HOW TO DESIGN MUSEUMS WITH A NATURALLY STABLE CLIMATE

Tim Padfield and Poul Klenz Larsen

This article is an extended version of the talk given by Tim Padfield to the Annual General Meeting of the International Institute for Conservation, January 2004.

Abstract

The architecture of museums has developed in a way that diminishes the natural protection previously afforded to collections by the thermal inertia of massive masonry construction, the limited solar radiation through relatively small glass areas and the release of internally generated heat through a large ratio of exposed wall to volume. Mechanical air conditioning is now nearly universal in new public buildings, even in climates where air conditioning has not previously been thought necessary, so that climate control has been decoupled from architecture. A paradox of modern design and modern materials is that passive humidity stability can now be provided more easily than before, because buildings are more airtight, while natural thermal stability is reduced, because structures are more lightweight, often have vast expanses of glass facade and have a small ratio of wall area to volume.

Relative humidity can be stabilised by moisture absorbent wall plasters and condensation can be minimised by porous walls. These methods of moderating the indoor climate have been pioneered by researchers in human health, designing dwellings. These innovations have not yet influenced the design of large public buildings, such as museums. This is probably because the demand for constancy in the museum climate is now so strict that it is impossible to achieve by non-mechanical means. In museum stores an annual temperature cycle is permitted. There are now several examples of stores whose climate is mainly controlled by passive methods, combined with simplified mechanical systems.

The evolution of museum buildings

Until the first quarter of the twentieth century, gravity defined the practical limits for the appearance of a building and gravitas described the appearance of museums. In the Pergamon Museum in Berlin (Figure 1), monumental outdoor art is enclosed in an even larger structure, itself encased in a classical collonade.

The modern movement in architecture allowed, but did not guarantee, a reaction to this portentous style. The Louisiana Museum of Modern Art north of Copenhagen (Figure 2) is one of the world's most unassuming art museums. Relief at its simplicity and human scale must be balanced against concern for the loss of secure containment. The flood of light is a visible cause of damage to the art, the lack of thermal inertia and moisture absorbing materials in the structure is both an invisible threat and a stress on the air conditioning equipment.

Architects have used the new science of accurately computed tensile constructions to make their mark with walls falling outwards at previously impossible angles, as in the The Royal Library in Copenhagen (Figure 3). This trend to press architecture to the limit, to make the enclosure for art itself the major artistic attraction, rather than just a sympathetic container, is exemplified by Frank Gehry's Guggenheim Museum in Bilbao (Figure 4).

These buildings, which appear to accept no limits to expressiveness, necessarily have limits to their ability to defend their contents by passive means. It is

Figure 1: The Pergamon Museum, Berlin. The huge Assyrian reliefs are housed in an immense building in neo classical style. Built in 1920–1930. Architect: Alfred Messel.

Figure 2: A gallery of the Louisiana Museum of Modern Art, north of Copenhagen, designed in the late 1950's by Wilhelm Wohlert and Jørgen Bo.

Figure 3: The Royal Library extension, Copenhagen, 1999. Designed by Schmidt, Hammer and Lassen.

Figure 4: The Guggenheim Museum in Bilbao, 1997. Architect: Frank Gehry. Photo: Perry Smith.

not easy to build a massive wall that leans out, so the thermal inertia of such a building must be low, unless it is provided by more orthodox internal structure.

Another trend in modern museum building is the enclosure of courtyards of existing buildings (Figure 5) and the linking of old and new parts by glass corridors (Figure 6). These glass enclosures reduce the surface area to volume ratio of the building, and provide negligible thermal inertia, resulting in a need to cool the building even in winter in a temperate climate. This is a design trend made possible only by cheap energy. Half the energy from the sun is light, so clear, uncoloured glass, however technologically advanced, can at best only halve the incoming solar power. At the same time as we are urged to reduce our consumption of fossil fuels, architects are designing air conditioned buildings in northern Europe, where air conditioning was considered unnecessary only a couple of decades ago.

The trend towards lightweight enclosures is reducing the margin for error in

Figure 5: The recently covered courtyard of the British Museum, London. 2000. Architect, Norman Foster.

Figure 6: The Danish National Gallery, Copenhagen, The glass atrium joins Wilhelm Dahlerup's building from 1896 to the extension designed by Anna Maria Indrio, opened in 1998.

Figure 7: The Nydam Boat, exhibited in an inflated structure but here shown in the middle of a power cut. Fortunately, the wires holding the condensation collector above the boat also held the entire canopy when the air pressure failed. Architect KHRAS. Photo: Ole Vanggaard.

Figure 8: The Museum of Modern Glass Art is housed in an abandoned cistern under a low hill in Copenhagen. The shine on the floor is water.

caring for artifacts. The Nydam boat, from the fourth century AD, normally enjoys a quiet retirement in Gottorp House in Schleswig. It was lent recently to the National Museum of Denmark which put it under an inflated structure (Figure 7). The thin envelope gives scant separation between the northern European climate and the warm humidified interior, so condensation dripped from the roof. The engineers then strung wires from end to end to hold a canopy to catch the drips. The wires also held the tent from falling into the boat when the power to the pumps failed. We must be thankful for the serendipitous modification which both deflected an unforeseen threat and prevented an unexpected disaster.

Figure 9: The Copenhagen Opera House, designed by Henning Larsen, seen under construction in 2003.

Massive construction, however, is not a guarantee of a good climate. The Copenhagen Museum of Modern Glass Art (Figure 8) is in a reservoir built within a low hill, which once provided water to the city. Here, one cannot criticise the immense thermal inertia of the semi-infinite walls but the relative humidity is not ideal, though its stability is ensured by the constant centimetre of water all over the floor.

In this frenzy to build, or adapt, unusual structures to contain art, we have lost sight of the protective role of enclosure. The environment of modern public buildings is now sustained by mechanical systems forcing conditioned air through a forest of ducts into a structure whose only inherent protective quality is thermal insulation. We can be certain that if the mechanical system fails the deterioration of the indoor climate will be rapid.

The construction methods and materials of modern buildings are now uniform worldwide. Even a prestige building, where there is no pressing need to save money, pays scant regard to local materials or adaptation of building style to the local climate. The Copenhagen Opera House (Figure 9) provides a visual list of the universal ingredients of a building: steel, precast concrete slabs, mineral wool insulation, glass, gypsum board, plastic paint and a thin surface veneer, in this case sandstone tiles. None of these materials has significant exchangeable moisture content and only concrete provides thermal capacity. In modern buildings it is only thermal insulation that counts. Until the last few years, national building regulations for minimising energy consumption have specified the thermal insulation required in a house. It is only very recently that the regulations in some countries have allowed a calculation of performance based on energy consumption, rather than thermal insulation.

This concentration of effort on thermal efficiency is understandable in the planning of an ordinary building because people have, until very recently, been assumed to be indifferent to variation of relative humidity if the temperature is moderate. However, hospitals, museums, printing works, weaving shops and computer rooms have long had humidity control, sometimes showing an ingenuity that long pre-dates the rise of ecological architecture, as in Marshall's Egyptian style Temple Mill in Leeds, England, from 1841, which had steam humidification aided by sheep grazing the turf on the roof to keep the evaporative cooling system close cropped.

The increasing reliance on computer aided design throws up another reason why humidity control by passive processes has not been taken up by modern architects. The flow of heat through materials and its transport by air are well understood. The movement of moisture, however, remains mysterious. Many computer programs have been written, but results are not entirely convincing

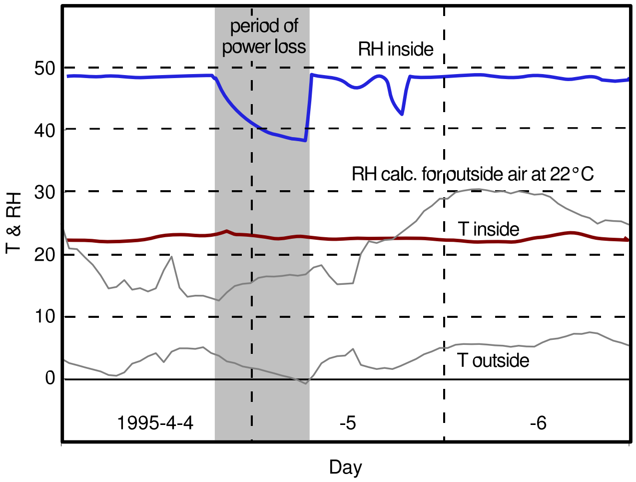

Figure 10: The course of the climate in a gallery of the National Museum of Denmark. During a twelve hour power failure the massive building held a steady temperature but the relative humidity descended steeply from its artificially high value towards the value corresponding to the outdoor air raised to the indoor temperature.

[1]. They all rely on the doubtful assumption that moisture moves through materials in the same way as heat. Even if this were true, a further difficulty is that although building imperfections may in bad cases account for 30% of the heat flow through the envelope, they can easily account for 98% of the moisture flow.

Heat and moisture buffering in buildings

Heat and moisture movement are inextricably interdependent in buildings. Our example comes from the only source of information on the natural performance of modern buildings: what happens when the power fails and the data logger is battery powered, or clockwork driven. The part of the National Museum of Denmark whose climate during a 12 hour power cut is shown in Figure 10 is made of concrete and brick. Heating is by air circulating within the concrete floors. The original courtyard has been covered to make a large room for temporary exhibitions. When the power failed the temperature remained high because of the great thermal inertia but the relative humidity fell, because the cold outside air with a low water vapour concentration filtered into the building through the windows. We learn from this that thermal inertia is not protective of the art without corresponding moisture inertia. The exhibits in this room were mostly behind glass, the walls were painted with acrylic emulsion and the floor was varnished wood. There is hardly any moisture buffering in this room to defend it when the mechanical humidification fails.

The argument of some building physicists [2], is that even if there are moisture absorbent surfaces in a room, the buffering effect, though real, is a quantitatively negligible influence on the indoor climate.

We examine the scanty evidence and come to a less pessimistic conclusion. Building materials, and the content of buildings, have a considerable potential for buffering the relative humidity, but this potential is seldom realised because water vapour passes through materials much more slowly than heat does. A stone wall a metre thick has the capacity to slow down the daily wave of heat passing into a building so that the peak temperature at the inner surface is

Figure 11: The military archive of the Castle of Segovia in Spain. On one side the room is bounded by the massive limestone of the castle rock. On the other side, small windows penetrate the massive outer wall. Photo: Victoria Smith.

Figure 12: The Cord Room, on the exhibition circuit at a higher level in the Castle of Segovia.

reached in the cool of the early morning - affording a considerable saving in both the daytime cooling need and the night time heating. During this same period, the moisture exchanged at the exposed surface of a plank of wood, for example, will cause a wave of moisture movement influencing no more than the underlying few millimetres of wood.

Interpretation of the climate in unheated rooms

When we look for evidence from buildings without climate control, to test the reality of humidity and thermal buffering, it turns out that there are almost no usable data. The kilometres of thermohygrograph charts and the gigabytes of digital climate data from museum interiors are of no use if there are not matching data from the outside climate.

We show first the data for the military archive of the castle of Segovia in Spain, a room (Figure 11) with enormous thermal and moisture inertia, having the massive limestone of the castle rock as the floor and one wall and a mass of paper records as its contents (Figure 13). Note how the thermal buffering also holds the RH steady, towards the right hand end of the graph, where the outside RH decreases swiftly, but the inside RH actually increases slightly, because the water content of the warm outside air increases as summer approaches.

We can also note some support for the assertion that moisture buffering is easily overpowered by air exchange. There are some downward blips in the RH record at the beginning of the sequence. These are caused by the curator opening the window as she starts work, and locking it again before she leaves. Each event leaves the RH a little lower, after the initial rapid recovery. As summer approaches, the curator's ventilation has the opposite effect, causing the RH to rise in small steps.

We turn now to the climate of an exhibition room in the upper part of the castle, with visitors, good ventilation and relatively sparse furnishing (Figure 12). The corresponding climate data (Figure 14) are much more typical of a museum, yet we can still see a considerable reduction of the RH cycle amplitude, compared with the outdoor values.

Our interpretation of the cause of the moderation of the interior RH is limited by a fundamental ambiguity. We can see immediately that the smaller cycle in

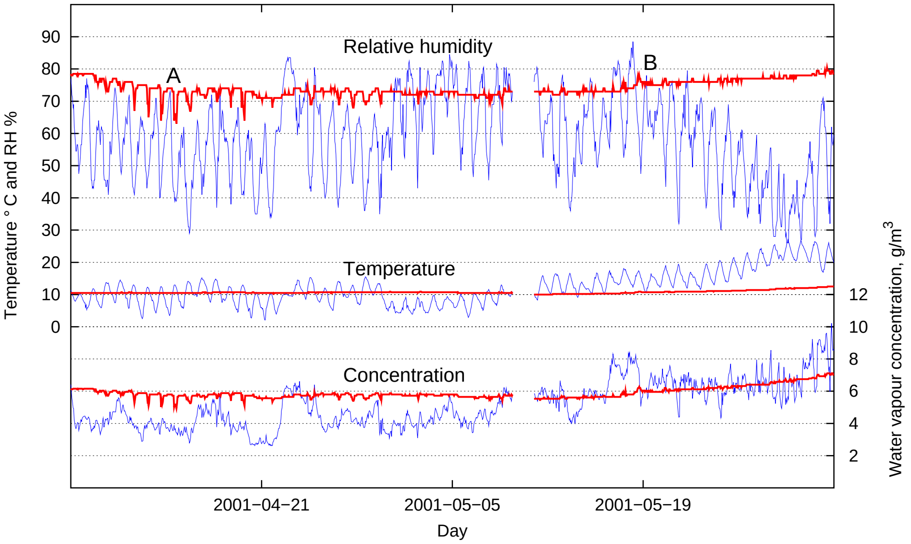

Figure 13: The microclimate in the military archive (bold lines), compared with the outside climate. The point **A** on the RH trace marks a period when opening a window during working hours pushed the RH to a lower value. At point **B**, in warmer weather, opening the window increased the RH. Data from Victoria Smith [3]

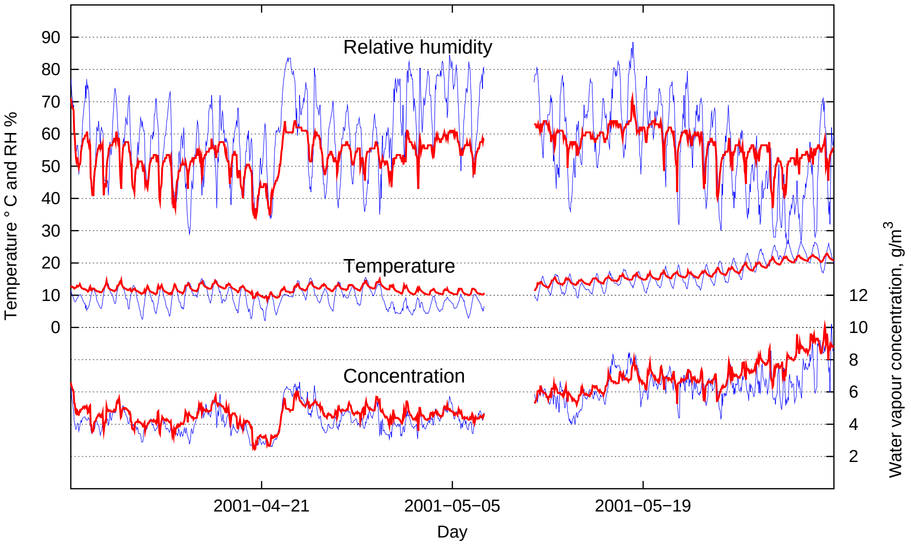

Figure 14: The climate within the Cord Room, compared with that outside. Note that the water vapour concentrations are not identical, indicating that the RH is not buffered by thermal inertia alone. Data from Victoria Smith [3]

indoor temperature, compared with that outside, has automatically reduced the RH variation indoors below the outdoor cycle, which is largely caused by the daily temperature cycle. Yet this cannot be the whole story, because the indoor water vapour concentration, though following the outdoor value on the scale of several days, deviates considerably on the scale of hours. We cannot tell how much of this deviation is due to variation in ventilation rate, how much is due to buffering by the surfaces in the room and how much is due to vapour from visitors. Without measurement of air exchange and wall surface temperatures at

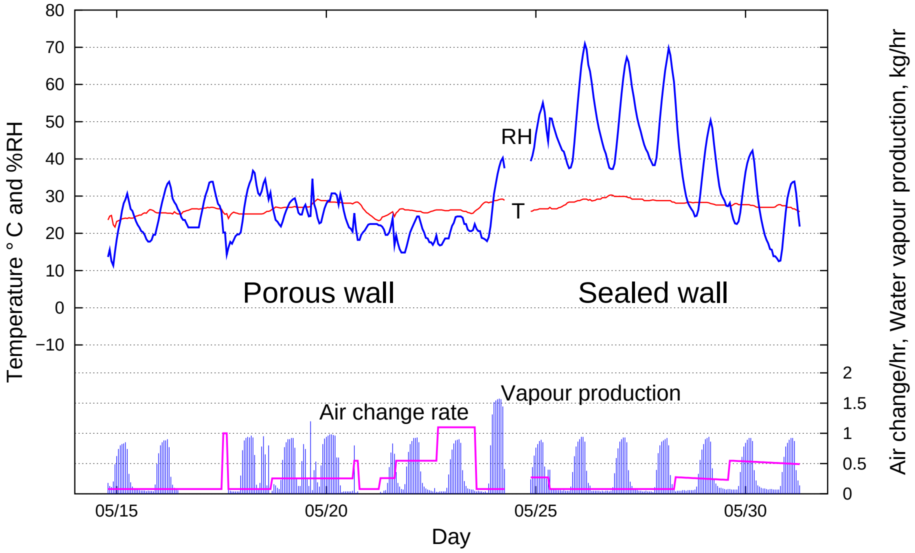

Figure 15: The climate within an experimental room in Tapanila ecological house, Espoo, Finland. During the first period, a humidifier blows water vapour intermittently into the room which has porous walls. During the second period, the walls are covered with polyethylene sheet. The ventilation rate is varied throughout the experiment. The better buffering with the porous walls is quite clear. Data re-plotted from Rode et al. [4].

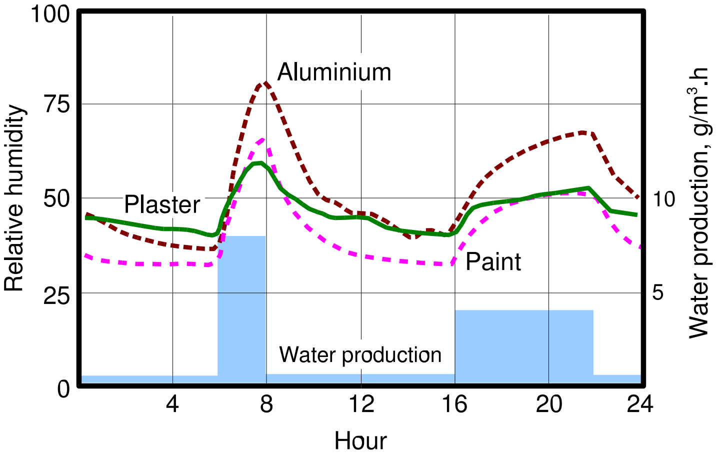

Figure 16: The climate within an experimental room at the Fraunhofer Institute for Building Physics in south Germany. The plaster walled room was compared with a similar room with aluminium walls and was finally painted. The porous bare plaster wall gives significant buffering against the typical daily water vapour production of a family. Data re-plotted from Holm et al. [5]

the same frequency as measurements of air temperature and relative humidity we can learn nothing about how the microclimate is generated in this room. The database for interpreting how buildings react to weather and patterns of use does not exist.

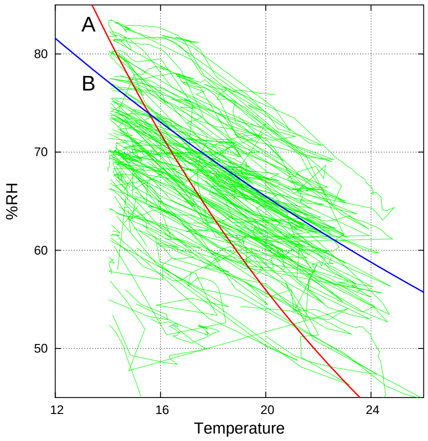

Figure 17: The overlapping cycles of RH against temperature in Gundsømagle Church, Denmark, during many periods of heating and cooling. If the walls were inert to moisture, the traces of the temperature cycles should lie parallel to the steep curve **A**, which marks the course of the RH as the temperature varies in an isolated space. In fact, the porous limestone walls buffer the RH, so it follows a set of shallower cycles, whose average gradient is shown by the flatter curve **B**. The angle between these two curves can be considered a figure of merit for buffer performance. Data re-plotted from Eshøj [7].

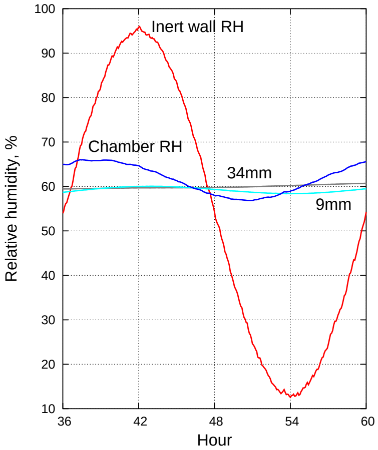

Figure 18: The RH buffering provided by 0.3 m^2 of lightweight clay plaster in a test chamber of 0.5 m^3. The large curve is the expected RH in the empty chamber, as a response to addition and withdrawal of water corresponding to the daily cycle of water production indoors and loss of water vapour by ventilation. The flatter curves are the measured RH within the chamber when the clay plaster was present and the RH measured at two depths within the plaster. From Padfield [8] page 76

Quantitative measurement of humidity buffering

We have thus reached the end of the road in reporting quantifiable experience from museums. The only precise measurements of humidity buffering with a known air exchange rate and moisture flux come from experimental rooms designed to improve the comfort of humans rather than of inanimate art. Figure 15 shows the course of the climate in Tapanila ecological house, Espoo, Finland. Similar results are reported from the Fraunhofer Institute for Building Physics in Holzkirchen, Germany (Figure 16) [5]. The expected effectiveness of wooden buildings in buffering the relative humidity with various rates of air change has been modelled by Simonson and co-workers [6].

Humidity buffering of large spaces

Large rooms with porous surfaces, more on the scale of museum galleries, are hard to find. In northern Europe they are usually stables or churches. Many investigations of the whitewashed Medieval churches of Denmark show that they buffer changes of relative humidity. The furnishing is sparse, and usually oil painted or varnished, so it is the walls that provide climatic stability. To give some quantitative idea of this effect we chose, as before, data that come from an unintended experiment. In Gundsømagle Church in Denmark, the temperature in winter is normally kept at about 12°C. The church is warmed for services and for the organist to practise. We have extracted from the climate record for one year just these brief periods of warming and cooling and have plotted the data as superimposed cycles of temperature against RH (Figure 17). Given an air change rate that is slow compared with the period of the temperature change, we can assume that an inert wall would result in a relationship between temperature and RH given by the steep bold curve in the diagram. This expresses the fact that a rise in temperature will cause a fall in RH in an isolated volume of air. The observed variation, averaged over many heating and cooling events, follows the shallower curve, indicating that the RH is not varying as much as it would in the room with moisture inert walls. As the temperature rises, the wall releases water vapour to maintian the RH, and absorbs it again as the temperature falls. If the walls were to buffer perfectly, the plot would be a maze of nearly horizontal lines. The angle of the squiggly lines to the horizontal can therefore be used as a figure of merit for RH buffering by the walls. This value is unique to the room, not to the material of the wall, because it is affected by the area to volume ratio. Experimentally, this is not an ideal method, because the thermal inertia of the wall interferes, reducing the moisture buffering effect.

The buffering afforded by church walls is far from negligible and definitely beneficial to the church furniture and wall paintings.

So far, we have discussed the performance of building materials that have not been chosen deliberately for their buffering capacity. Padfield [8] has experimented with optimising wall surfaces for moisture buffering, while retaining a smooth appearance, easy application and low cost. Figure 18 shows the buffering afforded by a lightweight, clay bonded plaster, designed to be a substitute for gypsum plaster as an indoor finish. The experimental conditions were broadly similar to the previously reported small room experiments, with a sinusoidal cycle of injection and withdrawal of water vapour but with no air exchange. The expected daily RH variation in an inert room is shown by the steep curve. The flatter curves show the measured RH in the chamber and at depth within the plaster surface. Not only is the buffering impressive but the thickness of buffer that is affected is only about one centimetre. This limits the ability of the buffer to counteract the influence of rapid air exchange, but it also means that a thin layer is also the optimal thickness for buffering the daily variation in RH.

One can be confident therefore that useful humidity buffer performance can be achieved without any revolutionary change in architectural practice, though thermal buffering, once an automatic side effect of the necessary wall thickness to bear tall structures, is more difficult to achieve in modern buildings.

The potential for moisture buffering in museums

All this may be academically interesting, but is the prospect of buffering real museum galleries anywhere near becoming reality? There are powerful forces influencing engineers to use mechanical systems, notably the tight limits set by conservators for permitted variation in temperature and relative humidity and the legally required minimum air exchange rate for public places. It is difficult to specify, or to predict, the performance of a room with climate stability provided by material means rather than by air rushing through ducts. The modelling mathematics is still regarded as insufficiently tested for large scale use in prominent building projects.

One can be reasonably certain of achieving short term stability that may actually be better than that provided by mechanical systems but some drift of

Figure 19: A museum store in Brede, north of Copenhagen. A new, thermally insulated, airtight and moisture buffering room has been built within an old machine hall, leaving a corridor between the old shell and the new room. Climate control is by heating and by pumping outside air into the room when the water vapour content is suitable.

Figure 20: A building of Copenhagen University, holding the archive of the Arnemagnæan Institute. The end wall of the archive is removed to show schematically the heavier insulation towards the interior of the building, the massive concrete wall and the cellular concrete humidity buffer.

the indoor climate around the ideal set point is inevitable. It is much easier to specify a tightly limited climate, knowing that modern engineering can provide it. It is then but a short step for the architect to exploit being freed from the constraint of designing for fundamental climatic stability.

Semi passive climate control in museum stores

At present, the deliberate use of humidity buffering is limited to museum stores, where the air exchange rate is small and the temperature may be allowed to fall below the narrow band that is acceptable to museum visitors.

Figure 19 shows a storage room at the National Museum of Denmark, glimpsed behind the original factory windows. The walls of the room are airtight and thermally insulated against the corridor which surrounds three sides. The air conditioning is by pumping air from the corridor, which is not sealed against entry of outside air, into the room when the air has by chance the right water vapour content to drive the room air to the desired 50% relative humidity. The air is sometimes heated as it is pumped in, so that the temperature in the insulated room drifts according to the time of year. In the winter, however, the air in the corridor is heated to 12°C, so the room also holds this constant temperature.

This method of relative humidity control requires careful adjustment of the room temperature through the seasons, so that the absolute water content of the outside air can be expected to vary both above and below the water content that will give the room the desired constant relative humidity. The room has to be ventilated reasonably often to prevent accumulation of air pollution generated from the stored objects, whose materials and history are both very varied, so that they outgas various chemicals, both natural and man-made. At present, the ventilation of stale air has priority, so the climate control resulting from this

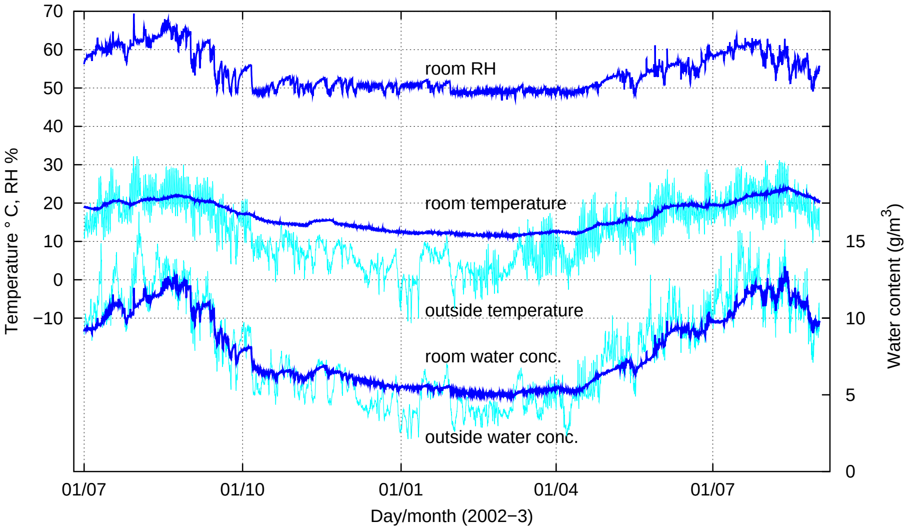

Figure 21: The climate in the Brede storeroom from July 2002 to August 2003. The set point is 50% RH. In summer the outside water vapour content is generally higher than that inside, so air is only pumped in when, by chance, the outside water vapour content dips below the water vapour content in the room (the two lowest traces). The optimal control is given by a subtle interplay of room temperature and the trend in outside temperature. One can see in the period immediately after 1/7/2003 that high outside water vapour content has resulted in a steady rise of inside RH, due to leakage but maybe also helped by rising temperature, which causes RH to rise in a well buffered enclosure. Data from Brian Simonsen [9]

system is not as perfect as can be obtained with full air conditioning (Figure 21), but it is cheap - costing about half what full air conditioning would cost to run. The initial investment is also less, because the ventilation equipment is small and simple.

There are many possible variations on this basic method of mechanically assisted air conditioning. One way to reduce the high summer RH would be to use the corridor more actively. On sunny summer days it gets very hot: over 30°C. If the back wall of the corridor were lined with black moisture-buffer material and the corridor were ventilated vigorously to the outside during the hot period, the RH of the buffer material would fall. The corridor could then be sealed from outside air at the approach of the cool of evening. The low equilibrium RH of the buffer will scarcely change as it cools. Now it can be used to dry air circulated between the corridor and the room.

Another variant is used in an archive in Copenhagen University [11]. Figure 20 shows the building, with the end wall of the archive removed to show how the insulation is arranged with a thinner layer towards the outside of the building and thicker insulation towards the inside. The carefully calculated insulation thicknesses, together with the thermal inertia of the massive concrete walls, hold the air in the archive at a temperature about half way between the central corridor of the building, always at about 20°C, and the running average of the outside temperature. This will give a yearly average RH of about 50%, but only if the buffer capacity of the room and its contents is used to even out the annual climatic cycle. The concrete is therefore lined with expanded cement blocks to provide moisture buffering. There are not yet data to demonstrate the performance of this room over the yearly cycle.

We have concentrated on the beneficial properties of moisture absorbent indoor surfaces. There are also good arguments for making walls which are porous right through. This allows the removal by diffusion of indoor pollutants, such as carbon dioxide, which is always at much higher concentration indoors than out. There are subtle advantages in porous walls whose relative permeability to inside and outside is adjusted to minimise the risk of condensation, which has caused spectacular failures in modern museums in cold climates. This matter is described in principle and in anecdote by Padfield [8]. The quantitative data are limited to research on houses [10].

Conclusion

There are large areas of the temperate zone where the decision to use mechanical air conditioning for public spaces is finely balanced and can be tipped over to using passive control by careful design to optimise heat loss from the building in summer and in sunlight, and by using natural light to reduce heat generation within the building. The use of buffers against temperature and humidity variation will even out the daily rythm and make air conditioning unnecessary. Even when a persistently unfavourable climate forces air conditioning, there is a case for using under-dimensioned equipment that can work round the clock, or at night supplied with cheap electricity, supported by buffering against the eight hour daytime load from solar radiation and human activity. The air conditioning can even be turned off to reduce noise during opening hours.

A good museum, from the point of view of the collection, has a carefully balanced area of window for its volume, and a ratio of outside wall area to volume that best fits the local climate and the expected heat generation in the building. The building should have high thermal mass and highly moisture sorptive interior surfaces, combined with a porous outer surface to minimise condensation in the structure and to permit outward diffusion of carbon dioxide. Optimising these characteristics is not incompatible with exciting architecture but it certainly is a constraint on freedom of expression. The one modification which is entirely free of risk and would incur hardly any visual or economic penalty is a shift to moisture absorbent interior plaster and moisture permeable paint.

The first recorded attempt to buffer the relative humidity in a museum gallery was published by MacIntyre in 1934 [12]. After seventy years of inactivity in this branch of preventive conservation, we see an increasing interest in the use of absorbent materials and clever design, rather than machinery, to control the indoor climate, but the initiative is coming from researchers concerned for the health of people rather than of museum objects [2]. The paradox of modern building practice is that its lightness reduces the stabilising influence of thermal inertia but its airtightness, combined with heat and moisture exchangers, makes possible relative humidity buffering, which rapid uncontrolled air exchange previously made ineffective.

References

[1] The first program for predicting moisture movement in buildings, which was sufficiently well presented that it could be used by consulting engineers and designers, appeared in 1990, written by Carsten Rode Pedersen at the Technical University of Denmark. It was followed in 1994 by WUFI, written at the Fraunhofer-Institut für Bauphysik in Germany. In both these programs the indoor relative humidity was entered as a starting point for the calculations, it was not a calculated value. The recent interest in moisture buffering in rooms is reflected in the latest version of WUFI, which,

since 2000 has had the relative humidity of the room as a calculated value. The Danish Building Research Institute has also incorporated a moisture buffering module into its comprehensive program for modelling everything about a building, called BSim2000.

[2] Carsten Rode, Andreas Holm and Tim Padfield, 'A review of humidity buffering in the interior spaces', *Journal of thermal envelope and building science*, **27** (2004) no 3 pp 221-226.
This is a summary of a workshop on the present state of modelling moisture movement in buildings. There is a fuller review of the workshop: 'Workshop on moisture buffer capacity, Summary report', August 21–22, 2003. Department of Civil Engineering, Technical University of Denmark, Report BYG-DTU R-067 (2003), ISSN 1601 2917, ISBN 87-7877-129-3.

[3] The collection of climate data from the Alcazar in Segovia is financed through the EU 5th Framework Program, MIMIC project.

[4] Rode, C., Salonvaara, M.,Ojanen, T.,Simonson, C., Grau, K., 'Integrated hygrothermal analysis of ecological buildings', *Proceedings of the Second International Conference on Building Physics*, Leuven, Belgium, September 2003.

[5] Holm, A., Kuenzel, H. M., Sedlbauer, K., 'Experimentelle Validierung eines neuentwickelten hygrothermischen Gebäudemodells'. Unpublished report, Fraunhofer-Institut für Bauphysik, Holzkirchen, (2003).

[6] Simonson, C.J.,Salonvaara, M., Ojanan, T. 'Improving indoor climate and comfort with wooden structures'. Technical Research Centre of Finland, Espoo. Publication 431 (2001) ISBN 951-38-5846-4.

[7] Climate data for Gundsømagle church were collected during a collaboration between the National Museum of Denmark and Bent Eshøj of the Conservation School of the Royal Danish Academy of Fine Art.

[8] Padfield, T. 'The role of absorbent building materials in moderating changes of relative humidity'. PhD thesis, Department of Structural Engineering and Materials, Technical University of Denmark, report no. 54 (1999). ISBN 87-7740-256-1, www.padfield.org/cfys/phd/phd-indx.php

[9] The design of the climate control of the National Museum store is a collaboration between the National Museum of Denmark and Birch & Krogboe, consulting engineers.

[10] Simonson, C.J. 'Moisture, thermal and ventilation performance of Tapanila ecological house'. Technical Research Centre of Finland, Espoo. Research Notes 2069 (2000), ISBN 951-38-5796-2.

[11] The design of the climate control of the Arnemagnæan vault is a collaboration between the National Museum of Denmark and Cowi consulting engineers.

[12] MacIntyre, J. 'Air conditioning for Mantegna's cartoons at Hampton Court Palace', *Technical Studies in the Field of the Fine Arts*, **2** no 4, (April 1934), pp 171–184.