Ten years experience of energy efficient climate control in archives and museum stores

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Summary: *Ten years experience of low energy museum storage in Denmark confirms the practicality of building lightweight stores on uninsulated floors, in contact with the ground which acts as a thermal buffer. The high summer RH is best reduced by dehumidification, which can be intermittent and therefore solar powered.*

Introduction

Energy efficient climate control has been used for archives and museum stores in Denmark for more than a decade. The challenge is to design the building to keep a moderate temperature and relative humidity all through the year by passive means. In the early days it was supposed that a very heavy building with high heat capacity would be the best. This idea emerged out of experience from historic buildings, and the design of many new archives was based on this assumption. But recent studies of archives and museum stores in use, combined with computer simulation, shows that this is only partly true. A well insulated, lightweight building with one level and an uninsulated floor laid directly on the ground has thermal stability just as good as a more heavily built structure. It is possible to achieve an annual temperature cycle between 8 °C and 16 °C without any heating or cooling. When combined with solar driven dehumidification, the relative humidity (RH) is kept around 50 % through the year. The use of a humidity buffer as the interior wall cladding will compensate for occasional periods of extreme weather. To achieve climatic stability, the infiltration of outside air must be low. External pollutants will be kept out of the store but internal pollutants must be limited by the use of inert materials and finishes.

Historic archives

It was not entirely by intuition that the first passive archives were designed with heavy outer walls. The experience from archives kept in historic buildings for centuries suggested that thermal stability was a key parameter for long term preservation. The military archive in Segovia Castle in Spain is one such example (fig. 1). The archive is situated in the basement, next to the limestone bedrock and with a 2 m thick wall to the outside [1]. The annual temperature variation in the vault is from 10 to 15 °C, compared to 0 –30 °C outside. The relative humidity is rather constant at 70–80 % due to the immense humidity buffer capacity of the many tons of paper. It is the archive itself that moderates the relative humidity, not the heavy walls.

The performance is helped by a very slow infiltration of outside air. The windows are few and small, and only opened occasionally for a few hours by the archivist. This archive has worked

Figure 1: *The Alcazar of Segovia, Spain, is home to the military archive located in the basement. The natural climate is cool and humid.*

for over a century without any active climate control. It does, however, have a disquietingly high RH, which inevitably moves towards the outside RH, because the average temperature inside is equal to the average temperature outside. Similar climatic conditions are observed in most of northern Europe.

A contrasting example of an uncontrolled environment inside a heavy building is St. Catherine's Monastery in Sinai (fig. 2). This desert fortress has been a safe refuge for the famous library for 1500 years. The solid walls were put up for security rather than for climate control. The annual temperature variation in this location is 20 – 30 °C and the RH is 15 –30%. The low RH is characteristic of this high desert environment. These climates are far outside the limits set by standards or recommendations for archives, yet the documents are well preserved.

Archives with heavy structures

The idea of using very heavy buildings for archives was adopted for the Cologne City Archive, built in 1971 as a pioneer effort at climate control without air conditioning (fig. 3). Behind the granite tile facade was half a metre of brick wall set in a concrete frame. The climate control in the archive was partly by thermal inertia, which flattened out the daily variation of outdoor temperature. This was supplemented by cross-ventilation through the narrow windows and by heating in winter. The RH was so strongly buffered by the archived material that it hardly changed over periods of many weeks.

Sadly, this building does not exist any more, but the 'Cologne model' survived in several archives that were built in the following years. The Suffolk Record Office in Ipswich (UK) shows the effectiveness of simple climate control without mechanical ventilation (fig. 4). This two storey building has cavity walls of brick and porous silicate blocks and a ventilated attic. The annual average RH is reduced by winter heating, enabling the archive to cruise through the summer, relying on humidity buffering by the contents [2].

This concept worked for many years, but the temperature of the archive was not always within the narrow limits set by the standard BS5454:2000, so an air conditioning system was installed a

Figure 2: *St. Catherine's Monastery in Sinai, Egypt has been a safe refuge for the famous library for 1500 years. The natural climate of the library is warm and dry.*

Figure 3: *The City Archive in Cologne (1971) was designed with thick outer walls for thermal inertia. The interior was heated and ventilated to control the RH.*

Figure 4: *The Suffolk Record Office, Ipswich, UK (1990), had winter heating to 16 °C. The RH was stabilised by the humidity buffer capacity of the documents.*

few years ago. Current standards and recommendations are not compatible with passive climate control. The international standard ISO 11799 quotes 14 –18 °C and 35 – 50% RH as the allowable range for temperature and humidity in archives and libraries in use [3]. The British Standard 5454 proposes 16 –19 °C and 45 – 60 % RH as limiting values for the specification, with even narrower limits for permitted variation [4]. It takes a brave conservator or librarian to speak against these strict limits for climatic variation.

A store with passive conservation heating

The director of the Arnamagnæan Institute in Copenhagen chose simple, fail-safe climate control over constant temperature and relative humidity ensured by full air conditioning when a new archive was designed for the collection of medieval documents. The archive was located on the second floor in an ordinary office building, next to heated spaces (fig. 5). A multi-layered structure encapsulated the archive [5]. The load bearing structure was 240 mm concrete walls and floors, which gave some thermal inertia to the archive. Thermal insulation was 200 mm mineral wool facing the heated offices but only 50 mm insulation in the outside wall. The thermal insulation was calculated to allow the temperature inside the archive to stay about half way between the outside temperature and the office temperature. An annual temperature variation between 15 and 23 °C was achieved without any regulation within the archive. The inside of the walls was lined with 50 mm porous lime silicate blocks to moderate variation in RH. A small ventilator takes in outside air on occasions when the water vapour content is right for pushing the interior RH towards the specified ideal. It raises the air exchange rate to 0.5 per hour, which has no significant effect on the temperature. As a consequence, the RH is within 50 – 60 % all year, with very little fluctuation. The climate control has worked for 8 years with impressive stability (fig. 6).

A store without forced ventilation

A similar concept of passive conservation heating was adapted for a new store for historic musical instruments in Copenhagen (fig. 7). The single level store was established in an industrial building. It is surrounded by workshops, which leak heat into the store in winter. The walls separating the store from the adjacent spaces are 190 mm porous lime silicate, offering a con-

Figure 5: *The Arnamagnæan collection of medieval books and documents is located on the second floor, behind the windowless section of wall, in an office building at the university campus in Copenhagen (2004).*

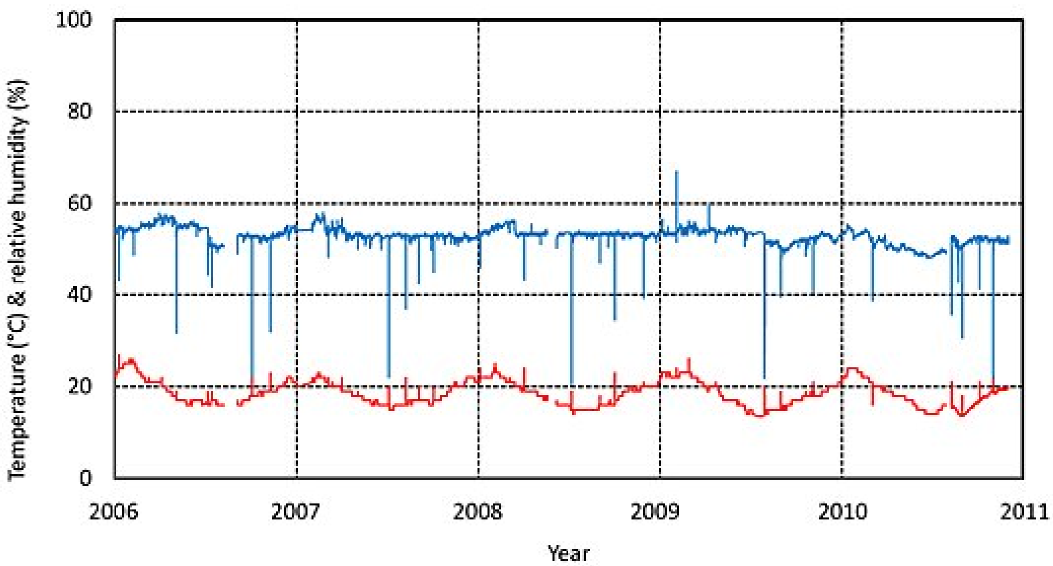

Figure 6: *The climate record for five years from the Arnamagnæan archive shows the annual variation in temperature between 15 and 23 °C (lower trace) and the stability of RH between 50 – 60 %. The intermittent blips in RH show the climate in the conservation workshop when the data logger was tapped*

Figure 7: *Interior view of a store for historic musical instruments, located in an industrial building. The temperature is 10–23 °C controlled by heat leaking from the adjacent spaces. This keeps the RH between 45 – 60%.*

siderable humidity buffer to the store. The instruments' thin wooden panels have little inherent humidity buffer capacity, but are very susceptible to variations in RH. However, there is no reason to worry about false notes. The annual variation has been within 45 – 60 %RH for many years. The store has no mechanical ventilation and depends on a low air exchange rate to work. The infiltration of outside air averages one room volume per day. This is much too low an air exchange for human health and comfort, but appropriate for the wellbeing of museum objects.

Outside air is a main source of pollutants and particles that cause corrosion on metals and chemical degradation of organic materials. Nitrogen oxides, which originate mainly from traffic and combustion, will engage in acid hydrolysis after transforming into nitric acid on indoor surfaces. Ozone, a natural component of outdoor air, deteriorates materials by oxidation. For a museum store with a high air exchange rate it would be necessary to filter the intake of new air for pollutant gases and particles. However, for a storage room with a very low air exchange rate (less than one exchange per day) the infiltration of ambient pollutants is just as efficiently retarded by the building fabric itself as can be achieved by mechanical ventilation and filtration. Internally generated pollutants, such as acetic acid, are best prevented by the choice of inert construction and furniture materials and finishes. For collections containing unstable objects, internal recirculation of the air through carbon filters is an option [6,7].

A store with dehumidification

The climate control in the musical instruments store may be passive, but it does use energy: it depends on the heat flow from the rest of the building to function. The annual temperature variation is much larger in an unheated building like the solid concrete shelter shown in Figure 8. It used to protect fighter airplanes in Værløse airfield (Denmark) against a nuclear attack, but is now in use as a temporary store for historic furniture. There is no daily fluctuation in temperature, but the annual cycle is from 0 °C in winter to 25 °C in summer (fig. 9). The large thermal inertia of the half metre thick roof is not enough to even out the temperature over the year. The inside temperature follows the outside daily average. The concrete roof would have

Figure 8: *The solid concrete shelter for fighter airplanes at Værløse, Denmark, now used as a temporary store for a collection of historic furniture. The annual temperature variation is 0–25 °C and the RH is controlled to 50% by dehumidification.*

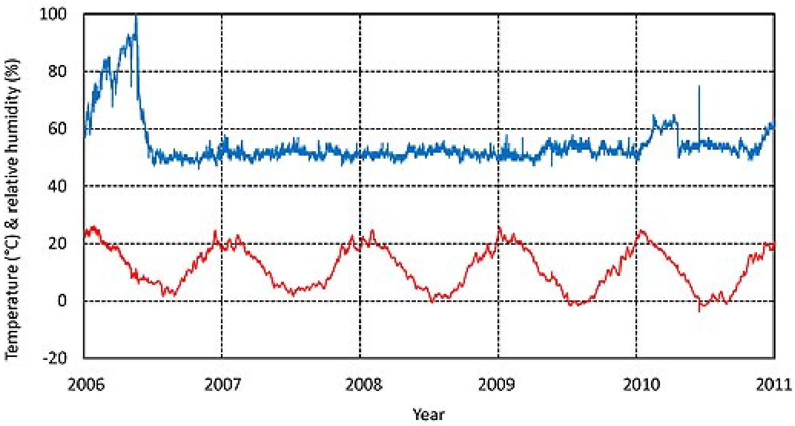

Figure 9: *Climate record over five years from the concrete shelter on Værløse airfield. The RH is controlled by dehumidification. Notice the initial rise in RH before the dehumidifiers were turned on.*

Place	Temperature °C	RH %	AER $hour^{-1}$	Energy $kWh/m^3.yr$	Control method
Arnamagnæan archive	15 – 23	50 – 60	0.05	15	heat
Musical instrument store	10 – 25	40 – 60	0.05	10	heat
Værløse hangar	0 – 25	45 – 55	0.03	5	dehumid.
Ribe museum store	8 – 16	50 – 55	0.04	2	dehumid.

Table 1: Specifications for the energy efficient archives and stores. AER = air exchange rate.

Figure 10: *A well insulated museum store for a local museum collection in Ribe (2006). The annual temperature variation is 8 – 16 °C and the RH is controlled to 50% by dehumidification.*

to be 4 m thick to give thermal stability, so only underground spaces can maintain a constant temperature over the year.

The RH in the store is controlled by an absorption dehumidifier. It is needed all year as the infiltrating air maintains a high RH, because the inside air temperature scarcely differs from the daily average outdoors. However, the dehumidification requirement is quite small, because the shelter is almost air tight. The air exchange rate is only 0.03 per hour, so it takes one and a half days to replace the air volume of the shelter with outside air. Though this store is not passively controlled, it takes only 5 kWh per cubic metre of storage space, per year, to keep this store dry (table 1).

A lightweight store

If the Værløse building had a roof of 500 mm mineral wool instead of concrete, the temperature variation would be much smaller. Such a building does not exist, but computer modeling predicts that the annual temperature variation inside a lightweight store will be 7 – 13 °C [8]. For temperature stability, a lightweight insulated structure is better than heavy weight without insulation. The stability depends on heat storage in the ground below the building. The floor should not be insulated, to allow the seasonal transfer of heat.

Temperature measurements in a recently built museum store in Ribe (Denmark) have confirmed that heat diffuses into the ground in summer and back into the space in winter [9]. Apart from being a store for thousands of museum artifacts, this building has a remarkable ability to store energy. In winter the temperature is just about right for lowering the RH to an acceptable level, but in summer the temperature is lower than that outside so there is a need for dehumidification. The annual energy use for this type of store is about 2 kWh/m^3. It is neither passive nor energy neutral, but it is very energy efficient (fig 10).

An off-grid store

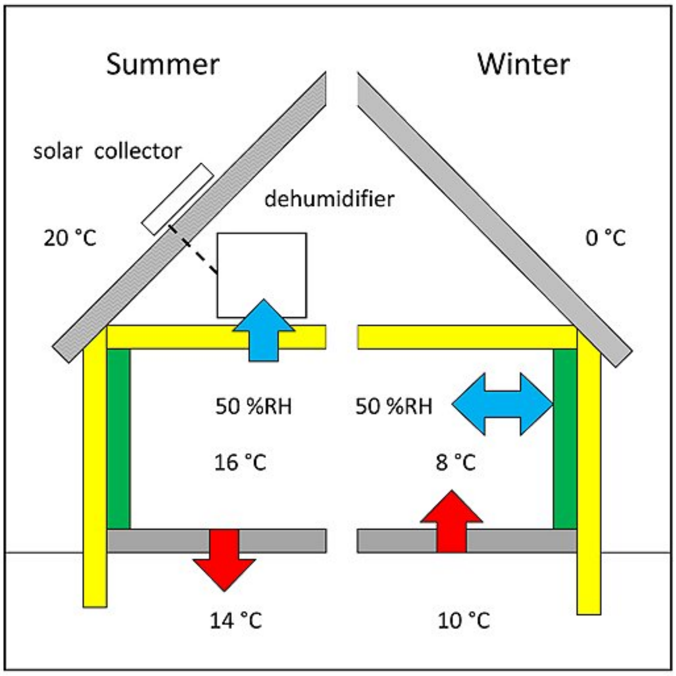

Figure 11: *Cross section of an off-grid museum store. Summer heat is stored in the ground below and released into the building during the winter. The RH is reduced by solar driven dehumidification in summer and by the raised temperature in winter.*

The actual storage building in Ribe has a connection to the power grid, but calculations show that with photovoltaic elements covering 5% of the roof surface the store would have a sufficient power supply, so the building would be entirely independent of external energy supply (fig. 11). Due to the unpredictable nature of solar power, the off-grid store needs a humidity buffer. Conventional building materials like brick and concrete are rather poor humidity buffers. The walls should be lined with unfired clay brick with open perforations to allow water vapour free and fast access [10]. Unfired brick is not a standard product in the local building materials supplier, but can be procured from the brickworks before firing. It therefore has the advantage of a relatively small carbon footprint. When combined with a lightweight structure, the embedded energy will be much less than for a massive building made of fired bricks or concrete. The total input of energy over the lifetime of the building is negligible compared with conventional museum stores and archives.

The influence of low temperature on preservation

The question remains, is the emphasis on energy conservation acceptable for the long term preservation of the artifacts? When light and air pollution are excluded, temperature is the main

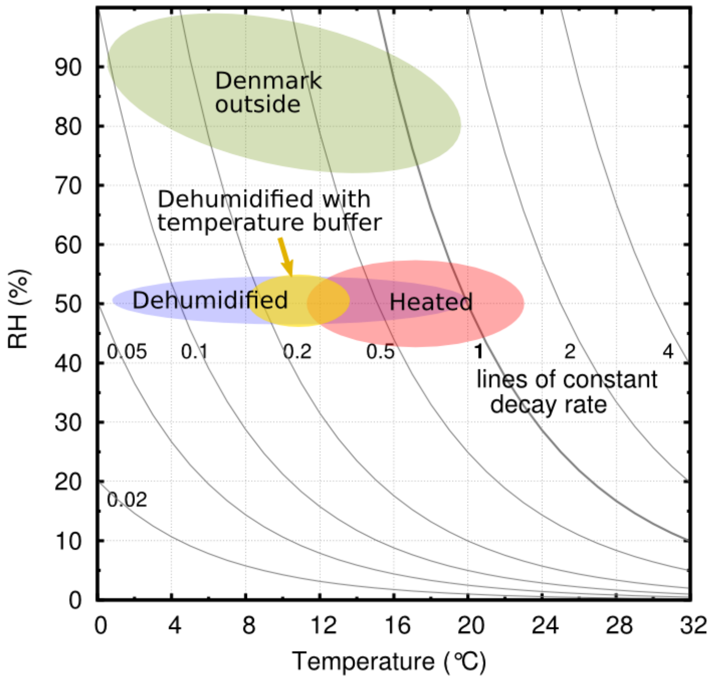

Figure 12: *Climate ranges for the different climate control strategies are superimposed on a diagram showing curves of equal hydrolysis reaction rate, as proposed by Sebera [11], modified by Padfield [12].*

driver for chemical degradation of organic materials. The rate of decay for reactions involving moisture (hydrolysis) depends also on the relative humidity. The combined effect of temperature and RH is described in figure 12 [11,12]. The decay rate is set to 1 for a constant 20 °C and 50% RH. The curved lines connect conditions causing a constant relative reaction rate. Low temperature and low relative humidity is obviously better than higher temperature and RH, and temperature is in general more important than relative humidity, over the acceptable range of RH, which cannot go too low because of damaging dimensional change in organic materials. From this point of view there is really no benefit in keeping a constant temperature. The temperature variation itself may be a hazard to objects that become brittle at low temperature, such as some paints and plastics, but only if the object at the same time is experiencing a mechanical shock e.g. during transport. There is no evidence of damage to objects in storage caused by the moderate temperature variation we propose.

The influence of climate control method on preservation

The decay rate depends on the choice of climate control strategy. Figure 13 shows the decay rate diagram superimposed with lines of equal dew point. The dew point is a measure of water vapour concentration. The diagram shows the effect on the decay rate of the two types of humidity control used in the examples presented in this article. In the case of dehumidification, water vapour is removed from the air, so the dew point falls. The decay rate decreases due to the lower RH, shown by the green arrow in the diagram. In the case of heating to reduce the RH, the dew point remains unaltered, shown by the red arrow. The RH is reduced to the same target level, but the chemical decay rate is higher for heating than for dehumidification. Not only is dehumidification more energy efficient than heating, it is also better for preservation.

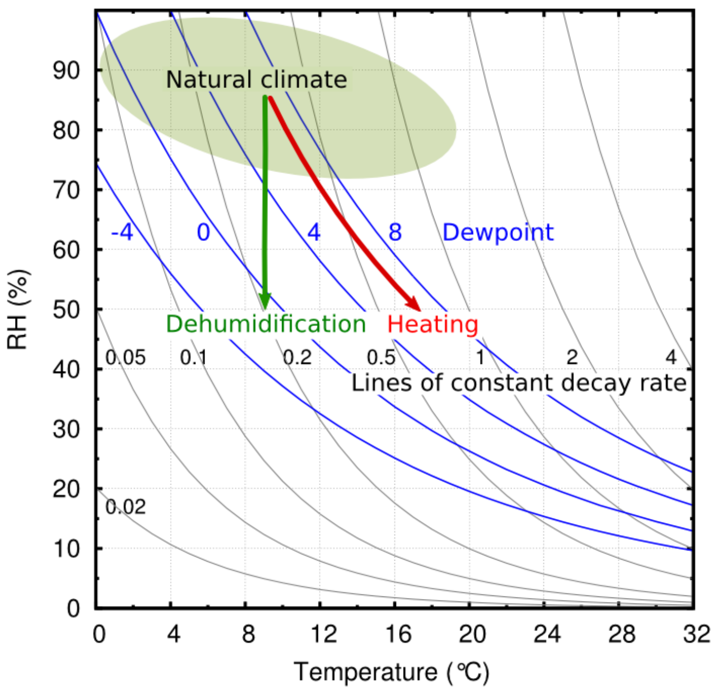

Figure 13: *Diagram with lines of equal dewpoint superimposed on the relative reaction rate diagram. Reducing the RH by heating does not alter the dewpoint (red arrow) while direct dehumidification by absorbing water from the air reduces the dew point (green arrow).*

There is no conflict between energy saving and conservation

Low energy museum storage can be built with no detriment to the collection. Indeed, a lower winter temperature than current standards permit will enhance durability. There is no evidence for a conflict between energy saving and conservation. Current standards evolved at a time when a constant climate, maintained by the best available technology, was implemented as a precautionary measure without regard for energy economy. There is no evidence that constancy of temperature, typically confined within a 5 degree window, is necessary for the preservation of the collection. Low energy storage requires a modest annual variation in temperature but is capable of maintaining the RH within a 10% window.

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