposite pattern of the RH cycle behind the unscreened painting confirms that the reasonable RH stability cannot be due to poor air circulation, because this would allow the canvas to buffer the RH just as it does for the screened picture. The wall is actually such a powerful stabiliser of RH that it overrides the influence of the canvas.

Summary of the Ledreborg experience

The climate measurements are unexpectedly reassuring: the climate behind the pictures is actually more stable than the climate in the room and is not significantly moister. The fungus which formed such a dramatic embellishment to the back of the original painting had not significantly attacked the painting or its frame: the observed damage can be attributed to the moisture oozing from the fruiting body. The dried residue on the back of the picture was the fruiting body of mycelium that was probably digesting the lower part of the roof construction, which is not far above the level of the top of the picture. There is no evidence that the wall is unusually damp at the level of the paintings and panelling in the chapel but there are bad constructional details at the edge of the roof which have caused dry rot within the roof timbers.

The climate in the chapel can be described as far from ideal for preservation of the splendid interior but not acutely dangerous. In particular there is no ground for special anxiety over the microclimate around the pictures mounted on the outside walls. They have the most stable climate in the room!

This conclusion is not particularly original: there are hundreds of houses, hundreds of years old, with wood panelling in perfect condition hard up against outer walls. All that we could add to this body of experience is that if you must have wooden panelling in a room, the best place for it is against the wall.

The nervous insistence that there should be good ventilation behind art against outer walls is therefore probably unnecessary and even wrong. If, however, the wall is painted the advice to ventilate is probably right, because the wall behind the picture will, in the winter, be colder than the rest of the wall and therefore the first place condensation will occur. This is another reason to keep walls porous.

The idea of protecting the back of the painting with polyester is not so bad: the microclimate is a bit more stable than that behind the unprotected picture but a more important reason is that it would dissuade the protected bats of Ledreborg from setting up home behind the pictures.

This story does not shed more light on the processes occurring in the outer wall. The temperature is about the same on both sides of the wall, so there is no way of distinguishing between vapour pressure and RH as the effective driving force for moisture movement.

Buildings which deliberately use humidity buffering by porous materials

The museum stores in Brede

The churches described in the previous sections were not intentionally built to provide a stable relative humidity. This was a beneficial by-product of their construction and is preserved by a continuing tradition of using a porous surface treatment both outside and inside.

The buildings described in this section were designed to provide a stable relative humidity.

The National Museum of Denmark transformed some old factory buildings in Brede into storage for museum objects. It also built a new store for large objects.

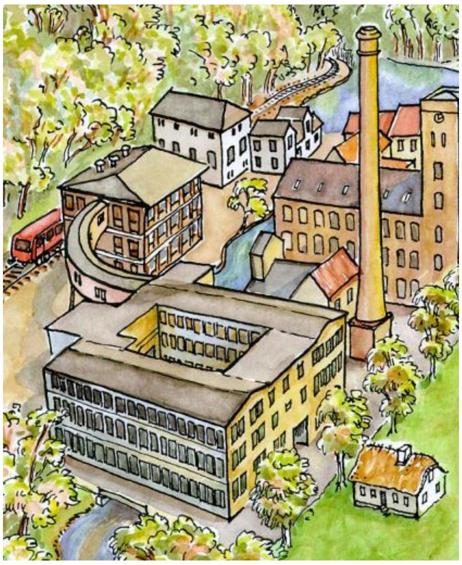

Figure 6.21 The complex of factory buildings in Brede, north of Copenhagen. The storage rooms are in the foreground.

The consulting engineering firm charged with doing all the technical things proposed an air conditioning system designed to maintain a constant relative humidity by adjusting the air temperature in the storerooms. This proposal is based on two ideas of doubtful validity. One is that museum objects are more sensitive to humidity variation than to temperature variation. The other is that it is possible to control the relative humidity by raising or lowering the temperature, to lower or raise the RH, respectively.

The first of these axioms, that RH is more important than temperature, is a complicated matter which I will not go into here. The second axiom, that RH in a storeroom can be controlled by adjusting the temperature, can be rebutted instantly by referring back to chapter 1, where the results of putting cotton into a sealed box are discussed. The RH in the empty box falls with rising temperature while the RH in the box full of cotton rises with rising temperature. A storeroom will surely contain a considerable, but not exactly known, quantity of cellulosic products, such as cardboard boxes and wooden shelves and wooden relics. There is therefore an ambiguity in the room's response to temperature change: it will either rise or fall in RH according to the ratio of available buffer to total volume, complicated by the effect of ventilation with outside air of unpredictable water vapour content.

There is therefore a risk that a rising signal from the RH sensor will cause heating that will cause a further rise in RH, a phenomenon known in the control industry as positive feedback.

The engineers were not convinced by this argument. It must be said that several conservators also expressed scepticism, pointing out that exactly this system, dignified by the name of "Conservation heating" has been used to keep the damp out of English country houses for several years. The English upper class, however, were never celebrated for putting comfort before pomp and their draughty ancestral piles are well enough ventilated, and coated on the inside with such heavily varnished art, that the buffer effect described for cotton does not happen. The climate graph for Ledreborg would apply to most country houses. The buffer effect of the few absorbent materials is swept away by the air rushing through the edges of the windows.

The Brede storerooms, however, were another matter. They would be built to be airtight, without windows and with a surrounding corridor to act as a buffer against infiltration through the old factory windows.

Computing the best control strategy for humidity control in a well sealed store room

Mechanical air conditioning is not an absolute necessity if one has a completely free hand. The building holding the archives of Schleswig-Holstein in northern Germany operates with great climatic stability without any mechanical climate control (this building will be described briefly later) but it was designed for the purpose. In the Brede buildings the natural humidity buffering by the building and by the stored objects is not quite good enough for a museum store. The concepts of passive humidity control needed to be supplemented by active control with a mechanical system. The aim of this research was therefore not the study of natural processes at work, as described up to now, but to develop a system of air conditioning that would use the natural processes to reduce the installation and running costs of the buildings.

Various alternative ways of controlling the RH in the store rooms were explored by computer simulations (28). These do not involve the outer walls of the rooms but calculate the humidity buffering by wood within the room, as an example of a common absorbent material. The temperature is of course included in the calculations and the wood could just as well be the walls of the room: the result would be the same. A certain zest was added to the computational effort by the knowledge that the results would be tested in reality.

The response of wood to changes of ambient RH and temperature was taken from unpublished work by Poul Jensen, who was studying the drying of wood during timber production. This core physics was written into a program which also calculated the heat and moisture changes in the room through diffusion and ventilations and as a result of the activities of various kinds of air conditioning methods.

The natural climate of the store

When we came on the scene the planning of the alterations to the old buildings was far advanced. The storerooms would be made of lightly built walls of gypsum board and plywood with mineral wool insulation. This wall was separated by a corridor from the original outer shell, from about 1920, which was of reinforced concrete with vast areas of window with a single layer of glass in iron frames.

The first exercise was to study the likely climate in the room if there were no climate control at all.

We used the following basic data in all the simulations: The room is 30 x 15 x 4.5 m high. It has two exterior walls of k-value (thermal transmission) 0.2 W/(m^2 ·°C) to simulate the outside weather moderated by the enclosing corridor. The ventilation is adjustable from 0.05 to 0.5 air changes per hour. The air is recirculated at one air change per hour and the air speed over the wood surface is 0.1 m/s. The apparently irrelevant air circulation rate becomes a necessary parameter when considering the effects of recirculation through an air conditioning device.

The natural buffering is provided by wood. Simulations were made with two levels of buffering. A lightly buffered room has 200 m^2 of wood , 10 mm thick, varnished on one side. A heavily buffered room is represented by 5000 m^2 of wood. This is a reasonable approximation to a well filled museum store with a mixed collection.

The starting RH, and the target for RH control was set to 50%, not as a suggestion for the ideal value but to simplify interpretation of the graphs.

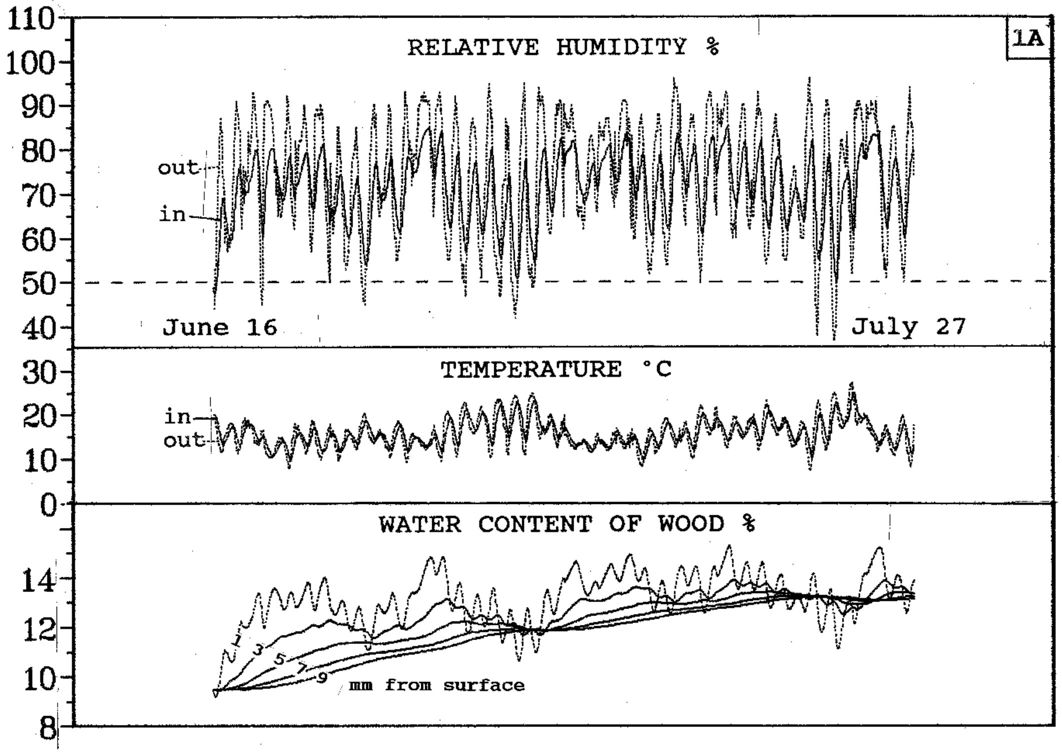

Figure 6.22 The modelled performance of the museum store with a small amount of wood. The outside climate is the dotted lines. The buffering is poor, worse than that of Ledreborg chapel shown earlier. Notice the rapidly varying water content in the surface layers of the wood: a sign of the physical stress suffered by museum objects stored in such conditions.

When the store room is reasonably full of objects and containers, including many that are water absorbent, the humidity buffering, and also the temperature buffering are much improved.

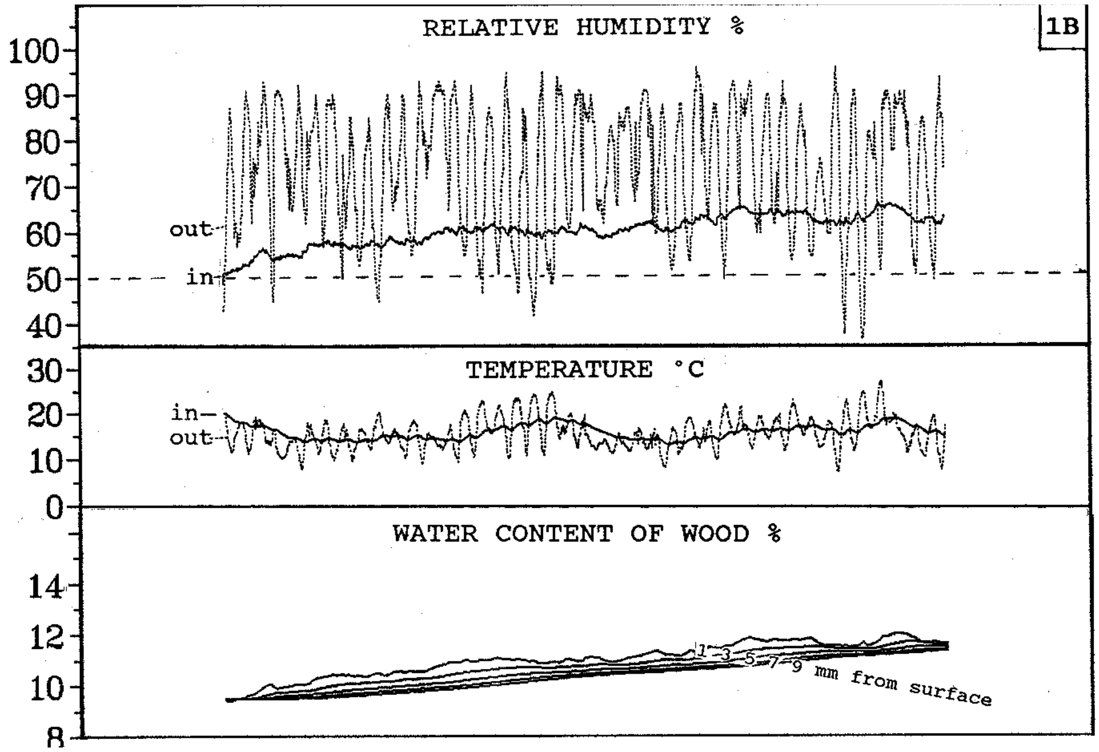

Figure 6.23 Climate buffering by an abundance of wood in a storeroom. Both RH and temperature are moderated but the room RH is slowly rising to the unacceptably high (for museum objects) average RH of the Danish climate.

The RH had risen from 50% to over 60% during the month and a half when the outdoor RH is at its lowest average value. This entirely passive climate control will not work.

There are several alternative methods of improving the situation. The one chosen by the design team was to heat to constant RH. This method relies on the fact that the saturation vapour pressure of water rises with temperature, while the actual vapour pressure of an isolated volume of air remains the same as it is heated. Therefore the ratio of actual to saturation vapour pressure, which is the RH, falls. This process works well in the lightly buffered room, as shown in the next diagram.

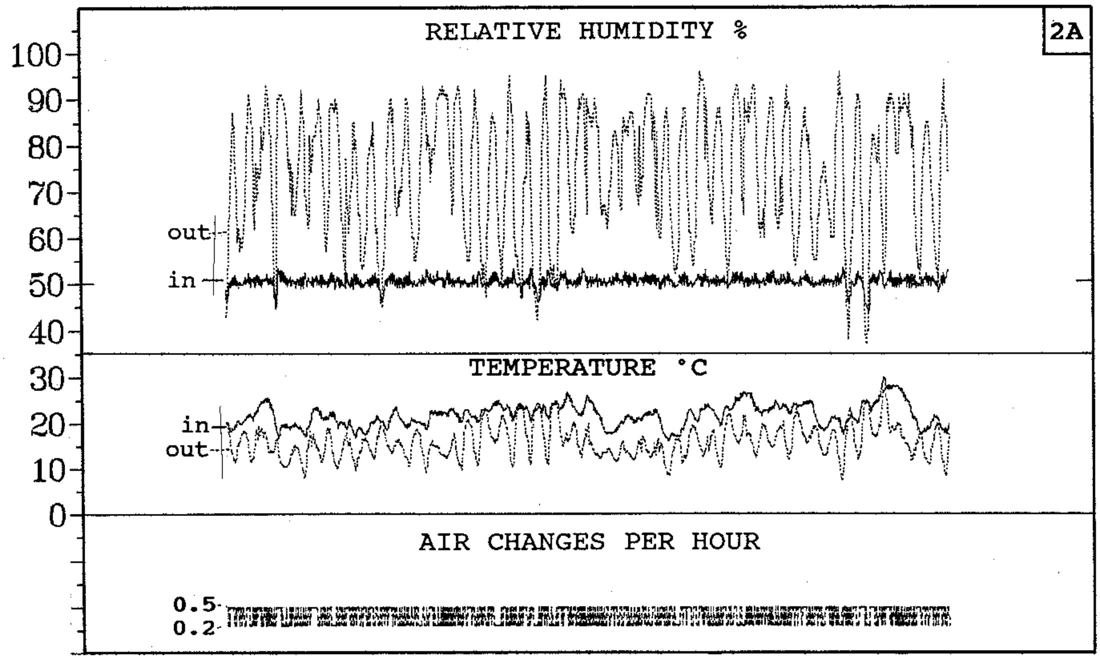

Figure 6.24 The control strategy used here is to warm the room to constant RH, using the fact that the RH of an enclosed body of air falls with rising temperature because the saturation vapour pressure increases while the actual vapour pressure remains the same. In the lightly buffered room the process works well.

When the room is filled with museum objects, some in cardboard boxes and laid out on wooden shelves, the climate follows a completely different pattern. Now the situation resembles that sketched in chapter 1. The air in the room can no longer be regarded as an isolated volume with no access to water. As the temperature rises the absorbent materials in the room will see a falling RH around them and will release water to maintain equilibrium with the air. They release so much water that the RH actually rises with increasing temperature, causing the control electronics to call for even more heat. The process runs amok in the mild, museum equivalent of a nuclear meltdown.

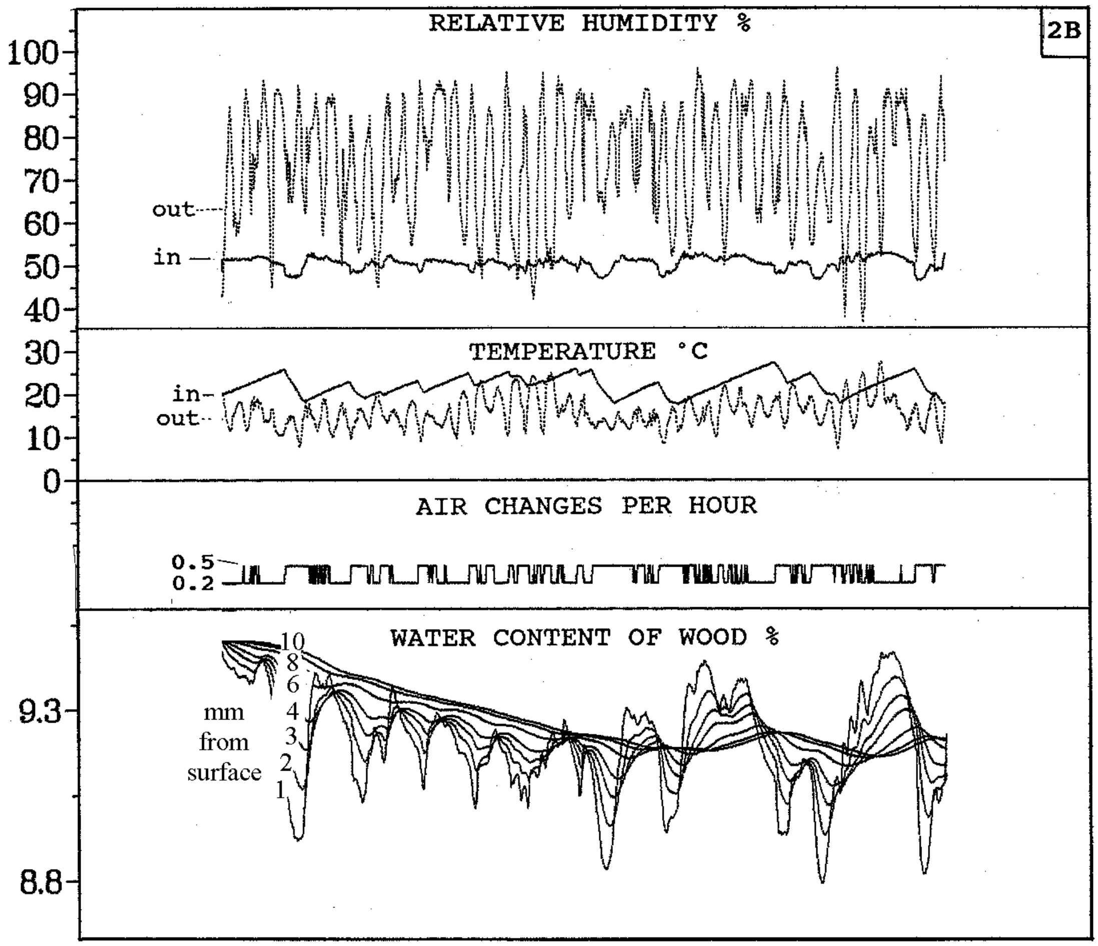

Figure 6.25 Heating to constant RH in a room full of absorbent materials. The sawtooth pattern of the temperature cycles is caused by positive feedback: a rise in RH provokes a rise in temperature, which causes a further rise in RH. The absolute water content of the air increases until the leakage of outside air with much lower water content puts a stop to the rise of the indoor water concentration. The temperature then nosedives as the fall in RH provokes a cooling response from the air conditioner.

All this was just theory. The system that heats to constant RH was installed in the only new building in the project. What happened next is not clear but at some point after the building was filled with the museum's collection of old boats and wagons a dehumidifier was installed. I watched the climate, ignorant of the modification, and wondered how I could have got my modelling so wrong.

One day, a year or two later, some visitors were taken round the showpiece museum storage facility. The Director of Conservation complained afterwards that it seemed very hot in there, so I looked up the recent data. It is shown in figure 6.26.

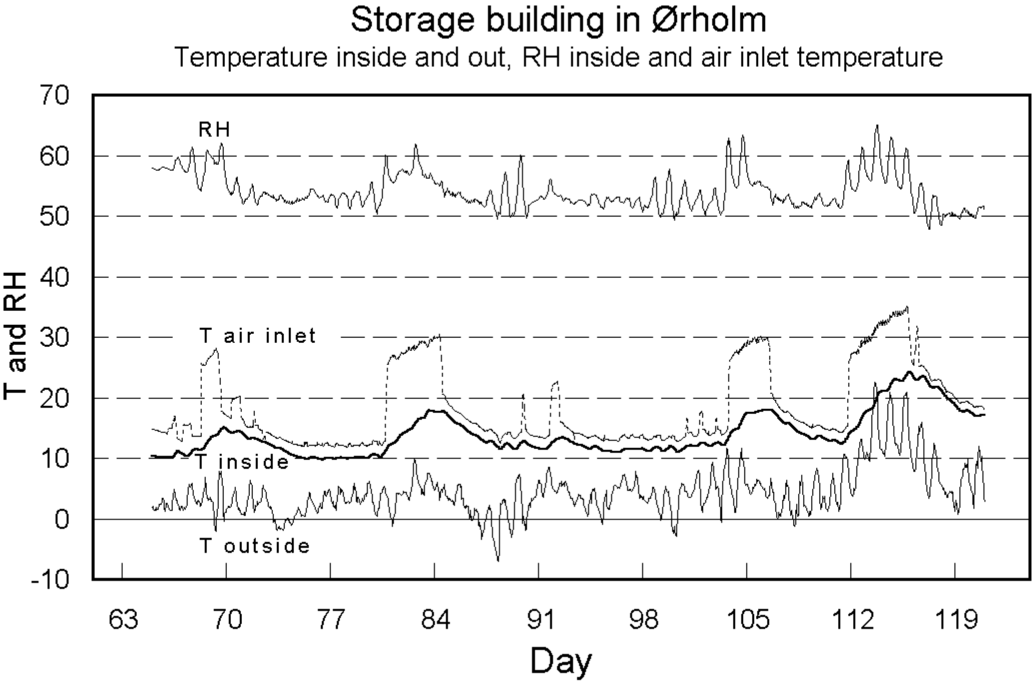

Figure 6.26 Climate data for nine weeks in the new museum storage building near Brede. Temperature oscillations are caused by positive feedback in the control system. A rising RH calls for more heating, which then causes a rise in RH because of release of water by the collected objects, supplemented by the cellular concrete walls. The dotted curve with sharp rise and fall is the temperature of air blown into the interior.

Further investigation revealed that the dehumidifier had failed. The control computer reacted to this failure by dredging up the old program which controlled the RH by heating. The real climate is a bit different from the model, but the model did not have the heating power of the real building, as shown in the sharp temperature rise of the air blown into the building (dotted line). Also, the model was capable of cooling the air by ventilation to the outside, a refinement not found in the real building.

I fed the actual outside climate data into the old computer model and got the graph shown in figure 6.27 (29).

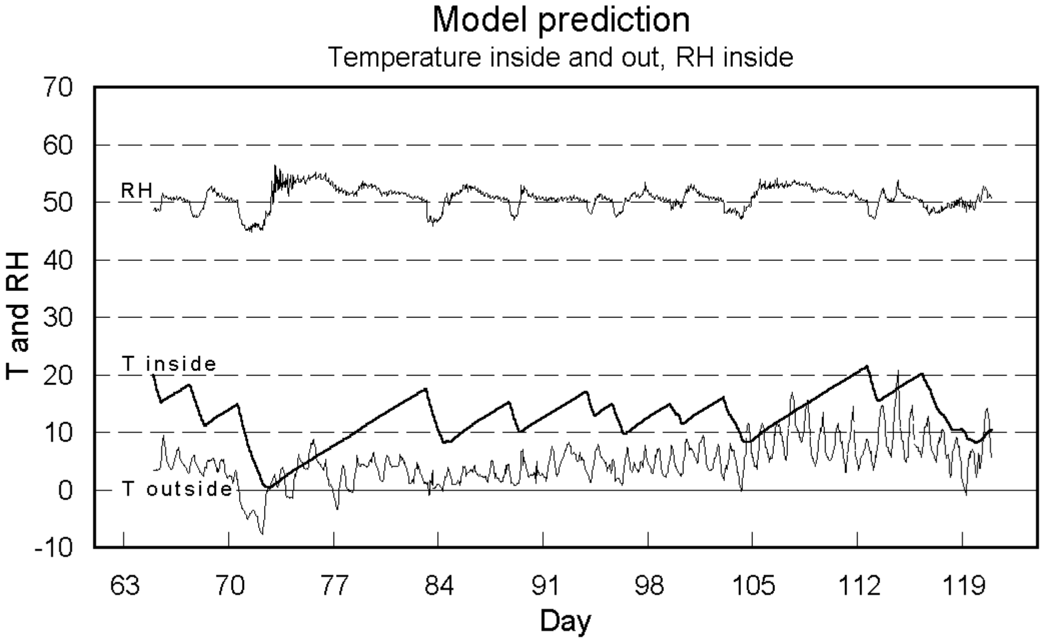

Figure 6.27 The computer model based on the outside climate for the period shown in figure 6.26. The heavy sawtooth line is the indoor temperature. The steeper decline in temperature is due to active cooling by ventilation in the model, which was not available in the real building.

There are two lessons to be learned from this affair. One of them is that mechanical air conditioning is only as safe as the quality of the supervision. The climate in this building ran amok for about three months without anyone noticing. This alone is a good reason to promote passive climate control. It may not be so accurate but it cannot go berserk nearly as effectively as mechanical systems.

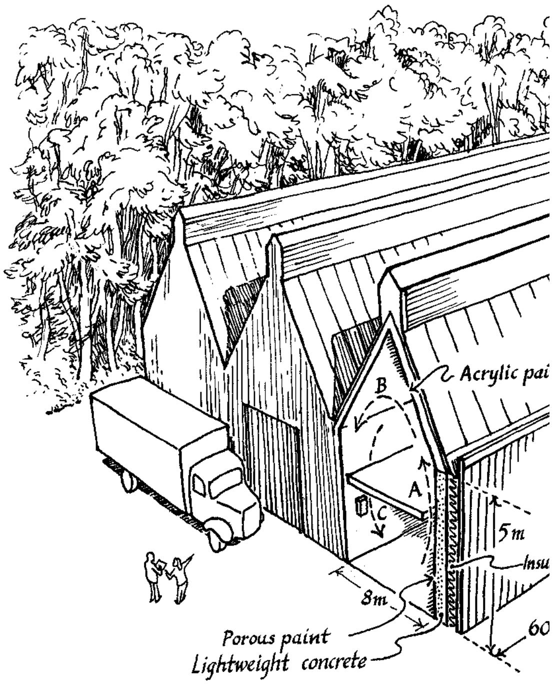

Figure 6.28 The large storage hall in Ørholm, north of Copenhagen. The climate is buffered to some extent by the cellular concrete walls, which are covered with limewash but most of the climate buffering comes from the stored objects. The mechanical air conditioning dehumidifies to achieve a reasonably constant RH.

Warming to constant relative humidity

The principle of warming to constant humidity can be used to control RH, so long as one does not use a RH sensor to control the air conditioning. The signal is ambiguous and cannot be used for direct control. Heating can be controlled according to the expected outside temperature and RH for the time of year. It can also be controlled by building a storage vault so massive that it responds only to the yearly average outside climate, moderated by waste heat from dim lighting.

This is the case with the State Archives of Schleswig-Holstein in Schleswig, north Germany. The climate control of this modern building is described by Lars Christoffersen (4). Briefly, the archival storage is built with a metre thick brick wall, insulated on the outside and with another brick rain shield outside that. This damps down and retards the annual temperature cycle very considerably. The waste heat from dim lights and people hunting down ancient documents provides exactly the right temperature rise to keep a moderate RH. The climate over a year and a half is shown in figure 6.29.

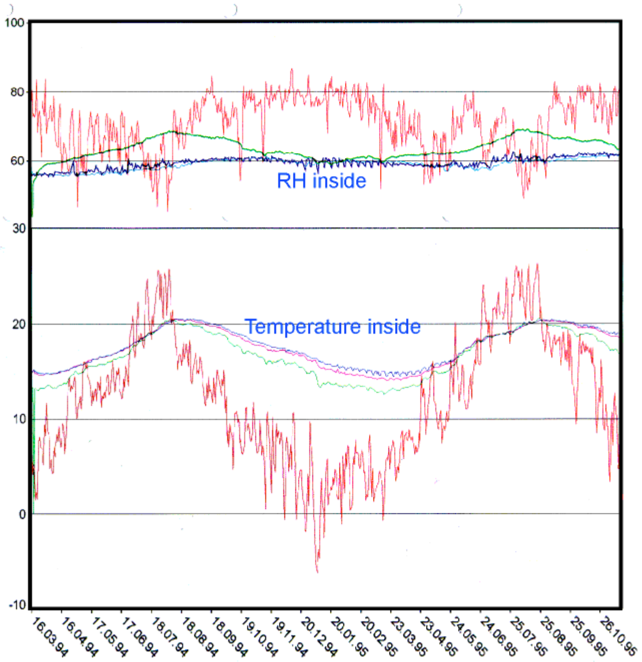

Figure 6.29 Climate in and around the State Archive of Schleswig-Holstein, in Schleswig. The massive brick building and the stored papers provide good temperature stability and very impressive RH stability. Data from Lars Christoffersen.

This building is a great success, compared with the Danish storehouse described earlier. One must point out, without detracting from the achievement, that the engineers did design an air conditioning unit, which lies with gleaming pipes, valves and dials, completely unused. The designer omitted to take into account the buffer effect of the stored items. The brick wall probably contributes very little to the humidity stability. It could be that half the number of bricks would have done the job, but this archive will resist heavy artillery.

Dehumidifying to constant relative humidity

The principle of warming to achieve a moderate RH is widely used, though it is difficult to control in rooms with good humidity buffering. In temperate climates human comfort also demands heating above ambient temperature.

The only reason for considering alternative strategies in a cool climate is to improve the durability of materials.

It is not really a good idea to heat an archive just to achieve a moderate RH. The higher temperature accelerates degradative chemical reactions: oxidation, hydrolysis and condensation reactions that slowly demolish many of the organic materials of museum and art collections, and particularly photographs and films.

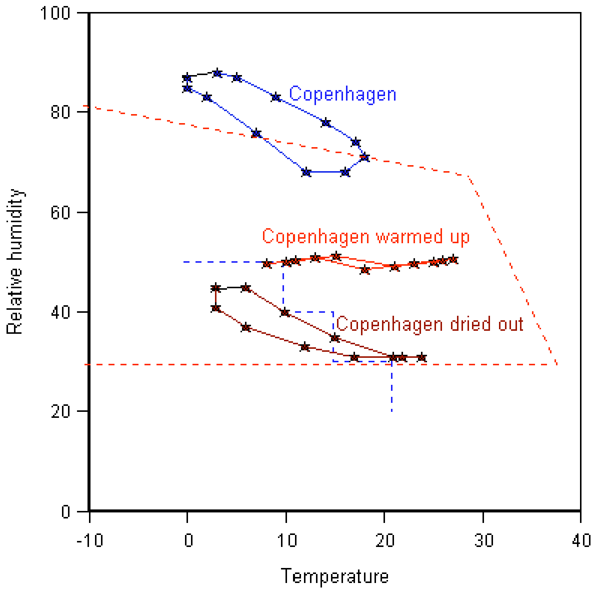

Figure 6.30 A diagram made by joining the RH and T values for each month into a ring of stars. The outdoor climate in Copenhagen, the upper constellation, is the starting point. If the air is warmed up to 50% RH the average temperature will rise, as shown by the rightward shift of the middle constellation. An alternative would be to dehumidify the air. This causes a smaller temperature rise, as shown in the lowest constellation. The zigzag line is the maximum RH and temperature allowed by the ANSI standard for storage of photographs. The large dotted trapezium encloses the area of non-destructive storage.

It would be better to dehumidify the air while keeping it cool.

The concept is summarised in figure 6.30, taken from Padfield and Johnsen (30). The dotted trapezium marks the boundary of the region of RH and temperature which can be regarded as responsible conservation.

The outdoor climate of Copenhagen is summarised by the ring of stars, each marking a combination of the monthly average RH and temperature. For most of the year the Copenhagen climate is too humid for the good of museum collections. It can be brought within the responsible limits by warming alone, giving the ring of stars in the middle of the diagram. The average temperature over the year has however increased from about 10 to 18 degrees.

A preferable strategy is to dehumidify the air. The temperature will still rise a bit, for rather technical reasons to do with the heat content of dry and wet air.

At this point the reader may wonder what this discussion has to do with porous walls. The answer is that the collaboration of porous walls, or porous materials in the room, is necessary for these simplified air conditioning systems to work. The outdoor climate often has a combination of temperature and relative humidity which is outside the limits for the warming or dehumidifying to a constant RH. The porous materials are needed to buffer the indoor climate during these periods when active control is impossible.

Dehumidification can reduce the temperature of a well buffered room at the same time as reducing the relative humidity. The standard condensation dehumidifier works by cooling the air below the required dew point, to condense the surplus water. The air is then re-warmed by passing it over the coil containing the hot, compressed refrigeration fluid. If the dehumidifier is outside the room it can lose this heat outside the room and pump the dehumidified, but still cold, air into the room. The RH of this air stream will be very high but if the balance of heat loss through the walls is right it will warm up to a temperature where the RH is correct but the temperature slightly below ambient.

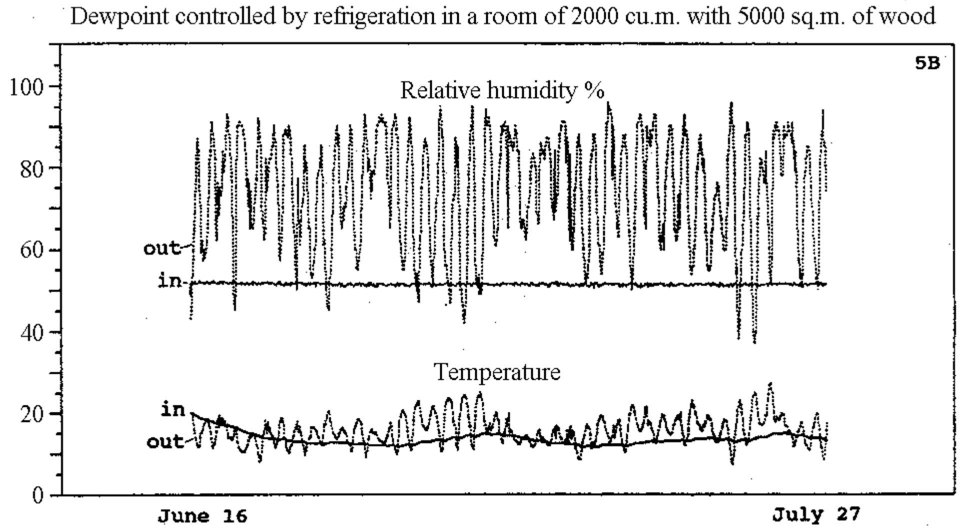

Figure 6.31 The calculated climate in a museum store dehumidified to 50% RH. The heat generated in the dehumidifier is discarded to the outside, rather than pumped into the room, as happens with a standard dehumidifier.

This method is modelled in the next diagram, which is taken from the set of calculations made to evaluate various methods of air conditioning the museum store in Brede.

This technique only works in a room with good humidity buffering. It is important to realise that absorbent porous walls are not only advantageous in houses without air conditioning, they also allow much simpler and more economical air conditioning in places where the requirement for accurate control does not permit a relaxed attitude to natural climatic forces.

Absorbent insulation

Absorbent insulation, like absorbent walls, is a traditional material that has fallen into disuse. A huge variety of plant fibres have been used for insulation, so has animal hair.

The important characteristic of absorbent insulation that sets it apart from absorbent solid building materials is that there is very little of it, by weight, per square metre of wall. Its buffer capacity is correspondingly limited. Furthermore, the little buffer capacity that it has is screened behind the hard interior finish of the house.

Absorbent insulation has an important role to play in buffering the climate in the interior of the wall. The volume is small, compared to the inner volume of a house, but the climate is more extreme. There is heat flow and water vapour flow. There is also radiant heating of exterior surfaces in the sun and there is driving rain forcing water into the wall.

The climate within the structure of walls is so extreme that the threats it poses seem to have deflected the attention of building engineers away from the interior climate of the house.

The basic problem, apart from faulty construction, is that warm air inside a house always contains more water, measured in kg/m^3, than the cool air outside. If the outside air temperature is lower than the dew point of the inside air, and the inside air moves through the wall and cools to the outside temperature then water will condense within the wall. This condensation inside the wall will threaten corrosion and rot and provide drinking water for plagues of insects.

If the wall is very open to air movement from the inside there is not much that absorbent insulation can do to ameliorate the situation. If, however, the wall is fairly well sealed against air flow, then the buffer effect of absorbent insulation can moderate the sudden swings of climate within the wall very substantially.

This is an assertion, based on calculations of the same type that have been presented for houses and for storage rooms. There is no body of research on the performance of absorbent insulation, because the modern building industry insulates almost exclusively with mineral fibre, mineral pellets and polystyrene. All these materials are non-absorbent. The paper fibre insulation industry has been established as a minor player in the business for many years but seems not to have sponsored research that really defines the properties of the material, as used within a wall.

All insulating fibres have roughly the same insulation value: that of the stagnant air between the solid fibres. The battle between the proponents of various materials has centred on issues of fire resistance and resistance to rot and insect attack. The subtle differences in performance due to moisture absorption at moderate RH has not figured in the debate.

It is difficult to find evidence for succesful performance. Disasters attract much more critical research. I therefore present a case history that emphasises the disadvantages of non absorbent insulation, with the purpose of opening a debate on the possible advantages of porous insulation. This may seem a weak excuse, but the story is amusing, and has not been told before.

The mysterious case of the building that rained inside, but only in fine sunny weather

The Arts and Industries Museum in Washington, D.C. was finished in 1881. It was designed as a museum, with ingenious use of the towers for ventilation. The advance of technology brought an orthodox air conditioning system with electric boilers for winter humidification.

Figure 6.32 The Arts and Industries Museum of the Smithsonian Institution in Washington D.C. The south front showing the towers beside the entrance, used for cooling by the stack effect.

The museum's roof was replaced in the late nineteen seventies. The new roof soon showed a magical ability to shower rain down on the interior in bright spring sunshine. The reason for this phenomenon is a fascinating illustration of the problems that arise when the whole apparatus of modern materials, modern standards and modern regulations are applied to ancient buildings.

It is also an example of what happens when one mixes absorbent and non absorbent materials in a multi-layer sandwich exposed to large temperature variations.

The old roof was replaced by a box-sandwich construction of two layers of plywood enclosing mineral fibre insulation. The outer surface was of lead-coated copper. The wood was impregnated with a mixture of water soluble salts for fire and rot resistance. A polyester membrane was laid on the bottom plywood as a vapour barrier. The structure is sketched in figure 6.33.

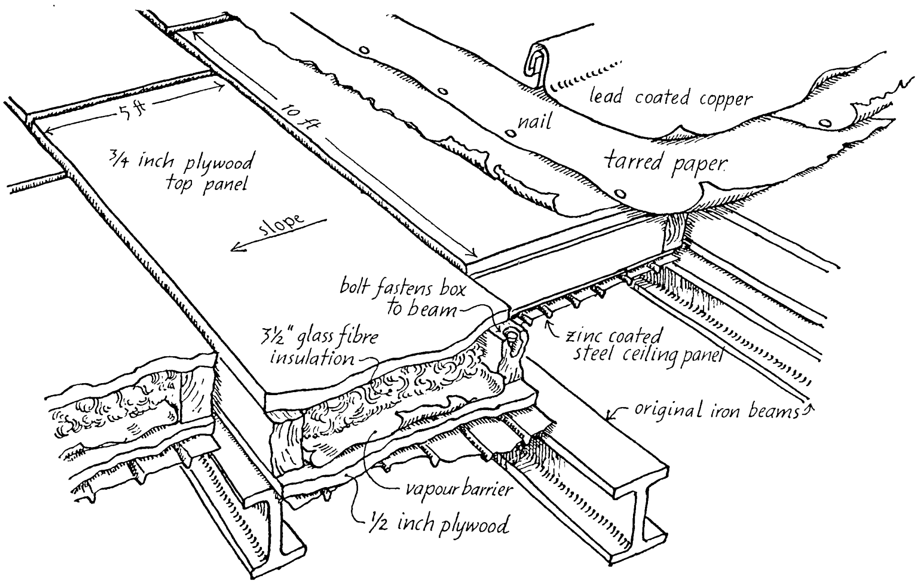

Figure 6.33 The design of the new roof of the Arts and Industries Museum

The rain in the building was not at first attributed to the roof but to some malfunction of the air conditioning. Eye witnesses reported seeing clouds in the high central rotunda.

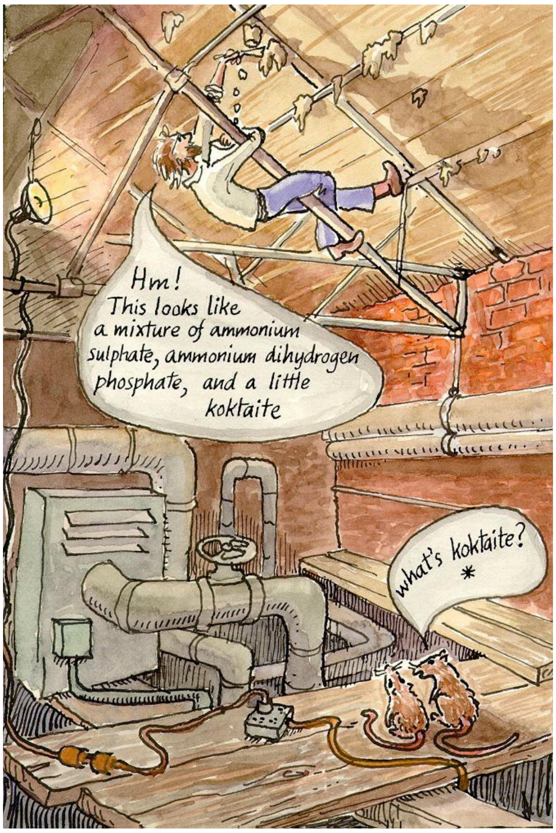

*Figure 6.34 Fireproofing salts formed stalactites hanging from the ceiling panels, revealing that the water came from the roof. *Koktaite is a hydrated calcium ammonium sulphate.*

An analysis of the rainwater, however, pointed to the roof as the cause of the problem. Ammonium and phosphate ions hinted at dissolution of the fireproofing salts in the plywood. A visit to the loft confirmed the suspicion.

In the U.S. all scientific evidence must be solid enough to be defended in court, so we set about installing sensors to reveal the exact processes at work within the roof. My colleague in this, and several other amusing technical detective jobs, was David Erhardt, a research chemist working at the Smithsonian Institution.

The temperature and RH was measured between every layer in the roof, and outside. Sensors for liquid water were placed on the vapour barrier and within the insulation. These were copper nails fixed close and parallel to each other. The direction of air movement was measured by placing an insulated tube through the roof with a temperature sensor in it. This sensor followed the indoor or the outdoor temperature,

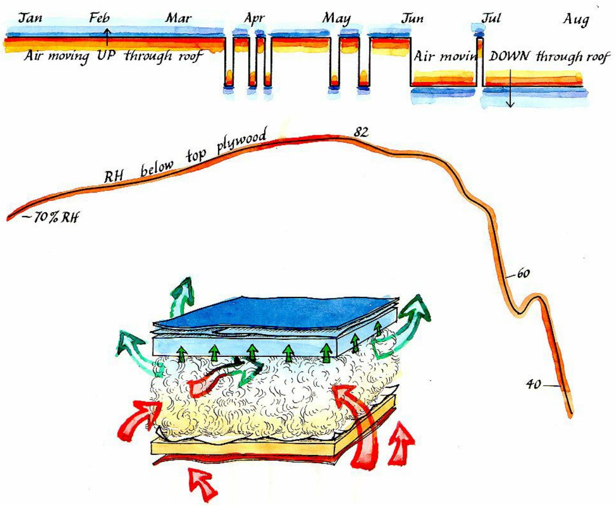

Figure 6.35 A plot of the direction of air flow through the roof is at the top. The curve below shows the steady increase of RH just below the upper plywood layer, indicating that water vapour from the humidified museum air is reaching the plywood and is being absorbed into the wood. The process is aided by the fireproofing salts that also absorb water at high RH.
In early summer the stack effect goes into reverse, air moves down through the roof, drying it rapidly.

according to the direction of air flow. Thermally driven air movement is a powerful process in buildings with high, unobstructed inside spaces.

Then we watched our tape punching data logger and waited for the hygrothermal crisis. The RH under the upper layer of plywood rose steadily through the winter and spring, while the air direction indicator showed nearly continuous outflow of air. In early summer the flow reversed and the roof began to dry out very quickly, as seen towards the right side of figure 6.35. It was just after the peak RH that the rain fell from the ceiling.

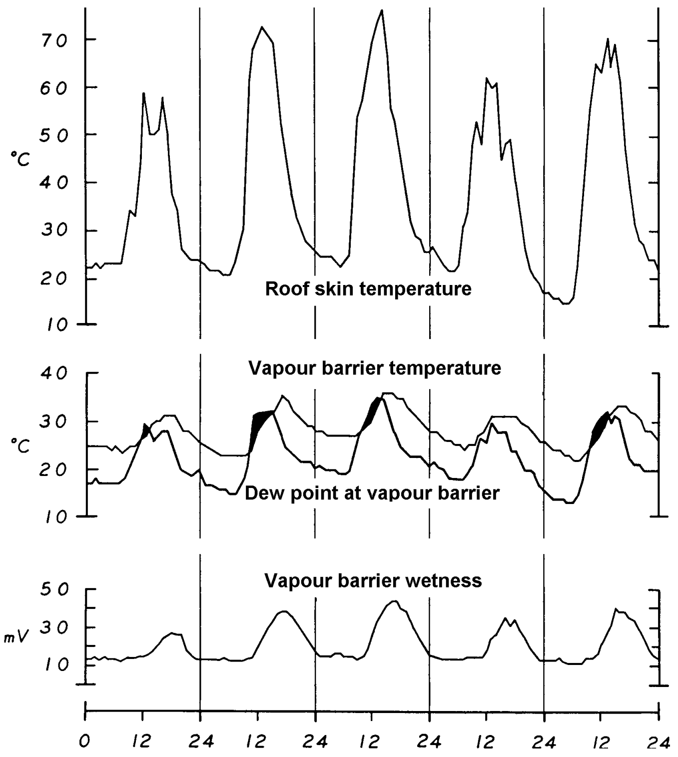

Figure 6.36 Traces over five days from several sensors mounted within the roof structure. Notice the solid black fill at times when the vapour barrier was cooler than the dew point of the air just above it. At these times water condensed on the polyester vapour barrier.

A composite diagram of the key sensor data for this short period is shown in figure 6.36.

The warm spring sunshine warmed the dark lead roof surface. The heat penetrated the upper plywood layer. The high moisture content of the plywood buffered the RH of the air just below it to about 70%, at the high temperature. This water vapour diffused through the air within the open structure of the glass fibre insulation, increasing its RH as it cooled. Dew formed on the lower part of the insulation or directly on the vapour barrier.

These short periods of dew formation are marked in black on figure 6.36. Notice that each period is quite short. There are two reasons for this. One is that the vapour barrier is heated by the condensation of moisture upon it. The other reason is that the dew point falls quite rapidly from its peak value in the early afternoon.

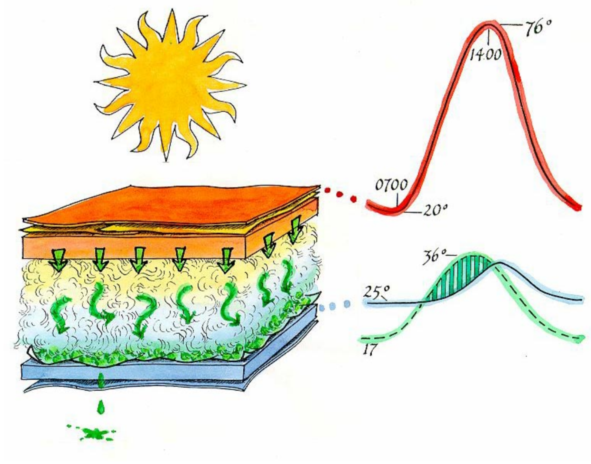

Figure 6.37 A pictorial summary of the condensation process in the roof of the Arts and Industries Museum on a sunny spring day.

Figure 6.38. Trickles of water emerging onto the roof. The water is distilled from the underlying damp plywood and condenses in periods when the roof skin is cooler than the wood below.

The same process occurs day after day until enough water has been evaporated from the plywood that the dew point never reaches the vapour barrier temperature.

The condensation process is summarised in figure 6.37.

One final detail is necessary to explain the dramatic rain showers. The condensate accumulated for some time as discrete drops on the water repellent surface of the polyester membrane. The roof tilts at a shallow angle, so a lot of water accumulates. Then, by chance two drops meet and coalesce, then run down into another and soon the entire mass of collected water streams towards the nearest downstream break in the construction.

This story encapsulates many of the themes touched in this thesis. Absorbent materials and unabsorbent materials interact in a temperature gradient. The absorbency of the plywood is artificially increased by the addition of fireproofing water soluble salts. The porosity of the unabsorbent insulation allows rapid moisture transfer through the temperature gradient. The discontinuous vapour barrier allows air to infiltrate from below. The humidification of the museum air increases the water uptake by the plywood. The amount of water released is limited by the hours of intense sunlight but also by the rather low permeability of the wood, which restricts the amount of water released on a single day but also allows a recharge rate that ensures daily rain during a period of two or three weeks, if the sun shines. The symptomless accumulation of condensed water during the whole winter is made possible by the absorptive capacity of the plywood, conceals the true nature of the problem.

There are also influences working against condensation. The roof dries rapidly when the direction of air flow reverses, so that dry (in kg/m^3) outside air comes easily through the unsealed seams of the roof covering. These same seams allow a portion of the water vapour to escape upwards, as shown in figure 6.38.

Such a relatively short period of rapid mobilisation of water in a structure is not uncommon. The conditions for condensation are usually only fulfilled in the transition from winter to summer. Nevertheless, much damage can be caused by these brief episodes. There was far more corrosion on the underside of the lead coated copper roof than on the outside. The fireproofing salts had migrated and recrystallised and a luxuriant growth of fungus wound its hyphæ around the nutritious crystals of ammonium dihydrogen phosphate while the borax added to prevent this had recrystallised far away.

The complexity of the roof was forced on the architect. The original roof was very thin, so the new roof had to match its dimensions while providing insulation and fire resistance to modern standards. It had to be placed in sections over a building that continued to function as a museum, making impossible the laying of a continuous air barrier. Given the circumstances there is no one to blame for this expensive mistake.

One solution to the problem was not only available but was being built just a few metres away at the same time, designed by the same architect. Another part of the roof of this vast building was constructed in almost the same way, but with slabs of foamed glass insulation instead of the glass fibre. This material is completely impermeable and so the distillation process described above cannot occur. The absorption of water vapour into the roof is certainly happening in the same way but the drying occurs predominantly to the outside.

One can speculate over other solutions to the problem. If there were no vapour barrier the condensate would be absorbed into the lower plywood. The process would go into reverse during the night so that no water would cascade into the interior. Another possibility would be to use absorbent insulation, such as wool or paper fibres. The

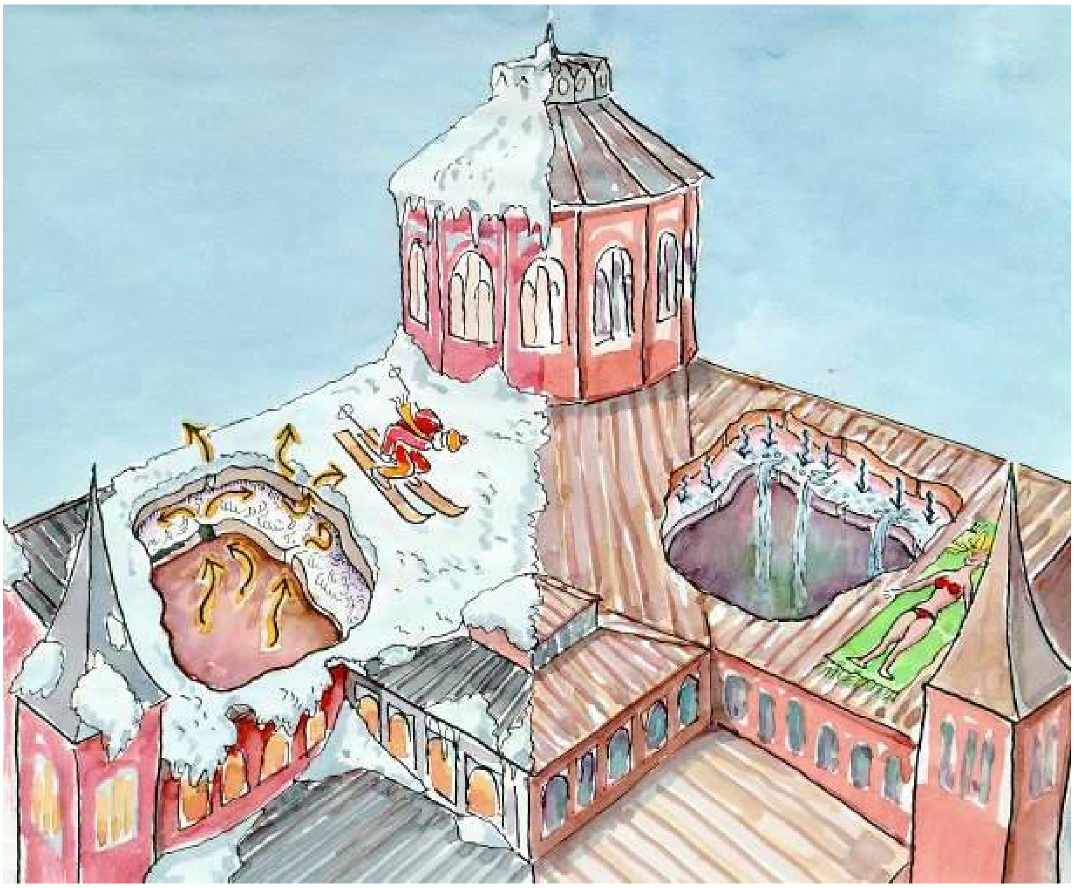

Figure 6.39 A summary of the annual cycle of water movement in the roof of the Arts and Industries Museum. In winter, on the left, warm, buoyant air forces its way up through the roof, depositing water in the cold upper plywood. In summer, on the right, the clear sunlight warms the roof. The water is released and diffuses down, helped by the downward flow of warm air into the now cooler interior. It condenses on the vapour barrier, accumulates in drops which, after a while, join together and move off down the shallow slope to the nearest crack in the ceiling. From there a shower of rain, with dissolved fireproofing salts from the wood, cascades into the exhibition hall below. The entire process is governed by the interplay of absorbent and non-absorbent materials in the complex roof structure.

lower, cooler parts would absorb water, possibly in sufficient amount to prevent the daily condensation. The insulation would dry out again during the night when the warmth of the building and radiation to the night sky from the dark roof would reverse the temperature gradient.

Such speculation can only be tested by making models, real models. It is difficult to imagine that a computer program could simulate the intricacy of water movement in the roof described above.

One can draw the conclusion from this tale that modern building practice has reached a degree of complexity whose consequences are unpredictable. There is a good case for investigating radical, but simple alternatives, such as massive walls which combine in one layer the functions of moisture absorption, thermal insulation, thermal inertia, fire resistance and physical strength.

Making a simple roof is more difficult, particularly in a cool, rainy temperate climate. Absorbent materials have a role to play in roof construction, because of their ability to absorb limited amounts of water, which can be released again when the temperature gradient reverses. The criterion for effective performance is therefore that the absorbent material must be able to take up the likely daily flux of vapour. The amount depends, of course, on the water capacity of the source.

Ideally the upper parts of the roof, those that are warmed in the spring sunshine, should have rather little water capacity, whereas the lower levels, at the relatively constant indoor temperature should be very absorbent.