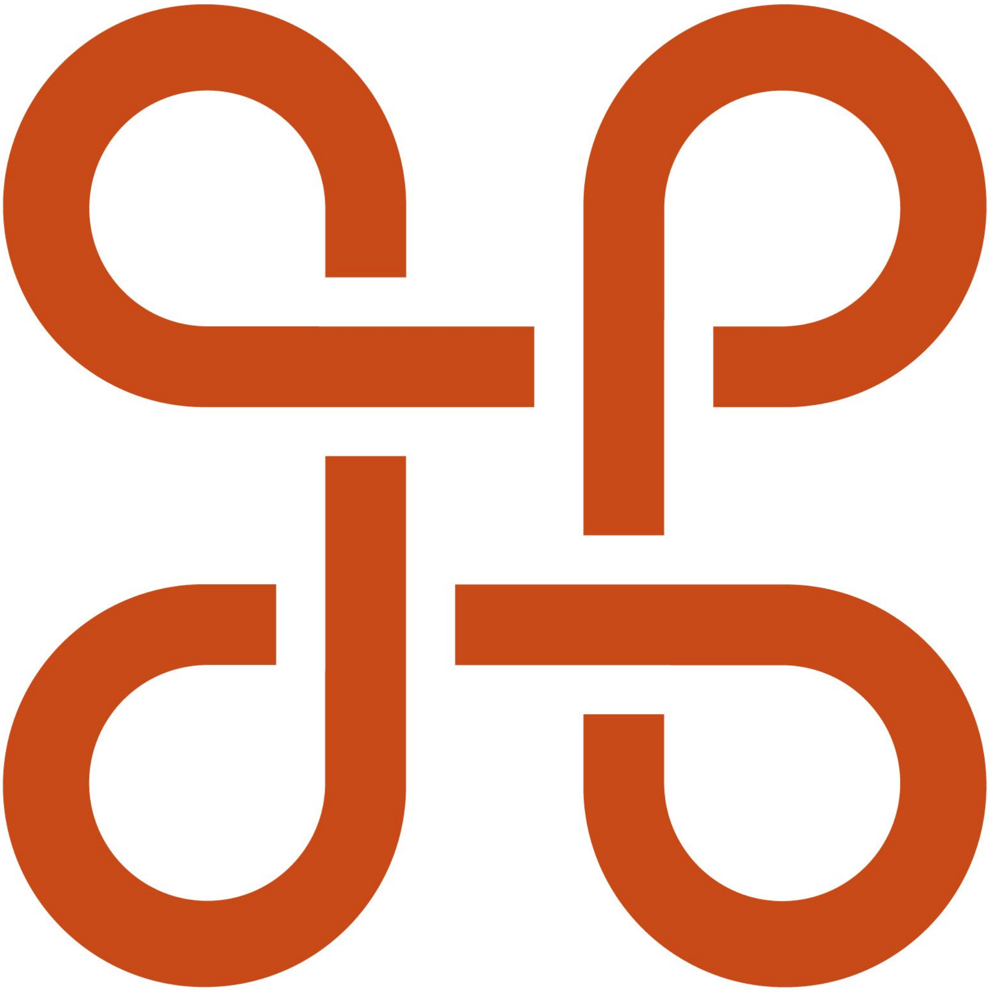
Poul Klenz Larsen

Sustainable museum storage buildings with low energy consumption

Three models from Denmark



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Sustainable museum storage buildings with low energy consumption: three models from Denmark
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Content

Abstract

This guide presents three generic models for museum storage and archives with low energy consumption. The main difference between this simple approach to climate control and conventional air conditioning is that the inside temperature is allowed to follow the outside annual cycle. The building structure is designed to provide moderate variations in temperature and relative humidity, with a combination of low ventilation rate, thermal insulation and thermal mass. The humidity control takes advantage of the weather pattern and combines humidity buffering with winter heating or summer dehumidification. The concept depends entirely on the ambient climatic conditions and therefore only works in temperate climate zones.

Three types of climate control are described in this text: unheated storage with dehumidification, temperature buffer with dehumidification and conservation heating with humidity buffer.

Svensk sammanfattning

I denna vägledning beskrivs tre generiska modeller för magasin med låg energiförbrukning. Den största skillnaden mellan detta förhållningssätt till klimatkontroll och konventionell luftkonditionering är att innetemperaturen tillåts följa den yttre årscykeln. Byggnaden är utformad för att ge måttliga variationer i temperatur och relativ luftfuktighet, genom en kombination av värmeisolering, låg ventilationshastighet och byggnadsmaterialens förmåga att lagra värme. Luftfuktigheten styrs av vädermönstret och kombinerar fuktbuffring med vinteruppvärmning eller sommaravfuktning. Konceptet är helt beroende av det lokala utomhusklimatet och fungerar därför endast i tempererade klimatzoner.

Tre olika typer av klimatkontroll beskrivs i denna skrift: ouppvärmt magasin med avfuktning, värmebuffring med avfuktning samt skyddsvärme med fuktbuffring.

Introduction

Sustainable buildings for museum storage must fulfil two objectives: On the one hand, the carbon footprint for the construction and maintenance must be as low as possible, and the climate control must be simple and rely only on renewable resources. On the other hand, the collection must be safe and protected the best possible against any agent of decay. This double purpose is summarized in the term: Save and preserve.

The basic concept of low energy climate control is to heat the building as little as needed. The temperature should never be so high, that the relative humidity becomes too low. Dehumidification is used for supplementary humidity control, whereas humidification should never be necessary. Compared to orthodox air conditioning, the climate control is simple to install and cheap to operate. The simplicity of the mechanical equipment affords better security against climatic failure than highly sophisticated machinery.

The concept depends entirely on the ambient climatic conditions and therefore only works in temperate climate zones. In arctic and tropical climate zones, auxiliary measures are needed to provide acceptable conditions for storage.

Most collections are well preserved at a moderate temperature variation and a moderate relative humidity. Cold storage for chemically unstable objects, such as photographic material, is not possible within the low energy concept. Storage of collections with special needs or challenges, such as explosives or poisonous substances, is not the subject of this guide.

The guide is related to the European Standard *Conservation of Cultural Heritage – Specifications for location, construction and modification of buildings or rooms intended for the storage or use of heritage collections* (EN 16893:2018). [8] Section 5.3.4 in this standard is about passive or low energy environment structures and gives supplementary guidance for the choice of materials and installations.

Climate specifications and the degradation of materials

The climate specifications for a museum storage or archive must relate to the content of the collection and its condition. Many collections have a variety of objects made of different materials, and a single object may consist of two or more components. Each group of materials has specific safe intervals for temperature and humidity. It is sometimes difficult to find a compromise that meets all demands.

One should always take into account the history of the objects. If a wooden object has acclimatized to a humid environment, it may not be safe to lower the average RH to museum standards. Contaminants or conservation treatments may have altered the sensibility of an object and thereby introduced other limits for acceptable climate.

Climate specifications should also reflect the expected lifetime of the collection, but this is a difficult task. Nothing lasts forever, but who wants to decide for a final date for an object? The best we can do is to reduce the decay best possible with as little energy as needed. Below is a presentation of the three main processes of material degradation: chemical, mechanical and biological degradation.

Chemical degradation

Oxidation is the most widespread type of chemical degradation, and it affects both organic and inorganic materials. The general definition of oxidation is the loss of electrons during a reaction with a molecule, ion or atom, and it is always accompanied by the opposite reaction, reduction. A large range of chemical processes belong to this category, and it does not necessarily involve oxygen. But for museum objects in storage, atmospheric oxygen is the main agent for oxidation. Oxidation reactions are slowed down at lower temperature, which is an argument for not heating a storage. A particular aggressive form of oxygen is ozone, a molecule with three oxygen atoms. Ozone is generated in the atmosphere by UV light, and enters the storage with ventilation. This is a good reason for keeping the ventilation rate as low as possible.

Another category of reactions leading to the decay of museum objects is called hydrolysis - the addition of water to a polymer resulting in the breaking of the polymer chain molecule. The potency of water in promoting these reactions is proportional to the relative humidity (RH), which is identical to the chemical and biological definition of water activity: the potential for water to engage in chemical reactions. The rate of decay increases exponentially with a rise in temperature. The effects of temperature and relative humidity are combined in the diagram in figure 1. [24] It shows curves of equal degradation rate, called isoperms, relative to a constant climate at 20 °C and 50%RH. At a moderate relative humidity level, temperature is the dominant factor. Reducing the temperature from 20 °C to 10 °C will slow down the reaction rate by of factor of 5, and thereby increase the lifetime of the object five times. This is a very good argument for not heating a museum storage to comfort temperature.

The diagram relates widely to organic reactions, but not to ionic and crystal re-arrangement reactions, such as phase transformations. These reactions 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 relative humidity, providing a thin surface film of aqueous solution, which facilitates ionic corrosion reactions. The tendency of separation of components, such as plasticizers, increases at low temperature [26], but their diffusion rate also diminishes, so cooling usually favors durability. Chemically unstable objects are best preserved in cold storage, such as photographic material.

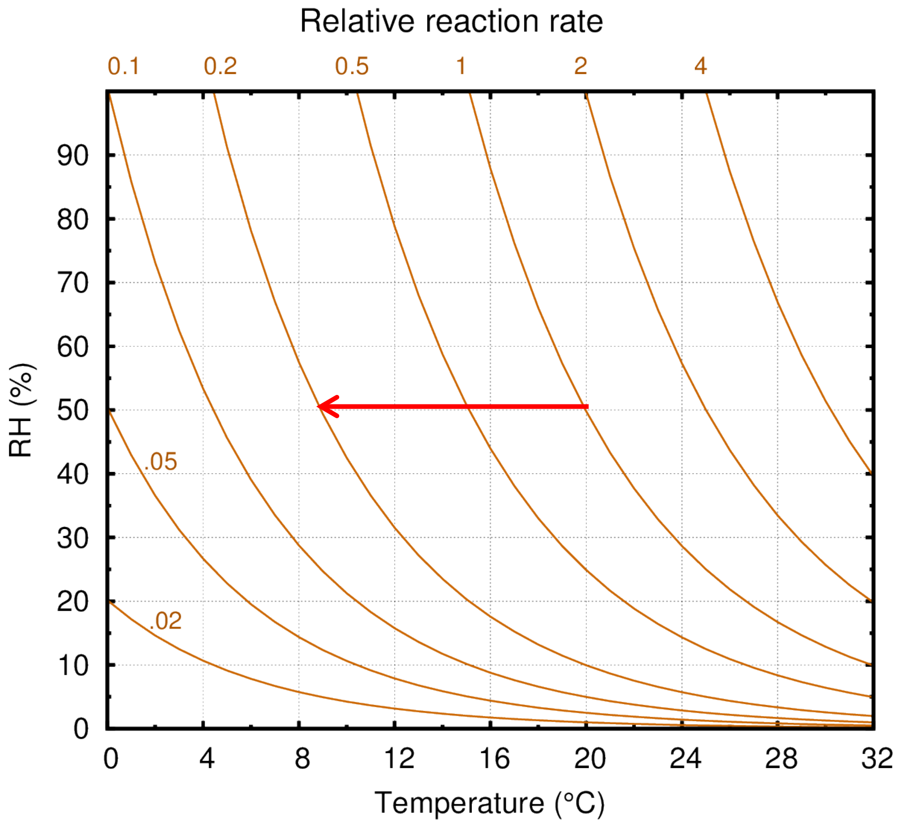

Figure 1. The Sebera diagram, showing the combined effect of temperature and relative humidity on the rate of reaction by hydrolysis. A reduction in temperature from 20 °C to 9 °C at 50%RF will slow down the reaction rate five times and thereby increase the lifetime of the object five times. Illustration: Tim Padfield ©.

Figure 2. Modern materials are sensitive to chemical degradation by oxidation. Diving suit, Imperial War Museum, Duxford Airfield, UK. Photo: Poul Klenz Larsen.

Figure 3. Organic polymers such as parchment is sensitive to chemical degradation by hydrolysis. Arnamagnean Collection, Copenhagen University, DK. Photo: Poul Klenz Larsen.

Mechanical degradation

Many organic materials such as wood, bone, ivory, textiles etc. are sensitive to variations in RH, because the moisture content of the porous structure depends on the RH in the surrounding air. The moisture uptake and release makes the material expand and contract, which can lead to deformation or cracks. Painted objects are particularly sensitive to climatic variations, due to the different response of the paint layers and the support. The duration of the RH fluctuations is an important parameter, because it takes some time to equilibrate. Slow variations like annual cycles allow the object to acclimatize evenly, which prevent bending and cracking, but may be harmful to paint layers.

The strain caused by temperature variations is small compared to the hygroscopic response, but temperature has an indirect influence on the mechanical reaction of wooden objects. The rate of water vapour diffusion is reduced at low temperature, so the response to RH changes is slower than at high temperatures. The limit for reversible strain in polychrome wooden objects is within the interval +/- 15%RH [5]. The vast majority of collections and objects will be safe within 40–60%RH.

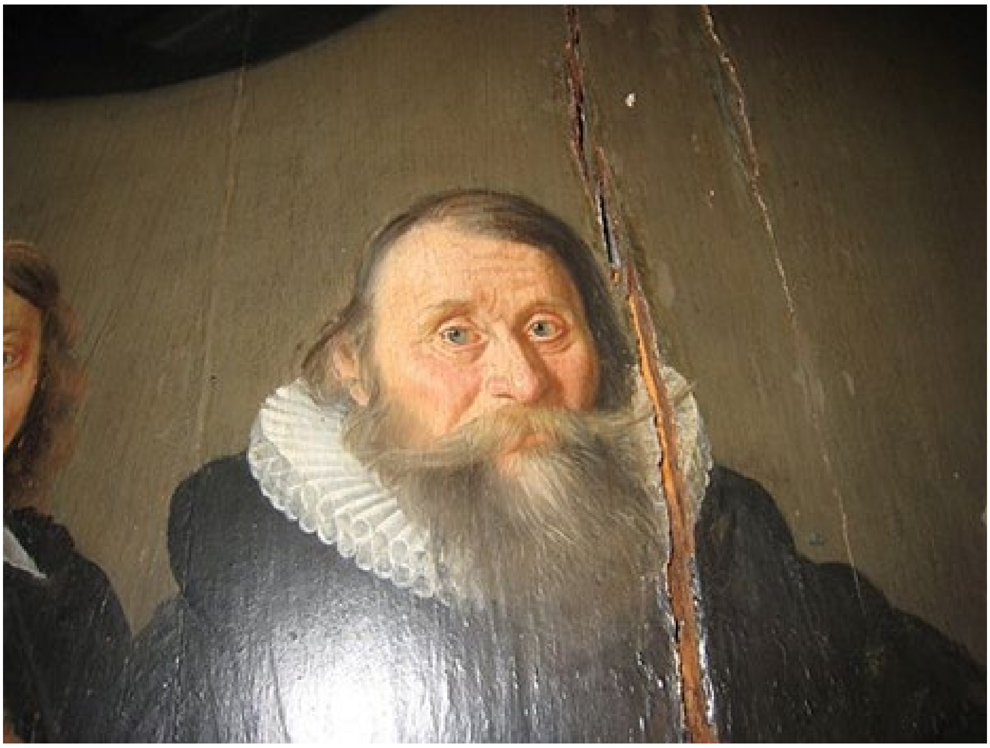

Figure 4. Wooden panel paintings are sensitive to large variations in relative humidity. Cracks develop due to shrinkage caused by drying at low RH. Photo: Poul Klenz Larsen.

Figure 5. Wooden music instruments with thin veneers are particularly sensitive to variations in relative humidity. Museum for Historic Musical instruments, Copenhagen, DK. Photo: Poul Klenz Larsen.

Some materials become stiffer when temperature decreases. For objects made of very soft materials, such as wax or grease, it is an important conservation advantage to store such materials at a cool temperature. This avoids deformation, which might otherwise occur on a warm summer day. Similarly, in cool conditions, dust will be less adherent to the surface of the materials, and soiling will be minimized.

For polymeric materials, the transition to the “glassy” state occurs at different temperatures for different materials. Below this so-called glass transition temperature, the material becomes more brittle, and will crack more easily than at a higher temperature. However, cold storage is still recommended for the optimal conservation of most plastic objects, regardless of the risk of rigidness, as the gain in chemical stability far outweighs the physical disadvantages. [25]

Paints and glued joints are among the materials that are susceptible to damage at low temperature, especially when adhered to supports, which allow flexing by physical impact, such as canvas. For oil paint, the transition to this state is below 0 °C. For acrylic paints, the range for the glass transition temperature is typically between 5 to 10 °C. [11, 12]

The increased stiffness at reduced temperatures entails a risk when combined with physical impacts (sudden shock, rough handling, etc.). There is no mechanical implication for objects which are simply stored at cool temperatures, even well below their glass transition temperature. Professional handling will reduce this risk, but stiffness due to low temperature should be taken into consideration when planning and carrying out object handling and logistics activity. Rolling a painting on canvas might for example not be a recommended procedure in a cold storage.

For a large, mixed collection, there will always be a few objects with special climate requirements, which are not fulfilled by the conditions maintained in a general storage environment. Most often, this will include materials, which require a relative humidity diverging from normal room conditions (e.g., rusty iron, which must be kept very dry). For such particularly fragile objects, it implies that alternative storage solutions must be found, if the general storage conditions allow for a winter temperature below the glass transition temperature.

Biological degradation

The climatic conditions for pests and insects to breed and thrive differ from species to species. All insects need water to survive. Some get it from the water absorbed by the host material and others produce water by the metabolism of dry food. A few species can absorb water directly from the water vapour in the ambient air. The general recommendation is that 60% RH is safe for all materials and types of biological degradation. Temperature is an important parameter for the insects to move around and to breed. Many insects can survive down below 0 °C, but they hibernate at temperatures below 10 °C. Most insects need 20 °C or more to reproduce. A low temperature is always a good precaution against insects.

Mold grows on the surface of most organic materials in damp environments. There is a large variety of species, each with specific climatic limits for germination and growth. The growth condition for mold is outlined in the so called isopleth system. [24] The lower limit for mold growth is 80%RH at 20 °C for most species, rising up to 90% RH at 5 °C and 100%RH at 0 °C. The RH limit at 20 °C is lowered to 70%RH if the surface is treated with oil, wax or other nutrients favorable for mold infestation. Recent studies indicate that some species grows at RH down to 60%RH. [3] The germination of the mold spores depends on the duration of appropriate climatic conditions. A minor violation of the risk threshold value leads to infestation only after a week or more, whereas a sudden warm and humid environment can cause mold growth in a day.

It is a common belief that stagnant air is favorable for mould growth, and that forced air movements can prevent infestation of mould. However, there is no scientific evidence for this assertion. The reason is more likely that stagnant air will maintain different temperatures, and therefore higher RH in cold areas. This is relevant for buildings with poor thermal insulation or in areas with thermal bridges. The concept of low winter temperature reduces the risk of large temperature differences and areas with too high RH.

Figure 6. Evidence of woodworms in a wooden panel painting. Icon collection, Zografu Monastry, Mount Athos, Greece. Photo: Poul Klenz Larsen.

Figure 7. Mould growth on a wooden artefact stored in humid conditions. The Open Air Museum, Sorgenfri, DK. Photo: Morten Ryhl-Svendsen (CC BY-NC-ND).

Standards and Guidelines

There are several recommendations and guidelines regarding the appropriate climate ranges for different materials and collections. The joint declaration of IIC and ICOM-CC defines the acceptable range for general collection material to 16–25 °C and 40–60%RF. [10] Short term fluctuation should be less than +/- 4 °C and +/- 5%RH in 24 hours. This is a best possible compromise intended for both storage, transport and exhibition. The temperature specification is surely defined by human comfort rather than durability of collections.

The European standard EN15757 focus on relative humidity and the mechanical damage to organic, hygroscopic materials. [7] It does not suggest a universal safe range for RH. For each object or collection, it defines a target range, which is based on a statistic evaluation of historical climate conditions. Allowable fluctuations should be within +/- 1.5 times the standard deviation in the monitoring period. A range of 10%RF on both sides of the annual average is considered to be safe in any case.

The North American guideline is the ASHRAE chapter 24, which has been influential in Europe for decades [2]. It defines a series of climate ranges for both temperature and relative humidity, based on the assumption, that narrow ranges provide better preservation. It gives recommendations on both short term fluctuations and seasonal adjustments. The best climate range (class A1) does not allow low winter temperature. This implies, that an annual temperature variation is more harmful to the collection than a constant temperature.

Three types of climate control

Three types of climate control are described in this section:

- Unheated with dehumidification
- Temperature buffer with dehumidification
- Conservation heating with humidity buffer

The climate ranges for each type is defined in table A. The temperature interval is based on the outside annual average (AA), which depend on the location of the building. The temperature ranges will be different for each part of Sweden. In the southern parts of Sweden, the average temperature is somewhere between 5 °C and 10 °C. [29] The ranges do not apply to the northern part of Sweden with very low winter temperature. In these regions, there is a need for humidification to keep a moderate relative humidity in winter.

Table 1. Climate ranges for three types of low energy storage. AA denotes the annual average temperature. The temperature intervals depend on the ambient climatic conditions at the specific geographical location.

Climate control	Relative humidity	Temperature
Unheated with dehumidification	40% < RH < 60%	AA -10 °C < T < AA +10 °C
Temperature buffer with dehumidification	40% < RH < 60%	AA -4 °C < T < AA +6 °C
Conservation heating with humidity buffer	40% < RH < 60%	AA -2 °C < T < AA +12 °C

Unheated store with dehumidification

This category is mainly relevant for existing building used for storage, either temporarily or permanently. It is typically a reused industrial building or warehouse, which may not have a suitable heating installation. In addition, the roof and ceiling may have poor thermal insulation, so the energy consumption for heating is large. The relative humidity in such an unheated building will be too high most of the year. The surplus of moisture is removed by mechanical dehumidification. The dehumidifier is located outside the storage and the dry air is distributed by ducts in a recirculating system. Only small volumes of air are needed, so the ducts can be rather small.

Figure 8. A solid concrete shelter reused for temporary storage of furniture. The roof thickness is 0.5 m and it has no thermal insulation. Værløse Airfield, DK. Photo: Poul Klenz Larsen.

Figure 9. The interior temperature follow the outside monthly average with no daily variations. The relative humidity of the shelter is kept at 50%RH all year by dehumidification. Photo: Poul Klenz Larsen.

The solid concrete shelter shown in fig. 8 is an example of unheated storage. It has been used for more than a decade as a temporary store for historic furniture. The annual temperature cycle is from 0 °C in winter to 22 °C in summer, which is almost the same as the outside daily average. There is no diurnal fluctuation in temperature, due to the large thermal inertia of the half meter thick concrete roof. The RH in the store is controlled with an absorption dehumidifier. It is needed all year as the infiltrating air maintains a high RH, because the air temperature is more or less unchanged from outdoors to the inside. However, the dehumidification capacity 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. The annual energy consumption is 6 kWh per m^3 per year of storage space to keep this store dry.

Temperature buffer with dehumidification

This climate control strategy is mainly relevant for purpose build storage facilities. The building envelope is designed to moderate the natural ambient temperature variations. The ground beneath the building is used as a heat store, combined with thermal insulation of the building envelope [6, 21]. The concrete floor is placed directly on the ground without thermal insulation. The floor functions as an effective cooling surface in summer, as heat is absorbed by the ground below. In winter, the heat is released to the space above to keep the temperature well above ambient. This design reduces the annual temperature variation to half the outside monthly average temperature span.

An example is the museum storage building in Ribe shown in figure 10 [22]. The main storage room has 6 m to the ceiling and an open mezzanine with racks and compactors. The temperature inside has an eight degree centigrade annual cycle, a moderation of the twenty degree outside temperature cycle. One could achieve a smaller amplitude but this would make humidity control more expensive. The temperature difference between floor and ceiling is rarely more than two degrees centigrade, corresponding to a six percent difference in relative humidity. There is no insulation 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.

The relative humidity arising from the diminished annual temperature cycle acting on the slowly infiltrating air will be moderate in winter due to the higher than ambient temperature. In the Ribe store, the temperature buffering from the ground gives a winter temperature sufficiently above ambient temperature so that it holds the relative humidity around 50%. During the summer, the indoor temperature is well below ambient, so the relative humidity would rise to 100% with no intervention. Therefore, dehumidification is used in summer to keep the RH moderate around 50%RH. The energy used for dehumidification is only 1.5 kWh per m3 per year. This is possible because the air exchange rate is less than 0.05 room volumes per hour in average.

It could be powered entirely by photovoltaic elements, covering approximately 5% of the roof of the building. Such a museum store or archive will work off grid and is therefore quite safe and sustainable. It will also be resilient to global climate change, but the temperature and humidity levels may be slightly altered according to the ambient conditions.

Figure 10. A purpose build storage for a collection of cultural history, Ribe, DK. The concrete floor has no thermal insulation to allow thermal buffering by the ground. The thermal insulation in the ceiling and walls is designed to allow an annual temperature variation between 8 °C and 16 °C. Photo: Poul Klenz Larsen.

Figure 11. The interior of the Ribe storage has a 6 m ceiling height and mezzanine with racks and compactors. The ducts below the ceiling is for inlet of dry air for humidity control in summer. Photo: Poul Klenz Larsen.

Conservation heating with humidity buffer

This concept is relevant for any new or existing storage space with good thermal insulation and inexpensive, sustainable heating. It is particularly useful if the store is an integrated part of a building heated to constant temperature for human comfort. The storage temperature is not constant but adjusted to keep the relative humidity moderate. Heating to low winter temperature for humidity control is an established practice for historic houses or churches, often referred to as conservation heating. Likewise, temperature control can be used all year to keep the RH moderate. The inside temperature will always be higher than the outside average and follow the gradual variation over the year.

The archive of the Arnamagnean Institute in Copenhagen has worked this way for many years with perfect stability (figures 12–13). The archive occupies one room on the second floor in an ordinary office building, next to heated spaces [14]. A multi-layered structure encapsulates the archive. The load bearing structure of the building is 240 mm concrete walls and floors, which gives some thermal inertia to the archive. Thermal insulation is 200 mm mineral wool between the archival room and the heated offices, but only 50 mm toward the outside. The thermal insulation was designed to allow the temperature inside the archive to drift half way between the outside temperature and the office temperature. An annual temperature variation between 14 and 23 °C was achieved without any regulation within the archive.

A small ventilator is installed to take in outside air on occasions when the water vapour content is right for pushing the interior RH towards the specified ideal. Supplementary humidity control is provided by an inside lining with porous lime-silicate blocks. This material has the ability to absorb and release water vapor as the ambient relative humidity changes. This combination of controlled ventilation and humidity buffer keeps the RH within 50–60% all year, with very little fluctuation.

Figure 12. The repository for the Arnamagnean Collection of medieval manuscripts is located in an office building behind the windowless part of the façade. Copenhagen University, DK. Photo: Morten Ryhl-Svendsen (CC BY-NC-ND).

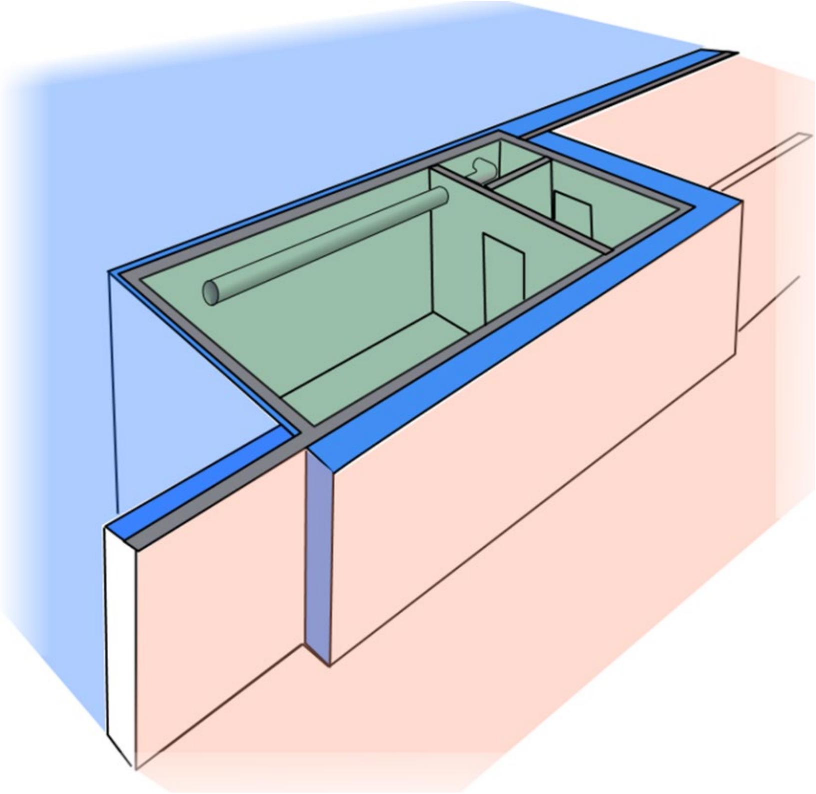

Figure 13. Principal skectch of the archive room located in the corner of the building. The adjacent office space is heated to comfort temperature in winter. The different thickness of thermal insulation (blue) is designed to give an annual temperature variation between 14 °C and 23 °C. Illustration: Tim Padfield ©.

Climate modelling

A simple way to predict the interior climate is by considering the monthly average for the outdoor climate. Statistical data is provided by the national meteorological institute or can be found in databases on the internet. Data for Visby, Sweden is shown in the table below.

Table 2. Statistical data for the monthly average temperature and relative humidity in Visby, Sweden. [6b]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°C)	-1	-1	0	4	9	14	17	17	12	6	4	2
Relative humidity (%RH)	85	83	82	77	73	74	77	80	83	84	85	87

The calculations are done in a spread sheet using the formula below.

Saturation vapour pressure:	p (sat) = 610,78*EKSP(T/(T+238,3)*17,2694))
Vapour pressure:	p = p(sat) * RH/100
Relative humidity:	RH = p/p(sat) *100

An example using the monthly average data from Visby is given in Figure 14–16. The outside average temperature and relative humidity is shown with blue points, each representing a month in the year. The connecting lines are only to help the eye and should not be interpreted as a continuous cycle. The monthly average temperature in Visby ranges from -1 °C in winter to 17 °C in summer. The daily maximum or minimum temperatures can be much different from this, but these extremes will not affect the interior conditions.

Unheated, dehumidified building

For an unheated, dehumidified building, the calculation is quite simple. The inside temperature is the same as the outside, so each point is moved vertically to get below 60%RH. The surplus of water vapour must be extracted from the air by dehumidification. As a consequence, the water vapour pressure of the inside air is reduced. This is shown with the grey diagonal lines in the diagram. In summer, the vapour pressure is lowered from 1500 Pa to 1000 Pa, and in winter from 500 to 300 Pa. Dehumidification is needed all year, but the dehumidifiers work hardest in summer.

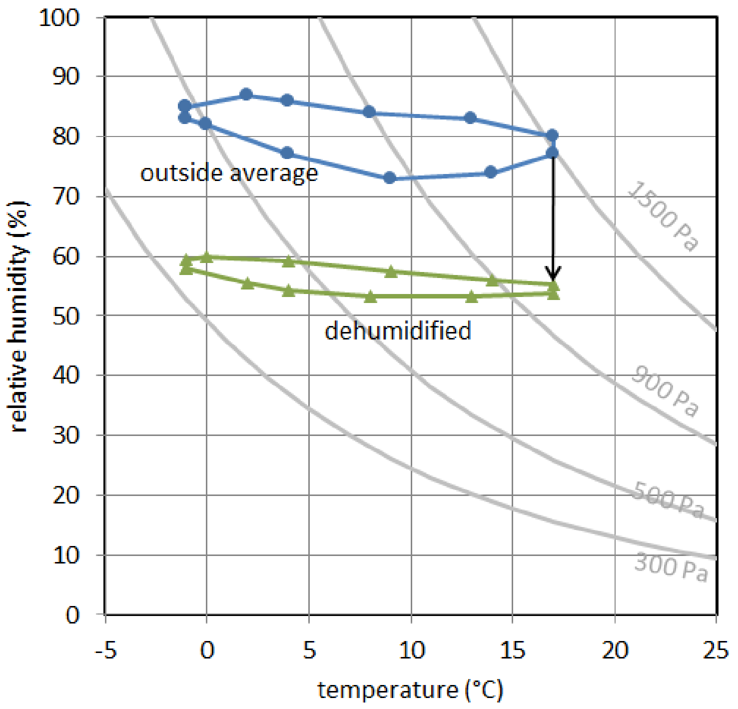

Figure 14. A simple calculation of the monthly average temperature and relative humidity in an unheated, dehumidified storage building, located in Visby, Gotland.

Building with conservation heating

Figure 15 shows the estimated climate for a store with conservation heating. The temperature for each month is adjusted so that the RH gets below 60%. To achieve this, the temperature range is between 5 °C in winter and 23 °C in summer. Heating is needed all year, also in summer. The is no removal (or addition) of water vapour, so the points move diagonally along the lines of equal vapour pressure.

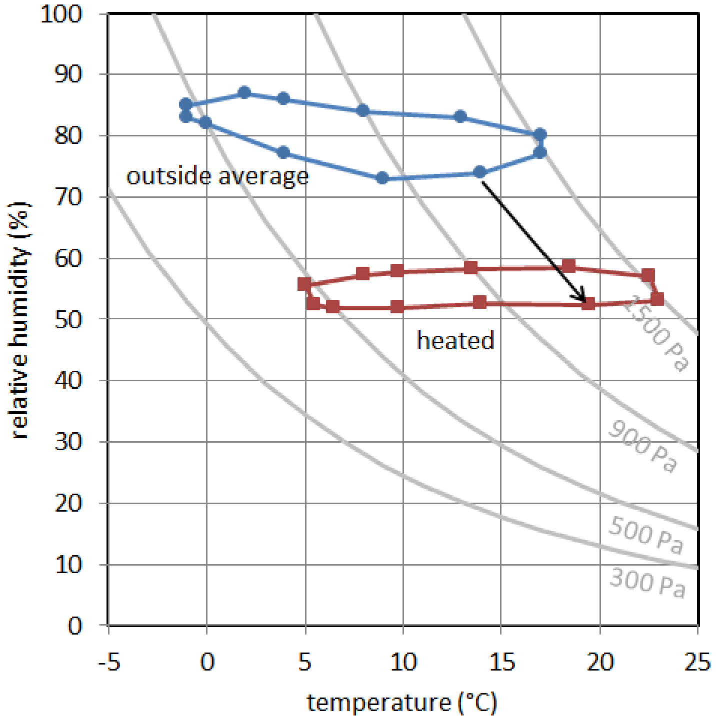

Figure 15. A simple calculation of the monthly average temperature and relative humidity in an storage building with conservation heating, located in Visby, Gotland.

Buildning using temperature buffer and dehumudification

Figure 16 shows the climate in a store with a combination of temperature buffer and dehumidification. First, the minimum and maximum temperature inside is determined by reducing the amplitude of the outside average cycle by 50%. This will give an annual temperature span of 9 degrees centigrade, ranging from 5 °C in winter to 14 °C in summer. The temperature is offset by 2 °C from the annual average because of the heat gain from the sun and internal loads.

The average indoor relative humidity for each month is calculated with this new temperature, assuming the vapour pressure inside is equal to the ambient. Without any humidity control, the relative humidity will be in the range 40–100%RH, shown graphically by the red cycle Dehumidification is needed to keep the RH below 60% most of the year, except for the winter. This is done by reducing the vapour pressure just enough to lower the RH, as shown with the green cycle.

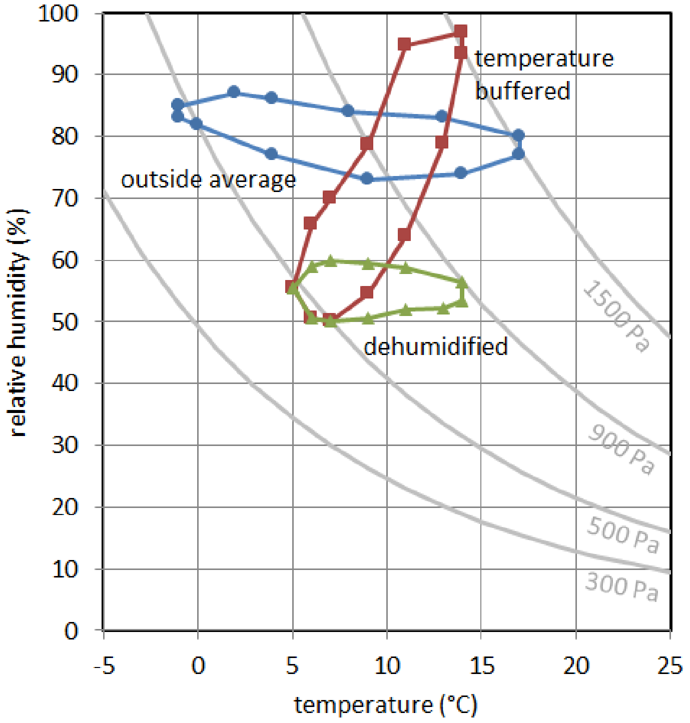

Figure 16. A simple calculation of the monthly average temperature and relative humidity in a temperature buffered and dehumidified storage building, located in Visby, Gotland.

Energy considerations

The energy consumption of several storage buildings in Denmark is shown in figure 17 and compared to conservation quality in terms of relative chemical reaction rate. The reaction rate is normalized to that of 20 °C and 50%RH, following the approach of Sebera [24]. All data points refer to places described in [22]. They are comparable in the sense that they are located above ground in a Danish temperate climate, but differs in the construction of the building envelope and climate control systems. Blue data points represent un-heated and dehumidified buildings. Green points are conservation heated in winter, and red points are buildings with various degrees of air-condition. There is a correlation between low energy consumption and good preservation. The linked reduction in cost and improvement in object durability is mainly attributable to allowing an annual variation in temperature.

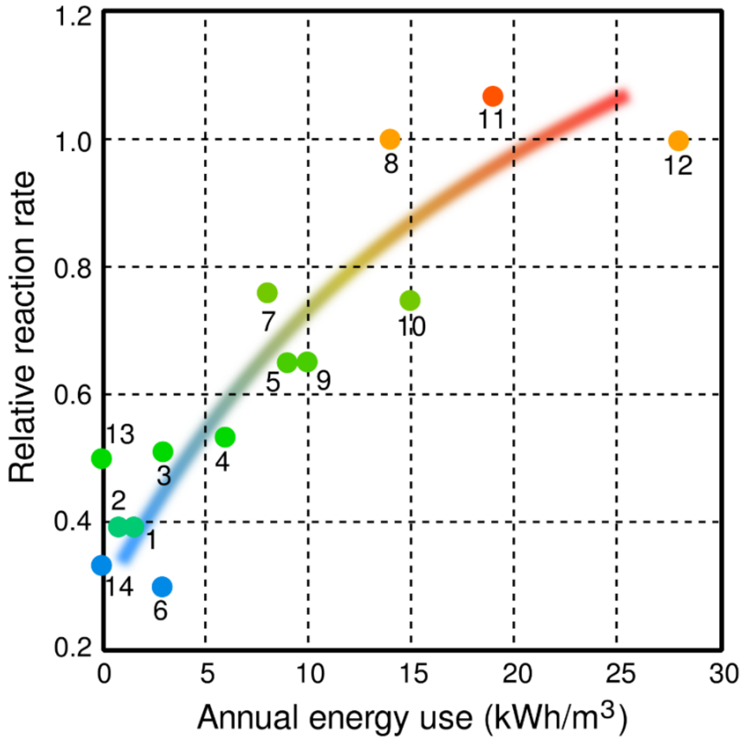

Figure 17. The link between energy consumption in several storage buildings in Denmark and the conservation quality in terms of relative reaction rate as shown in figure 1. Illustration: Morten Ryhl-Svendsen (CC BY-NC-ND).

The principles of low energy climate control do not need a constant feed of energy. The buildings will cruise over temporary interruptions in supply without noticeable deterioration in the interior conditions. This makes them ideally suited to solar energy or wind power, which is naturally variable. In the case of a building the size of the Ribe store, about 5% of the roof covered with solar panels will provide the necessary energy for dehumidification, which is mostly needed in summer [23]. A small wind turbine will give enough power for conservation heating in winter. This gives an opportunity to run a museum store or an archive entirely without external energy supply.

Air quality

Air pollution

Air pollution includes gases or particles in the air [28, 18]. Gases can interact with materials by oxidation or via acid formation with the humidity of the air, and thereby participate in chemical reactions such as corrosion, salt formation or acid hydrolysis. Salts in particle form can attract moisture and, for example, initiate corrosion of metals. Particles can physically affect material surfaces with dirt, scratches, be a food source for insect pests and microorganisms. A high dust load can make it necessary to clean objects frequently. This can cause greater wear and tear on the objects.

Air pollution originates from natural or man-made sources in the outdoor environment [4]. These include ozone (O_3) which is formed atmospherically, nitrogen oxides (NOx) which are formed by combustion, primarily from car traffic, and sulfur compounds which can have both industrial (SO_2) and natural sources (H_2S). Particles can have very different sources and thereby different chemical composition. The smallest fractions are formed primarily by combustion, including car traffic, while the coarser particles are formed by wear and tear of materials, e.g. sand, plant residues, etc. In coastal areas, the air may contain salt particles.

Indoors, air pollution occurs as evaporation from building materials or other objects, especially if these are stored in large quantities. Here, a distinction can be made between substances released for a short time, but in high quantity when new materials are dried, or by lower but constant degassing of substances throughout the entire lifetime of a material. The first can occur, for example, with new paint, varnish, sealant, etc., where volatile organic compounds (VOC) are released when the material hardens. Examples of continuous degassing from materials are acetic and formic acid from wood and wood products. Some types of plastic can release acid during the materials own decomposition. In some cases AD strips can be used as a cost effective way for showing if the air is acidic. [16]

Ventilation

The purpose of mechanical ventilation in workspaces or homes is to take in ‘fresh’ outside air and remove ‘used’ air from the interior. It is mainly used to reduce a surplus of heat, moisture, pollutants or smells. Ventilation is usually assuming the outside air is a benefit, but this is not the case for a museum storage or archive. As described above, the outside air is not clean and needs filtering before it is let into the building. Filters reduce air speed and increase the energy consumption for ventilation. If the outside air is dirty, the filters need frequent replacement, which is expensive. There is a good argument for keeping the ventilation rate low.

Museum stores and archives described in this publication are not intended for permanent occupation by people. Workshops and offices are therefore separated from collections. By separating people and collections, there is little need for ventilation to provide for human health and comfort in a store. The intake of outside air should be limited to keep away external pollutants and to minimize climatic disturbance. However, the outgassing of components from the collection or from the building itself may reach high concentrations due to the low ventilation rate. The balance between internal and external pollutant is illustrated in figure 18.

Internal pollutants are partly prevented by the proper choice of inert materials and finishes for the building and the storage shelving. [15] Wooden materials should be avoided because of the emission of corrosive volatile compounds, especially acetic acid. Contaminants originating from the collection itself can be removed by air filtration through carbon filters in a recirculating system. [17] However, the cost and effort of air filtration can be questioned from a cost-benefit perspective [9]. Some interior finishes also provide some control by passive absorption of pollutants [20]

Measurements in the Ribe storage building and other Danish low-energy museum stores have revealed lower than expected concentrations of indoor pollutants. This is attributed to the low temperature inside those buildings, which slows down the off-gassing from materials – yet another benefit of maintaining an unheated environment. A recent study has confirmed, that low temperature does indeed reduce the concentration of internally generated pollutants [27].

A special problem exists for collections, which have previously been treated with biocides. These must be cleaned before they are stored at a low ventilation rate, in order to minimize the potential re-evaporation of biocides into the air. In such cases, health regulations may require constant ventilation, which will make low-energy storage impossible.

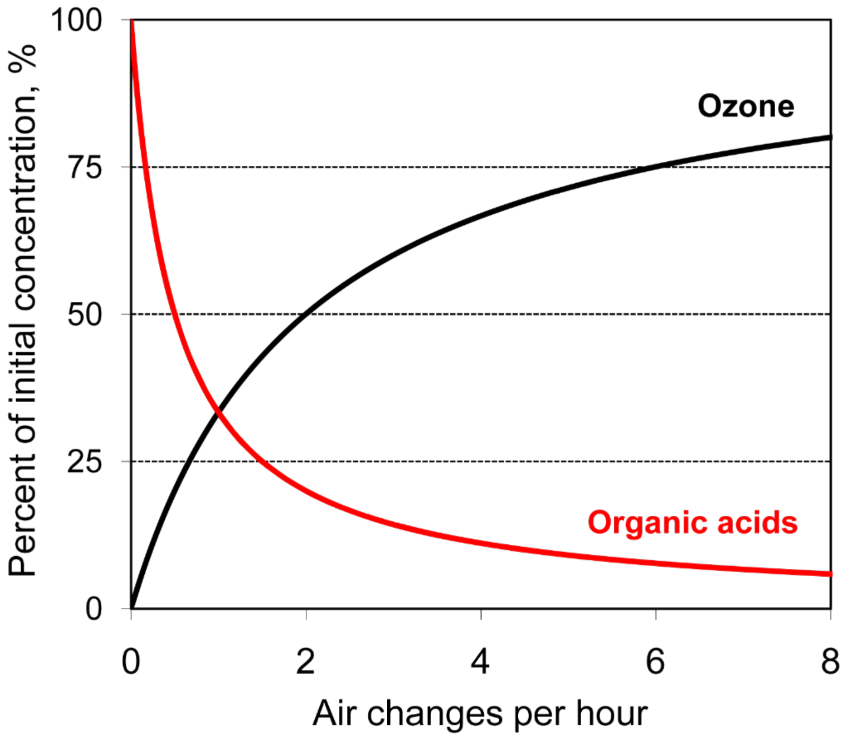

Figure 18. The balance between internal and external pollutants depend on the air exchange rate. A large intake of outside air will reduce internal pollutants such as organic acids, but at the same time increase the concentration of ozone and other external contaminants. Illustration: Morten Ryhl-Svendsen (CC BY-NC-ND).

Methods for dehumidification and heating

Condensing dehumidifier: There are two methods for removing water vapour from atmospheric air. One is by condensing the moisture in a cooling coil and drain the water away. This method is used in standard air handling units as the first stage for air conditioning (figure 22). It is also common in moveable units intended for temporary use in building sites or for drying after water damage. The moveable dehumidifiers are available in numerous shapes and sizes, but they all contain the same basic elements: A compressor and a reservoir for the cooling liquid, a heating unit and a cooling coil, and an electric fan to move the air through the assembly. The dehumidifier is controlled by a humidistat, either external or build-in. The condensing dehumidifier does not work below 8–10˚C unless it has intermittent defrosting to remove ice on the cooling unit. This method is appropriate for buildings with some basic heating or where dehumidification is used mainly when the ambient temperature is above 10 ˚C.

Absorption dehumidifier: The other method for dehumidification is by absorption of moisture in a desiccant and subsequently releasing the moisture by warm air (figure 20, 21). Most products contain a rotating desiccant wheel, where the silica gel is integrated in a perforated metal cylinder. This way the accessible surface is enlarged to facilitate the fast uptake and release of the water vapour. The process air is led through one segment of the cylinder, whereas the regeneration air passes through a different segment. As the cylinder slowly revolves both processes takes place at the same time. In most models, the warm and humid air is released to the outside. The absorption dehumidifier works at low temperatures, even below zero, but at a higher cost. This method is therefore favorable in unheated storage rooms or buildings.

The capacity needed depend on the size of the room or building, the air exchange and the moisture sources in the building. Most suppliers offer diagrams of performance for each model, which may be useful when choosing the appropriate type and size. The volume of the building or room multiplied by the air exchange rate gives the volume of air, which needs dehumidification. This volume is then multiplied by the difference in absolute humidity between inside and outside to give the amount of water in grams. The difference in absolute humidity is estimated by the climate specification and statistical data for the outside conditions.

The capacity of the dehumidifier depends on temperature. Less water is extracted at lower temperature, but this is compensated by the fact, that the water vapour content is lower at low temperature. The energy use of a dehumidifier depends on the temperature and relative humidity. Both condensing and absorption dehumidifiers perform best at normal comfort temperature and high RH. Empirical data for the condensing dehumidifier give an energy consumption of 0.5–2.0 kWh/kg at 20 °C and 60% RH [1]. This energy input is retained as heat within the building. An absorption dehumidifier uses more energy than a condensing dehumidifier per kg of water removed from the air. The energy use is 1.5–2.5 kW/kg at 50% RH in the temperature range 0–20 °C. Of the energy used, the heat of evaporation for water is 0.67 kWh/kg, This energy is lost, unless the dehumidifier has heat recovery or a condensing unit.

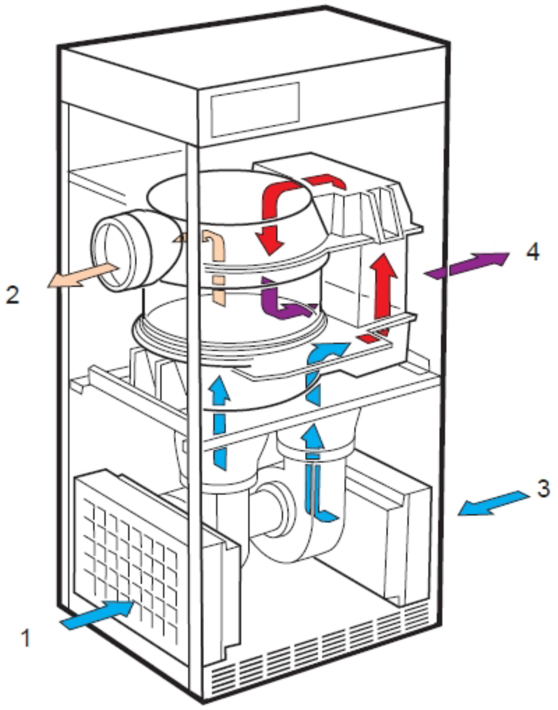

Figure 19. The principle of operation for an absorption dehumidifier. Air from the store room (1) passes through a filter and the desiccant unit and let back again as dry air (2). A separate stream of outside air is drawn through a filter and a heater, and then passes another segment of the desiccant unit to remove the humidity to the outside (4).
Design: Munters AB ©.

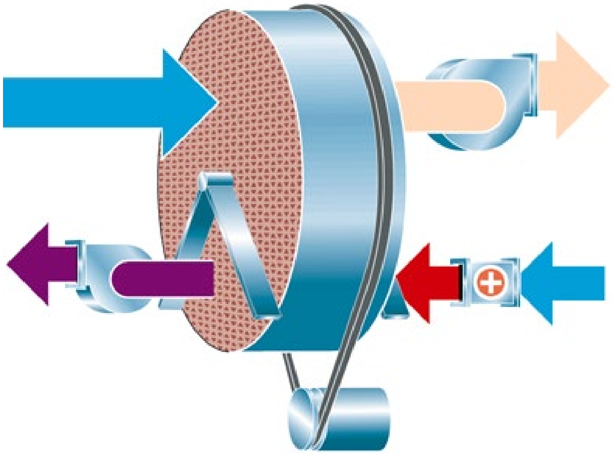

Figure 20. The desiccant unit contains a revolving cylinder with many narrow perforations. The internal surface of each narrow tube has a desiccating surface coating. When the humid air passes through the tubes, water molecules are absorbed by the coating. A separate warm air stream forces the water molecules to evaporate from the desiccant and removes it from the unit. Design: Munters AB ©.

Heating

The safest way to heat a space or a building is to locate the heat source outside and let the heat in by transmission through the walls. Warm air heating systems are also quite safe, because they use air as a conveyor of heat. The warm air is distributed through ducts which connect to a unit with a fan to recirculate the air through a heat exchanger and dust filters to remove particles from the returned air. Sometimes an air heating system is integrated with dehumidification in an air handling unit (figure 22). Automatic valves are compulsory as a precaution against smoke, fire or water.

The inlet temperature should not be more than 40 °C to avoid large temperature differences within the room. Still the warm air tends to rise up fast and develop a vertical temperature gradient in rooms with high ceilings. Air has poor thermal capacity, so much air need to be circulated in order to bring enough heat into the room or building. The ducts therefore need to be quite large. Usually the ducts are installed in the attic, in the basement or below the floor. Warm air heating systems are powered by electricity, hot water from district heating or by heat pumps.

Electric heaters are not recommended for museum stores due to the risk of fire. Central heating with radiators and heat pipes located in the storage spaces is also not appropriate, because a leak can cause much damage to the collection.

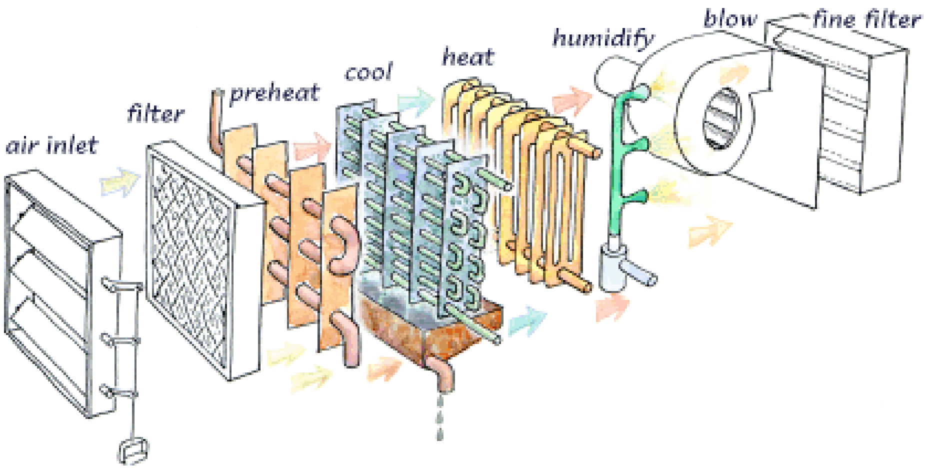

Figure 21. The basic components of an air handling unit. A fan to move the air and filters to remove dust and particles. A cooling coil to dehumidify the air, and a heating unit to raise the temperature. The humidifier is not needed in the low energy climate control concept. Illustration: Tim Padfield ©.

Building structures and materials

The building envelope

The building envelope is continuously exposed to the climatic conditions given by the natural environment. It is the outside temperature and humidity that governs the loss and gain of heat and moisture in buildings. The ability of the building to shield the interior climate against the exterior influence depends on the location, the architectural design and the materials and thickness of the structures. Of particular importance is the size and orientation of the windows, because they are sources of heat gain and loss by radiation. A purpose built storage should not have windows. In a reused building, the windows should be blinded. The air tightness of the building also has significant influence on the climatic stability, because heat and humidity is exchanged by infiltration of air.

For a purpose built storage, the building envelope is designed by computer modelling of the hygro thermal performance. A virtual model of the building allows for testing many different designs of the walls and ceiling, particularly the thickness of the thermal insulation. In general, building simulation can predict the temperature quite precisely, whereas the relative humidity is not always so reliable. In stores with a large quantity of hygroscopic material, such as archives, the humidity buffer effect is often under estimated.

Modelling of the ground temperature in stores with uninsulated floors is also a challenge. Most programs use a fixed ground temperature or an annual sinusoidal variation, which may lead to a false result. The model must incorporate the soil below the building into the calculation in order to reproduce the dynamic change in temperature over the seasons. This is not a standard feature for commercial programs for building simulation. Figure 22 shows a computer generated model of the ground temperature below a storage building with an uninsulated floor [6].

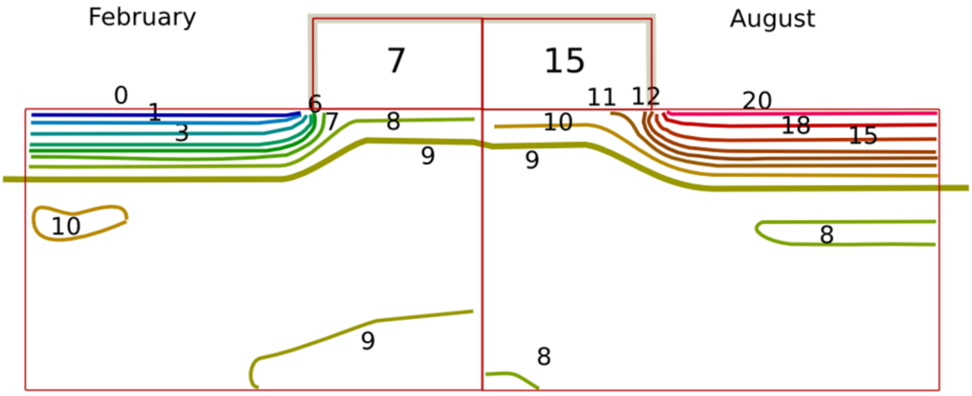

Figure 22. Computer modelling of the ground temperature below a storage building with an uninsulated floor, similar to the Ribe store in figures 10–11. Illustration: Morten Ryhl-Svendsen (CC BY-NC-ND).

Thermal inertia

Thermal inertia is a combination of the thermal conductance and heat capacity of a material. Heat capacity is the amount of heat required to change the temperature of a material by a given amount. Heat capacity is almost proportional to the density of the material, whereas heat conductivity is inverse proportional to the density. A concrete wall has a large thermal capacity and thermal conductance, whereas a light weight wall filled with mineral wool has small heat capacity and thermal conductance. Because the two thermal properties combine, the two walls provide the same thermal inertia.

The typical northern European weather has two superimposed temperature cycles: The annual cycle, which ranges from an average of -10 °C in winter to 20 °C in summer, and the daily cycle, which may span over 15 degrees centigrade in summer. There are two ways to moderate the daily cycle. One is to make the walls and ceiling heavy so that it has a large heat capacity, like the Vaerlose shelter shown in figure 9. This construction does not impede heat flow, but concrete absorbs the heat so it does not reach the inner space. However, it is not necessary. The same damping of the daily cycle can be attained by lightweight thermal insulation. The difference is that the heat flow into the wall is much smaller, and less heat is absorbed by the structure.

Figure 23. Heavy walls and ceilings have a large thermal inertia, which can even out the daily temperature fluctuations, but not the change in temperature from winter to summer. New library, Zografu Monastery, Mount Athos, Greece. Photo: Poul Klenz Larsen.

Dampening the annual cycle by absorbing the heat flow in the same way as for the daily cycle would require much thicker walls, of about four meters. Some historic houses or military bunkers have very heavy structures to resist bombardments. Basements also benefit from the inherent temperature stability of the ground. They maintain a stable temperature which is close to the annual average of the ambient temperature above ground. The main problem with underground spaces is the risk of flooding. Natural caves and tunnels have been used for museum storage in times of war for security reasons. More recently, abandoned underground facilities have been adapted for permanent storage (National Library, Mo-i-Rana, Norway).

Humidity buffer

Humidity buffering by water vapour reactive materials (also called hygroscopic) has been used for many years for showcases and transport boxes. Likewise, the relative humidity inside storage spaces with a low air exchange rate can be moderated by an abundance of hygroscopic materials. The main benefit of humidity buffering in museum stores is on the short time scale, hours or days. Most industrial building materials have little humidity buffer capacity, but a wall lining of unfired brick will provide this effect. Buffering for weeks or months is only feasible for collections with so much cellulosic material, as paper records and cardboard containers, that itself provides sufficient humidity buffering.

The humidity buffer effect in a dynamic situation was studied in [13]. The sorption of water vapour by a test surface was continuously measured during a regular relative humidity cycle. The vapour absorbed by one square metre of exposed surface on the upward swing of the relative humidity was re-calculated to the equivalent volume of space, which will experience the same change of relative humidity with the same injection of water vapour as has entered the absorbent material. This equivalent volume will depend on the time required for a relative humidity cycle, because of slow diffusion within the material. Some experimental results are given in table B.

Table 3. Experimental data for the humidity buffer capacity (or B-value) of some building materials in the range 40–60%RH. The numbers indicate the virtual volume with the same humidity absorption capacity as one square meter surface in a 24 hours or 92 hours cycle. Static is the value for complete moisture equilibrium throughout the thickness of the specimen.

Material	Thickness (mm)	24 hours	96 hours	Static
Cellular concrete	50 mm	7	9	17
End grain pine wood	40 mm	15	34	122
Unfired clay brick	53 mm	10	21	165
Unfired perforated clay brick	53 mm	27	58	136
Unfired perforated clay brick	106 mm	39	95	272

A wall lining of 106 mm unfired, perforated clay brick has a humidity buffer value (B-value) of about 100 for a four-day cycle of relative humidity. This means that one square meter of wall imitates the sorptive capacity of 100 m^3 of space. When all the absorbent surface B-values are summed up this way, the building will have a virtual volume many times its actual volume. For a museum store, with mostly metal objects and little absorbent material, this 'virtual volume ratio' may be about 10 or less. A storage containing a large amount of hygroscopic objects and wall lining, could have a virtual volume ratio around 50. For an archive filled with paper, the ratio can on the order of several 100s to 1000 times the actual room volume.

The concept of virtual volume (or B-value) can be used for building simulations this way: The virtual model is defined with interior surfaces impermeable to water vapour. The air exchange rate is set to a value, which is the expected infiltration rate divided by the B-value. This will generate a simulation of RH, which takes into account the humidity buffer effect.

CO_2 footprint and life cycle analysis

In a low-energy storage building, the energy used for the building materials becomes dominant from a life cycle perspective. Most industrially manufactured materials need large amounts of (fossil) energy for the production and transport. The embedded energy in concrete and brick is large compared to a building made of wood or unfired clay. The CO_2 footprint over the lifetime of a concrete building may be large even if it is not heated in winter. As previously mentioned there is no need for a low-energy storage to have heavy walls. The thermal stability can be achieved in a light weight building with highly insulated walls and ceiling. However, there are other requirements such as fire safety or security, which may not be fulfilled by light weight structures.

Existing buildings represent energy and CO_2 emissions, which has already been spent. If the building can be reused for storage with little energy consumption for climate control, this may be advantageous in terms of CO_2 emission in a life cycle analysis.

Conclusion

Most materials and objects are well preserved at a gentle, annual temperature variation and a moderate relative humidity. A low temperature will retard chemical degradation and prevent biological attack. Therefore the inside temperature in museum stores and archives should not be constant all year for human comfort, but allowed to follow the outside annual cycle. A storage building should only be heated as little as needed, and the temperature should never be so high, that the relative humidity becomes too low. Dehumidification is used for supplementary humidity control, whereas humidification should never be necessary. This will ensure a moderate relative humidity and reduce the risk of mechanical damage.

This is the fundamental concept for sustainable museum storage, which is developed into three generic models. The simplest is to avoid winter heating and control the relative humidity by dehumidification all year. This category is mainly relevant for existing buildings used for storage, either temporarily or permanently. A more refined model is to use the ground as temperature buffer in combination with dehumidification in summer. This climate control strategy is mainly relevant for purpose build storage facilities. A third possibility is to combine conservation heating with humidity buffer. This concept is relevant for any new or existing storage space which is an integrated part of a building heated to constant temperature for human comfort.

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