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A review of the physics and the building science which underpins methods of low energy storage of museum and archive collections

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Abstract

The need to keep things cool for durability should be the single most powerful influence on storage design. The simplest temperature control is to moderate the outside temperature by a combination of thermal insulation and heat capacity. The low energy storage building is a lightweight, thermally insulated, airtight building put on top of an uninsulated floor slab laid directly on the ground. The thermal insulation is calculated to even out the daily temperature cycle but to allow an annual temperature cycle which is about half the amplitude, but much smoother, than the annual temperature cycle outside. The winter temperature inside will nearly always be above ambient and so will maintain a moderate RH without need for either humidification or dehumidification. The temperature inside in summer will be below ambient and thus will force dehumidification of the infiltrating air. However, the airtightness of the building allows intermittent dehumidification with low energy consumption, less than one kWh/m^3 per year. There now exist enough buildings designed on this principle to reassure curators that highly valued collections can be stored in a space with a gentle temperature cycle and with a RH stability as good as air conditioning usually achieves.

Introduction

There is abundant evidence for the beneficial effect of low temperature in increasing the durability of artefacts. The lowest temperature which can be achieved by simple means, using no energy at all, is the annual ambient average temperature. The areas on earth which have an average temperature below the human comfort zone (which lies above 20 °C) comprise most of north America, Europe and Asia north of the Himalaya (National Center for Atmospheric Research 2015). The climate control principles described below can also be used in warm climates but one loses the benefit in better durability provided by storage below human comfort temperature.

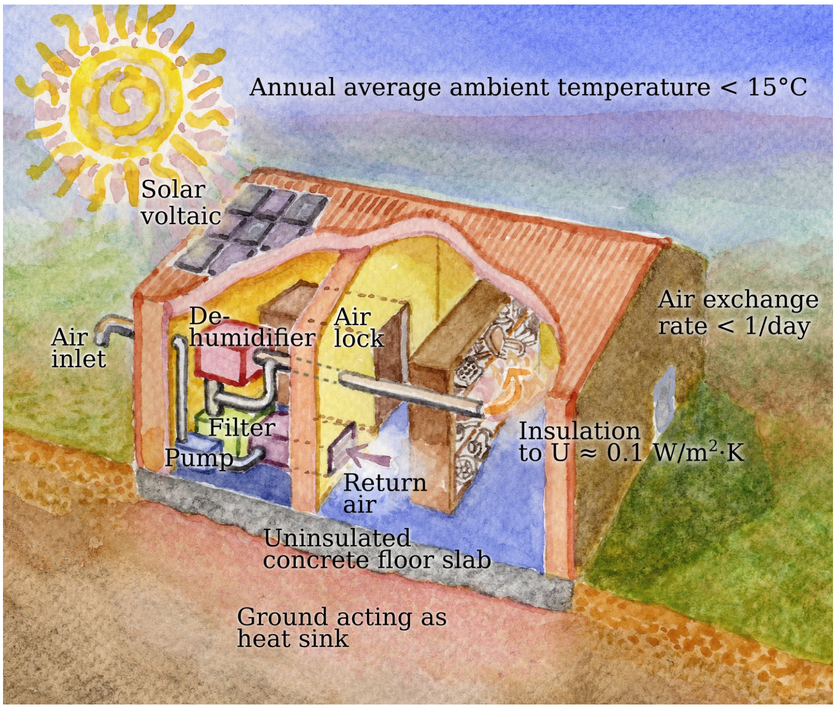

Figure 1: A diagram combining the two principles of operation of low energy storage. In the preferred principle, temperature control is entirely passive, through the immense heat capacity of the ground below the uninsulated floor and the good insulation (low U–value) of the building walls and roof. RH control is by summer dehumidification only. The air is re-circulated at about 0.2 air changes per hour through a single duct to the remote end of the space. The return air is recirculated either through the dehumidifier, or bypassing the dehumidifier. The outside air pump only operates when, by chance of the weather, the outside air is of suitable water vapour content to drive the interior towards its target RH. In the alternative principle, there is no dehumidifier but the air is warmed in winter to a constant temperature, around 15 °C.

An economic and simple solution for museum and archive storage, is to allow a slowly varying temperature following the seasons, but reduced in amplitude. The summer temperature in the store will usually be below ambient. This will cause the relative humidity (RH) to rise above ambient. Summer dehumidification is necessary. The low point of the temperature cycle in winter can be adjusted to make humidification unnecessary.

This storage principle requires a very large heat storage capacity and an airtight building. It also benefits from humidity buffering. This permits intermittent dehumidification, allowing direct powering from solar voltaic panels on the roof. All these considerations are gathered into the principle sketch, Figure 1.

The design of storage to provide the lowest temperature attainable without using energy for cooling

The building can be of lightweight construction, the vital requirement being a U-value (heat conductivity) of the above ground structure approximately 0.1 W/m^2·K. This value, combined with the heat capacity of the stored materials and of the floor, will greatly diminish the daily temperature cycle. A lower U value risks accumulating heat from lighting and equipment. This careful balance between controlling heat gain from the environment yet allowing heat loss from people and equipment within the building is discussed in Padfield (2010). Ways of calculating the required thermal properties of the building using computer modelling are presented in Bøhm and Ryhl-Svendsen (2011) and Christensen, Janssen, and Tognolo (2010).

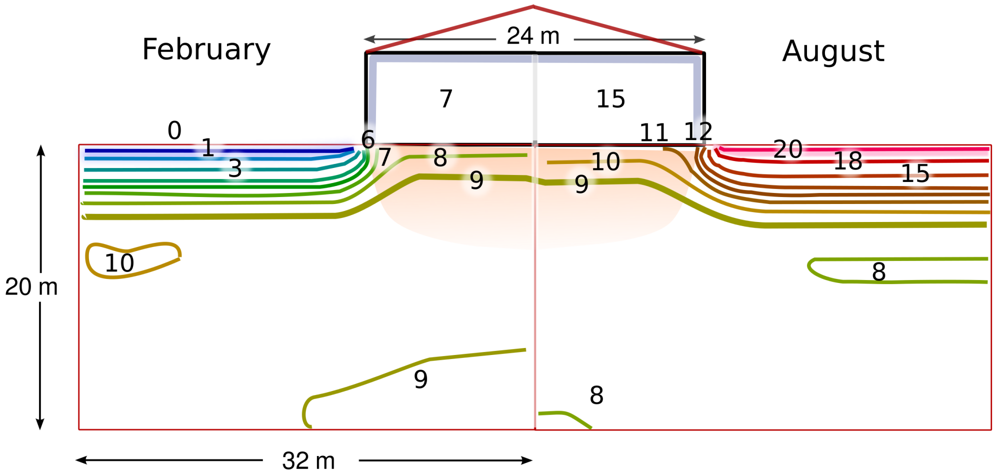

Figure 2: A computer model of the temperature below ground in February (left) and August (right), in Ribe, Denmark. The slab of ground under the building has a much reduced temperature cycle through the year and functions as a heat sink for the building. The heat flow through the contour for 9 °C is negligible, as shown by the wide spacing of the contours at depth. Therefore, no insulation is needed. The calculation is by Bøhm and Ryhl-Svendsen (2011).

The long period temperature stabiliser is the floor and the ground beneath it. A computer prediction for the coldest and the warmest months in Ribe, Denmark, is shown in Figure 2. The ground under a building of reasonable size for a museum store behaves thermally as part of the building, after a year or two of acclimatisation. The heat flow is negligible below 3 m, so there is no need for insulation at depth.

This simple construction gives a smooth annual cycle with an amplitude about half the span of the monthly averages outside. Figure 3 shows the measured temperature gradients in the ground underneath the museum store in Ribe, compared with the open field beside it. The lower graph continues the measurement up through the building. The vertical temperature span within the store never exceeds two degrees Celsius.

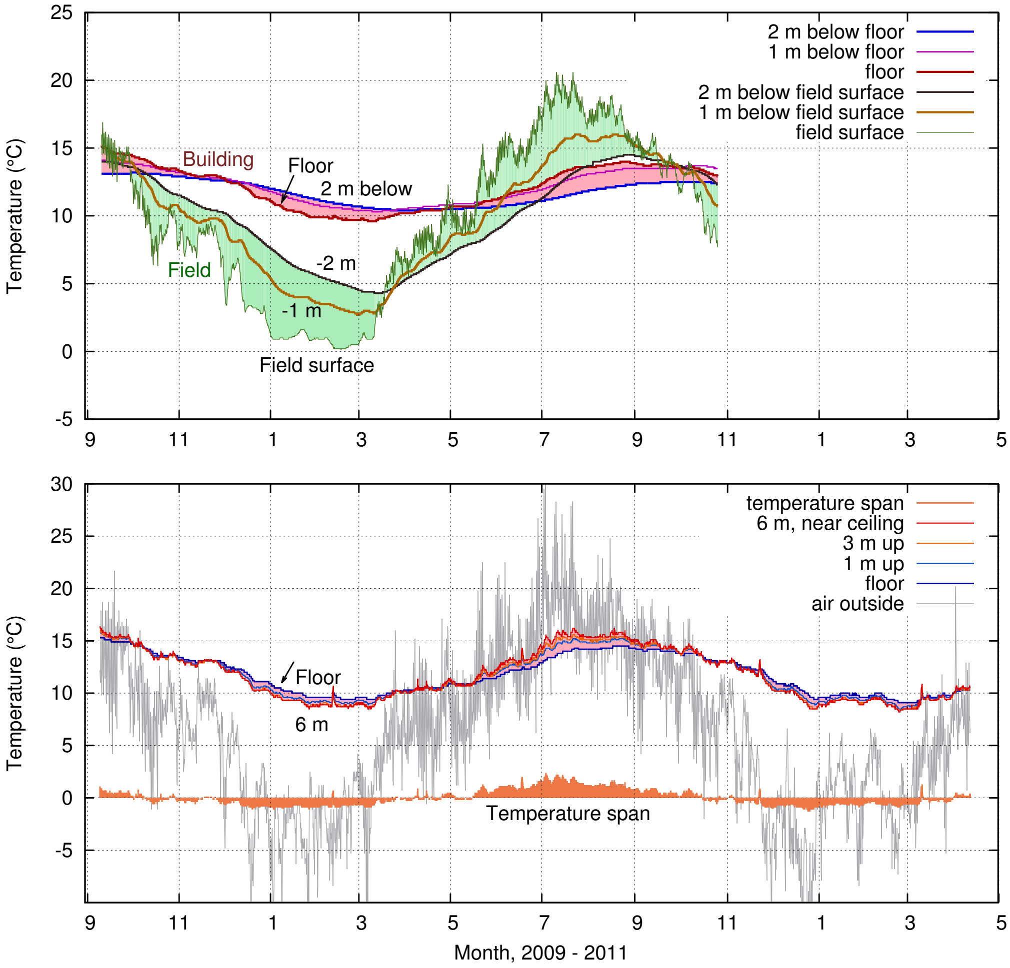

Figure 3: Above: the measured temperatures in the ground beneath the Ribe museum store, and under an open field beside the building. Below: the temperature gradient within the 6 m high storage room. The temperature span from floor to ceiling is never more than 2 °C.

Humidity control

Since only dehumidification is installed, the winter temperature must be designed to keep the RH moderate as outside air slowly infiltrates. In Europe this means a February temperature approximately 7 °C above ambient. This will keep the interior at about 50% RH. The interior temperature should be modelled to ensure this temperature difference.

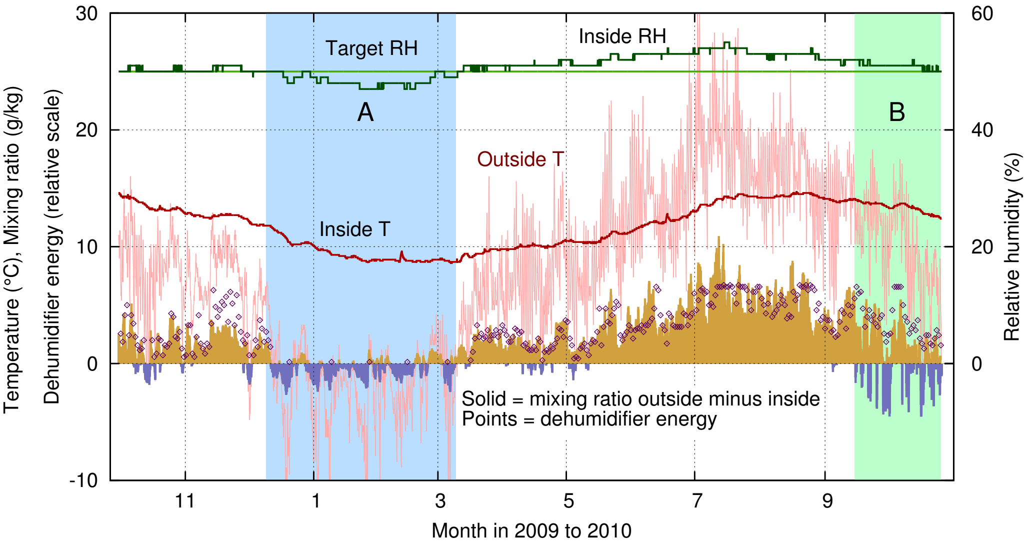

Figure 4: Dehumidification of the Ribe store. In winter (shaded area A), no humidification is available, so the RH drops a few points below the 50% set point. In July, the dehumidifier is working at full capacity and the RH increases slightly. In autumn, period B, the dehumidifier is still operating, even though the outside air often contains less water vapour than inside, so pumping outside air would be more efficient.

Figure 4 shows a measured example of such a floating temperature regime, from the cool temperate climate of Ribe. One notices that there is dehumidification continuing during the period shaded B, while at the same time the outside air has a lower water vapour content than that inside. During this period it would be more efficient simply to pump outside air in, rather than dehumidify recirculated inside air. This refinement was not installed in the Ribe store but the effectiveness of pumping is well displayed in the record from the small archive of the Arnamagnæan Institute of Copenhagen University, which has no dehumidifier; instead, it pumps in outside air when the vapour content will push the inside RH towards the target 50% (Padfield et al. 2018).

Efficient dehumidification

Condensation dehumidifiers use around 1 kWh/kg of water collected. At 10 °C and 50% RH the condensing surface must be below zero and thus be covered with ice. There has to be intermittent defrosting of the cold surface, but such a brief interruption is entirely smoothed out by humidity buffering by the stored materials and by the very low air exchange rate.

Absorption dehumidifiers operate at around 2–3 kWh/kg but can reach a lower RH. The measured energy consumption of absorption dehumidifiers in real conditions in several museum stores has been reported by Ræder Knudsen and Lundbye (2017).

Recently designed stores use less than one kWh/m^3 per year, using absorption dehumidifiers. In comparison, an archive controlled by air conditioning uses about 25 kWh/m^3 per year (Ryhl-Svendsen et al. 2010).

Pumping outside air when it is of suitable vapour content is the most energy efficient form of RH control, but for long periods the weather prevents it, so mechanical dehumidification cannot be avoided. The choice of dehumidifier depends on the local climate and the RH set point. The energy consumption is so low that it can be supplied by rooftop solar power, so the choice of dehumidification principle is not important.

Ventilation

Both RH and temperature buffering rely on minimal exchange of moisture and heat with the outside air.

Ventilation, or forcible movement of recycled air, is often advocated to hinder mould growth. It works by forcing a uniform temperature. There is no evidence that air velocity alone influences fungal growth. However, in a purpose-built store the insulation alone will ensure a uniform temperature. Furthermore, the temperature difference between inside and outside will be smaller than in a dwelling, thus reducing the influence of uneven heat movement through the wall.

In a store with only occasional human presence, there is no need for ‘fresh’ air, together with the outdoor pollutants it entrains.

Museum stores cannot completely avoid using modern materials which outgas volatile substances; also the stored objects will contribute their own volatile components. At the winter temperature minimum, the production, diffusion and reaction of internally generated pollutants is low (Ryhl-Svendsen et al. 2012; Ryhl-Svendsen, Jensen, and Larsen 2014). However, a simple duct network is necessary to distribute the dehumidified air, so a precautionary pollutant filter can be incorporated in the air stream.

Humidity buffering

Because of the lack of reliable predictive calculations, and the uncertainty about the nature and quantity of the stored artefacts, designers have understandably ignored the influence of the stored objects on their microclimate and thus provide far too powerful mechanical control (Bonandrini 2017).

However, for archives in particular, buffering by the paper provides an enormous stability to the RH.

Padfield and Jensen (2011) attempted to remedy the uncertain reliability of involving the stored materials at the building design stage. They proposed a simple way to estimate the buffer capacity of an unbuilt storage space. They attribute to each stored item, a box of papers for example, a buffer value (B-value) which is equal to the volume of space whose RH would change by exactly the same amount as the equilibrium RH change of the box content when subjected to the same addition of water. The B-values of each box in the store add up to give a "virtual volume" for the store, which is many times greater than its actual volume, several hundred times in the case of a well-filled paper archive. Infiltrating water vapour disperses into this virtual volume, thus giving a much smaller change in RH than would be experienced in the empty space. This calculation method combines well with digital methods for assigning artefacts to shelf space according to their dimensions, to ensure close packing (Criollo and Bres 2017).

For buildings which use dehumidification as the climate control mechanism, strong buffering by the artefacts and the building materials is not essential. It does nothing to save energy, merely displacing in time the activity of the dehumidifier, whose role is essentially removal of moisture which leaks in. The main contribution to RH stability comes from the combination of a very low air exchange rate and a very slow change of temperature.

Humidity control by winter warming

There is an essential role for humidity buffering in the alternative method of climate control through winter heating. This is well displayed by the performance of the Suffolk Record Office in Ipswich, UK. In this building there is no mechanical dehumidification to interfere with the natural progress of the indoor climate. The annual average RH within is kept below the annual average outside by winter heating alone. The extent of the disequilibrium between the interior and the air outside is shown by the difference in the mixing ratio (the water vapour concentration expressed in kg/kg of dry air), shown at the bottom of Figure 5. The summer mixing ratio outside is nearly always higher than that inside, meaning that infiltration will tend to increase the indoor RH, by adding to the water vapour concentration. Absorption by the paper greatly reduces the increase in RH.

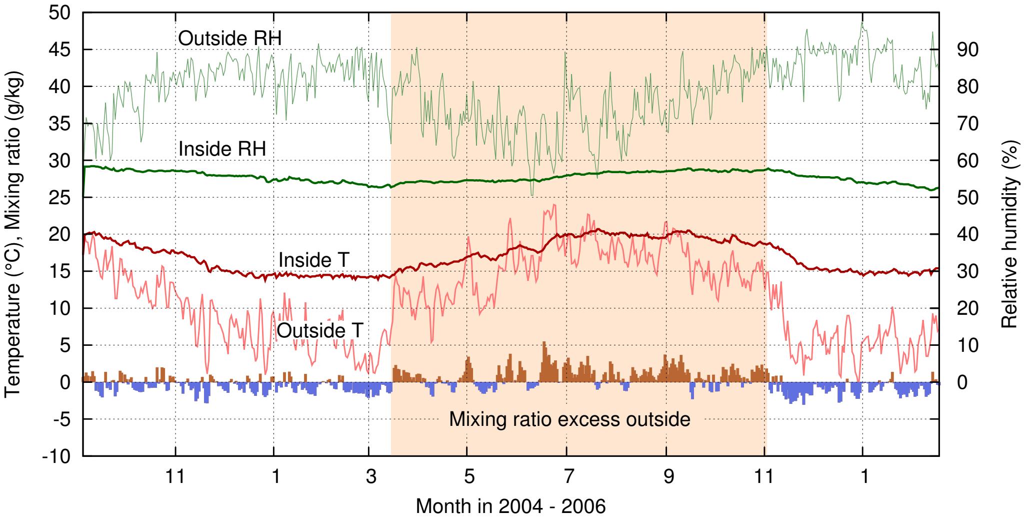

Figure 5: The RH in the Suffolk Record Office, UK. In this building there is no dehumidification; the moderate annual RH is attained by winter heating to a minimum 15 °C. The RH continues steady over the summer months even though the mixing ratio shows an almost continuously higher concentration of water vapour outside, which would raise the interior RH as it leaked in. The humidity buffering by the abundant paper prevents significant change of RH.

Another archive that operates in a similar way is the Arnamagnæan archive of Copenhagen University (Padfield et al. 2018). It does not even have a thermostat to control its RH, which is maintained by a balance between heat flow from the warm interior of the office building and the heat flow through two outside walls. Fine control is however achieved by occasional pumping of outside air.

Winter warming uses more energy than dehumidification in a new building with a low air exchange rate, but it may be a useful solution for busy archives or those whose curator demands storage closer to the human comfort zone. A chart comparing energy use by these alternative techniques is given by Larsen (2018).

Be warned that active RH control by heating to correct too high an RH (commonly called "conservation heating") is catastrophic in a tightly packed store with absorbent materials and low air exchange, because raising the temperature will raise the RH (Padfield 1996), causing a dramatic positive feedback loop.

Damage by cold

Most artefacts have been made for use within the human comfort range of temperature, 20 °C to 25 °C. Few artefacts have a composition designed with the primary aim to endure as museum objects in long term cool storage. Cold storage slows many chemical degradation reactions but it also causes separation through immiscibility of chemicals which remain mixed at room temperature. The cool storage facility at Vejle in Denmark provided an example of exudation of chemicals from the polyvinylchloride bodies of dolls (Lauridsen et al. 2017) which was reversed on warming. The authoritative British Standard advice for archives PD5454:2012 (BSI 2012b) cites a paper about efflorescence of pure beeswax seals (Novotná and Dernovšková 2002) as justification for setting a lower temperature limit of 13 °C. We recommend recourse to risk analysis for filtering out artefacts unsuited for cool storage, which benefits the great majority of artefacts and has long been standard practice for film.

Convergent technologies

As environmental standards become less rigid, reliance on orthodox air conditioning continues. One reaches a point where air conditioning is used when the same specification can be attained without it. An example is the Pierrefitte archive in Paris (Bonandrini 2017). This is fully air conditioned to a specification of 16–24 °C and 40–57% RH. However, its performance is so close to that of the Suffolk archive that a very small change of operating point, lowering the target RH to 40%, would make air conditioning unnecessary (Padfield 2017).

The role of environmental standards

The Suffolk archive is now air conditioned, because its upper room occasionally got warmer than permitted by a standard that has now been superseded. The Pierrefitte archive is air conditioned because it was explicitly designed to hold its specification in an empty building, destined to be filled with archived material.

Standards have become less strict over the last decade. The British Standards Institution's PAS198 (BSI 2012a) introduced the concept that the curator should be given the information to make her own judgement about storage conditions for a particular collection, providing wide limits for temperature. We hope that this trend to choose a climate that suits the particular collection in its geographical position will gain support. Standards exert huge influence over the cost and complexity of museum buildings. We must include a wider group of conservation professionals in the process of refining standards.

Conclusions

There is now abundant evidence from measured buildings for the effectiveness and cheapness of low energy air conditioning for museum stores and archives. The preferred option is to allow the temperature to drift freely in a gentle cycle centred on, but with a span approximately half that of, the outdoor cycle of monthly temperature averages. This diminished annual cycle is enforced by the thermal inertia of the ground beneath the building, supplemented by the heat capacity of the stored materials and of the building itself, and by thermal insulation of the walls and roof. Getting this balance right means calculating fairly exactly the heat transfer through the building envelope. However, high heat capacity and moisture exchange capacity in the stored materials is not critical to the performance of this climate control concept.

In the temperate zone, summer dehumidification will be needed. This climate control consumes less than a tenth of the energy required by air conditioning.

Some busy archives will choose to run at a temperature nearer to the human comfort zone. This also can be achieved relatively cheaply by winter heating to approximately 15 °C (in northern Europe). This method does require strong humidity buffering by the archived papers as well as good airtightness. If the internal buffering is not quite adequate, the RH can be adjusted by intermittent pumping of outside air when, by chance of the weather, it has a water content that will tend to push the interior RH towards its target.

Current environmental standards are getting less dogmatic in asserting exact temperature limits, a tendency prompted originally by the aim to reduce carbon dioxide emission. Conservators have long prioritised RH stability over temperature stability. We can achieve the RH stability by allowing, indeed requiring, a limited and smooth annual temperature cycle. This permits control by dehumidification alone, or by winter heating combined with humidity buffering, both methods giving an approximately 8 °C annual temperature cycle in a typical temperate zone locality.

Acknowledgements

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Notes

An extended version of this article is available at Padfield et al. (2017). Many relevant, detailed articles are on the conservationphysics.org website.

References

Bøhm, B. and M. Ryhl-Svendsen. 2011. "Analysis of the thermal conditions in an unheated museum store in a temperate climate. On the thermal interaction of earth and store." Energy and Buildings, 43: 3337–3342.

Bonandrini, B. 2017. "Le batiment de conservation des archives." In Les nouvelles rencontres de la conservation préventive, edited by A. Gall-Ortlik, 81–105. (Includes English translation).

BSI 2012a. PAS198:2012: Specification for managing environmental conditions for cultural collections. London: British Standards Institution.

BSI 2012b. PD5454:2012:Guide for the storage and exhibition of archival materials. London: British Standards Institution.

Christensen, J. E., H. Janssen, and B. Tognolo. 2010. "Hygrothermal performance optimization of a museum storage building." In Performance of the Exterior Envelopes of Whole Buildings XI International Conference. Florida, USA, 1: 68–71.

Criollo, A. and C. Bres. 2017. "Evaluation volumétrique d'une collection: l'informatique au service de la conservation préventive." In Les nouvelles rencontres de la conservation préventive, edited by A. Gall-Ortlik, 149–169. (Includes English translation).

Larsen, P. K. 2018. "Humidity control in historic buildings in Denmark." In Preventive Conservation: The State of the Art, edited by A. Nevin, J.H. Townsend, M. Strlič, N. Blades and D, Thickett. Studies in Conservation, 63:sup1 164-169.

Lauridsen, C. B., L. W. Hansen, T. Brock-Nannestad, J. Bendix, and K. P. Simonsen. 2017. "A study of stearyl alcohol bloom on Dan Hill PVC dolls and the influence of temperature." Studies in Conservation 66(8): 445–455. doi/full/10.1080/00393630.2016.1206651.

National Center for Atmospheric Research. 2015. The Climate Data Guide: Global surface temperatures (Berkeley Earth Surface Temperatures). climatedataguide.ucar.edu/climate-data/ global-surface-temperatures-best-berkeley-earth-surface-temperatures.

Novotná P. and J. Dernovšková. 2002. "Surface Crystallisation on Beeswax Seals." Restaurator 23: 256–269.

Padfield, T. 1996. "Low Energy Climate Control in Museum Stores: a postscript." In ICOM-CC 11th Triennial Meeting Edinburgh Preprints, edited by J. Bridgland. London: James and James, 1: 68–71. http://www.conservationphysics.org/woodstor/p_hall_01.php

Padfield, T. 2010. "Requiem for the Cologne City Archive." www.conservationphysics.org/koeln/koeln01.php.

Padfield, T. 2017. “Preventive conservation in libraries and archives.
www.conservationphysics.org/aprevu_lecture_padfield_en.pdf.

Padfield, T. and L. Aasbjerg Jensen. 2011. “Humidity buffering of building interiors by absorbent materials.” In 9th Nordic Symposium on Building Physics, 1:475–482.
www.conservationphysics.org/ ppubs/
humidity_buffering_building_interiors_nsb2011.pdf.

Padfield, T., M. Ryhl-Svendsen, P. K. Larsen, M. Jakobsen, and L. Aasbjerg Jensen. 2018. “The climate control of the Arnamagnæan Archive.” In 16th Seminar on the Care and Conservation of Manuscripts.
www.conservationphysics.org/arna/arnamagnaean-CC16.pdf

Padfield, T., M. Ryhl-Svendsen, P. K. Larsen, and L. Aasbjerg Jensen. 2017. “A review of the physics and the building science which underpins methods of low energy storage of museum and archive collections.”
www.conservationphysics.org/coolstorage

Ræder Knudsen, L., and S. R. Lundbye. 2017. “Performance of Danish low-energy museum storage buildings.” In ICOM-CC 18th Triennial Meeting Copenhagen Preprints, edited by J. Bridgland. Paris.ICOM-CC.
icom-cc-publications-online.org/

Ryhl-Svendsen, M., L. Aasbjerg Jensen, B Bøhm, and P. K. Larsen. 2012. Low energy Museum Storage Buildings: Climate, Energy Consumption and Air Quality. Technical report. Copenhagen: National Museum of Denmark.
www.conservationphysics.org/storage/
low-energy_museum_storage_buildings.pdf.

Ryhl-Svendsen, M., L. Aasbjerg Jensen, and P. K. Larsen. 2014. “Air quality in low-ventilated museum storage buildings.” In ICOM-CC 17th Triennial Meeting Preprints Copenhagen, edited by J. Bridgland. Paris: ICOM-CC. Article 1512, 8 pp.

Ryhl-Svendsen, M., L. Aasbjerg Jensen, P. K. Larsen, and T. Padfield. 2010. “Does a standard temperature need to be constant?” Meddelelser om konservering, 1: 13–19.
www.conservationphysics.org/ppubs/standard_temperature.pdf