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Poul Klenz Larsen[1] and Morten Ryhl-Svendsen[2]*

ABSTRACT. The energy needed for climate control in a museum storage building can be greatly reduced by allowing a moderate annual temperature cycle. The energy saving is achieved partly by abandoning heating or cooling and partly by a less strict humidity control. Temperature moderation can be provided by the building itself. The proposed system is a highly thermally insulated building envelope with an uninsulated floor directly on the ground. The inside temperature is allowed to vary freely, buffered by the large heat store of the ground. Such a structure will completely even out the daily temperature variation and reduce the annual temperature amplitude to about half the average outside cycle. In a northern European temperate climate, the inside temperature will span less than 10°C. The relative humidity is buffered by hygroscopic materials or controlled by mechanical dehumidification. This climate control strategy relies on an almost airtight building with an air exchange rate of less than one air change per day and consumes annually as little as 1 kWh per cubic meter space. Relative humidity is easily controlled within the 40%–60% range, which is acceptable for most materials and conforms to all standards. Mechanical failure caused by this temperature variation is unlikely for most objects. However, some standards propose contradictory temperature limits. The reason might be due to recommendations that are intended for both storage and exhibition spaces, whereas temperature constancy is mainly for the benefit of human comfort and should be implemented only in permanently occupied buildings.

INTRODUCTION

This paper presents a generic model for museum and archive storage with very low energy consumption. The principle is being applied in two different locations, Ribe, Denmark, and Washington, D.C., but is suitable for any temperate climate zone. 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 humidity control takes advantage of the weather pattern and combines humidity buffering with either winter heating or summer dehumidification. The building structure is designed to provide moderate variations in temperature and relative humidity, which calls for unusual but less expensive solutions. Orthodox air conditioning is not needed, as the described climate control system is simple to install and cheap to operate. The simplicity of the mechanical equipment affords better security against climatic failure than highly sophisticated machinery.

Unfortunately, the most influential environmental advice for museums is incompatible with the most economical climate control system. The latest version of the former British Standard 5454, now a "published document" (PD 5454), recommends 13°C–20°C for mixed archives (British Standards Institution [BSI], 2012), and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) guidelines for museums, galleries, archives, and libraries suggest

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15°C–25°C for class A control (ASHRAE, 2015). This temperature range was also adopted by the joint declaration by the International Institute for Conservation of Historic and Artistic Works (IIC) and International Council of Museums–Committee for Conservation on environmental guidelines (IIC, 2014). However, the lower limit, 13°C–15°C, cannot be maintained by buildings that follow the annual average temperature.

If the standards are rigidly imposed, these limits will prevent the implementation of the simplest and cheapest temperature control in museum and archive storage. However, scientific studies of the degradation of materials provide slender evidence that these temperature ranges are justified. Broader impacts can affect historic structures where upgrading may be restricted.

CONSERVATION CONSIDERATIONS

Chemical Degradation

A large number of reactions leading to the decay of museum objects belong in the general category called hydrolysis: the addition of water to a polymer, resulting in the breaking of the polymer chain molecule. The rate of decay increases exponentially with rising temperatures. The water required for the hydrolysis reactions is provided by the relative humidity (RH), and its potential to engage in chemical reactions—the so-called water activity—is directly proportional to the RH.

The effects of temperature and relative humidity were elegantly combined by Sebera (1994) into curves of equal degradation rate, which he called isoperms. The diagram in Figure 1 shows the curves of equal degradation rate relative to a constant climate at 20°C and 50% RH, which is set to 1. It is evident that at a moderate relative humidity level, temperature is the dominant factor. Superimposed on the diagram are the climate ranges proposed by PD 5454 (BSI, 2012) and by ASHRAE (2015) class A. The blue oval representing a dehumidified indoor climate reflects the climate range in the purpose-built, low-energy storage building in Ribe, which will be described later. This store does not comply with the recommendations, yet the chemical durability of the collection is better because of the lower winter temperature.

The Sebera diagram relates widely to organic reactions but not to ionic and crystal rearrangement 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 (Shashoua, 2008), but their diffusion rate also diminishes, so cooling usually favors durability. The history of good preservation of movie film in cold storage demonstrates this.

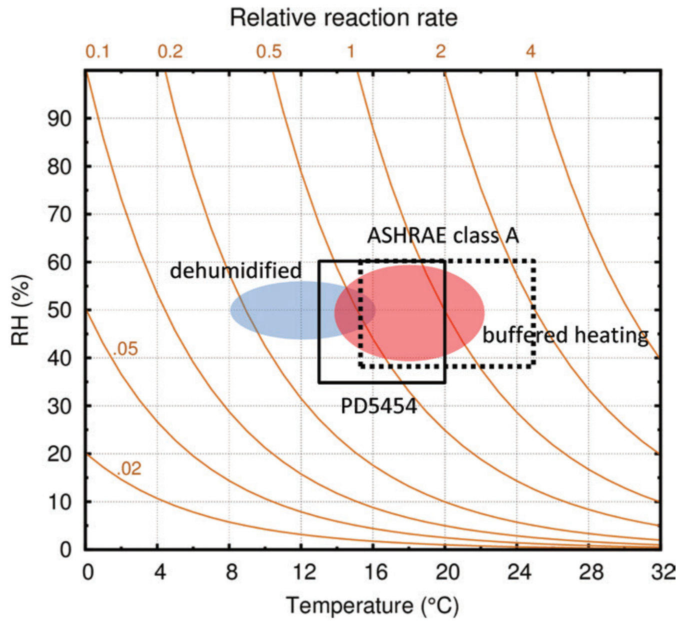

FIGURE 1. The Sebera isoperm diagram showing curves of equal chemical reaction rate relative to the rate at 20°C and 50% RH. The relative reaction rate is marked on each curve. The curves are calculated for an activation energy of 100 kJ. The preservative effect of low temperature is evident, but low relative humidity only really gives improved durability when it is very low, at a value that would cause serious mechanical stresses to the many laminated and jointed hygroscopic objects in museum collections. The climate envelopes for PD 5454 (BSI, 2012) and ASHRAE (2015) class A and two low-energy climate-control principles are superimposed on the diagram.

Mechanical Degradation

Mechanical damage caused by too high or too low temperature is a source of worry for many conservators. A variety of materials have the capability of losing flexibility, that is, an increase in rigidness, when temperature decreases. Therefore, for objects made of very soft materials, such as wax or grease, storing at a cool temperature is critical for their conservation. 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 (T_g), 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 (Shashoua, 2008).

It must be emphasized that damage following the increased stiffness at decreasing temperature is only a problem in combination with physical impacts (sudden shock, rough handling, etc.). There is no mechanical implication for objects that are simply stored at cool temperatures, even well below their glass transition temperature. Delamination issues when materials with different dimensional change upon cooling react with each other become a real problem only well below 0°C.

Paints are among the materials that are susceptible to damage at low temperature, especially when adhered to a support, such as canvas, which allows flexing by physical impact. For oil paint, T_g is below 0°C. For acrylic paints, T_g is typically between 5°C and 10°C (Michalski, 1991; Mecklenburg, 2007).

For a large, mixed collection, there will always be a few objects with special climate requirements that are not fulfilled by the conditions maintained in a general storage environment. Most often, these materials require a relative humidity diverging from normal room conditions (e.g., rusty iron, which must be kept very dry). Acrylic paint with zinc white is another such material; it becomes very stiff and delaminates easily at low temperature, as reported by Mecklenburg (2007). For such particularly fragile objects, alternative storage solutions must be found if, for example, the general storage conditions allow for a winter temperature below T_g of a component. Still, temperature has little significance with regard to mechanical damage to such objects during normal and professional handling of the general collection.

Biological Degradation

Biological activity is mainly controlled by keeping relative humidity below about 60%. This level will prevent breeding of most insects and germination of most species of mold. An additional benefit of a cold environment is the inactivity of most insects at temperatures below about 10°C. The development of mold and fungus is also prevented by low temperatures.

TEMPERATURE CONTROL

Our starting point is typical northern European weather. There are two superimposed cycles: the annual cycle, which ranges from an average of –5°C in winter to 20°C in summer, and the daily cycle, which may span over 15°C. There are two ways to moderate the daily cycle inside a building. One is to increase the heat capacity of the wall. This does not impede heat flow, but concrete or brick absorbs heat, so it does not reach the inner space. High thermal mass is advocated in the standards and guidelines for museum storage, notably PD 5454 (BSI, 2012). However, it is not necessary because 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. 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 4 m. The necessary thickness of an insulated wall could be reduced, depending on the heat capacity of the stored collection. A cheaper solution combines thermal inertia with insulation, using the ground beneath the building as a heat store, combined with thermal insulation of the superstructure (Bøhm and Ryhl-Svendsen, 2011; Ryhl-Svendsen et al., 2011).

The museum storage building in Ribe has insulated walls and ceiling but an uninsulated floor, placed directly on the ground. Its floor dimension is 24 × 45 m, and the undivided interior space is 6.3 m high. It was described in detail by Ryhl-Svendsen et al. (2011, 2012a), and a detail from the storage hall can be seen in Figure 2. The measured temperature inside and outside the building is shown in Figure 3. The 8°C annual temperature cycle amplitude is an easily attainable moderation of the outside temperature. One could achieve a smaller amplitude, but that would make humidity control more expensive, as discussed later. The floor functions as an effective cooling surface in summer, but the temperature difference between the floor and ceiling is rarely more than 2°C, corresponding to a 6% difference in relative humidity. There is no need to insulate the area beneath the perimeter of the building. The edge effects are small, and after a few years of operation, the ground beneath the building becomes, thermally, part of the building (Figure 4).

RELATIVE HUMIDITY CONTROL

Dehumidification

The relative humidity arising from the diminished annual temperature cycle acting on the slowly infiltrating air will be moderate in winter because of the higher than ambient temperature. At the Ribe storage site, the temperature buffering from the ground gives a winter temperature sufficiently above ambient temperature that it holds the relative humidity above 45% (Figure 5). The water vapor concentration balance is almost even during the period from December to March. However, during the summer, dehumidification is necessary because the indoor temperature is well below the ambient one, so the relative humidity would rise to 100% with no intervention. The relative humidity could be reduced by allowing more direct solar heating of the building through the roof. But the advantage of maintaining a lower temperature is improved collection durability, and a better use of solar energy is running the dehumidifiers, rather than direct heating (Ryhl-Svendsen et al., 2013). As shown in Figure 5,

FIGURE 2. A section of the compact shelving inside the Ribe storage building. The height is about 6 m. Objects made from wood, textile, cardboard, and other hygroscopic materials are present in large quantities.

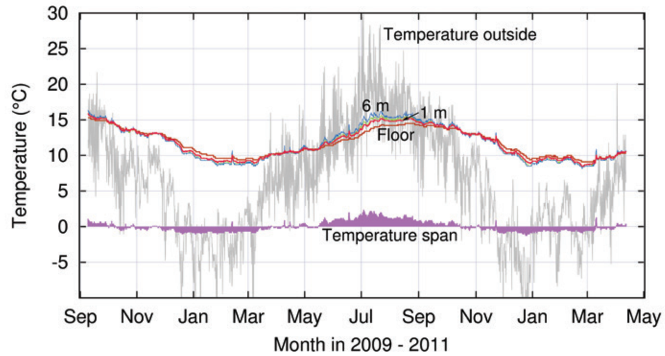

FIGURE 3. The temperatures measured in the Ribe storage building. The inside temperature cycle is reduced to an 8°C amplitude by temperature buffering from the floor. The graph also shows the very small variation in temperature with height inside the storage room. The filled trace shows the maximum temperature difference within the building. Even in summer, when warm air would be expected to accumulate at the ceiling, there is less than 3°C temperature difference between the floor and the ceiling 6 m above. The gray trace is the outside temperature.

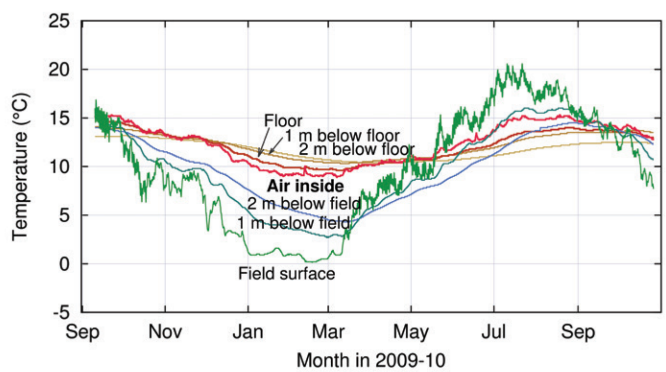

FIGURE 4. The temperature distribution under the uninsulated floor at the center of the Ribe storage building after several years, compared with the temperature at various depths as well as of the surface of the nearby open field.

the dehumidifiers use energy almost only in summer, when solar power is abundant. If a building is airtight, the dehumidification load is very small, and sufficient power can be provided by solar voltaic panels on the roof (see Energy Considerations).

Humidity Buffering

Hygroscopic materials absorb and release water vapor as the ambient relative humidity changes. The relative humidity can be moderated by an abundance of hygroscopic materials within a confined space. Humidity buffering has long been used in small enclosures such as showcases and transport crates. The same principle can be applied to an entire building, provided the air infiltration rate is low. It is also important that the buffer be cheap and easily accessible because of the large quantities needed. Fortunately, many museum storage sites contain so much cellulosic material, as paper records and cardboard containers, that the collection itself may provide sufficient humidity buffering. Otherwise, clay plaster or a wall lining of unfired brick will offer the same effect.

Padfield and Jensen (2011) studied the quantification of this effect in a dynamic situation. In that study, the sorption of water vapor by a test surface was continuously measured during a regular relative humidity cycle. The vapor absorbed by 1 m^2 of exposed surface on the upward swing of the relative

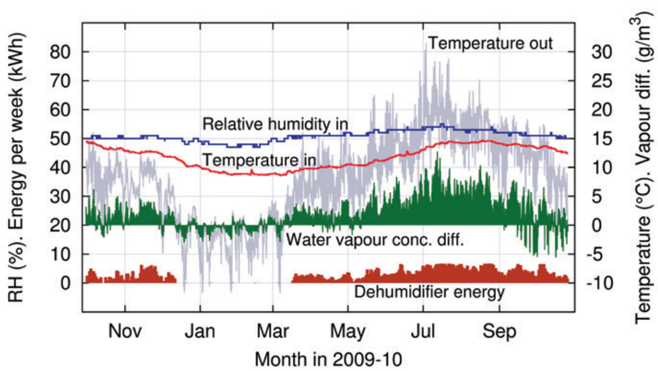

FIGURE 5. Climate data acquired at the Ribe storage site. The relative humidity is kept close to the 50% target by only dehumidification. In winter, the relative humidity dips below this value; in summer it rises above it because of the slightly underdimensioned dehumidifier. The energy consumption for dehumidification is shown below in the diagram.

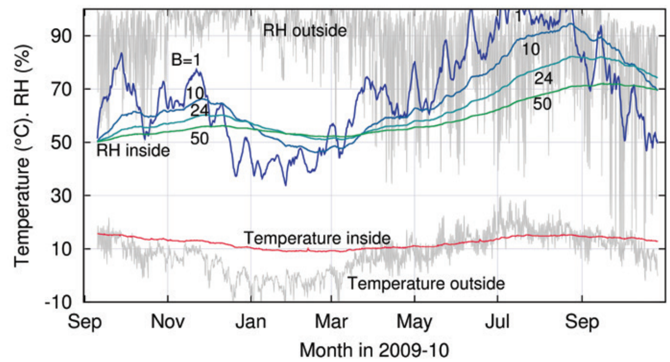

FIGURE 6. A theoretical model of the course of the relative humidity at the Ribe storage site, starting from an arbitrary 50% RH. The trace marked B=1 shows the RH in a space with no moisture-absorbent materials (inert room), given an air exchange rate of 0.03 per hour. It reaches 100% in summer when the outside air is warmer than inside. The other traces show the moderating effect of humidity buffer capacity illustrated by an increasing virtual room ratio (*B*). Note the general upward trend of RH with time, indicating the need for dehumidification.

humidity was recalculated to the equivalent volume of space, which will experience the same change in relative humidity with the same injection of water vapor as that taken up by the absorbent material. This equivalent volume will depend on the time required for a relative humidity cycle because of the slow diffusion within the material. A textured clay wall plaster, for example, has a buffer value (*B* value) of about 100 for a four-day cycle of relative humidity. This means that 1 m^2 of wall has a sorptive capacity similar to 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. This number is then divided by the actual room volume. For museum storage, with mostly metal objects and little absorbent material, this "virtual volume ratio" may be about 10 or lower. A building such as the Ribe storage, containing a large number of hygroscopic objects and wall lining, could have a virtual volume ratio around 50. For an archive filled with paper, the ratio can be on the order of several hundred to 1,000 times the actual room volume.

A theoretical model of the course of the relative humidity at the Ribe storage site is shown in Figure 6. The model shows several scenarios with increasing humidity buffer capacity. What is important to note, however, is that no matter the amount of buffer available, the relative humidity increases with time toward the average value outside, which in Denmark is near 80%. For this reason dehumidification is necessary.

Buffered Conservation Heating

If a low winter temperature is not acceptable, climate control can be achieved by moderate winter heating. This periodic heating will also increase the summer temperature, as the ground below the building gradually equilibrates over several years to the higher average indoor temperature. However, the temperature will remain quite moderate; for example, in Denmark it will always be below ~22°C. The relative humidity will stabilize at an average value around 55% with an annual cycle, which depends on the humidity buffer value.

A virtual volume ratio over 50 is needed to avoid a disturbingly high relative humidity in summer, when the outside temperature is often higher than inside. A virtual volume ratio of 1,000 is achievable in storage areas containing paper and cardboard boxes filled to capacity. This gives a very stable relative humidity, with an annual cycle within a 5% envelope, better than can usually be achieved by air conditioning and well within all museum standards. The relative humidity need not be measured constantly and is never directly controlled. The winter heating alone defines the annual average relative humidity. Thermostats are more reliable than relative humidity sensors and the associated computer-controlled air conditioning. We call this method of climate control "buffered conservation heating" by analogy with the gentle winter heating used to keep moderate relative humidity in historic buildings that are closed in winter (see also Figure 1).

VENTILATION AND AIR QUALITY

Museum storage sites and archives are not intended for permanent occupation by people. Workshops and offices should never be located together with the collections. There is little need for ventilation to provide for human health and comfort in a storage building. The intake of outside air should be limited as much as possible to keep away external pollutants and to minimize climatic disturbance. The Ribe storage site has an air exchange rate of 0.03 room volume per hour throughout the year. The outside air mainly enters through the door when objects are moved in and out. There is no mechanical air intake, and the building is very airtight. The outgassing of components from the collection or from the building itself may reach high concentrations due to the low ventilation rate. It is partly prevented by the proper choice of inert materials and finishes for the building and the storage shelving. Wooden construction materials should be avoided because of the emission of corrosive volatile compounds, especially acetic acid. However, the collection itself may be another source of contaminants, and these can be removed by air filtration through a recirculating system. In addition, some interior finishes, such as the clay material previously mentioned with regard to humidity buffering, also provide some control by passive sorption of pollutants (Ryhl-Svendsen and Clausen, 2009; Ryhl-Svendsen, 2011). Measurements in the Ribe storage building and other Danish low-energy museum storage sites have revealed lower than expected concentrations of indoor pollutants. We attribute this to the mostly cool temperature inside those buildings, which slows down the off-gassing from materials, yet another benefit of maintaining an unheated environment. The museum guidelines and standards are usually vague on advice about safe levels for indoor air pollutants. Especially for paper-based collections, the cost and effort of air filtration have been questioned from a cost-benefit perspective (Di Pietro et al., 2016). The issues related to air quality control in low-energy buildings still pose many unanswered questions.

A special problem exists for collections that have previously been treated with organic insecticides. They must be cleaned before they are stored at a low ventilation rate in order to minimize the potential reevaporation of insecticides into the air. In such cases, health regulations may require constant ventilation, which will make low-energy storage impossible. This is a problem that poses big challenges and deserves attention in future research and innovation.

ENERGY CONSIDERATIONS

The energy used by heating to moderate the relative humidity depends on the heat transmission through the walls and ceiling of the building. The heat loss to the ground will diminish as the years pass. The energy used by dehumidification depends entirely on the humidity of the outdoor air and the air exchange rate, which can be reduced to below one air change per day in modern buildings with simple geometry. The power consumed by the Ribe storage site dehumidification is 1.5 kWh per year for each cubic meter of storage space.

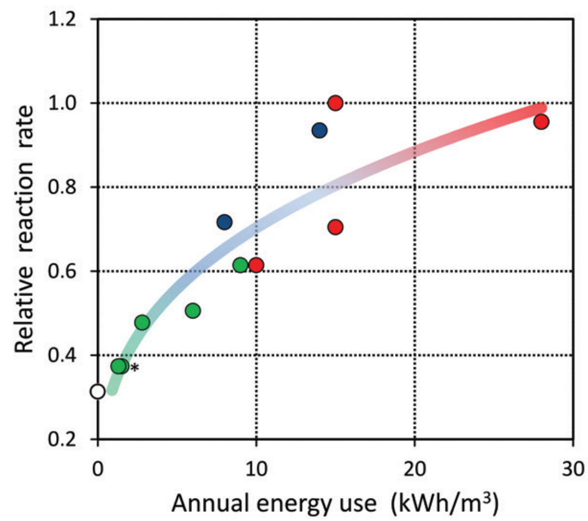

FIGURE 7. The link between the chemical reaction rate within a storage environment and the energy used for climate control. The reaction rate is normalized to that of 20°C and 50% RH, following the approach of Sebera (1994). All data points refer to places described in Ryhl-Svendsen et al. (2012a) and are comparable in the sense that they are located above ground in a Danish temperate climate but differ in the construction of the building envelope and climate control systems. The point next to the asterisk (*) is the Ribe storage site. Green data points represent unheated and dehumidified buildings. Blue points are conservation heated in winter, and red points are buildings with various degrees of air conditioning. The white point shows the reaction rate for unheated outdoor air, conditioned to 50% RH, assuming complete airtightness of a building.

Other Danish storage facilities perform even better. The energy consumption of several storage buildings in Denmark is shown in Figure 7 and compared to conservation quality in terms of chemical reaction rate (Ryhl-Svendsen et al., 2012a). There is a correlation between low energy consumption and good preservation, as predicted by the Sebera diagram. The linked reduction in cost and improvement in object durability is mainly attributable to allowing an annual variation in temperature.

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 their 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 storage site, having about 5% of the roof covered with solar panels will provide the necessary energy for dehumidification, which is mostly needed in summer (Ryhl-Svendsen et al., 2011, 2013). A small wind turbine will give enough power for conservation heating in winter. This gives an opportunity to run a museum storage site or an archive entirely without external energy supply.

A STORAGE BUILDING MODEL: WASHINGTON, D.C.

The outside climate defines the inside climate of a building. This fact must be considered when the model is applied to a location with a natural climate different from that in Denmark. There are two ways to predict the inside climate and the need for supplementary climate control. One is by computer modeling of the building's hygrothermal performance, as presented in Figure 6 for the Ribe storage building. Previously, we demonstrated a similar model for a storage building in Canberra, Australia (Ryhl-Svendsen et al., 2012b). A simpler approach is by considering the monthly average of the outdoor climate. An example from Washington, D.C., is given in Figure 8 (EnergyPlus, 2016). The monthly average temperature ranges from 1°C in winter to 27°C in summer. The daily maximum and minimum temperatures can be far different from these values, but these extremes will not affect the interior conditions. The minimum and maximum temperatures inside a storage building, similar to that in the Ribe facility, are determined by reducing the amplitude of the outside average cycle by half. This will give an annual temperature span of 13°C, ranging from 9°C in winter to 22°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 such as electric light.

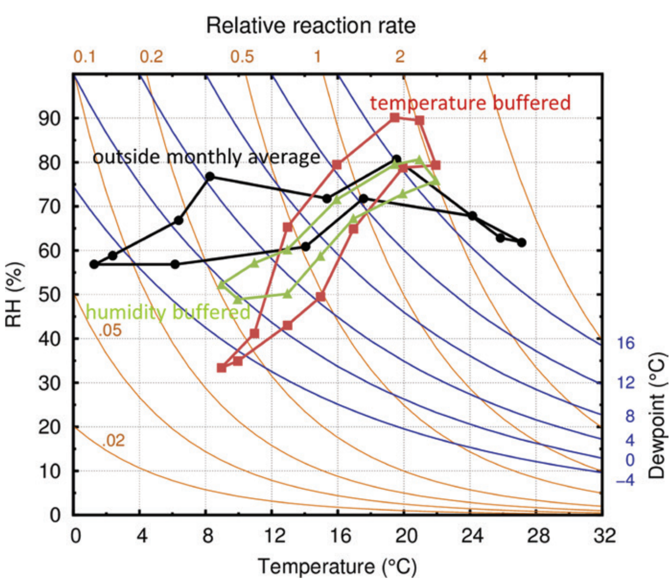

FIGURE 8. The predicted climate inside a Ribe-type store when located in Washington, D.C. The statistic climate data for the monthly average of the outside temperature and humidity is shown in black (EnergyPlus, 2016). The temperature-buffered store is marked in red, and the humidity-buffered store is marked in green.

The resulting average indoor relative humidity for each month is calculated with this new temperature, assuming the same moisture content of the air as for outdoors. In Figure 8, this is shown graphically by the dew point lines. Without any control, the relative humidity will be in the range of 30%–90%. With a good humidity buffer, it will be possible to keep the relative humidity between 50% and 80%. Dehumidification is needed to keep the relative humidity below 60%, but only from May to October. As for the case of the Ribe building, it can be powered entirely by photovoltaic elements on the roof of the building. Such a museum storage or archive will work with little energy consumption 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.

CONCLUSIONS

We presented an alternative way of building museum storage to minimize energy cost and mechanical complexity without compromising the longevity of the collection, as expressed by the relative rate of organic hydrolysis reactions, risk of physical damage, or biological attack. The essential change from previous practice is to allow an annual cycle of temperature that exceeds the limits given by most recommendations. The amplitude of this cycle is limited by using a highly insulated building envelope and an uninsulated floor as a heat store. The relatively high winter temperature then gives a moderate relative humidity without mechanical aid. During the summer, dehumidification is needed in humid temperate climates such as northern Europe that have a high relative humidity throughout the year. For collections that cannot endure low temperature, buffered conservation heating can be used to moderate the relative humidity. A large humidity buffer capacity is then needed to hold down the increase in summer relative humidity. In drier locations humidity buffering by the building or the collection will keep the relative humidity moderate all year.

In northern Europe, the typical temperature cycle for an unheated but dehumidified store will be 8°C to 16°C; for a winter-heated store, it will be 14°C to 23°C. In other parts of the world with a temperate climate, for example, Washington, D.C., the temperature will be different but still acceptable for most objects. Neither of these temperature ranges conforms to PD 5454 or ASHRAE class A. At present, the limits are set at apparently arbitrary, precautionary numbers, without consideration for the energy cost and the complexity of the air conditioning. There is no doubt that the temperature variation, which we advocate, touches upon or passes through the theoretical phase changes of some materials found in mixed collections. However, does preventing the possibility of phase change warrant the tenfold penalty in energy costs and the considerable complexity of air conditioning?

Acknowledgments

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