Low energy museum storage

Tim Padfield, Poul Klenz Larsen, Morten Ryhl-Svendsen
and Lars Aasbjerg Jensen

Abstract

Allowing a moderate annual temperature cycle in a museum store greatly reduces the energy needed to control the climate. The system preferred for new buildings is to allow the temperature to vary freely in a space which uses an uninsulated floor directly on the ground as a large heat buffer, while the superstructure is well insulated. For buildings which already exist, or which cannot conveniently use the ground as a heat store, an alternative strategy is to allow the temperature to vary with the seasons but to ensure a minimum winter temperature at around 15 degrees. This must be combined with considerable humidity buffering, by the building or by its content. This will prevent both low winter relative humidity and high summer relative humidity. Both these control strategies rely on an air exchange rate less than once per day.

Introduction

We present two generic models for museum and archive storage in northern Europe which take account of the weather pattern by allowing a gentle annual temperature cycle combined with dehumidification either by winter heating, or by summer dehumidification. Orthodox air conditioning is not needed, so the climate control is much simpler and cheaper to operate. An influential recent environmental advice document for museums (PD5454:2012) has relaxed the demand for temperature constancy through the year, but the temperature limits which it allows are still incompatible with the most economical control system. There is slender evidence that this restrictive temperature range is justified by scientific studies of the degradation of materials, when one takes into account the general increase in durability provided by a cooler environment and the security afforded by the simplicity of the mechanical equipment.

Temperature control

Our starting point is the typical northern European weather, shown in figure 1 as one and a half years of the temperature in Ribe, west Denmark. There are two superimposed cycles - the annual cycle and the daily cycle which is shown expanded at the top right of the graph.

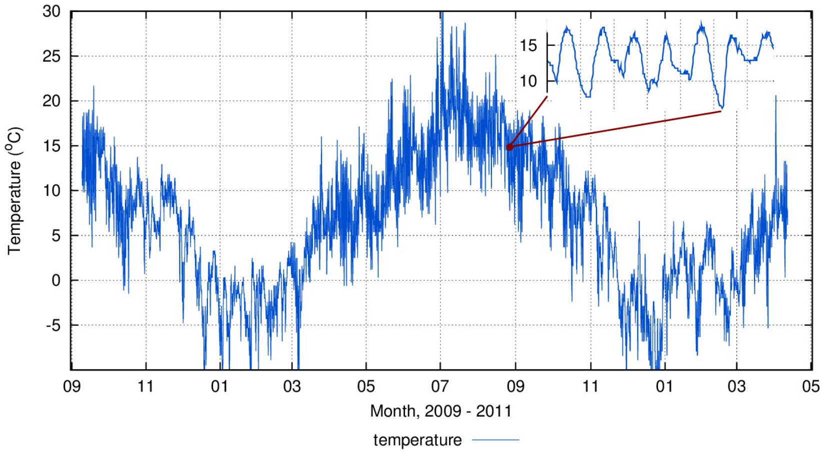

Figure 1: The weather pattern in Ribe, Western Denmark. The pattern of daily temperature cycles for one week is expanded at the top right.

Suppression of the daily cycle

There are two ways to moderate the daily cycle. One is to make the wall heavy so that it has a large heat capacity. Figure 2 shows the pattern of temperature through a solid brick wall, 240 mm thick.

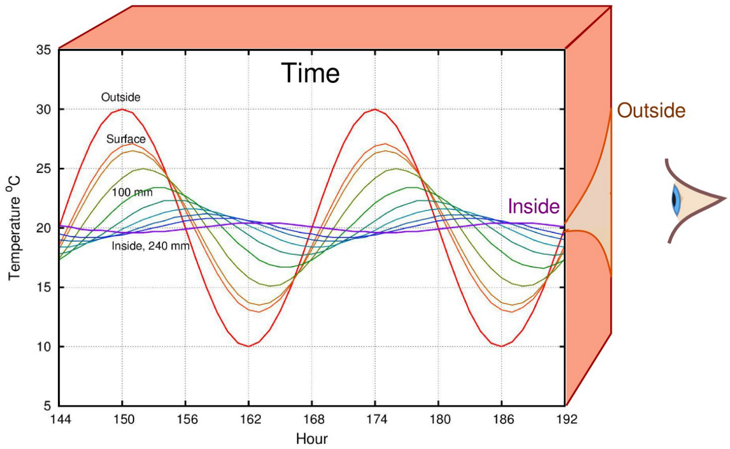

Figure 2: The pattern of daily temperature flow through a 240 mm thick massive brick wall. As daytime heat enters the wall it is partly absorbed and partly re-radiated, resulting in a wave of temperature passing through the wall, attenuating on the way so that at the inside surface it has only about one degree amplitude.

This construction does not impede heat flow. This is shown by the considerable difference between the air temperature and the surface temperature, indicating a large heat flow through the surface. However, the heat is absorbed and re-emitted by the molecules of the wall materials so a wave of temperature passes through the wall with ever diminishing amplitude until at the inside surface it is scarcely detectable and delayed by about twelve hours.

An example of thermal inertia, with no insulation, is provided by the NATO-standard fighter plane shelter in Værløse, Denmark.

Figure 3: A fighter jet shelter from the cold war, at Værløse, north of Copenhagen. The reinforced concrete shell is 600 mm thick. It is now used as a furniture store, mechanically dehumidified to 50% RH.

The thermal capacity of the shell has no effect on the seasonal variation within the store but entirely suppresses the daily variation.

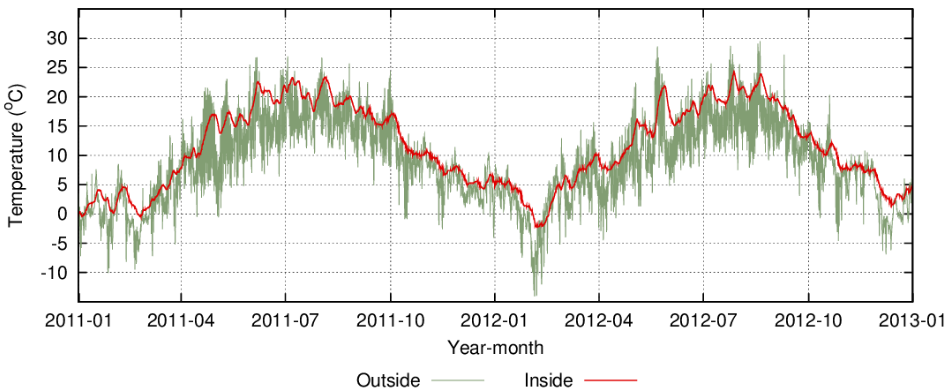

Figure 4: The temperature inside and outside the shelter over a two year period.

Attenuation of the daily temperature cycle by insulation

High thermal mass is advocated in the standards for museum storage, notably PD5454:2012. However, it is not necessary. The same damping of the daily cycle can be attained by lightweight thermal insulation, as shown in figure 6.

The pattern of heat flow is different, though the temperature cycle amplitude at the inner surface is the same as with the heavy wall. The difference

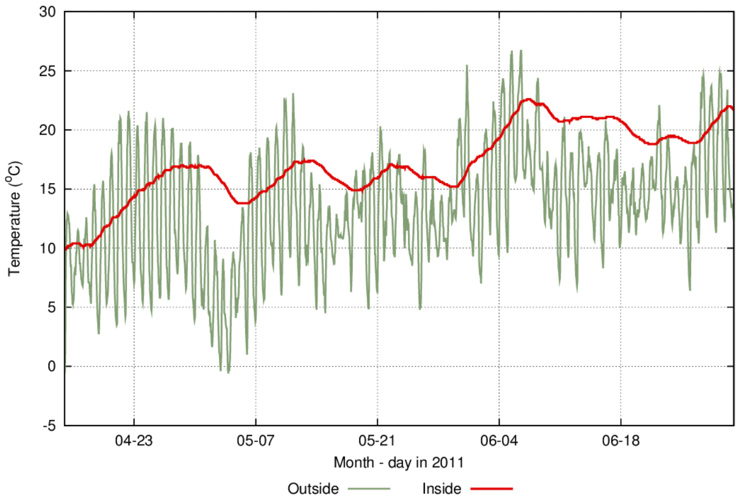

Figure 5: An expanded period from figure 4, showing the good suppression of the daily temperature cycle but quite rapid adjustment to longer weather patterns. The air exchange rate is about 0.04 h^{-1}. We cannot explain the approximately 5 degree excess temperature inside the building.

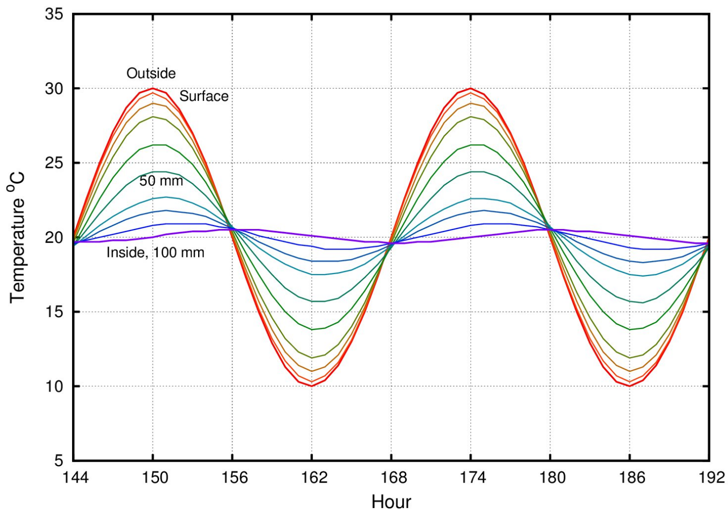

Figure 6: Attenuation of the daily temperature cycle by a foam wall 100 mm thick. The pattern of temperature through the wall is quite different from that shown in figure 2. However, the amplitude of the indoor cycle is the same.

is that the heat flow is much smaller, as shown by the closeness of the curves for the outside air and the outside surface. An important consequence of this thermal resistance is that if there are heat sources within the room, the temperature will rise to a steady difference above the running average outside temperature. In the absence of heat sources, however, as in a store or archive, the two wall types will give identical indoor climates.

Attenuation of the annual temperature cycle

The annual cycle would require much thicker walls, about four metres, to absorb the heat flow in the same way as illustrated in figure 2 for the daily cycle. The thickness of an insulated wall would be smaller, dependent on the heat capacity of the stored collection. There is a cheaper solution which combines thermal inertia with insulation, using the ground beneath the building as a heat store, combined with thermal insulation of the superstructure.

Figure 7: The museum store in Ribe, west Denmark.

The museum storage building in Ribe shown in figure 7 has insulated walls and ceiling but an uninsulated floor sitting on the earth. Its floor dimension is 24 x 45 m. The undivided interior space is 6.3 m high. The measured temperature is shown in figure 8.

The eight degree temperature cycle amplitude is an easily attainable moderation of the outside temperature. One could achieve a smaller amplitude but this would make humidity control more expensive, as discussed later. Surprisingly, the floor functions as an effective cooling surface in summer, the temperature difference between floor and ceiling is never more than two degrees, corresponding to a six percent difference in RH.

There is no need to insulate beneath the perimeter of the building. The edge effects are small and after a few years of operation the ground beneath the building becomes, thermally, part of the building.

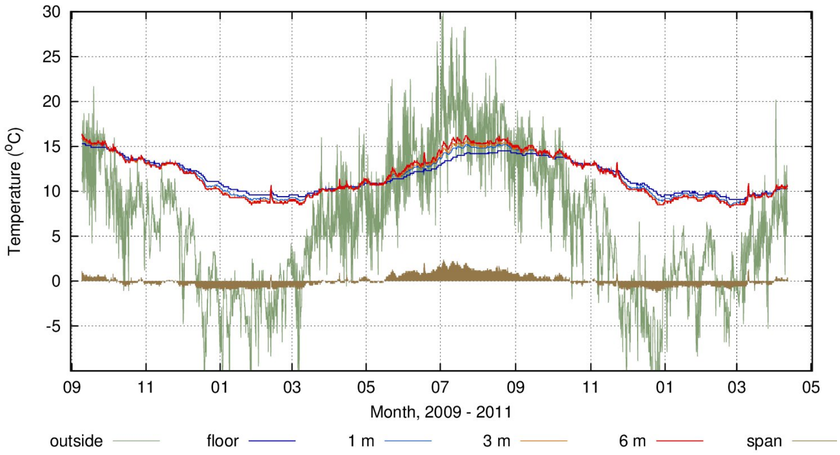

Figure 8: The temperatures measured in the Ribe storage building. The inside temperature cycle is reduced to an eight degree amplitude by temperature buffering from the floor. The graph also shows the very small variation in temperature with height. Even in summer, when the warm air would be expected to accumulate at the ceiling, there is less than 2K temperature difference between floor and the ceiling six metres above.

Relative humidity control

The RH arising from the diminished annual temperature cycle acting on the slowly infiltrating air will be moderate in winter, on account of the higher than ambient temperature, but it will be too high in summer - reaching 100% occasionally when the outdoor temperature rises well above the indoor temperature.

This is illustrated in figure 9. This shows the simulated RH within the Ribe store if it were empty and with non-absorbent walls. The course of the RH is moderated by the low air exchange rate, set to once per day in this simulation. The daily variation in RH is suppressed but there will be periods of condensation, particularly in early summer, when the indoor temperature is so strongly buffered that it is much lower than the outside temperature.

An important observation is that temperature buffering of a museum store must be matched by correspondingly good humidity buffering, to prevent these transient episodes of high RH. Humidity buffering has long been used in small enclosures such as showcases and transport cases. The same principle can be applied to a whole building, provided the air infiltration rate is low. It is also important that the buffer is cheap, because a large quantity is needed. Fortunately, many museum stores contain so much cellulosic material, as paper records and cardboard containers, that the collection itself provides sufficient humidity buffering. Otherwise, clay plaster or a wall lining of unfired brick will provide humidity buffering.

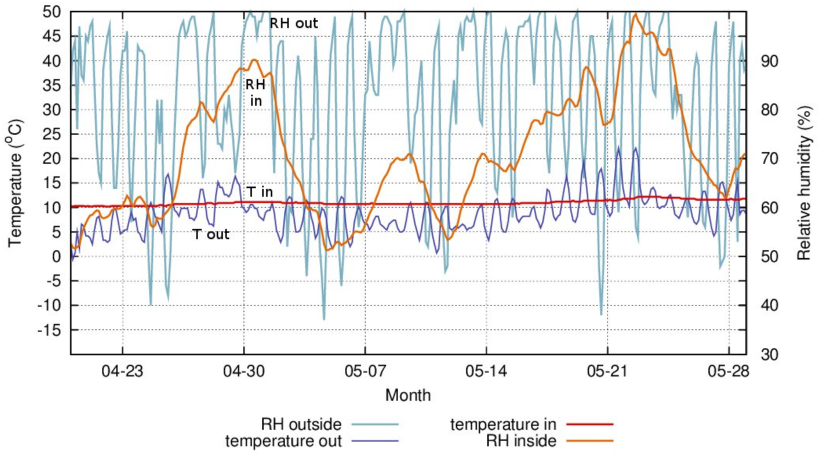

Figure 9: The simulated course of the relative humidity in an empty space with non-absorbent walls whose temperature is strongly buffered by heat exchange with the ground beneath. At the point 05-23 the inside RH touches 100%, because the outside RH has been high for a few days and also the outside temperature is higher than inside.

Moderating the short-term relative humidity

Relative humidity buffering

Water vapour reactive materials, commonly called hygroscopic, absorb and release water vapour as the ambient relative humidity changes.

The RH can be moderated by an abundance of hygroscopic materials within the space, provided the air exchange rate is small. Quantifying this effect in a dynamic situation has been studied by (Padfield et al. 2011). In this treatment, the sorption of water vapour by a test surface is continuously measured during a regular RH cycle. The vapour absorbed by one square metre of exposed surface on the upward swing of the RH is re-calculated to the equivalent volume of space which will experience the same change of RH with the same injection of water vapour as has entered the absorbent material. This equivalent volume will depend on the RH cycle time, because of slow diffusion within the material. A textured clay wall plaster, for example, has a buffer value (B-value) of about 100 for a four day cycle of RH. This means that one square metre of wall imitates the sorptive capacity of 100 m^3 of space. When all the absorbent surface B-values are summed up in this way, the building will have a virtual volume many times its actual volume. The effect of this is equivalent to diminishing the air exchange rate: multiplying its measured value by the actual volume divided by the virtual volume. An archive room filled with papers will have a total B-value around 1000. A museum store with mostly metal machinery and little absorbent material may have a B-value around 50.

Controlling the long-term relative humidity

A buffer value around 100 will prevent transient high RH. However, in the northern European climate the RH will eventually rise to about 75% within a store whose temperature cycle is centered on the average outside temperature. The inside RH must be held down below the average outside RH. This can be done by winter heating, or by summer dehumidification. Strong humidity buffering will ensure that both methods are never needed in a single building.

Winter heating

Figure 10 shows the predicted course of the inside RH when a room built directly over the ground is heated in winter to hold a minimum 14°C [1]. This periodic heating will also increase the summer temperature, as the ground below the building gradually equilibrates over several years to the higher average indoor temperature. However, the temperature will remain quite moderate, always below 20°C. The RH will stabilise at an average value around 55% with an annual cycle amplitude which depends on the humidity buffer value.

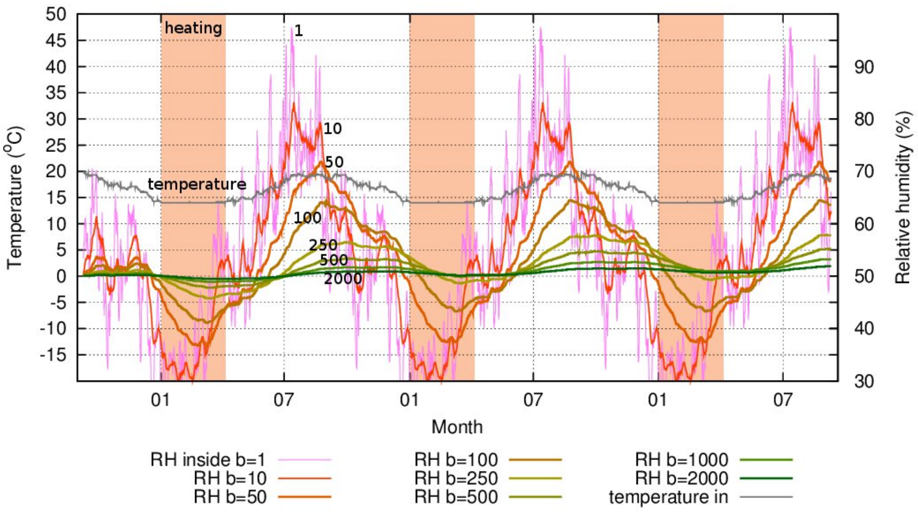

Figure 10: The predicted indoor RH when the room is heated to 14°C in winter. The curves show the RH prediction for various values of humidity buffer capacity. The first year is twice repeated to show how the buffer materials within the room react slowly, taking several years to attain equilibrium. The air exchange rate is set to once per day.

Notice that a B-value over 50 is needed to avoid a worryingly high RH in summer, when the outside temperature is often higher than inside. A B-value of 1000 is typical of a well filled store with paper and boxes. This gives a very stable RH with an annual cycle within a five percent envelope

- better than can usually be achieved by air conditioning and well within all museum standards. The RH need not be measured constantly and is never directly controlled. The winter heating alone defines the annual average RH. Thermostats are more reliable than RH sensors and the associated computer control of air conditioning. This method of climate control we call 'buffered conservation heating', by analogy with the gentle winter heating used to keep the RH moderate in historic buildings which are closed in winter [2].

Figure 11: The Suffolk Record Office, Ipswich, UK. It was built to work with only winter heating to control the climate. The walls are both massive and thermally insulated.

A measured example is provided by the Suffolk Record Office in eastern England, with similar outdoor weather to Ribe (figures 11 and 12).

Summer dehumidification

An alternative, and usually preferable, method of humidity control is mechanical dehumidification. Humidity buffering is still necessary, because there will be periods in winter when the outdoor temperature is so low, with correspondingly low water vapour content, that infiltrating air will cause the RH to drop below the set value.

A measured example of a dehumidified store is the Ribe museums store, whose climate is shown in figure 13.

In this store, the temperature buffering from the ground gives a winter temperature sufficiently above ambient that it holds the RH above 45%. The water vapour concentration balance is almost even from December to March. During the summer, dehumidification is necessary because the indoor temperature is well below ambient, so the RH would rise to 100% without intervention.

Dehumidification has several advantages over the alternative winter heating. It results in a lower temperature, giving better durability to the collection. It uses energy only in summer, when solar power is abundant. If the build-

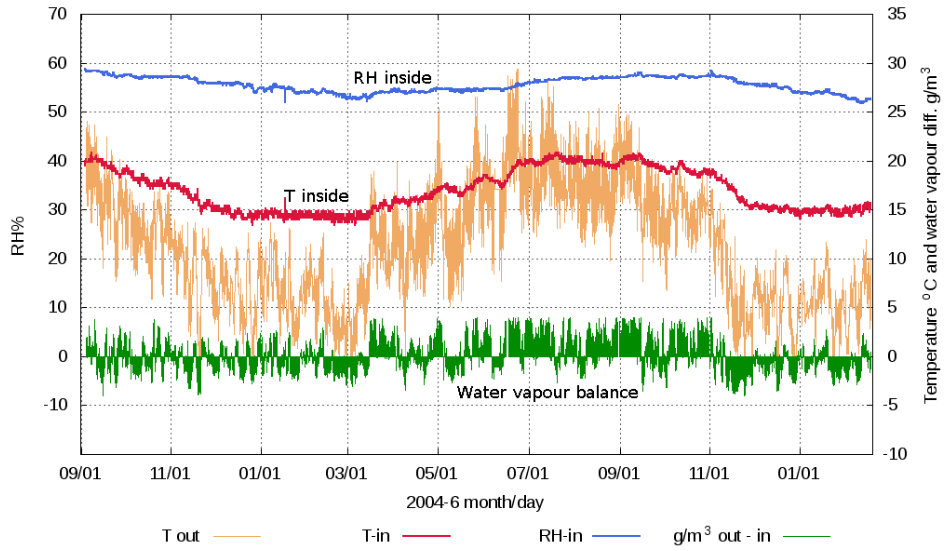

Figure 12: The measured climate in the Suffolk Record Office. The archive was heated to 14°C in winter. This kept the RH within a 5% envelope centered on 55%. The green trace displays the imbalance between the outside and the inside water vapour concentrations. The consistent excess water vapour in the outside air during the summer indicates effective buffering by the archive content (data from Dominic Wall).

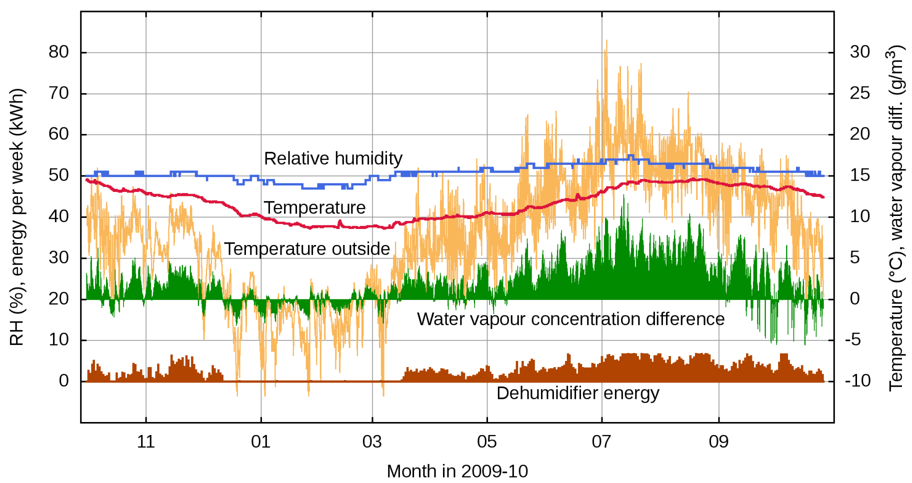

Figure 13: The climate in the Ribe store. The RH is kept close to the 50% target by dehumidification only. In winter the RH dips below this value, in summer it rises above due to the slightly under-dimensioned dehumidifier.

ing is airtight, the dehumidification load is very small, so power for it can be provided by solar voltaic panels on the roof.

Conservation considerations

The main difference between our simple approach to museum storage climate and air conditioning to climatic constancy is that we allow, indeed we need, the temperature to decline in the winter.

A large number of reactions leading to the decay of museum objects belong in the general category called hydrolysis - the addition of water to a polymer with breaking of the polymer chain molecule. The temperature dependence of these reactions accords with the general theory put forward by Svante Arrhenius in the late nineteenth century. The rate of decay increases exponentially with temperature. Hydrolysis also requires water. The potency of water in promoting these reactions is proportional to the RH, which is identical to the chemists' and biologists' definition of water activity - the potential for water to engage in chemical reactions.

The effects of temperature and relative humidity were elegantly combined by (Sebera 1994) into curves of equal degradation rate, which he called isoperms. This applies widely to organic reactions but not to ionic and crystal re-arrangement reactions, such as the phase transformations of hydrated minerals, which are both temperature and humidity sensitive in a way that depends on the individual chemical species. Furthermore widespread inorganic salts on the surface of objects will deliquesce at high RH, providing a thin surface film of aqueous solution which facilitates ionic corrosion reactions. The tendency to separation of components such as plasticisers increases at low temperature, but their diffusion rate also diminishes, so cooling usually favours durability. The history of good preservation of movie film at -20°C demonstrates this.

Conservation standards have, until very recently, advocated a constant temperature throughout the year. The influential quasi-standard PD5454:2012 from the British Standards Institution allows a range from 13°C to 20°C for sensitive collections. The lower limit is too high for buildings which follow the annual average temperature. This limit is based partly on a single article describing the separation of stearic acid from freshly made beeswax seals. It may also be influenced by the desire of the standard committee to keep the recommended temperature within the envelope of the previous set of recommendations made in BS5454:2000. If rigidly imposed, this standard would prevent the simplest and cheapest temperature control of museum and archive storage. The 'buffered conservation heating' control system, described earlier, has a better chance of conforming with this standard, though the temperature may occasionally rise above 20°C. However, there is no scientific reason to set an abrupt upper limit to the temperature. It forces air conditioning of buildings which would otherwise exceed this temperature for just a few days in the

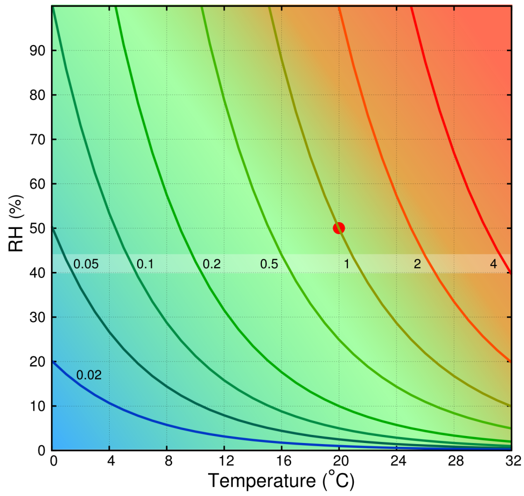

Figure 14: Curves of equal chemical reaction rate relative to the rate at 20°C and 50% RH. The relative reaction rate is marked on each curve. The curves are calculated for an activation energy of 100kJ. The preservative effect of low temperature is evident, but low RH only really gives improved durability when it is very low, at a value which would cause serious mechanical stresses to the many laminated and jointed hygroscopic objects in museum collections.

year. Museum standards are still filled with temperature and RH limits which are chosen without quantitative risk analysis and seemingly without reference to what can be achieved simply in specialised buildings.

Energy considerations

The energy used by heating to moderate the RH can be calculated from the U-value, which is the heat transmission through the walls and ceiling of the building. The loss to the ground will diminish as the years pass. The energy used by dehumidification depends entirely on the air exchange rate, which can be reduced to below once per day in modern buildings of simple geometry. In this section we compare the measured energy consumption of several buildings and place them on the Sebera diagram to explore the relationship between conservation quality and energy consumption. The starting point for the energy comparison shown in figure 15 is a modern fully air-conditioned building, the Royal Library in Copenhagen.

There is a correlation between low energy consumption and good preservation as it is predicted by the Sebera diagram. In figure 16 we extend the survey to several museum stores which are described in more detail in (Ryhl-Svendsen et al. 2012:78).

The linked reduction in cost and improvement in object durability is mainly attributable to allowing an annual variation in temperature.

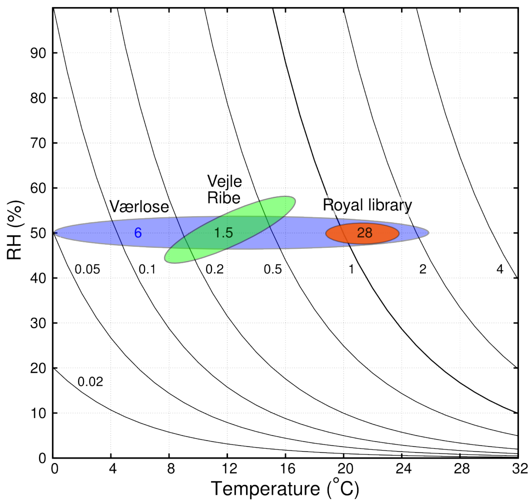

Figure 15: The climate envelopes for four museum stores superimposed on the isoperm diagram. The annual energy consumption is displayed as kWh/m^3 per year.

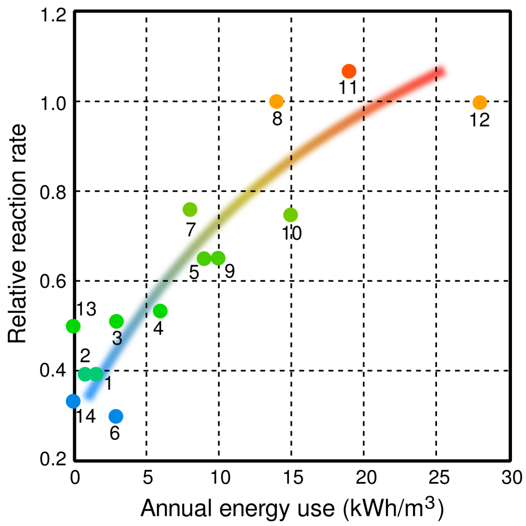

Figure 16: The link between energy consumption and reaction rate. The numbers refer to places described in (Ryhl-Svendsen et al. 2012:78). Point 12 is typical of an air conditioned store with constant temperature and RH; point 13 is the reaction rate on exposure to the outside climate in Denmark, point 14 is the reaction rate for the outdoor temperature and 50% RH, assuming complete airtightness of the building.

Solar energy

All the buildings which we have described have a connection to the national energy grid. However, they do not need a constant feed of energy because the temperature and humidity buffering means that they will cruise over temporary interruptions in supply without noticeable deterioration in the interior conditions. This makes them ideally suited to solar energy, which is naturally variable. About one fifth of the roof covered with solar panels will provide the necessary energy for dehumidification, which is mostly needed in summer.

It is possible to design storage buildings which have no active control at all, able to keep a moderate climate without human intervention or any form of automation.

Buffered conservation heating by solar power

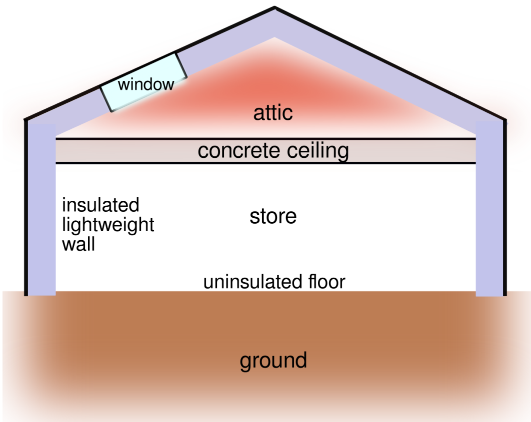

Figure 17: Diagram of a building with an attic window which allows solar radiation to heat a massive concrete ceiling. This moderates the daily solar energy cycle and radiates an even flow of heat down to the uninsulated floor which acts as a heat buffer.

Solar energy let in through an attic window will heat a massive ceiling slab. This will radiate down to the floor, which buffers the temperature rise (figure 17). One might think that intense summer radiation would produce a very high summer temperature in the building. The under-floor heat reservoir plays a vital role here, absorbing the summer heat and re-emitting it during the winter (figure 18). Although the average temperature indoors is around nine degrees above the ambient average there will be little heat loss from the floor because over a period of years the earth deep under the floor will rise in temperature so the gradient becomes negligible and therefore the heat loss will be tiny. If the building above ground is well insulated, there is no need for a large summer heat input from the sun. In the simulated building the

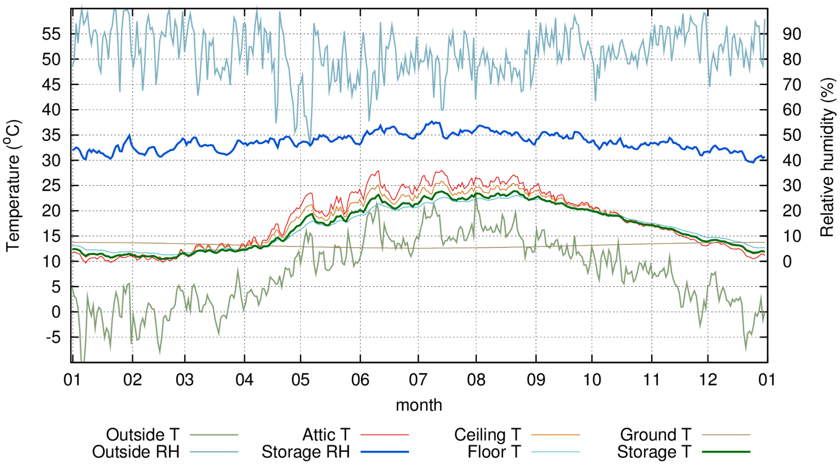

Figure 18: Simulated climate within the building sketched in figure 17. Although the main solar gain is in summer, the strong moderating influence of the heat buffer provided by the earth beneath the building ensures that the summer temperature does not rise dangerously high. The biggest temperature excess is in the winter.

temperature excess is greatest in winter and the annual average temperature is around 18°C.

Conclusions

We present several alternative ways of building museum storage to minimise energy cost and mechanical complexity while actually increasing the durability of the collection, as reflected in the relative rate of organic hydrolysis reactions. The essential change from previous practice is to allow an annual cycle of temperature. The amplitude of this cycle is limited by using the uninsulated floor as a heat store. The relatively high winter temperature then gives a moderate RH without mechanical aid. During the summer, dehumidification is needed because the temperature will be below ambient and northern Europe has a high RH throughout the year. For buildings which cannot use the ground as an energy store, winter heating can be used to drive down the RH a little. Humidity buffer capacity will then hold down the increase in summer RH.

In northern Europe, the typical temperature cycle for a dehumidified store will be 8 to 16 degrees; for a winter heated store it will be 15 to 23 degrees. For the passive solar heated store it is predicted to be 10 to 25 degrees. It would be good if the museum standards committees which establish acceptable climate conditions would consider the safety of these particular cycles which provide the optimal energy efficiency and simplicity of operation. At present the limits are set at apparently arbitrary, precautionary numbers, without consideration of the energy cost and the complexity of the air conditioning. There is no doubt that the temperature variation which we advocate passes through the theoretical phase changes of several minerals which are found in mineral collections, corrosion layers and in wall paintings. But does preventing the possibility of phase change warrant the tenfold penalty in energy, the doubling of organic reaction rates and the considerable penalty in complexity of air conditioning? Even the disclaimer in PD5454 that it is an advisory document has not prevented it being used as a specification with absolute limits, which still can only reliably be achieved with air conditioning.

Notes and References

1. Building regulations in many countries insist on under floor insulation in a heated building. In this article we are explaining building physics rather than laws intended for ordinary dwellings. A building with a large floor area intended for long term storage will not benefit from under floor insulation because over a period of years the floor temperature, though above the natural ground temperature, will develop such a small temperature gradient through the ground that the heat loss will become negligible.

2. Conservation heating usually means heating to a constant relative humidity, controlled by a humidistat. In a storage building with a moderate buffer value, the RH may rise or fall with rising temperature, so a humidistat will not work. However, holding a constant winter temperature will automatically control the RH throughout the year, without the need constantly to measure the RH.

References

PD 5454:2012. (2012). 'Guide for the storage and exhibition of archival materials'. British Standards Institution.

Padfield, T; Jensen, L.A. (2011), 'Humidity buffering of building interiors by absorbent materials'. Proceedings of the 9th Nordic Symposium on Building Physics, Tampere, Finland, pp 475 - 482. *www.conservationphysics.org/ppubs/humidity_buffering_building_interiors_nsb2011.pdf*

Sebera, D. (1994), 'Isoperms: An Environmental Management Tool'. *cool.conservation-us.org/byauth/sebera/isoperm/*

Ryhl-Svendsen, M; Jensen, L.A; Bøhm, B; Larsen, P.K. (2012). 'Low-energy Museum Storage Buildings: Climate, Energy Consumption, and Air Quality'. UMTS Research Project 2007-2011: Final Data Report. : Project no. 10821521, Copenhagen, Nationalmuseet, Bevaringsafdelingen. *forskning.natmus.dk/fbspretrieve/73/UMTS-FINAL-DATA-REPORT-2012.pdf* (at 2013-12-10). The numbers on the figure represent: 1 Ribe, 2 Vejle, 3 Randers, 4 Værløse, 5 Moesgaard, 6 Arsenal, 7 Music museum, 8 Arnamagnæan archive, 9 Ørholm, 10 Brede building 9, 11 Iron mountain, 12 Royal library.

Authors

Tim Padfield is an independent consultant in museum microclimate, working from Devon UK. *tim@padfield.dk*. His publications are on *www.conservationphysics.org*

Poul Klenz Larsen has a master degree (1990) and a PhD (1998) in building physics from the Technical University of Denmark. He is a senior consultant for historic buildings at the National Museum of Denmark. His main working areas are energy efficient heating and climate control, salt and moisture in historic masonry structures and traditional mortars for restoration. *poul.klenz.larsen@natmus.dk*

Morten Ryhl-Svendsen is a senior researcher in preventive conservation at The National Museum of Denmark. *morten@ryhl.dk*

Lars Aasbjerg Jensen has a MA from The School of Conservation of the Danish Academy of Art. He works at the National Museum of Denmark, specialising in climate measurement and control in exhibitions and storage spaces. *lars.aasbjerg.jensen@natmus.dk*