Basic building physics for designing museum stores

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Abstract

There are four fundamental concepts in building physics which define the possibilities for passive and low-energy design of museum stores and archives. These fundamentals are thermal inertia, thermal resistance, air infiltration and humidity buffering. Thermal inertia is best provided by the ground under the building. The building itself should be constructed with lightweight insulation. Air infiltration should be low, around one air change per day. This allows thermal and humidity buffering to operate to moderate the yearly climate cycle. Humidity buffering is practical at the scale of a building, if the infiltration rate is kept low.

Introduction

The British Standard for archives has recently been replaced by the more diffidently titled ‘Published Document PD5454:2012’. This document together with its accompanying materials properties document, PAS 198, relaxes the previously onerous requirement for temperature constancy. Now it is officially acceptable to allow an annual variation in temperature in archives and by natural extension to museum buildings generally. A variable temperature can be exploited to provide a constant RH without full air conditioning. This article describes the relevant building physics.

Moderating the daily temperature cycle

Figure 1 shows the course of the temperature over a year and a half in west Denmark. It has a notably mild climate, on the cool side, which suits the preservation of artefacts.

There are many irregularities in the temperature but fundamentally there are two regular cycles superimposed, the daily cycle, shown in the insert, and the annual cycle. In a few places, such as the Brazilian rain forest, there is no annual cycling at all, and only a small daily cycle, but for northern Europe this is a typical pattern.

Smoothing the daily cycle within a building is easy. There are two ways to do this, one is to build a heavy, heat absorbing wall. This is currently

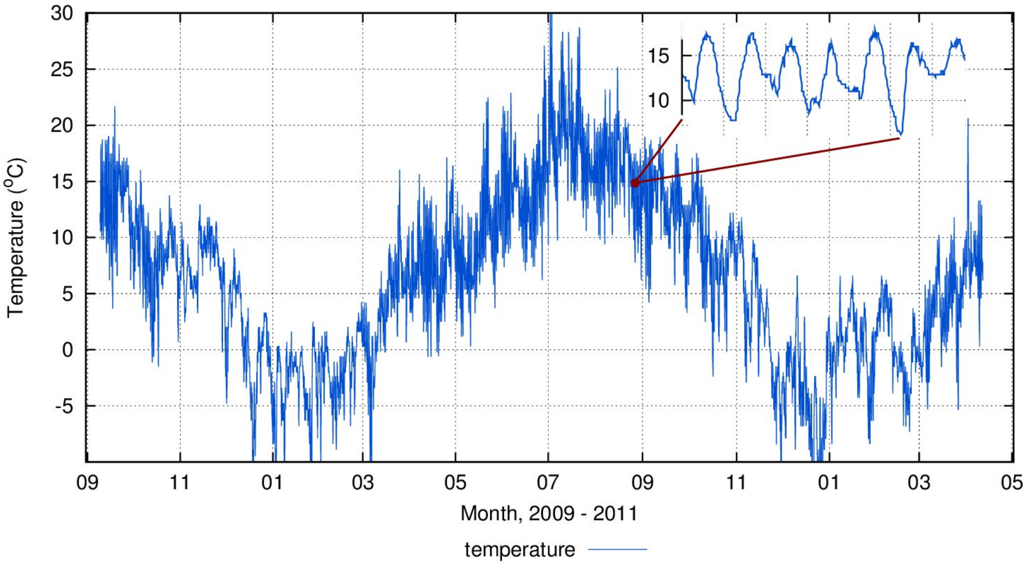

Figure 1: The temperature in Ribe, western Denmark. The expanded portion shows a week of daily cycles.

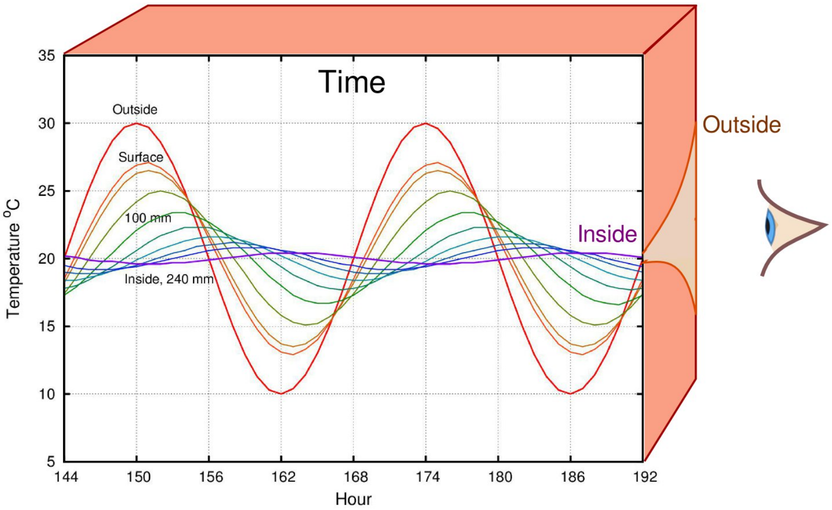

Figure 2: The diffusion of temperature through a brick wall, 240 mm thick. The graph shows the evolution of temperature at different depths within the wall as time passes. The perspective section at the right shows the time-independent envelope containing these temperature cycles.

unfashionable architecturally but figure 2 shows the strong absorption of heat by the wall.

Notice that the wave of temperature change through the wall is delayed by absorption and re-emission of heat by the substance of the wall. The slight penetration of heat to the interior is delayed by 12 hours. Note also the distance between the outside air temperature and the surface temperature of the wall. This gradient indicates considerable heat flow, since the flow is proportional to the gradient. This wall does not stop a steady underlying heat flow.

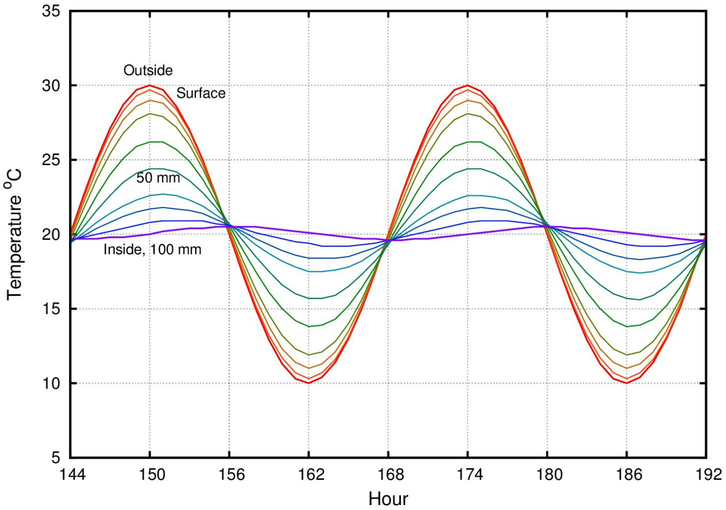

Figure 3: The diffusion of temperature through foam insulation, 100 mm thick. Note the much smaller difference between the air temperature and the surface temperature, compared with the brick wall. This indicates a smaller heat flow than through the brick wall, even though the temperature variation at the inside surface is similar.

The other way is to insulate the wall. There are two things to notice particularly in figure 3. There is hardly any storage of heat in the lightweight material, so the temperature at the inside peaks only 6 hours after the peak outdoors. Notice also the relatively small difference between the air temperature and the surface temperature. This indicates a small heat flow.

There is a fundamental difference in behaviour of these two wall constructions, even though they both appear to provide the same protection against the daily temperature cycle.

The difference first shows when there is a heat source within the building. Figure 4 shows on the left the construction whose performance is shown in the figures above. On the right is the situation modelled in the graphs shown in figure 5 below, with internal heat generation of 10W/m^2 of wall, for 12 hours in the middle of the day, simulating an exhibition gallery.

The brick wall has a U-value of $5\text{W/m}^2{\cdot}\text{K}$, the foam wall has one tenth of this. The U-value defines the steady heat loss through the wall as a con-

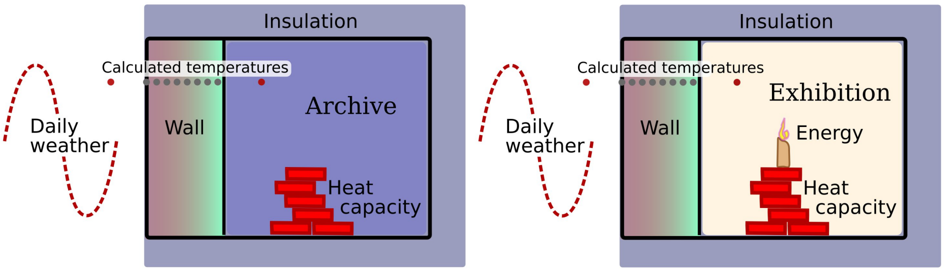

Figure 4: The image on the left is the situation modelled in the previous figures. On the right is the basis for modelling the heat flow when energy is released within the building.

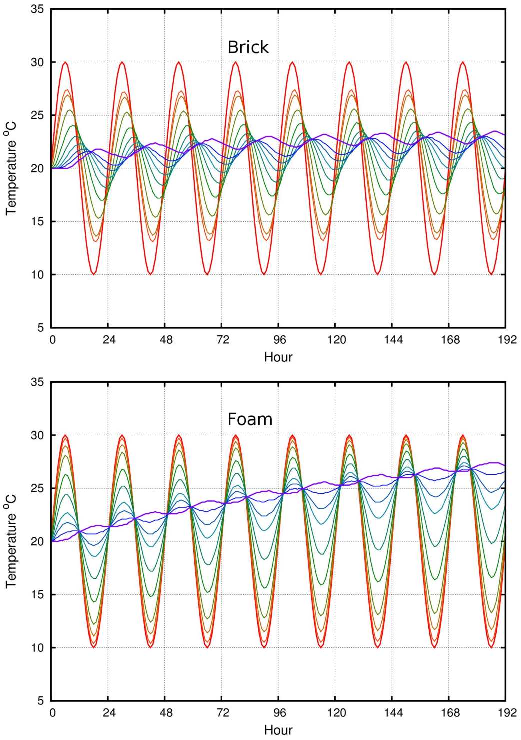

Figure 5: Top: the evolution of the temperature within a space with brick walls and with an energy source. Bottom, the temperature evolution within an insulated space. For both simulations the energy released within the room was $10\mathrm{W/m}^2$ of outside wall, for 12 hours in the middle of the day.

sequence of a one degree temperature difference across it (conventionally expressed in degrees kelvin). Heat accumulates within the insulated space but rapidly penetrates the brick wall.

For an archive or museum store it is better to insulate but for an exhibition space in a mild climate it is better to use heat absorbing but conducting walls to ameliorate the daily cycle of outside temperature, which coincides with the daily cycle of heat generation by visitors and lighting.

This is one reason, among several, why people in the Mediterranean region build massive stone houses, to even out night and day in a climate that on average is not too bad (fig.6). In the far north (fig.7) the daily average weather is hardly ever warm enough for comfort so the emphasis is on insulation, with wood turnings as the locally sourced insulation material, replacing the soft limestone heat sink of the Mediterranean region.

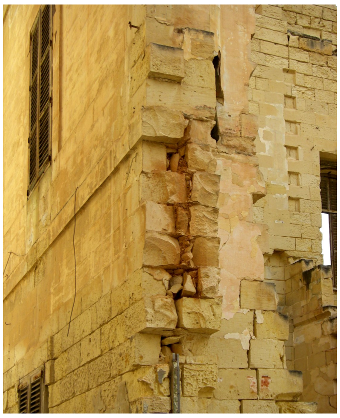

Figure 6: In regions with hot days and cool nights, where the daily average temperature is comfortable, massive heat absorbing walls ameliorate the heat of the day.

Figure 7: In the north, where it is nearly always too cool for human comfort, lightweight insulated structures are common. This house in Sweden is insulated with wood shavings.

Calming the annual temperature cycle

The annual temperature cycle requires about four metres of heat absorbing material to reduce its amplitude significantly. This is provided by the ground beneath the building.

Figure 8 shows the computed temperature contours in the ground five years after construction of an unheated building, insulated against the air but not against the ground. The ground beneath the building has come to equilibrium with the altered climate above it and is functioning as an extension of the construction, providing massive thermal buffering.

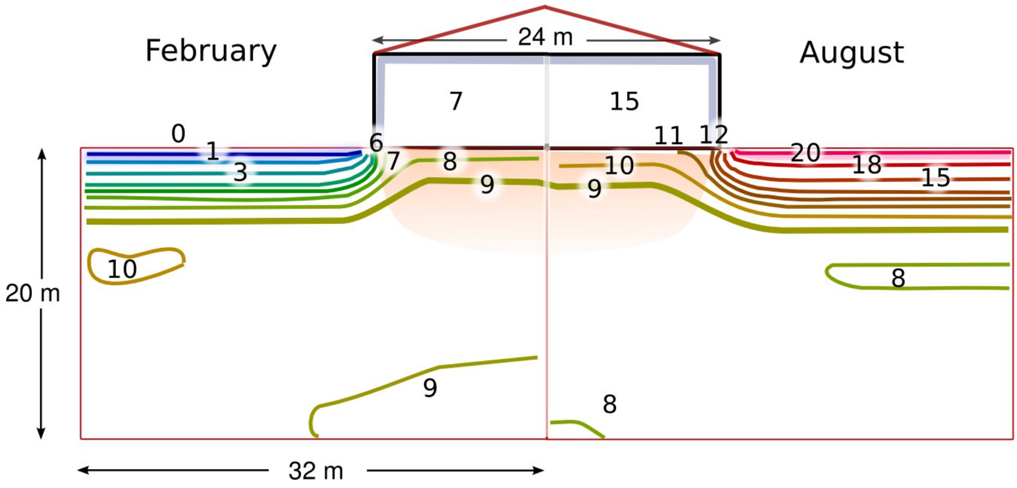

Figure 8: A simulation of the temperature contours in the ground underneath an unheated building. On the left is the situation in February, on the right the August gradient. After several years, the ground beneath a large building becomes thermally part of the building. Heat movement horizontally at the perimeter is quite limited. Insulation below ground is not necessary. (after Benny Bøhm)

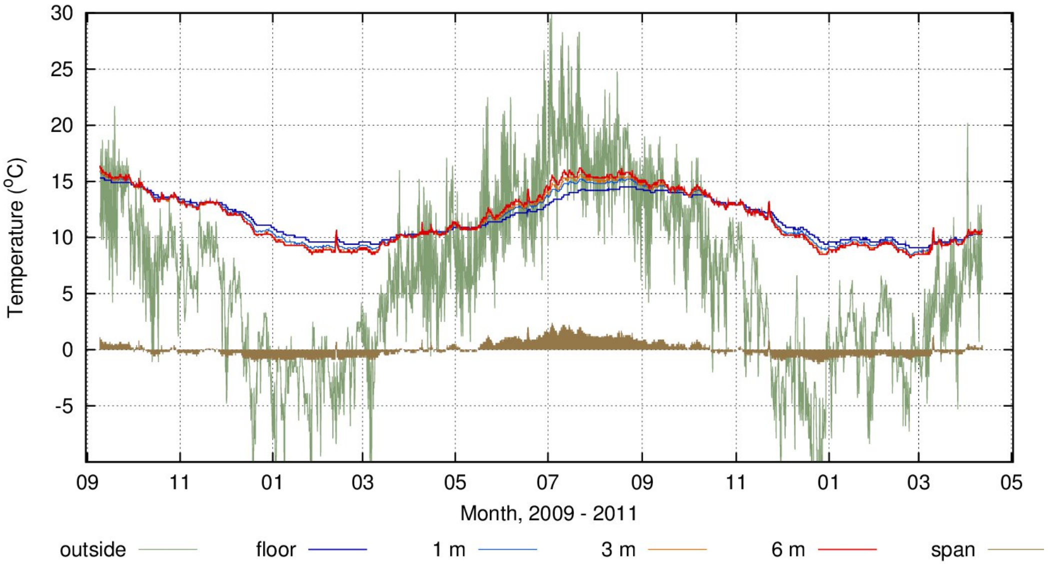

Figure 9: The measured temperature at several heights within a storage building in Ribe, Denmark. The ground acts as a heat sink. There is very little temperature stratification. The solid trace shows the vertical temperature span. (data from Morten Ryhl-Svendsen)

Within the building, the temperature is quite uniform throughout, as shown in figure 9. This is because there is only a small temperature difference between inside and outside, and because the above ground building is insulated. The floor will be relatively cold in summer, giving a gravitationally stable stratification. However, the span, shown as the shaded trace at the bottom of the graph, is still less than two degrees. This corresponds to less than six percent relative humidity variation, assuming a uniform water vapour distribution throughout the interior.

Conformity with the museum standards

The latest edition of the British Standards Institution guidance for archive climate, which has long been influential world-wide as setting the limits for acceptable climate around antiquities of all kinds, recommends a minimum temperature at 13°C for a general collection. This conflicts with an entirely passive temperature variation in an archive in northern Europe. The reasons for setting this limit are briefly explained in the document.

There is a single article describing separation of stearic acid from newly constructed beeswax seals below 13°C. The other, more complicated argument is that objects holding a particular water content are in equilibrium with a steadily decreasing ambient RH as the temperature falls, so that an object equilibrated to 50% RH at 20°C will, at 13°C impose on its immediate surroundings a RH around 48%. This is hardly a devastating change and much less than has for decades been accepted as a consequence of cold storage of movie films at –20°C.

So, for the sake of beeswax seals that may be present in the collection, and have never previously been exposed to less that 13°C, all museum storage must install winter heating. There is surely a case here for risk analysis of the extraordinary power assigned to beeswax seals in setting conditions for general collections which force some form of energy consuming air conditioning.

Airtightness

A building with high thermal inertia is at risk of water damage if the air exchange rate is high. Figure 10 shows a 5000 year old construction of very high thermal inertia, whose interior is now protected by a metal lattice gate, permitting unhindered air exchange.

At the rapid onset of spring in mid April 2013, the warm and humid outside air penetrated into the still cool interior. The dew point of the outside air was higher than the inside surface temperature, as indicated by the bars along the bottom of figure 12. At the first occurrence of the high dew point however (point **B**), the inside RH did not rise immediately to 100%. The process took several days. This is due to humidity buffering by the absorbent surfaces of

Figure 10: The grave chamber Maglehøj in Denmark. Built around 5000 years ago with a refined technique to keep the interior dry.

Figure 11: Condensation on the ceiling of the grave chamber caused by unhindered entry of relatively warm and humid ambient air.

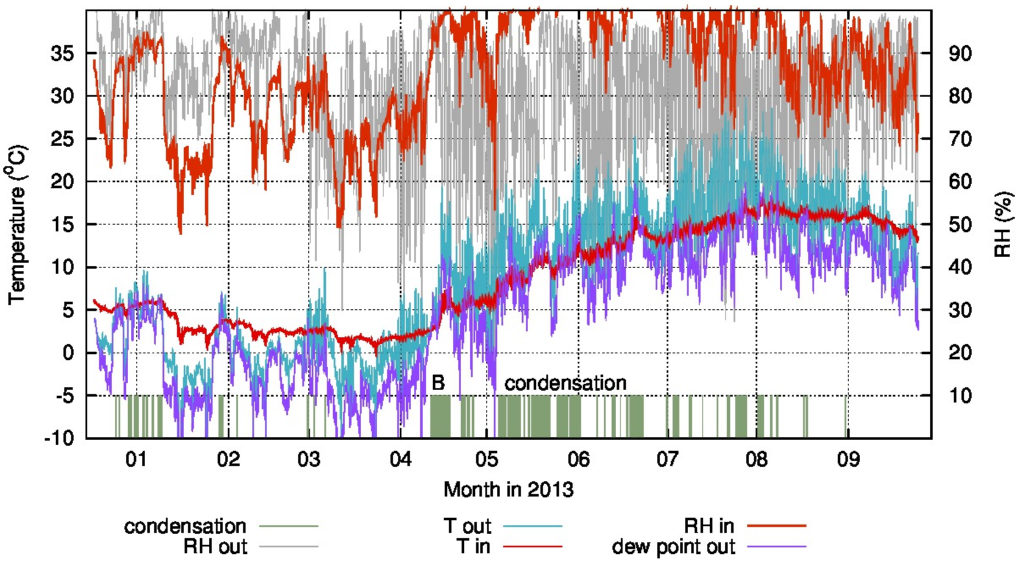

Figure 12: The temperature and relative humidity outside and within the Maglehøj grave chamber. The dew point of the outside air is also shown. The bars along the bottom define periods when the outside dew point is higher than the inside temperature. (photos and data from Lars Aasbjerg Jensen)

the tomb. Later in the year, the buffer capacity being exhausted, periods of dew point above tomb temperature caused condensation (figure 11) which is rapidly destroying the birch bark which seals the gaps between the stones in the finely constructed tomb. We cannot blame the new standard for this, but the previous standard, and advice stretching back many years, have asserted the need to ventilate to avoid decay. This is a durable myth based on correlation without causation; the ventilation serves to force a uniform temperature, and thus a uniform RH.

Air exchange rate

If thermal buffering is to play a significant part in the climate control of a building, the air exchange rate must be kept low. Recent advances in building materials make it quite easy to hold the air exchange rate at about once per day in a storage space. Continuous carbon dioxide measurement allows approximate measurement of the rate of air exchange in spaces which are intermittently visited by people.

Apart from eliminating the risk of transient condensation, a low air exchange rate reduces heat flow. More important, however, is its effect on humidity control.

Relative humidity

Relative humidity constancy is regarded as essential for preserving museum artefacts. It is also surprisingly easy to achieve with very simple control methods, particularly when the temperature is allowed to fluctuate in an annual cycle.

Figure 13 shows that the RH in equilibrium with the water sorbed into cotton is only slightly influenced by temperature. All absorbent materials show similar curves. The graph can be read in two ways: cotton exposed to the air will attain a water content defined by the ambient RH. However, if the cotton is enclosed in a small space, such as a plastic envelope, the immediately surrounding air will assume a RH defined by the water content of the cotton. If now the envelope is moved to a lower temperature, the RH will re-equilibrate to an only slightly lower value. In an archive, the paper is so abundant that it entirely controls the RH [1], assuming a low air exchange rate. This is illustrated by the climate in the Suffolk Record Office shown in figure 14. The temperature accords with the standard, being warmed to around 15°C in winter. The RH

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[1] To those who will object that priceless heritage should not have the burden of looking after its own climate, I point out that the residence time of a water molecule sorbed onto a cellulose molecule at moderate RH is very short, so the object does not own its sorbed water, it just borrows it in repeated exchange with the environment, regardless of how that environment is controlled.

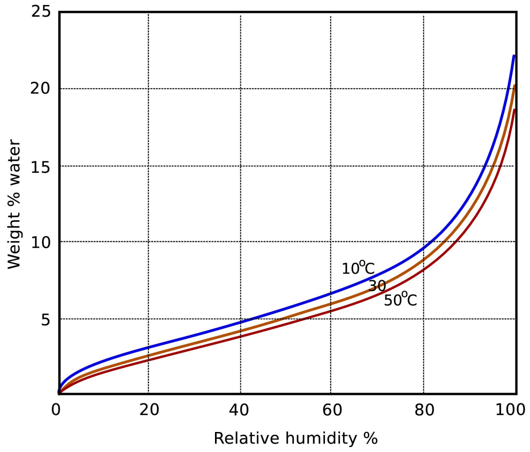

Figure 13: The equilibrium between the ambient relative humidity and the water content of cotton cellulose, at various temperatures. The equilibrium is little affected by temperature. (After Urquhart)

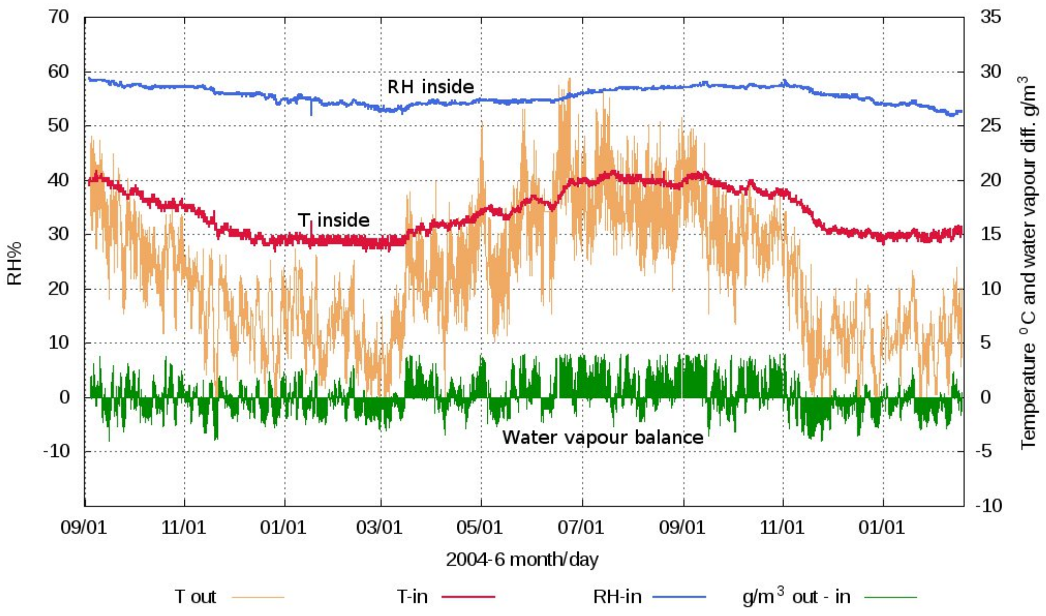

Figure 14: The relative humidity and temperature within the Suffolk Record Office, UK. The abundant paper documents buffer the RH to within a 5% span, while the average RH is set by winter heating alone. The strength of the summer buffering by the paper is shown by the almost continuous excess of water vapour in the outside air compared to inside. (data from Dominic Wall)

remains within a 5% envelope through the year, buffered by the abundant paper records. The vapour balance trace at the bottom of the graph shows that the indoor air is often of different water vapour content to the outside air. The combination of buffering and low air exchange rate ensures a stable RH. The average value of the RH is set by the winter heating. This can be described as *buffered conservation heating.* The winter warming reduces the RH and would, without buffering, reduce it too far. However summer heating is not required because the buffer capacity of the paper prevents the rise in RH that would result from infiltration of summer air into the relatively cool interior.

The average outside RH in northern Europe is rather high for good conservation so it must be reduced in museum environments, either by winter heating, as described above, or by dehumidification. For a new building designed to be airtight, dehumidification is the best solution, because it allows a lower average temperature and because it is primarily needed in summer, when there is abundant solar energy for dehumidification.

RH buffering without absorbent artefacts

Archives are a special case, stuffed with absorbent materials which effortlessly stabilise their own water content. Other museum stores have metal objects and in future even archives will be filling with relatively non-absorbent CDs and tapes.

Is it possible to build humidity buffering into the structure of the building? Humidity buffering materials are generally thought to be expensive specialised materials, suitable for packaging and for showcases with unusually valuable objects. To buffer humidity on the scale of a storage room a much cheaper material is needed. Such a material is readily available in the form of unfired brick – the dry, pressed clay intermediate product, snatched from the production line just before the final firing.

Figure 15 shows a room partly lined with unfired clay bricks. The measured temperature and relative humidity are shown in figure 16.

The calculated RH shown in figure 16 is derived from the simple model described by Padfield and Jensen. The currently used mathematical models incorporated in whole building simulation programs do not have convincing treatment of RH in rooms with absorbent walls, content, people and air exchange. The simpler published methods for showcase calculations assume that the entire mass of buffer is always in equilibrium with the RH in the space. This cannot be true for the relatively rapid air exchange and moisture generation in a room. This uncertainty in prediction is hampering the design of buildings which can provide useful daily humidity buffering against the vapour emitted by museum guests.

Figure 15: A corner of the experimental room, empty but for a lining of unfired clay bricks, with various experimental surface coatings to prevent dusting while permitting water vapour diffusion.

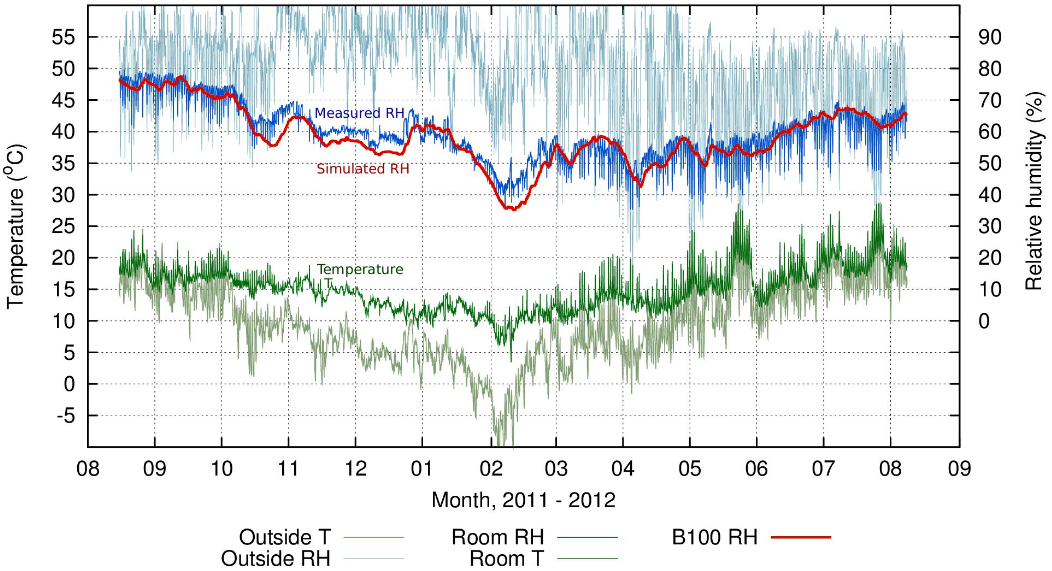

Figure 16: The temperature and relative humidity measured in the clay room, with the calculated prediction of the RH. The daily spikes are caused by direct sunlight affecting the room at a rate which the buffer material cannot respond to.

Cold storage

A space running below the annual average temperature, around 10°C in northern Europe, needs mechanical cooling. It also needs dehumidification because the average dew point of the outside air is around 6°C. Infiltrating air will therefore become saturated and deposit dew or ice as it enters the system. Confidence in the saturation of the infiltrating air can be used to advantage in a cold store. If the store is run at say –5°C, then a slow trickle of air allowed to seep in at –15°C will deposit ice and enter the cold space at 100% RH. As it warms to –5°C the RH will automatically reduce to 50%. Only two temperatures need to be measured and controlled. This air conditioning principle is most easily understood when applied within an ordinary domestic freezer, as shown in figure 17. The same principle, somewhat elaborated, can be used for a large cold store (figure 18). The principle of using an uninsulated cold block of ground beneath (and around) a cold storage space is used in the Svalbard seed store in Norway.

Turning now to PD5454:2012 one finds the astonishing advice that there need be no RH value set for cold stores because all the artefacts, commonly photographic film, should be individually encased in sealed envelopes with a humidity buffer and RH indicator held within the micro-enclosure. We have returned full circle to the time when humidity buffering was only for small enclosures, not for whole rooms full of unwrapped artefacts:

Citation from PD5454:2012:

> 4.3.3 Cold storage
>
> Cold storage is defined in this Published Document as -15 °C ±5 °C.
>
> ...
>
> The RH in a freezing environment is determined by the level of RH present at the time the document was sealed up inside its freezer packaging. The maximum RH at which the document formats listed in 4.3.3 should be packaged is 50 %RH.
>
> All materials selected for cold storage should be prepared and packaged depending on their type and format. Packages should be sealable and airtight polypropylene or polyethylene bags or boxes. Humidity indicators should be incorporated inside freezer packaging, along with a humidity buffer that absorbs moisture when archival material is removed from the cold storage environment.

RH buffering by sorbent materials is very effective at low temperature because the amount of water vapour in the air is tiny, while the quantity of exchangeable water in the buffer material remains much the same as at higher temperatures, so buffering will last for many more air exchanges in a cold store. There is no reason not to control the RH in a cold room intended for long term storage, so that the stored items do not need their individual buffered container. There is no logic in the PD instruction to encapsulate items intended for long term undisturbed storage in plastic envelopes of small but finite permeability to water vapour and then put them in a fundamentally hostile environment at about 80% RH.[2]

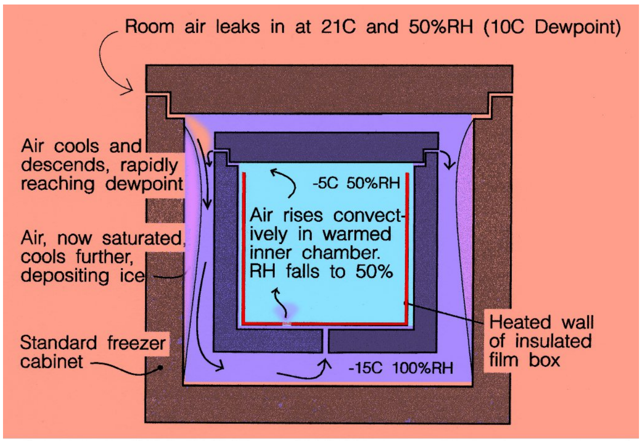

Figure 17: An ordinary freezer adapted to maintain 50% RH around film stored in the inner insulated container, which is heated to about –5°C from the –15°C in the freezer. Minimal energy is needed to maintain the temperature difference in the insulated internal space.

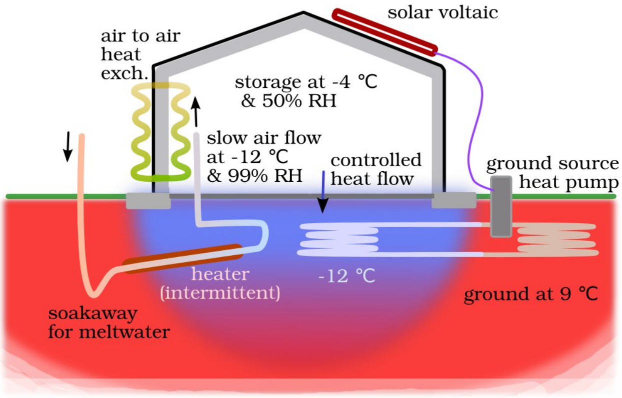

Figure 18: The same principle as in figure 17 applied to a whole building. Using the ground as a massive heat sink makes this building fail safe, provided there is humidity buffering, and precautions against frost heave under the building.

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[2] PD5454 makes frequent use of the word ‘freezing’ in situations where freezing, in the sense of ice formation, does not happen. For objects whose water content is at equilibrium with a moderate RH at room temperature, reducing their temperature below zero is no trauma. It is only pure water that changes to ice at zero degrees. The general use of ‘freezing’ to describe storage below zero is unnecessarily scary.

Figure 19: PD5454:2012 directs that all items for cold storage shall be encapsulated together with a RH buffer and humidity indicator, thus imposing a large burden of continuous quality control of every package, which will be exposed to the typical 80% RH of a cold store without RH control.

Extension of low energy techniques to exhibition spaces

Exhibition spaces have been successfully run with no energy expenditure during the summer opening period combined with conservation heating while closed for the winter. Museums that are open year round need winter heating, which in turn forces winter humidification in cold regions. However, the general acceptance that the temperature can vary through the year will reduce the humidification demand and avoid the need altogether in warmer places. It will also save condensation damage to the museum building itself. Humidity buffering in occupied spaces can realistically be employed only to buffer against the daily cycle of moisture emission from visitors. Year round buffering of RH in exhibition galleries is unrealistic.

Summary and conclusions

This article presents the essential building and atmospheric physics, and material sorption properties needed to understand how best to preserve artefacts with minimal use of mechanical and energy-using equipment. For museum stores and archives the argument is overwhelming that they should be lightweight insulated structures spread out over the ground without floor insulation. If such a building is constrained to be taller, there are ways of using the ground as a buffer by circulating water through bore holes.

Unfortunately, the current influential standard for archives sets a high limit to the lowest acceptable temperature, making a freely wandering temperature officially inadvisable for archives in northern Europe. It is not good that a vital numerical value in a standard is based on a single technical article, concerning a relatively rarely used material, and seems to have been decided without an analysis of the consequences in energy use and equipment which it forces on the archive designer.

The advice in PD5454:2012 to individually wrap items for cold storage is baffling, and extraordinarily demanding in quality control of the initial sealing, and continuing testing of the quality of the seal.

Museum environment standards are currently composed by small groups of people selected from prestigious institutions. There seems to be no requirement to test ideas against the implacable force of natural laws and the world's climates, and the potentials for subtly simple solutions which save energy and complexity are arbitrarily excluded. Although the standards have relaxed from their previous enforcement of the best available technology, they have not really reformed to embrace the principle of flowing with nature rather than controlling it. I suggest that in future, museum standards should evolve through an open process using a wiki style development tool.

Acknowledgements

I thank colleagues in the National Museum of Denmark: Poul Klenz Larsen, Morten Ryhl-Svendsen, Lars Aasbjerg Jensen and Benny Bøhm. Together we have collected and analysed the data which confirm the validity and usefulness of the principles described in this article. Data from the Suffolk Record Office is from Dominic Wall.

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http://www.conservationphysics.org/wallbuff/padfield_jensen_humidity_buffering_2011.pdf

An unpublished postscript to the article above, describing the clay buffered room:
http://www.conservationphysics.org/wallbuff/Bvalue_postscript2012.pdf