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Passive Climate Control

How Air Conditioning in the Storage Rooms of Archives, Libraries and Museums can be Replaced with Passive Systems

A stable room climate which remains within rigid set points is widely considered to be the best place to preserve written records. Therefore archives, libraries and museum storage facilities are often air conditioned because it is considered that the desired values cannot be maintained without full climate control. However, since the seventies many studies have shown that archives with passive climate control are less expensive, energy saving and more environmentally friendly both during construction and operation and still guarantee a stable climate. New systems with passive climate control usually have controlled ventilation in combination with passive or active heating. The effect of temperature and humidity variations outside of the building on the interior of the room is greatly reduced due to the thermal inertia of the building envelope and the use of hygroscopic materials inside the archives, a technique which has been proven for centuries in old monastic libraries. The harmful effects of significant climatic fluctuations which may occur in fully air conditioned rooms during a system failure are entirely eliminated with passive climate control. However, the temperate latitudes of central Europe require a conservational method of heating if the risk of mould infestation is to be prevented with absolute certainty. Passive systems are not only cheaper to build and maintain they are also energy saving, trouble-free and yet still provide a climate which is beneficial for written records. Numerous historical buildings have proven this fact over hundreds of years. More recently a number of new buildings and building renovations in Europe have demonstrated the advantages of passive climate control in practice.

Passive Klimasteuerung: Wie Klimaanlagen in Depoträumen von Archiven, Bibliotheken und Museen durch passive Systeme ersetzt werden können

Ein stabiles Raumklima, daß sich an starre Sollwerte hält, wird vielerorts als optimal angesehen, um Schriftgut zu konservieren. Oft werden deshalb Depots von Archiven, Bibliotheken und Museen klimatisiert, denn ohne Vollklimatisierung können solche Werte nicht eingehalten werden. Seit den 1970er Jahren haben zahlreiche Untersuchungen gezeigt, daß Depots mit passiver Klimasteuerung in Erstellung und Betrieb kostengünstiger, energiesparend und umweltfreundlicher sind und trotzdem stabile Klimawerte garantieren. Neue Systeme mit passiver Klimasteuerung verfügen meist über eine kontrollierte Lüftung in Kombination mit passivem oder aktivem Heizen. Dank thermischer Trägheit der Gebäudehülle sowie dem Einsatz hygroskopischer Baumaterialien im Inneren der Depots, welche sich in alten Klosterbibliotheken über Jahrhunderte bewährt haben, werden Schwankungen von Temperatur und Luftfeuchtigkeit außerhalb des Gebäudes nur verzögert an das Rauminnere abgegeben. Die schädlichen starken Klimaschwankungen, zu denen es in vollklimatisierten Räumen bei Systemausfällen kommen kann, entfallen bei passiver Klimasteuerung ganz. Allerdings ist in den Breitengraden Mitteleuropas konservatorisches Heizen angezeigt, wenn das Risiko eines Schimmelbefalls mit absoluter Sicherheit ausgeschlossen werden soll. Passive Systeme sind nicht nur billiger in der Anschaffung und Wartung, sondern auch energiesparend, kaum störungsanfällig und ermöglichen trotzdem ein für Schriftgut zuträgliches Klima. Viele historische Bauten habend den Beweis dafür seit hunderten von Jahren erbracht, ebenso wie jüngere Neubauten und Sanierungen in Europa.

Is there an ideal climate for storage rooms? The definition of an ideal climate for archives, libraries and museums has been a topic hotly debated by experts for years. In his dissertation published by the University of Lund, Sweden, Lars Christoffersen speaks of widespread bewilderment (Christoffersen 1995). In fact, since the sixties, scientifically based publications have contributed to the confusion rather than clearly answering the questions on the appropriate climate for books, archives, museum artefacts or digital media.

Some experts consider that, of the two parameters which influence the chemical and biological degradation processes, the relative humidity (RH) [1] plays a more important role than the temperature (T). Therefore, the relative humidity in storage rooms should have the lowest possible fluctuation (Müller-Straten 2005). A change in the relative humidity level leads to a change in moisture content of hygroscopic materials and can eventually cause dimensional changes (stretching or shrinking). According to Thomson temperature changes have less impact in this relationship. He states that a change in relative humidity of 10 % corresponds to a temperature change of 30°C with respect to their effects on organic archive materials (Thomson 1978: 213). The relative humidity should be kept below the limit which enables microbiological growth. Based on current information growing risk of mould occurs from 65 % RH. On the other hand if the relative humidity drops below 35 % over a long period there is a risk that hygroscopic archive materials will dry out and become brittle. Although there is no consensus on the ideal temperature there is a rule of thumb which can be applied: the colder the better, as low temperatures slow the chemical and biological decay. Under the 'PaperTreat' research project a number of European libraries and archives cooperated with research laboratories to examine the possibilities for extending the life of paper (PaperTreat 2005-2008: Evaluation of mass deacidification processes). The project came to the conclusion that lowering the storage temperature by 5°C extended the lifetime of paper by a factor of two (Balažic et al. 2007).

Development of Climate Standards

One of the first systematic studies on the impact of environment on cultural heritage in museums was recorded in 1936 in London. In this year I.G. Rawlins took the first measurements intended to show the damaging effects of air pollutants on the art objects in the National Gallery (Burmester 2000: 12; Saunders 2000). During the war, these objects were stored in an underground shelter in Wales which had a constant relative humidity of 100 %. The temperature in the shelter was 8°C. Raising the temperature to 17°C lowered the relative humidity to 58 % and enabled the climate to be kept relatively stable with only slight fluctuations. This could be seen as the birth of the air monitoring as Rawlins noted that the low variations of temperature and relative humidity had very positive effects in the conservation of paintings.

When it comes to data on climate the values published in 1960 by the International Council of Museums ICOM (Kilian et al. 2005) are very often cited. Based on a survey of around 30 museums, the authors J. Plenderleith and P. Philippot concluded that a relative humidity of between 50 and 60 % is to be favoured; no information on temperature was given. The survey did not indicate whether the museum buildings included in the study were air conditioned, how the values were determined and whether actual or set values were recorded. There is little evidence of a scientific approach being applied.

The International Organization for Standardization (ISO) has published several guidelines for the climate in archive and library storage facilities. They are, however, non-committal recommendations. Published in January 2003, ISO 11799:2003 is considered a relevant standard in conservation and is the result of a long-term development process (Padfield 2003). The publication of this work was delayed by more than six years because no agreement could be found on fixed climate values. ISO 11799:2003 consistently bases its recommendations on previously published articles on the subject and represents a compilation of climate recommendations for each type of material including paper documents, leather, parchment, film, magnetic tapes, etc. Furthermore, the standard also points out that the archive building should form a thermally inert building envelope and that as many hygroscopic materials [2] as possible should be used in its construction. The standard also stresses that the dependency on artificial climate control systems should be kept to a minimum (Padfield 2009a).

In contrast to the above mentioned ISO standard the British Standard BS 5454: 2000 defines a tight straightjacket around the climate values. Compliance with these values is required by various British organisations. The British standard calls for a temperature range between 16 and 19°C with a tolerance of ±1°C. Such small temperature fluctuations are also difficult to maintain with climate control systems and the range is far too narrowly defined. The relative humidity set values lie between 45 and 60 %, with a tolerance of ± 5 %. The standard requires that neither the maximum or minimum value may be exceeded for either the temperature or the relative humidity.

In German-speaking regions the last years have also seen narrow temperature ranges being recommended. Over time these values have become somewhat the norm. The target ranges are set at a temperature of 16 to 18°C. This led to a rapid growth in the use of artificial climate control systems as these values are unobtainable with passive climate control (Sagstetter 2004).

Observations on Climate Control in Historical Buildings: Moving away from Rigid Standards

Several historic buildings have proven that library and archive material can survive for many centuries without artificial climate control. Although the temperature in such buildings is often subject to strong seasonal fluctuations it was found that the relative humidity varies very little throughout the year. Notable examples include: the manuscript room of the library in the Abbey of St. Gallen in Switzerland, whose manuscripts—dating from the 7th to the 18th centuries—show no climate-related damage (Fig 1); and the collegiate libraries of the Einsiedeln and Engelberg monasteries in Switzerland. Even in non-European climates such as in Saint Catherine's Monastery in Sinai, where over the year temperature fluctuations in the range of 8 to 30°C can occur and where the relative humidity might decrease to values of 10 to 15 %, no climatic damage is evident on the manuscripts dating from the 4th to the 12th centuries. The relative humidity—although extremely low from the conservation point of view—is very stable and causes only slight short-term fluctuations (Pickwoad 2009).

In the baroque manuscript room of the library in the Abbey of St. Gallen the temperature varies between 10°C in February and 27°C in August. These large fluctuations have caused no climate-related damage (e.g. mould) to the library items since the baroque monastery library was established (not later than 1767). The relative humidity remains extremely constant. Presumably the reason for this lies in the thermal inertia of the building envelope, the solid wood-cabinets which act as a moisture buffer, the untreated solid wood-flooring, and ceiling plaster. Measurements made in 2001 showed that the relative humidity in the first four months of the year varied between 44 and 46 % and the temperature between 12 and 17.5°C (Fig 2). During the three summer months of July to September, these values ranged between 44 and 50 % and the temperature between 18 and 26.5°C. The fluctuations in the relative humidity are low and only reflect the expected seasonal climatic influences, which are somewhat larger in summer than in the winter. The relatively low fluctuations in the relative humidity were confirmed by measurements taken in the following years. Padfield has

1 St. Gallen Abbey Library: historic interior of the manuscript chamber.

shown that moisture buffering by hygroscopic materials is only effective if the air exchange volume is less than 1 room volume per 10 hours. The lower the air exchange volume the greater the buffer effect of hygroscopic materials (Padfield and Jensen 2011). The manuscript room of the library in the Abbey of St. Gallen is only aired once a month through an open window. the above-ground storage rooms in the State Archives of Lucerne are only aired twice a year for half a day, provided the outdoor climate is suitable for airing. Climate measurements in these institutions show that the sparse airing policy has a stabilizing effect on the climate (Bansa 2006).

Modern Building Concepts with Passive Climate Control

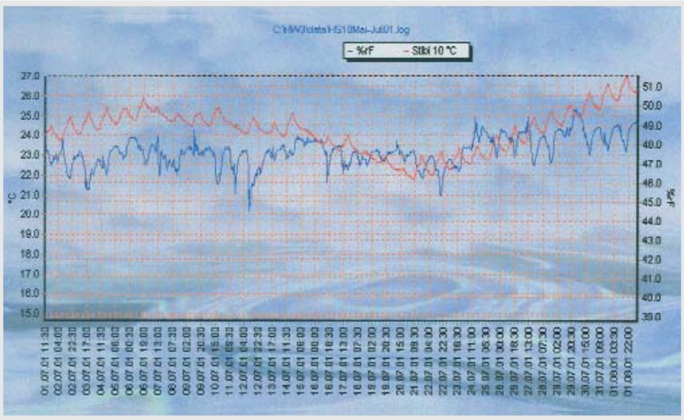
An ever increasing number of experts now agree that the temperature and relative humidity in storage rooms may fluctuate with the seasons (Burmester 2000). Due to the thermal inertia of the building envelope seasonal temperature changes have only a very slight effect on the interior of the rooms (Wischhöfer 1998). This means that in Central Europe the room temperature in an archive may be allowed to rise in summer and fall again in winter. However, it must be ensured that no abrupt changes occur. Thick walls of stone, brick or concrete can prevent such fluctuations. These thermally inert materials noticeably delay the transfer of changes in the outside environment to the interior of the rooms—provided that the building envelope is sealed. This objective can also be achieved with light construction buildings if the necessary insulation against internal and external heat and cold sources is correctly calculated. Dynamic simulation is used to evaluate the insulation thicknesses required. Fig 3 shows such a dynamic simulation, here for the renovation and new construction project in the Einsiedeln monastery archives. The curves show the simulated average heat flux densities [3] on the floor, walls and ceiling of the archive over a period of two years. They illustrate the relatively even temperature near the floor which occurs because of heating from below (ground heating). The heat flux on the walls is neutral while the ceiling, which is only covered with a 50 cm thick soil layer, shows the greatest fluctuations.

Economic and Environmental Aspects

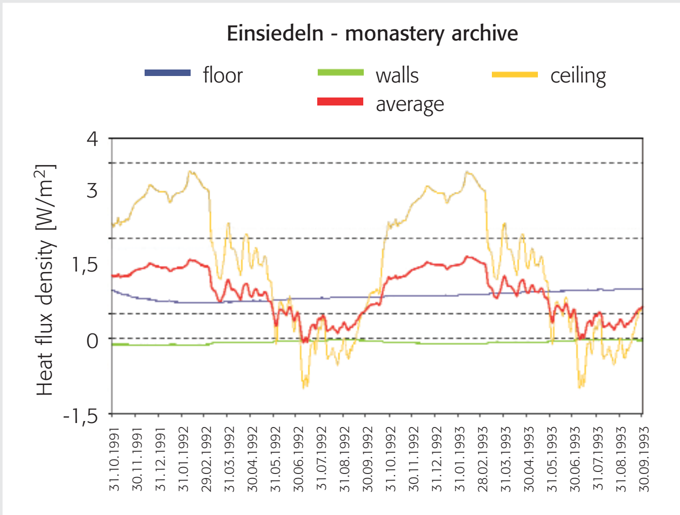
In comparison to active full climate control, passive climate control has the great advantage that it necessitates far lower investment and maintenance costs and, in contrast to an air conditioning system, is less susceptible to malfunction. A particularly significant negative aspect to active climate control is the high energy costs which may become financially unsustainable in the future. It is also expected that pressure from public administrations to shut down air conditioning systems for economic and ecological reasons will increase. In the case of new buildings this trend has already begun. For example, for new buildings the city of Basel in Switzerland only permits a maximum energy ratio of 5 W/m^2 for cooling and air ventilation, meaning that the use of air conditioners requiring high power consumption is barely feasible.

Despite this fact the general acceptance of passive systems still requires persistent campaigning. Many of today's ventilation engineers and construction physicists are accustomed to meeting climate targets with complicated building services. They often find it difficult to imagine that a passive climate system can function successfully. If these experts are asked for their opinion the result is generally predictable. Passive 'low-tech' solutions are at best viewed with skepticism, mostly they are rejected. Technically incorrect arguments are made because of the lack of knowledge about passive systems. Time and again apprehension is expressed about a new technique that is neither known nor yet mastered.

But the author has seen on more than one occasion that there are experts who are interested in passive air systems or do not want to install air-conditioning systems on energy saving grounds. This is a possible indication that this trend will grow in the future and that passive systems are likely to become the standard in the near future. The fact that passive systems indeed work, has already been proven by independent studies as part of the European research project Climate in Museums and Historical Buildings (EUREKA EU-Project 1383 PREVENT 1990-95).



2 The graph indicates the seasonal fluctuations in temperature (red) and the stable relative humidity (blue) in the manuscript chamber of the St. Gallen Abbey Library between 1 July and 1 August 2001.



3 Dynamic simulation of heat flux densities necessary to calculate the insulation thickness prior to construction.

Basic Elements of Passive Climate Control

Passive climate control makes use of one or more of the following options to compensate for changes in temperature and relative humidity. These include: the thermal inertia of the building envelope, the ability to heat the storage room, controlled ventilation, and the hygroscopic buffer capacity of building materials.

> *Thermally Inert Building:* Passive climate control can function in both historical buildings as well as new buildings provided that the building envelope is sealed and thermally inert. The thermal inertia of the building envelope can be achieved by thick walls or by carefully calculated insulation of the building envelope.

> *Heating:* Since the outside air is very humid at the average Central European latitudes (approximately 70-80 % RH), it is recommended to supplement passive climate control through passive or active heating.

> *Controlled Ventilation:* Conventional ventilation based on instinct and guesswork by opening a window is not used for passive climate control. After all, humans have no sense which enables them to judge the humidity of the air. Suitable are digitally controlled ventilation systems such as the 'light signal' [4], which only ventilate the archive when the climate is not adversely affected.

> *Hygroscopic Materials:* A low air-exchange rate also helps to ensure the stability of the indoor climate in the storage facility, as only then can hygroscopic materials be fully effective. The stored books or archival materials broadly contribute to the stabilization of the climate, because paper is highly hygroscopic. When stored packed tightly it forms a significant moisture buffer, even if it is a carrier medium. The rate of moisture buffering in archives is dependent on the nature of the stored material. Creating a model for the stored material for measurement purposes is a tedious task, because each collection is very different. Padfield measured the moisture absorption capacity of the body of a book (Padfield 2006). If an empty archive is filled with written records as a rule it can be assumed that the climate will become more stable. This fact should not lead to the assumption that the storage of paper alone over time can compensate for a poor climate.

Thermal Inertion of Building Envelope

In all cases an airtight building envelope is essential. In historic buildings this is by no means always the case but it can be achieved by renovation of the building structure, for example by re-grouting loose masonry and effectively sealing the windows and window frames. Due to thermal inertia the outdoor climate fluctuations are weakened and penetration into the interior space is delayed by up to 12 hours. Thus the midday heat from the building walls does not penetrate into the interior space until around midnight. The same applies to the cooling effect of the night air, which only affect the interior space around midday when the cooling effect is beneficial.

Passive and Active Heating

Historic Approach: Passive Climate Control without Controlled Ventilation and without Heating

In monastery libraries and archives passive climate control was based almost exclusively on thermally inert masonry of at least 50 cm thickness, hygroscopic materials such as lime mortar, stucco ceilings (plaster) on a hollow slatted board base, flooring and cabinets from solid wood, plasterwork and a room arrangement that ideally included no exterior walls. The latter is most commonly encountered in small archive rooms in monasteries. The ventilation of the archive and library space was, if at all, by a window. It is not known if the weather was taken into account when airing, but it cannot be excluded. Usually no means of heating were available.

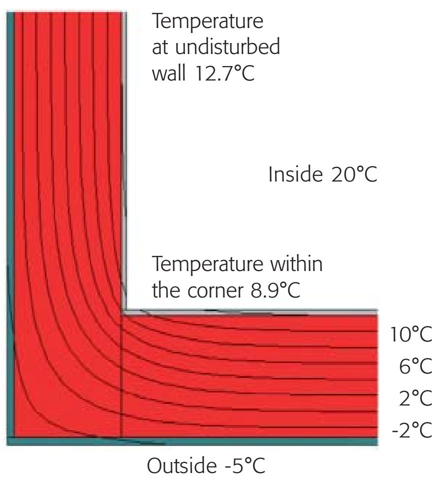
The Necessity of Heating

Based on his experience in historic buildings without mechanical systems, the conservator Henning Großeschmidt recognized that passive systems without additional heating posed a latent risk of mould formation. Cold walls can fall below the dew point [5] if the humidity should suddenly increase unchecked. Condensation with a subsequent risk of mould occurs especially at points known as geometric thermal bridges (Fig 4) [6] and exterior walls. This is referred to as cold-wall problem [7] (Ranacher 2004: 170-187), which cannot be brought under control with absolute certainty even with the large-scale use of hygroscopic materials. The danger of falling below the dew point can only be excluded through additional heating (Käferhaus 2005).

Two basic types of passive climate control can be distinguished, both of which have been used in Europe since 1972. In addition to controlled ventilation both variants include passive or active heating (Padfield et al. 2007).

Passive Climate Control with Controlled Ventilation and Passive Heating

In this type of passive climate control a controlled ventilation system is incorporated which is passively heated. The heat originates from heated rooms adjacent to the archive. In this case heat penetrates the archive through a section of the archive walls or floor, and a cooling effect is provided through an exterior wall (Padfield 1996).



[Source: www.wissenwiki.de/Datei:Bauphys_Wärmebrücke_(2).png]

4 Geometric thermal bridges occur on exterior corners where the outer surface is larger than the inner surface. Temperatures of inside corners are much lower than of adjacent walls.

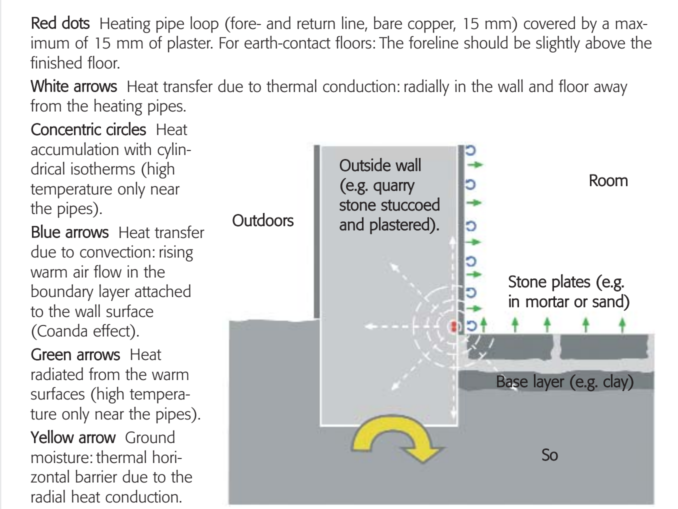
Passive Climate Control with Controlled Ventilation and Active Heating

With active heating a distinction is made between three systems: wall heating (temperature control) according to the 'Vienna model', concrete core activation (thermal construction element activation) and baseboard heating.

> *Wall Heating (Vienna Model):* Wall heating is based on the principle of Roman hypocaust heating, in which warm air circulates through clay pipes in the walls. The installations for wall heating are simple and require only a few structural alterations (Fig 5). This system is equally suitable for both old and new buildings and the intended use of the building does not matter. There are museums, archives, libraries, palaces, schools and private homes equipped with this system (Großeschmidt 2004).

Wall heating works by actively heating the building envelope, typically using two in-wall heating pipes (flow and return), in the base area of all walls in contact with the ground on all floors at a wall height of about 90 cm. In storage facilities which lie just below the ground surface a third heating circuit is installed along the wall to ceiling joint.

The walls and the building structure are warmed up and in turn radiate heat [8] to the interior air. Unlike with convective heating systems [9] that use the air in the building to convey heat, the creation of a dust cloud can be avoided. Radiant heat systems also have the advantage of enabling the archive shelves to be placed at 5-10 cm from the walls. With convective heating systems the shelves need to be placed 40 cm from the walls to prevent the creation of microclimates at the corners. Convective heating systems also increase the vapour pressure in the room and expel moisture, often resulting in the need for moisture to be added. The wall heating method was developed by the non-State Museums in Bavaria, Germany, in an effort to create a building heating system which could guarantee a stable climate at low energy input.



5 Schematic of the function of the wall heating and temperature control in an 'historical' setting: walls without thermal insulation or vapour barriers are kept dry by contiuous heating. Based on a diagram by © Miha Praznik, 61-ZBMK, Ljubljana.

In contrast to the convection heat emitted by radiators and air conditioners wall heating and hypocaust heating both emit thermal radiation. Radiant heat means that the walls are slightly warmer than the interior air, preventing the formation of condensation and mould. Moisture can lead to capillary condensation on cool construction component surfaces which offer an ideal environment for mould growth. Active heating can remove the risk of falling below the dew point temperature. In historic buildings with damp walls, the increase of the wall moisture can be prevented by temperature control (Fig 6). The reason is the higher vapour pressure of the moisture in the heated part of the wall with respect to the lower vapour pressure of the moisture in the foundation of the wall.

Wall heating has a wide potential for savings. The investment costs are significantly lower compared with a conventional heating system with air, let alone against a full climate control, as are maintenance costs due to no service requirements. The system is also very durable, whereas air conditioning units must usually be renewed after 20 years. Also, the energy requirements of a wall heating are significantly less compared to an air conditioning. The savings potential is around 16 % compared to a conventional radiator heating (Leipoldt 2004); this was measured repeatedly in the context of the European research project Climate in Museums and Historical Buildings (EUREKA EU 1383 PREVENT 1990-95). Compared to an air conditioning unit, the energy savings are multiple. The relatively low temperature of the water in the heating tubes (25-50°C) can also be achieved through alternative forms of heating such as solar collectors. Wall heating has proven itself as a passive air conditioning system long ago. It is spreading increasingly in Europe (Käferhaus 2004a, b, c and d), because it guarantees a stable climate, and is also interesting from a cost point of view. Over a hundred systems are already in operation in historical buildings, churches, museums and storage facilities in Germany as well as Austria, Switzerland, Liechtenstein, Italy, Slovenia, Croatia and Sweden.

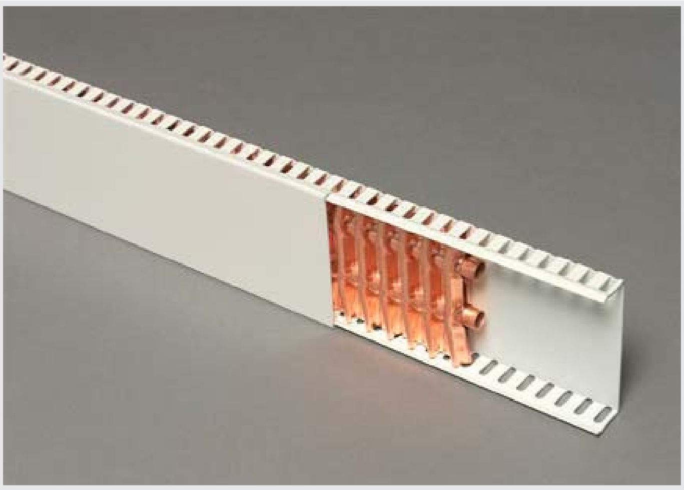
> *Concrete Core Activation:* The concrete core activation uses the building mass for temperature regulation. For this purpose, plastic pipes are laid in solid ceilings or solid walls, through which water flows as a heating or cooling medium. The entire traver-

6 Decreasing moisture in external walls with wall heating. The in-wall pipes (flow and return) are visible. State prior to plastering in the church at Gerling (Austria).

sed solid ceiling or wall is thermally activated and is used as a transfer and storage mass. A heat exchange takes place across the entire surface. The system can be used for heating or cooling in storage facilities, but the activated concrete surfaces may not be covered (suspended ceilings, wall coverings). Concrete core activation is not possible in older buildings unless new concrete ceilings are suspended. Due to the relatively large transfer surface the flow temperatures of the water can be kept significantly lower than that, for example of a central heating. This makes it possible to control the temperature of the water with energy-efficient heat pumps or through surface collectors cooled with night-air. Cooling may also take place without compressors via groundwater (free cooling). The biggest disadvantage of the controlling technological demanding system is its inertia.

This disadvantage can be avoided by a diffusion-tight capillary tube system plastered in the ceiling, as this type of heating system reacts quickly and still has all the advantages of the concrete core. However no holes can be drilled or lamps mounted thereafter. Another disadvantage is the higher construction costs of the system compared with other passive systems mentioned here. In addition, leaks in the heating system can only be localised and repaired with great expense and effort. In storage facilities with concrete core activation often additional air conditioning equipment must be installed (such as at the Canton of Thurgau State Archives in Frauenfeld, Switzerland) which means this system is actually no longer a passive system.

> *Baseboard Heating:* Baseboard heating is realized by surface mounted narrow radiators at the level of the skirting boards (Fig 7). They form a hot air curtain in the form of a small convective roll in front of a cold outer wall. The warm air rises up to the walls and transfers the heat to the cold wall. The heated wall then radiates into the room. This is in principle a very good system but has one disadvantage: blackening due to dust on the wall. The dust is agitated by air convection and settles on the wall. Baseboards, which are made entirely of copper (without aluminium slats), can be earthed via the outlet socket so that less dust is transported and spread. Hot water serves as the heating medium, as with radiators or wall heating. Baseboards are expensive to purchase, but they are easy to install and have low life cycle costs compared to other systems. Baseboards are ideal on timber walls, for example, in the wooden buildings where the dust markings are not as visible. Baseboards can be used both in storage rooms as well as in housing. They are also used when heating pipes can not be placed in the wall, for example due to building conservation regulations. The baseboards relatively high flow temperature of approx. 50°C however, means that neither solar energy nor heat pumps can be used.



7 Example of a copper baseboard without slats.

Controlled Ventilation

The installation of controlled ventilation is useful for all passive systems. An integral part of such (mostly digitally controlled) fresh air supply in storage facilities is the balance of the external environment with the internal environment. It should only be fed fresh air, when no unfavourable climatic conditions can be brought into the storage facility from outside. This contributes to lower energy consumption. Ventilation units from the field of passive house construction have proven to ensure more than 90 % heat recovery. If additionally a special heat exchanger is used which provides moisture recovery, the re-moisture requirements of the winter season are almost omitted. Attention must be paid to the air exchange rate if hygroscopic materials are installed in the storage facility for additional buffering of the relative humidity.

A humidity buffering by hygroscopic materials can only function properly if the air exchange is low. Padfield mentions a maximum exchange rate of 1 room volume of fresh air per 10 hours (Padfield 2008).

The required fresh air can be additionally preconditioned via a geothermal heat exchanger. The incoming fresh air is passed through fired clay or concrete pipes that are buried at least three feet deep in the ground. The average temperature in the ground of 8-12°C is used to cool the fresh air in the summer and to heat the air in the winter. In Schönbrunn Palace in Vienna, Austria, for example, an existing old underground water passage was used as a geothermal heat exchanger. Given the stable low temperatures in the ground it is advantageous to build storage facilities underground, unless there is risk of flooding. The energy consumption is reduced due to the protective earth's crust.

Hygroscopic Material as Moisture Buffer

Hygroscopic materials continuously strive to achieve a balance with the relative humidity of the surrounding air. Therefore the presence of hygroscopic materials within a room can compensate for fluctuations in relative humidity (Padfield 2008, 2009b). The most effective way is when the surface area of hygroscopic materials is as large as possible and the air exchange within the room is as low as possible. Buffer performance is improved at lower room temperatures, as due to the lower water content of the air, less moisture needs to be implemented, in order to keep the relative humidity under control. Paper can store large amounts of moisture. But it is in many cases insufficient as a buffer for the daily moisture balance. It takes a long time for a paper to release moisture into a room when the climate is too dry. According to Padfield the buffering capacity of clay and end grain wood is superior to other materials (Padfield 2011).

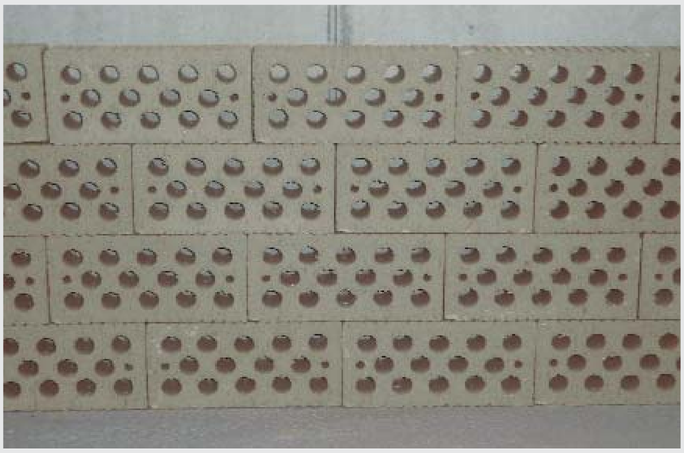
For humidity control clay can be in the shape of either clay plaster or brick lining with perforated unfired clay bricks. A 2-3 cm thick clay plaster has a good hygro capacity. Applying a thicker plaster is not necessary, because the moisture does not penetrate deeper than 2-3 cm. By using perforated clay bricks, the hygroscopic surface can be further increased (Fig 8). Unfired, perforated clay bricks 6-12 cm thick form a very good moisture buffer, if the bricks are lined in front of a concrete wall (Padfield 2009b). The efficiency of such a brick lining can be increased significantly, by mounting small fans on the perforated clay bricks at one end, which blow the room air out through the horizontally extending channels. The brick lining must end on the right and left about 20-30 cm from the edge in order to leave enough room for the free entry and exit of air. The buffering properties of unfired clay vary greatly, depending on the minerals contained in the clay. Clay will contain hygroscopic inert minerals such as kaolin, but also materials that take in so much water vapour that they swell considerably (e.g. sodium montmorillonite). The sorption curve [11] of the clay gives a good indication of its buffering capacity. In conventional building materials concrete stone performs best with regards to humidity control. Lime and gypsum have a poor hygric capacity (Padfield 2011).

End grain wood in the form of parquet blocks was often installed decades ago in factory rooms. Alas, for newly built storage facilities it is not suitable, since concrete has a long drying period (up to several years). Residual moisture might cause the parquet to swell and thereby partially lift.

If hygroscopic materials are used as construction material in the storage facilities, it must be ensured that their surface is not blocked by impermeable coats as their hygro capacity then is strongly reduced or even eliminated. In the case of wall heating (Vienna model) hygroscopic building materials are usually unnecessary; this system also works well without them. The hygro capacity cannot develop in the narrow environment of the heating pipes, thus the entire wall surface is not available for the hydrical balance.

Avoidance of Waste Loads

In a passive climate control concept it is essential to ensure that the room air does not get too warm from the waste heat of technical devices (e.g. mobile dehumidifiers). In a well-functioning passive climate control such devices are unnecessary. Lighting also contributes massively to the heating of the room air. Consider that the discharge of warm air is difficult. An upper limit of 10 W/m^2 should not be exceeded for the irradiance. Only fluorescent tubes without UV or with a very low UV content should be used. Using light emitting diodes (LEDs) has the advantage that only a small amount of heat and no UV radiation arises. A further important factor is the ability to turn on the lights in the storage facility by sector.



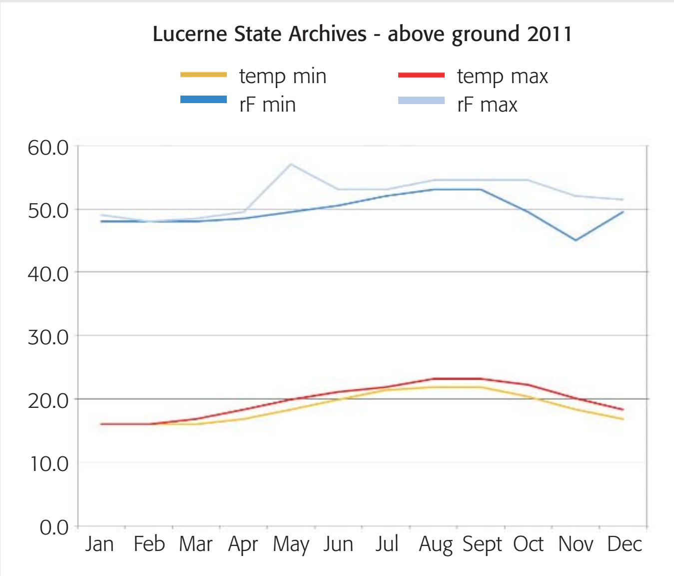
8 Brick lining from perforated clay bricks.

Practical Construction and Renovation Examples

Passive Climate Control without Heating

> *Cologne City Archive (Germany):* A reorientation in archive construction began with the building of the Cologne City Archive in 1971. The idea was, to find a solution for the new archive which offered the best possible climate created primarily by the building itself and only use additional technology when necessary. In this context one speaks of the so-called Cologne model ('Kölner Modell'). Typical for this model are solid brick walls of 49 cm thickness and an outer casing made from granite slabs. The interior walls are plastered with lime plaster. The decision in this construction project not to install any mechanical ventilation or air conditioning in the floors above ground was at that time a bold move against the principal opinion. The basement of the Cologne city archive was air conditioned, because the knowledge of the time with respect to a natural climate was not yet at the level to equip storage facilities in the basement with a passive climate control. The potential for thermal inertia in the basements remained therefore unused.

Those in charge of this project were encouraged because municipal documents and files from the ground floor of the Town Hall Tower—a tower vault with meter-thick exterior walls and very small windows—had survived almost 5 centuries and were in much better condition than they were after just 80 years



9 Year-round climate measurements in above ground storage facilities of Lucerne State Archives from 2011 show that the design provides a relatively constant indoor climate.

in the storeroom building at Gereon Monastery, which was built in 1894-97 and was too robustly heated via steam heating.

The Cologne model does not correspond to all points in the modern picture of a passive climate control. It requires, for example, personnel who open and close the windows at the right time of the day, namely, when the outside air is not too damp. The Cologne model was subsequently tested in other buildings and slightly changed time and time again, with more or less success (Kissling 2000).

> *Lucerne State Archives (Switzerland):* The new building of the Lucerne State Archives from 1993 was based on the Cologne model (Gössi 2007: 93). The climate in the above ground storage facilities with passive climate control system is stable and comparable to the climate in good historical monastery libraries (Fig 9). The above ground storeroom is aired 2-3 times each year for about half a day, if it is determined through measuring the indoor and outdoor environments that the outside conditions are such that they do not deteriorate the indoor climate. Three small windows are opened per storeroom; a cross ventilation is not possible.

> *Episcopal Archives Chur (Switzerland):* The Episcopal Archives in Chur have been in the Marsöl Tower definitely since 1730, a square medieval tower from the 13th century with walls of natural stone up to 4.5 m thick. The tower (Fig 10) belongs to the court of the bishop's residence complex in Chur.

In contrast to the two upper floors where the baroque library and chapel are housed, the archive room of the old Rhaetian diocese can boast of only one window to the north, which was always sealed from the inside with two iron wings.

As part of a renovation from 2005 to 2007 the active woodworm infested storage facility equipment was renewed and it was also necessary to bring the high humidity levels in the archive room under control. In the midsummer these were on average between 75-78 % RH (at 18-19°C) in the winter months 65 % RH (at 12-15°C). Causes of the high humidity in the archive were, firstly, the stored moisture in the thick walls on east and west side, and the small vaulted room beneath the archive with a constant year-round humidity of nearly 95 %. The slope of the mid-mountain, on whose rock outlets the Romans had built their administrative headquarters and on whose foundations the Marsöl tower was erected, acts almost as a moisture reservoir.

In the vault room the humidity was to be reduced by controlled ventilation. An extraction and an exhaust pipe were laid in two core holes in the massive wall of Marsöl Tower and connected to a ventilator (Fig 11). This ventilator runs whenever the humidity outside is lower than in the vault room, in addition a comparative measurement is performed internally and externally. The humidity in the vault room remained at almost 90 % RH even after the installation of ventilation, thus the investment in the dehumidification of the vaulted cellar was in vain. The reason is probably the steady flow of ground water on the rocky base of the tower, which forms the floor of the vault room.

The floor and the access hatch in the archive room above were sealed (Fig 12). The humidity levels in the archive room dropped significantly and became very stable after the renova-

11 Front ventilation input and rear ventilation exhaust to the vaulted room beneath the archive room in the Marsöl Tower.

10 The Episcopal Archives of the Diocese of Chur can be found in the Marsöl Tower in Chur (at the lowermost window).

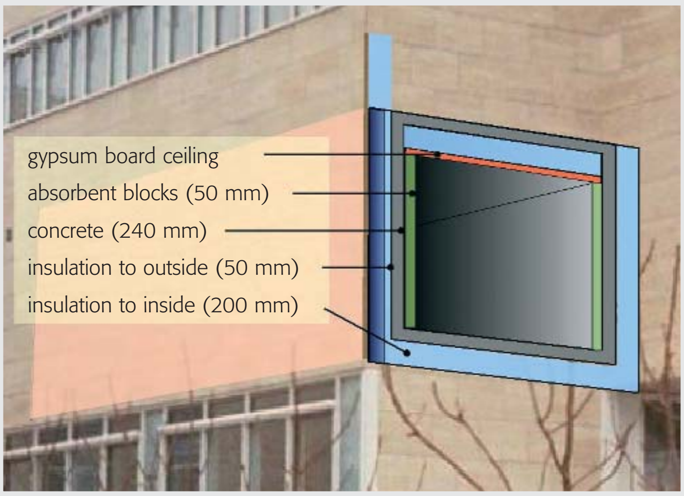
12 Access hatch from the archive room to the vaulted room.

tion. In the summer months they are now between 58-61 % RH (at 17-19°C) and in the winter months around 55 % RH (at 12° -15°C). The resulting stability clearly demonstrates how historical walls with sufficient thickness can be an excellent climate buffer, provided that the building envelope is sealed. In the case of the Marsöl Tower the problem of high humidity in the vault could not be eradicated with built-in ventilation. The simple measure of sealing the hatch to the vaulted cellar, however, led to a stable climate within the accepted climate guidelines in the archive room. The renovated storage facility behind the entrance door to the archive room, which is not heated and also has very thick stone walls, assumes the function of an air lock to the historical archive in the Marsöl Tower. The renovation of the Marsöl Tower is an impressive example of how, through sealing measures, an unstable climate can be converted to a stable climate.

Passive Climate Control with Passive Heating

> *Arnemagnæan Institute, Copenhagen (Denmark):* In this Institute, Icelandic and Nordic manuscripts which date back to the 12th century are stored. Cornerstone of the climate control here is the passive heating of the 10 x 4m archive room through heat gained from the adjacent offices, in which temperatures of 18 to 25°C prevail throughout the year. The heat from the offices penetrates through to the adjacent corridor and from there through the long wall of the archive into the storage facility. The temperature in the archive room is further influenced by the outdoor climate of Copenhagen, which can vary from –10°C to +30°C, whereby the thermal inertia of the building envelope plays a crucial role in regulating the climate through the 24 cm thick prefabricated concrete elements. By carefully controlling the temperature, the external insulation including the floor and ceiling, the moisture buffering as well as a low air exchange, it is possible to settle the relative humidity in the archive to around 45 %.

The different insulation thicknesses of the archive walls, ceiling and floor are interesting. The floor, the ceiling and the right hand wall bordering the heated offices are with 20 cm the most insulated; otherwise too much heat would penetrate into the storage facility. The outer wall is insulated with 5 cm to allow sufficient cool air to enter the storage facility. 5 cm thick boards of porous concrete were installed on the inner walls and plasterboards installed on the ceiling, both are hygroscopic materials that stabilize the relative air moisture (Fig 13).



13 Insulation thicknesses of the archives in the Arnemagnæan Institute. © Tim Padfield.

To maintain the desired humidity level of 45 %, given that the humid outdoor air in Copenhagen has an average relative humidity of 70 % the temperature in the archive room must be raised. The fine regulation of the humidity in the room is carried out by a controlled supply of fresh air. However, the supply of outside air is only allowed if the water vapour content does not negatively influence the RH in the archive. Thus there are, for example, only a few days in winter when the water vapour content of the outside air is high enough to increase the RH in the archive and vice versa in the summer only a few days when the outside air is dry enough to provide for dehumidification of the archive climate. Given these local climatic requirements, the climate in the archive will only work if the thermal inertia of the building envelope, a precisely calculated thermal insulation, a balance of heat supply and heat dissipation, sufficient moisture buffering by hygroscopic materials and low air exchange rate are given. Added to this is the humidity buffering by the archive material itself. At the beginning of the commissioning of the archive the difficulty was that the water contained in the fresh concrete diffused into the room during the first 5 years. Open doors also led to moist air from the building being fed through. In the beginning, these disturbances were monitored by a computerised control system. In the Arnamagnæan Institute the outside air is supplied through a pipe in the outer wall, where a ventilator is controlled via a temperature sensor. The natural air exchange rate for the archive is 1 room volume in 10 hours, with an active ventilator it is 1 room volume in 2 hours. This is a relatively low air exchange rate. For comparison it should be noted that air conditioning can have an air exchange rate of up to 20 room volumes per hour.

Passive Climate Control with Active Heating

> *Einsiedeln Monastery Archives (Switzerland):* The collections at the Einsiedeln Monastery Archives date back to the 10th century. An inventory and cataloguing of the archives and simultaneously the development of a new construction project, as the existing historic rooms offered too little space for modern storage, began in 2005 on the initiative of the Monastery. In 2010/11 a new underground storage facility (new construction) arose in Einsiedeln Monastery as well as a reading room and offices for the monastery archive due to the conversion of historical rooms. The starting point of the considerations for an underground storage facility was the observation that basements (such as wine cellars) are known to have a constant, cool climate. In addition to a transfer of the storage rooms below ground, the Viennese engineer's office Käferhaus decided to install wall heating according to the so-called Wiener Modell (Vienna model) in combination with a controlled ventilation. In the underground storage facility, the walls are heated by copper pipes with diameter of 15-18 mm, which were installed in direct contact to the wall (Fig 14, 15). In order to allow for a problem-free repair of any damage to the wall heating pipes, the copper

pipes should be soldered, so they can be easily repaired in case of damage.

The wall heating was combined with controlled ventilation and a 2-3 cm layer of clay plaster on the walls. Controlled ventilation in the storage facility works mainly with fresh air. Exterior and interior sensors compare the absolute humidity inside and out and ensure that only fresh air is supplied, if this does not cause negative affects to the climate conditions. The storage facility could already be stocked just 6 months after the completion of the building envelope, as the climate had stabilized to the required range as a result of the installed wall heating. The ventilation in the reading room and offices is, for financial reasons, carried out manually via the windows, which is not optimal, as external adverse climate conditions can enter the premises and lead to climate shocks to the archive material.

After construction was completed, three parallel working systems can be observed today in Einsiedeln Monastery: the underground storage facility of the new archive as well as reading room and offices are equipped with wall heating according to the Vienna Model, the 10 year old shelter for cultural assets is fully air-conditioned while the climate in the baroque hall is controlled naturally, without the additional use of technology.

Passive climate systems are preferable to air conditioning from both a financial and environmental point of view. Although both systems create good conditions for documents, provided that the air conditioning system can offer long lasting reliability. Even passive systems do not automatically guarantee good climate conditions. Good planning and execution of the wall heating is crucial. The experience of the author shows that ventilation engineers tend to change the wall heating system according to their own ideas, which often lead to technical errors and subsequently unjustly put the system in a bad light. The correct uses as well as the structural conditions are critical with passive climate systems. Only interfering factors from the user (bad ventilation through windows, masses of people who stay in the storage facility for long periods, etc.) prevent the whole system from functioning in the correct manner.

14 Prior to plastering the heating pipes mounted on the concrete walls (height 2.43 m).

15 The wall heating pipes (arrows) prior to embedding in the window embrasures of the reading room and the archive office.

Climate Recommendations for Storage Facilities

Burmester (Burmester 2000) recommends the following values:

> *Relative Humidity Ranges during the Year:* 45-50 %, during a week +5 % (summer), –5 % (winter) compared to weekly values. Note: The history of the objects (storage to-date), site conditions and local circumstances (climate) can also be responsible for the decision to decrease or increase the relative humidity.

> *Relative Humidity Fluctuation during a Day:* ± 5.0 %. Note: The change should be as low as possible and the frequency of fluctuations should be kept as small as possible.

> *Relative Humidity Fluctuation during an Hour:* ± 2.5 %. Note: The change should be as low as possible and the frequency of fluctuations should be kept as small as possible.

> *Temperature Ranges during the Year:* 4-28°C with seasonal modulation. Note: From a preservation point of view lower temperatures are favourable for the majority of materials. The internal temperature is based on the average monthly external value, wherein the difference between the two should be as small as possible. Elevated temperatures in the range 24 to 28°C are permitted to a maximum of 150 hours per year.

> *Temperature Fluctuation during an Hour:* ±1°C. Note: The change should be as low as possible and the frequency of fluctuations should be kept as small as possible.

Climate reference values are as the term implies not rigid values but should be adhered to whenever possible. However, there are often compelling reasons to resort to air conditioning because in some hot summer weeks the temperature rises higher than the reference values. It is precisely these fluctuations that have always been present in historical libraries without technology and they are not responsible for damage to bindings, paper and parchment. The relative humidity can remain very stable even at elevated temperatures provided hygroscopic materials are available in storage rooms.

Concluding Remarks

For reasons of energy efficiency and low maintenance, the construction of fully air-conditioned storage rooms, both under and above ground, are no longer practical. There are several reasons why in Europe air-conditioning systems are still being installed. Often passive climate control concepts are still little known to local engineers and architects. Also there is a lack of desire or willingness to take risks and engage new things and therefore reduce costs, as from an economic perspective this is not interesting for architects and engineers as long as their fees are coupled with the built-in sum. Energy saving offers little reward with this method. Another reason lies with the building authorities, where the principle of sustainability is not widely regarded as the utmost objective. When it comes to buildings for archives, libraries and museums with an advantageous energy balance, these offices really play a key role, even more so than that of the institute directors. Institute directors can make it much easier for the urban construction offices to build energetically sustainable, if they avoid using the existing reference values which have been circulated without any basis for decades and were never intended as such. And last but not least are the conservators, the most zealous advocates of the old climate values, are required to move away from rigid so-called reference values (40-60 % RH, 16-18°C), and in doing so show that documents also survived well with a climate customised to season, just as the many collections that are located in historic buildings have proven.

With the choice of passive climate control it is important to carefully tune the concept to the respective construction. In our climate zone it should be remembered that mould can only be safely prevented through a passive climate control with conservational heating. If conservational heating is wavered, a residual risk remains. It is up to those involved in the construction to decide whether the risk is acceptable. When the idea of sustainability is logically thought through, it is obvious that energy, which is necessary for heating, is provided via alternative systems (e.g. solar panels, etc.). That this is also possible on buildings which are under preservation protection has been proven with the two churches in Aflenz and Gerling in Austria. There the water for the wall heating is heated by solar panels.

The climate values proposed over the last decades from various sides do not hold up to critical questioning. Ultimately, it is secondary whether the values and the annual fluctuations are slightly lower or higher. But one of them must be observed: the short-term fluctuations (per hour, day and week) of the relative humidity should be as low as possible. A great long-term constancy of the relative humidity is almost exclusively common in good historical storage rooms. In new buildings, because of the constant temperature of the ground the possibility of underground storage should be checked, assuming that the building is not in a flood hazard zone.

A confident look to the future is at least possible as more storage rooms are being built with passive climate control and the trend will continue. Hopefully also is the fact that, for example, in Germany the construction of archives is mostly carried out with passive climate systems. In Switzerland, there is hope that the new thinking will prevail over the next ten years also, to the benefit of environmental, energy and cost efficiency as well as the written material itself. Besides the new monastery archives and the music library of the Benedictine Monastery Einsiedeln, which went into operation in 2012, there are also new storage facilities under construction for the Franciscan Monastery in Fribourg, the Diocesan Archives of the Diocese of Chur and the State Archives of the Canton Appenzell Ausserrhoden. A storage room for the archive expansion of the Benedictine Monastery Engelberg is in the planning stages. A common in all of these construction projects is that they will employ passive climate systems and thus will manage without air conditioning.

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Endnotes

[1] Relative humidity (RH) is the ratio between the actual amount of water vapor present in the air and the amount of water vapor contained in saturated air at the same temperature. RH is expressed in %. If the air is saturated with water vapor, the relative humidity is 100 % and the dew point is reached. At this point, water molecules collect together and enter liquid state. They form droplets in the atmosphere (clouds or fog), or on surfaces (dew). The absolute humidity (AH) is the water content of air. AH changes as air temperature or pressure changes. It is expressed in grams per kilogram of dry air or in grams per cubic meter of air (Andrea Giovannini [2004]: De Tutela Librorum. La conservation des livres et des documents d'archives. Die Erhaltung von Büchern und Archivalien. Genf: Edition ies (Institut d'Études sociales); see also Tim Padfield <www.conservationphysics.org/intro/fundamentals.php>.

[2] Many of the earlier used building materials are hygroscopic. Rediscovered in building biology about 30 years ago, one knows, for example, the good moisture absorption of clay, which is being increasingly used today in the new construction and renovation of libraries, archives and museums. Hygroscopic materials, especially porous materials such as clay, wood, brick, plaster, textiles, etc., absorb humidity on contact with moist air. The exact behaviour of hygroscopic materials must be determined by means of the sorption curve; see also RH Humidity buffering by hygroscopic materials <www.conservationphysics.org/intro/fundamentals.php> .

[3] Heat flux density is the amount of heat transferred through a given surface unit (unit W/m^2).

[4] The light signal was developed about 10 years ago by the technical consulting office Käferhaus and other experts, and is already in use in many buildings. Similar to a traffic light signal, it informs the user through colours when he may and may not air the room, thus no harmful influences from the outside are brought into the storage facility; whereby a dense, thermally inert building envelope, hygroscopic materials, mechanical ventilation systems, as well as the conservation heating play a crucial role (Käferhaus 2004a: 49).

[5] Below dew point: part of the air is invisible, gaseous water. In a cubic meter of air at 20°C, depending on the air pressure, there is a maximum of 16 g of water vapour, which corresponds to a relative humidity of 100 %. The absorption capacity of air to absorb this water vapour is dependent on temperature: if by dropping temperatures the capacity limit falls, the water vapour condenses into dew: liquid water that condenses at a solid surface. This formation of dew occurs with saturated air with a relative humidity of 100 % rather than with unsaturated air. Provided one cubic meter of air at 20°C contains only 8 grams of water vapour, the relative humidity is i.e. 50 %, comparatively the absorption capacity would also persist even at a lower temperature. Depending on the ambient temperature and the relative humidity a limit on the absorption capacity of water vapour in air is thus created. This is called the dew point and as with the surrounding air, is indicated in °C; see also <www.conservationphysics.org/intro/fundamentals.php>.

[6] It is important to detect geometrical thermal bridges within a building, since these areas have a high risk of mould growth and

odor formation. Geometrical thermal bridges are a result of the shape (or geometry) of the thermal envelope. They can be 2-dimensional (where 2 planes intersect) or 3-dimensional (where 3 or more planes intersect). Typical examples include: the corner of an external wall, wall/roof junctions, wall/floor junctions, junctions between windows/doors and walls or junctions between adjacent walls <www.leedsmet.ac.uk/teaching/vsite/low_carbon_housing/thermal_bridging/types/index.htm>). At low ambient temperatures, the room-side surface-temperature of thermal bridges decreases more than in other areas. When dropping below the dew point, water condensates, forming dew drops. Because of the internal heat transfer resistance of the walls it can be the case even with a relative humidity of 70 % of the room air. Thermal bridges lead to higher demand for heat transmission and thus to higher heating demand and heating costs.

[7] Cold-wall-problem: exterior walls that are much colder than the room air bear the risk of dropping below the dew point. This is almost always the case with convective heating (air conditioning, radiators). In combination with organic wall coverings (e.g. paint), the high moisture content of the wall provides optimal conditions for mould growth.

[8] Radiant heat: heat radiation or thermal radiation is electromagnetic radiation that every body emits. Colloquially, under heat radiation usually only the infrared portion of the thermal radiation is understood, that that gives the warming sensation.

[9] Convection heat: convection is, in addition to the competing methods heat conduction and heat radiation, a mechanism for the heat transfer of thermal energy from one place to another. Convection is always associated with the transport of particles that carry the thermal energy.

[10] Heat exchanger: the heat transferor (colloquially heat exchanger) is an apparatus which transfers the thermal energy from one substance current to another.

[11] The sorption curve: the sorption curve from 40 to 60 % RH can be easily measured to sufficient accuracy by the weighing of clay building bricks (cut to fine pieces) in different atmospheres, which are produced by saturated salt solutions in small containers. Clay bricks usually contains a mixture of kaolin minerals and more absorbent minerals, which means that each clay source should be checked for the hygroscopic properties.

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