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The Tempered Building: Renovated Architecture - Comfortable Rooms - A "Giant Display Case"

Abstract

Tempering is an alternative method of *distributing* heat that has been developed since 1982 by the Landesstelle für die nichtstaatlichen Museen in Bayern (Bavarian Museum Service of the Bavarian State conservation Office) in public building projects, in cooperation with local building authorities. Its main characteristic is the continuous heating of the building shell, which normally is done with two heating tubes installed under the inside plaster at the base of outside walls on all floors. Without additional measures, tempering stops capillary rise of moisture, condensation, and damaging salt effects while stabilizing room climate and providing physiologically and conservationally appropriate as well as energy saving room heating. It is applicable to all sorts of buildings in old or modern construction such as museums, monuments, churches, dwelling houses etc..
In its minimal form it serves for the preservation of open air museums buildings and housed excavations.

Das temperierte Haus: Sanierte Architektur - behagliche Räume - „Großvitrine

Die „Temperierung" ist eine alternative Methode der Wärme-Verteilung, die seit 1982 von der Landesstelle für die nichtstaatlichen Museen in Bayern beim Bayerischen Landesamt für Denkmalpflege in Zusammenarbeit mit Baubehörden in öffentlichen Bauvorhaben entwickelt wurde. Ihr Hauptmerkmal ist die kontinuierliche Beheizung der Gebäudehülle, die in der Regel durch zwei Heizrohre unter Putz an den Außenwandsockeln aller Geschosse geschieht und ohne Zusatzmaßnahmen folgende Wirkungen hervorruft: Ausschaltung von aufsteigender Feuchte, Kondensation und Schadsalzwirkung, Stabilisierung des Raumklimas, physiologisch wie konservatorisch zuträgliche und energiesparende Raumbeheizung. Wegen des Fehlens von Raumluftkonvektion sind auch Großräume beherrschbar. Dank der minimalen Installationstechnik eignet sich die Methode ferner für die Konservierung von Exponatgebäuden in Freilichtmuseen und behausten archäologischen Ausgrabungen.

contents

Summary

As a result of long-term experience with "tempering” (pure wall-base heating as the simplest forms of wall heating) and controlled natural ventilation, the architectural and technical requirements for a conservationally as well as physiologically ideal building can be described as follows: The buffering ability of its envelope for reducing variations of outside temperature and solar radiation should be as high as possible. For this purpose, the walls must be airtight and possess more than a minimum amount of mass (rather than thermal insulation) while the windows must have double glazing (modern or historic styles) with seals, external shading, and light protection devices. Two heating tubes (foreline and return line, together forming a loop, with diameters of 15 or 18 mm, up to 22 mm in churches) are installed one above the other at the base of all walls belonging to the building envelope, including both the exterior and interior walls of cellar rooms. The tube for hotter outward flowing water is referred to as a foreline and not as a supply or feed line because it has no destination, the tubes themselves are the heaters (the journey is the destination), and at some point in the loop each tube turns around and retraces its path as the cooler return line. With this minimal form of tempering (two tubes at the wall base) conservational requirements are safely met. For dwellings, the return line is mounted at the height of the windowsill or two separate loops are used, one at the wall base and one at the bottom of the windowsills, which allows lower foreline temperatures.

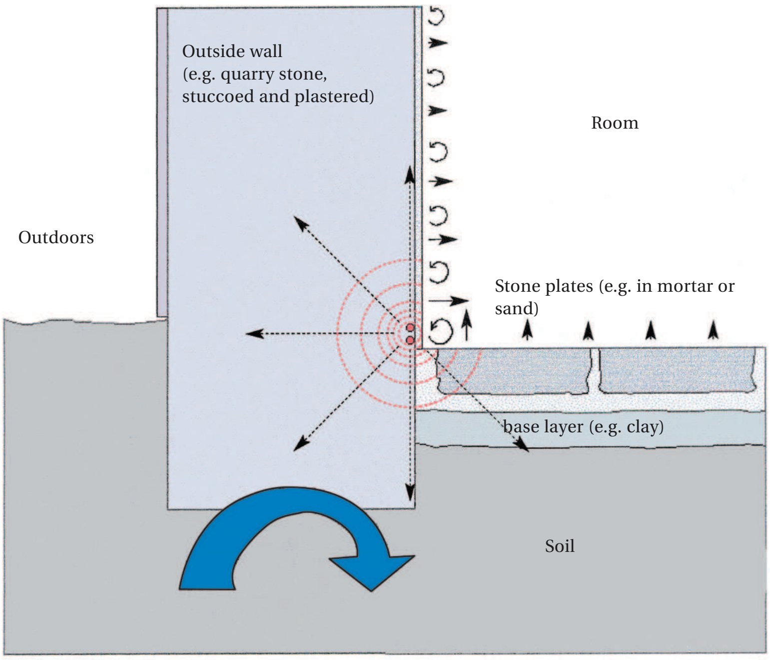
The hot strip of wall created at the wall base drives convection in the boundary layer between the bulk room air and the wall surface, uniformly heating the wall surface above the hot strip. The warm outer walls then radiatively heat the rest of the building, which results in a completely draft-free warm building with dust free air. Because there is no convection in the bulk of the room air, there are no air currents that entrain dust from the floor – as there are with conventional room-air convection heating systems. The walls are continuously heated, which means 24 hours per day, during the whole year for walls with earth contact (in summer with foreline temperatures of 30 °C and less) and only during the heating season for other walls.

In museum buildings, the heating capacity of the tempering tubes is limited for conservational purposes. Thus the room temperature, especially in win-

Figure 1:
Tempering. Mechanism of its functioning in an ”historical” setting: Walls without thermal insulation or vapor barriers are kept dry by continuous heating (see Fig. 4)

Red dots:
Heating pipe loop (fore- and return line, bare copper, 15 mm) covered by a maximum of 15 mm of plaster
For earth-contact floors: The foreline should be slightly above the finished floor.
Long arrows:
Heat transfer due to thermal conduction: radially in the wall and floor away from the heating pipes
Red circles:
Heat accumulation with cylindrical isotherms (high temperature only near the pipes, see Fig. 9)
Round arrows:
Heat transfer due to convection: rising warm air flow in the boundary layer attached to the wall surface (Coanda effect)
Short arrows:
Heat radiated from the warm surfaces (high temperature only near the pipes, see Fig. 9)
Blue arrow:
Ground moisture. Thermal horizontal barrier due to the radial heat conduction

Based on a diagram by Miha Praznik, 61–ZRMK, Ljubljana.



ter, varies gradually in a range based on the mean outside temperature and thus on the mean absolute humidity of the outside air. In the same context, ventilation should be performed by means of exhaust fans which are under-sized by the usual standards (maximum exchange rate of 1 room volume per hour = 1 air change per hour = 1 ACH) and which are operated only "if needed,” i.e. when people are present. (Exception: cooling at night during the hottest part of the summer.) In museums with a high number of visitors, a simple fresh air system has to be installed, which can be restricted to only the small flow rate necessary for renewing the air (max. 1 ACH) if the cooling load due to lighting and solar radiation is kept low.

Such an ideal building fulfills its conservational purpose by providing optimal room conditions, achieved at low cost through the use of the simplest technology, with low energy consumption (see below). In particular, the room climate is homogeneous – it is the same in all parts of the room and on all floors of the building – and it changes only slowly during the course of a day or a season. The relative air humidity (RH) is constant in the short term and varies slowly about a moderate mean value, which results in a slowly varying equilibrium moisture content of the stored artifacts. The need for air humidification is low; dehumidifiers are not necessary.

As a side effect of the continuous heating of the walls, the building substance is conserved due to moisture removal, protection against condensation, and inactivation of damaging salts. Because of these effects, the method does not only apply to the renovation of "normal” and old (historic) buildings but also to the conservation of open-air museum buildings and their furnishings. For this purpose two single-tube loops for every floor are sufficient, with the foreline of each loop making a ring around one half of every floor and the return line following the internal partition walls. Similarly, enclosed ("housed”) archeological excavations are conserved by single-tube loops around their circumferences. Here, our experience that neither vapor barriers nor thermal insulation are necessary for floors with ground contact in wall-heated rooms becomes understandable. Their functions are provided as side effects of tempering. This is true even in dwellings.

The negligible conservational damage potential resulting from these design principles, compared to conventional technology, and the fact that the heat distribution concept aims at the whole building envelope, including the stairwells, establish the special suitability of tempering as a heating system for museum buildings of any size. The homogeneous climate and the dust-free air are found throughout the building volume, so that the building functions as a "giant display case." The features described above provide the ideal basis for planning museums and other buildings with low capital and operating costs.

For the heating of living and office spaces, light protection, limitation of the heating capacity, and control of the air exchange rate are not needed. Ventilating by opening windows is possible: On the one hand, there is no need for a constant RH and, on the other hand, it does not result in significant energy losses because the heat is stored in walls and other massive parts of the building. In the case of thin-walled offices or dwellings, as in half-timbered houses, or for lowering the foreline water temperature, a second loop is mounted at the height of the lower edge of the windowsills, whose return line makes detours along the sides of the windows.

Energy consumption with tempering, in general, is lower than with the usual air heating because, in addition to the lower temperature of the room air, the drying out of the building envelope results in a lasting improvement of its U-value. Both effects make the influence of people on energy consumption negligible. This is of great importance for historic buildings, since the goal of (in Germany, government mandated regulations for) energy savings is achieved by directly heating the building envelope, which at the same time conserves the material – rather than through use of more modern implementations of false heat distribution concepts such as radiator/convector heating and installation of thermal insulation, which alters the external appearance, eliminates heat accumulation from solar radiation, and prevents the drying out of the walls.

1. Long-term experience with tempering

This year the Landesstelle (Landesstelle für die nichtstaatlichen Museen in Bayern beim Bayerischen Landesamt für Denkmalpflege, Munich, or Bavarian Museum Service of the Bavarian State Conservation Office) looks back on 21 years of experience with the dehumidification of air and the stabilization of climate in museum exhibition rooms and storerooms. From the beginning, emphasis has not been on the use of air conditioning or other mechanical room air systems, but on the testing of wall heating techniques in combination with the simplest measures for controlling air exchange. On this "long march of empiricism against the theories of HVAC-experts," it has been shown that the holistic effect of tempering (pure wall-base heating as the most simple wall heating technology) occurs in all types of buildings, independent of how they are built and used, and that this effect allows a great simplification of building renovation, climate control and heating technology, in general. This has led to an increased use of tempering, the details of which will be presented below (see Section 6.3). Before that, however, the three most important results of long-term experience with this minimal heating method will be discussed and, based on that, the requirements for room climate for everyday use will be defined.

1.1. Lowering the costs of eliminating wall dampness and stabilizing room climate through tempering

The first of these results is of great economic importance, especially in the case of historic buildings. Buildings whose envelopes exceed a minimum of mass (e.g. half-timbered constructions with massive fillings, log houses, or buildings with stone walls of any size) can be optimized for conservation of their furnishings (including earth-contacted levels) in a simple and user friendly way and can, at the same time, themselves be preserved through installation of only a minimal amount of new hardware (Minimum installation: two wall-base heating tubes in or on the surface of each outer wall, one wall-base heating tube on each side of earth-contact partition walls, and one or more simple exhaust fans).

Expulsion of moisture from walls, deactivation of damaging salts, protection from condensation, thermal insulation and moisture isolation of floors with earth contact are side effects of tempering (Fig. 1). In addition, annual heating costs, despite the energy required for heating earth-contact walls during the summer, are lower than with conventional heating and air conditioning. This is because the amount of energy used during the heating season decreases by an even greater amount than that used during the summer, due to the lower rate of heat transfer through dry walls and the lower room air temperature (compared to convector heating) – independent of the behavior of humans. The above-mentioned effects occur already for the wall thickness of half-timbered houses. With respect to climate stabilization, however, this does not apply for light-walled structures, such as sheds with only external siding or glass walls. For such buildings, the structural prerequisites must first be satisfied, independent of the heating and air conditioning equipment. The ability of the building envelope to dampen the effect of changing outside temperatures and solar radiation must be improved by increasing the mass of the outer walls and by installing external shades.

1.2 Conservationally and physiologically favorable room conditions through tempering

It has been found that, through the simple means of a minimal tempering installation, quality of climate can be achieved in both conservational as well as physiological respects, which is contrary to the usual assumption that this can only be achieved with air conditioning systems. Thus the term "climate control" usually implies that room air must be conditioned to given values of temperature and RH throughout the year and that this can only be achieved by circulating the air continuously by means of an expensive "air conditioning system."

Particularly the basic functions of air conditioning systems – constantly moving the room air, treating it mechanically, and circulating it through ducts – result in certain flaws. Air conditioning has a negative effect on the feeling of comfort as well and, often, on short-term climate stability. It causes a higher demand for heat due to drafts, which often also cause unnecessary accumulation of dust on all surfaces. Through overheating or overcooling, germ infestation (when improperly maintained), and deionization, air conditioning reduces the quality of the "most important human nutrient," the air. Furthermore, it is difficult to determine the direction that conditioned air will take, as air rises when it leaves an outlet not only when heated but also when humidified, since both processes reduce its density. Similarly, both cooled and dehumidified air sink, since both processes increase air density. Most of these disadvantages also apply to radiator/convector heating, especially when combined with air humidifiers (see Section 4.1). Considering these characteristics, the use of the bulk of the air within rooms as a heat transfer medium should be avoided, if only for physiological reasons.

In contrast, a "radiation climate" – the room climate which results from the outside walls being heated directly and the inside wall surfaces being heated by radiation from facing walls, which occurs without heating and circulating the room air, as is the case with air heating systems – fulfills the two most important conservational criteria for climate. First, short-term fluctuations cannot occur either in closed-off rooms, if the joints of doors and windows are sealed, or in rooms in use, if the air exchange rate is controlled by use of ventilating fans. Second, the way by which this type of room climate is produced results inevitably in its homogeneity, which means the temperature is nearly identical in all parts of the room. Thus, there are no limits on the location of furniture or hanging objects, if a small distance (15 to 20 mm) is maintained between objects and the wall, in order to allow the warm air needed to heat the wall surface to rise.

Additionally, during the heating season, this method of wall heating causes a comfortable climate for visitors and staff in exhibition rooms and storerooms, since the unavoidable flaws of "air heating" or air conditioning described above, in particular drafts, do not occur. Thus, lower room temperatures than commonly assumed, especially much lower room air temperatures, are still perceived as comfortable. Thereby the need for and thus the costs of air humidification as well as the risk of condensation are considerably reduced; with air conditioning systems also the costs of heating fresh air. Further, there is no more need for air dehumidification (see Sections 3.2.2 and 6.2.1). From this it becomes clear that, contrary to common opinion, visitor friendly room conditions in museums can be produced without compromising conservation, if one deviates from the state (!) of the art. As this alternative concept of heat distribution includes the exterior walls of staircases, even there no convection occurs in the bulk of the air, even if the entrance doors of the several floors are open. The homogeneity of climate and the dust-free air therefore are found in the whole building, so that a tempered building has the quality of a "giant display case."

1.3 Tempering and air exchange control produce a "Universal Climate"

Another result is increasingly being acknowledged by specialists. With continuous "wall heating" and control of the air exchange rate, a "Universal Climate" can be produced that is suitable for almost all materials found in museum collections. Thus, not only the basic requirements of conservation are fulfilled. Even more the scientific requirements can more easily be satisfied on this basis: The statement made by an exhibition concept can be optimized because the combination of materials in one room is not limited. It is not necessary to create various climate zones, which not only restrict the concept of a museum but also are costly. This applies equally to exhibition rooms and storerooms. And not only the additional costs and effort are eliminated, but also the potential for climate related damage, damage which is enhanced by two factors: the flaws of room air conditioning technology with regard to operating safety and the unpredictable behavior of visitors and staff. Because of its already mentioned main criterion, the absence of short-term fluctuations, such a Universal Climate is valid for all materials (with the exception of photographic materials, which at least in the storeroom should be stored only at low temperature and humidity, e.g. in a refrigerator). Even glass corrosion is determined not so much by the height of the RH as by the short-term fluctuations. On the other hand, artifacts from excavations – even at moderate RH – are safe only if they are completely desalinated.

2. "ICOM Recommendations"

As early as 1983, observations of the climate in tempered rooms (in the pilot project at the Starnberg City Museum) were reason for the Landesstelle to redefine its room climate guidelines in deviation from prevailing opinion, in particular deviating from the so-called "ICOM Recommendations." In fact, upon closer study these "recommendations" turn out to be an illusion, as Holmberg found out in 1995 in his study of world literature on RH [1].

In 1960, the International Council of Museums (ICOM) published a list of climate values from 37 locations, obtained from questioning archives, libraries, museums, and individual specialists. Evaluating this list, Holmberg's study found that: The values are not based on sufficient research; the list did not state whether the listed values were those followed by the various institutions, their goals, or rather just what they considered desirable; more than half of those asked recommended allowing considerable seasonal variation (up to 14 K and 20% RH). In the time following, nevertheless, a worldwide consensus formed in museum circles that the values "a constant 18 °C and 50% ± 5% RH" – the mean values of the list (!) – were ICOM recommendations. Until the 1990s, this narrow climate band was considered the ideal basis for planning air conditioning systems, despite the directly resulting high capital costs and without any consideration of the region or the construction of the building (see Section 3.1). Temperatures here are quoted in the familiar unit °C which is referenced to water. The internationally accepted (S.I) unit of temperature, however, is the Kelvin (K) referenced to absolute zero (see Fig. 2). Two examples show the importance of the Kelvin scale for energetic considerations:

- Even at 0 °C the energy radiated by a surface, proportional to (273 K) 4 is still substantial.
- Basement rooms are surrounded by soil at 10 °C (283 K, see Fig. 3). After being heated for some weeks with wall base heating for the first time, the drying room shell reaches a temperature of 20 °C (293 K). The heating capacity needed to maintain this room temperature cannot be high (some hundreds of watts).

As explained in Section 1.1, empirically derived criteria for climate planning are advantageous not only for conservational but also for economical reasons, since their application enables considerable savings on climate control costs. Especially in times of reduced budgets, this is of particular importance for museums. Since the late 1980s, examples of this can increasingly be found, not only in the specialized literature but (35 years after the ICOM survey) also in Holmberg's study. This study was the first Swedish contribution to the PREVENT Project, whose main theme, besides the advantages of "natural ventilation" and the flaws of climate measuring techniques, was the effect of tempering.

3. Climate criteria for everyday use

The criteria explicitly confirmed by the PREVENT Project are:

- the "fundamental role of the building envelope" in the stabilization of room climate,
- that "slowly varying room climate" must be a design requirement, and
- the "international 'standard' values for climate are not generally valid," since they take into account neither the regional and seasonal characteristics of the location nor the construction of the building and its method of heating or air conditioning.

Since every exhibition room functions as a storeroom outside of opening hours, the following discussion of criteria does not differentiate between exhibition or storage rooms.

3.1 Fundamental role of the building envelope

Worldwide during the last 20 years, in museums with full air conditioning, damage to museum collections and building elements due to spectacular climate changes and condensation have been observed, particularly if – while putting up with high annual energy costs – the limits of the "ICOM recommendations" were aimed for, which are extremely narrow considering the seasonal changes of the outside climate.

This applies not only to old buildings with massive walls that were "renovated" by installation of the most modern air conditioning systems, such as the Semper Gallery in Dresden, where the damages showed soon after its reopening, or the Alte Pinakothek in Munich, where the dew point safety of the north wall of the upper floor is guaranteed not by the air conditioning system but rather by additional wall-base heating (an electrical resistance heating wire installed into the wall-base plaster shortly before the reopening). Particularly in buildings in which "modern" construction techniques were joined with climate control based on pure air conditioning, these flaws have often appeared unexpectedly. Examples are the "old" new building of the German National Museum in Nuremberg and the "Kunstbau" of the Lenbachhaus in Munich, which both have continuous condensation on their glass walls in winter, and the new building of the Kunst-

Figure 2:
Comparison of the Celsius and Kelvin temperature scales
The Celsius scale is based on the change of state of water.

The absolute temperature in Kelvin (K) is a measure of the vibration of the molecules

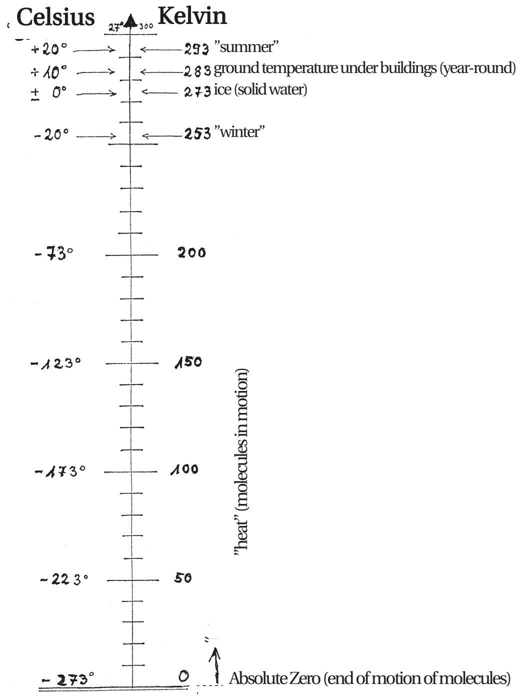
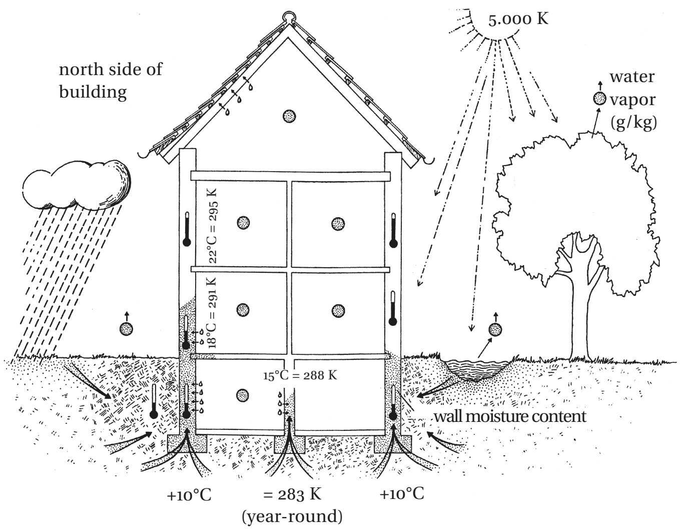


Figure 3:
Summer moisture in unheated buildings
Drawing: Hans Stölzl, Bavarian State Conservation Office, Munich



halle Bern, where in winter there was condensation on its light-construction outside walls and maximum air humidity next to the paintings hanging there, while during summer, as inevitably is the case with light construction, energy costs for cooling were high.

As a result of these experiences, the opinion in the museum world has gradually come to be that the building, particularly its envelope (its windows, roof, and outer walls), plays a fundamental role in climate control. In order to design a sensible climate control system, with economically justifiable capital and annual energy costs, above all the impact of changes in the outside climate and in solar radiation energy flow must be reduced. In the past, this was performed by a massive-walled building envelope with "airtight" joints and outside-shaded glass surfaces in combination with controlled air exchange. At the same time, heat from the artificial lighting – usually considered part of the "inside cooling load" – must be reduced by the choice and mounting of the lighting.

If, for example, solid connection of the lighting with building elements is avoided, the buffer effect of the inner heat storage masses is maintained, since they are not unnecessarily heated by heat from the lamps themselves through heat conduction from the lamp fixture and short-range heat radiation from the backside of the lamps. The distance of the lighting from the surfaces of exhibited or stored artifacts also plays an important role. It should not be determined only by esthetic/architectural considerations, but also by the simple physical fact that the light intensity at the object is reduced by the square of the distance – i.e., for the same light intensity at the object, the output of the lighting has to be increased by the square of the distance ratio.

In high-ceilinged rooms, therefore, mounting the lighting at the ceiling level means a greater amount of lamp power is required, which results not only in an avoidable higher energy consumption for lighting but also in a much higher amount of heat being given off by the artificial lighting. The main purpose of the air conditioning system, however, should be the treatment of fresh air when people are present and not, as is usually the case, compensation for the faulty buffering effect of the building envelope and internal building parts on outer and inner energy flows. On the contrary, it should only further reduce their impact on the room climate, after this impact has already been reduced by the buffering effect of the mass of the walls without the use of energy.

3.2 Slowly changing room climate as a goal of planning

As experience shows, the conservational quality of room climate, in contrast to the commonly held opinion discussed in Chapter 2, does not result from rigidly maintaining the room climate values against continuously changing natural and use-dependent influences, through the use of high capacity cooling and heating systems whose output is varied constantly by their control systems. The conservational quality results from letting the climate values vary slowly with changes in external and internal energy flows, which are reduced by the mass of the building and the deliberately under-sized heating and ventilating systems.

3.2.1 Conservational goal: Slow variation of the equilibrium humidity

The direct result of such an alternative climate concept is a room climate which varies slowly with the seasonally and time of day dependent mean outside climate values. The main conservational advantage of this "dynamic room climate" is that, for the greatest part of the year, particularly in winter and summer, the differences in both air temperature and vapor pressure between inside and outside is lower than with the conventional concept with its goal of a "static room climate." This has a controlling influence on a key conservational quantity, the "equilibrium humidity," which is of importance for almost all materials of the room shell and for artifacts and furnishings.

The equilibrium humidity is the humidity in the pores or fibers of a hygroscopic material. It depends on the temperature of the material and on the relative humidity of the surrounding air. When the temperatures of walls, room air, and artifacts are equal – i.e. in summer or during the heating period, in the case of "wall heating" – the humidity content changes constantly with ("is in equilibrium with") the relative humidity of the surrounding air. Due to the hysteresis effect, however, this accommodation cannot be continuous in both directions: With increasing water vapor content of the air, a hygroscopic material is quickly "invaded" by water molecules and capillary condensation takes place (sorption phase), caused by hydrogen bonding (see 4.1). In a comparable following drying phase (desorption phase), the drying is discontinuous due to this adhesion effect, as the water molecules tend to cling to the fine structures of the material. So, "the material retains" a certain quantity of the previously absorbed vapor, or, more correctly, these water molecules leave the material only at a lower value of the RH, compared to that of the sorption phase. In consequence, a drying phase, being discontinuous, causes more stress in the material than an analogous sorption phase.

In the case of conventional heating or air conditioning, i.e. when the material of the outer walls and of the objects near them are colder than the room air, this vicious circle creates an even greater damage potential: The lower temperature of the solid bodies means a lower amplitude or kinetic energy of the vibration of their molecules, which reinforces the adhesive effect of the gaseous molecules (vapor) and, at the same time, the hysteresis effect.

With the dynamic climate concept, the unavoidable climate variations are slowed-down and their amplitude is smaller. So, the equilibrium humidity can adjust itself in such a way that no relevant material stresses occur. In contrast,

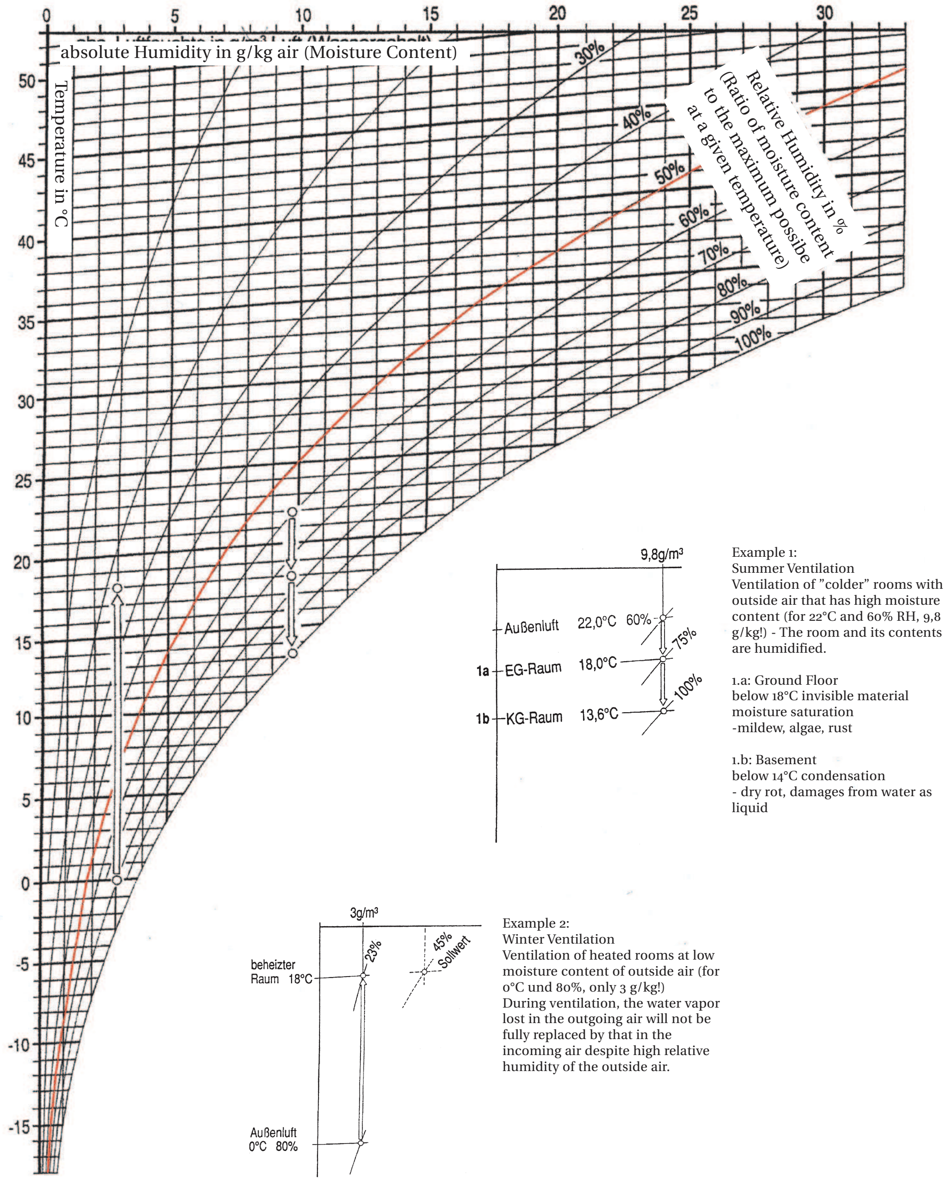


Figure 7:
Mollier-h, x-Diagram (Psychromatic Chart)
Dependence of the local value of the relative room air humidity on the moisture content of the outside air and the room air temperature as well as on the surface temperature of the building element.

Drawing: Erich Hackl, Munich

with static climate concepts – not considering very expensive or elaborate solutions – in addition to the above mentioned stress occurring during normal functioning of the hardware, further stresses are repeatedly caused by regulation errors or breakdowns of units, e.g. of the air humidity control system. So, "even" with air conditioning systems, sudden damages are possible, e.g. the flaking of paint. With a slowly varying room climate, however, for long stretches of the year it is unnecessary to interfere with this natural process through air humidification or dehumidification. This dramatically reduces the dependence of the room climate on hardware and its maintenance or on regulating software. Thus, the capital costs, energy consumption, conservational and building preservation risks, and the danger of control errors are reduced. Furthermore, the physiological inconvenience of drafts and the constant manipulation of the breathed-in air are eliminated.

3.2.2 *Conservationally sensible band of variation of the room climate*

In the usual case, i.e. in buildings without expensive climate control systems and without technical staff, the most important conservational goal is slowing down variations of the equilibrium humidity. In order to achieve this without major effort, the large seasonal differences in the degree of the absolute outside air humidity (humidity ratio in grams moisture per kg dry air, see Section 4.1) must serve as a basis for planning. These differences are caused by the fact that the absolute humidity depends directly on the average outside temperature.

In the course of the year, therefore, large but slowly varying changes of room temperature and relative room air humidity must be allowed, e.g.

- Temperature range of 15 K: low of 12 C, for hard frosts, high of 27 C, for extreme solar radiation;
- Humidity range of 30% RH:
- low of 38% RH, for frost, if the room temperature shall be above 12 C, with as little humidification as possible; high of 68% RH, for times of extreme absolute humidity of the outer air in summer in rooms in contact with the ground or in very massive buildings, when the dehumidification is not done using dehumidifiers but rather through minimal room tempering.

Because of the periodic impact of daylight and artificial lighting, slow variations must also be allowed during the course of the day, however on a much smaller scale (e.g. 4 K and 8% RH), with their degree highly dependent on the fundamental role of the building envelope. When this is optimized as described above (Section 3.1), the installed capacity of the artificial lighting is held beneath 20 W/m2, the air exchange rate is held under 1 ACH in the presence of visitors, and the transmission heat demand is covered by tempering, then the climate fluctuation rate can be held at values of 0.5 K/h and 2% RH/h and the hysteresis effect has no conservational importance.

Only then are both heating and cooling system-caused short-term fluctuations and the totally unacceptable climate variations avoidable which frequently occur, even in totally climate controlled rooms, due to breakdowns or false reaction of control system components.

3.2.3 *Dynamic room climate as a goal of planning*

Equally favorable conservational, structural, energetical, and physiological effects overall, however, can only be achieved if slow variation of the room climate is fixed as a planning goal and thus becomes the decisive guideline for building construction, lighting, and climate control planning. With respect to air conditioning systems, this means that they should not have the task of room heating (wall heating should be used instead of air heating). Thus, the planning should be based on correspondingly lower capacities for air humidification and dehumidification, cooling, and air reheating, and on far lower amounts of air exchange. The air exchange rate should be limited to 1 m3 of fresh air per person per hour, to the extent that it is necessary for need-oriented air renewal when rooms are used by people, for which, even for groups of persons, a maximum air exchange rate of 1 ACH is sufficient in most cases. With tempering, the solution of this task results directly from the slowly varying operation of the wall-base heating tubes (if building construction and lighting are optimized) and from the use of small ventilation fans, depending on room occupancy (see Section 6.2).

4. No internationally valid standard climate values possible

Simple considerations demonstrate that internationally valid standard climate values are not possible. The seasonal means, extremes, and rates of change of temperature and absolute humidity (which is temperature dependent) of outside air vary strongly with region. These values are additionally influenced by factors such as latitude, presence and size of bodies of water, and degree of forestation (see Fig. 3). Thomson [2], who is usually cited as the source of the call for maintaining a minimum RH of 50% year round, warned as early as 1986 against having this as a goal during winter in colder regions because of the danger of condensation on outside walls and ceilings under roofs, as well as nearby objects, when outside temperatures are low. He did not mention that this danger is an inherent flaw of the modern "air heating" concept, meaning convector heating or actual air heating and air conditioning (see Section 1.2).

4.1 U-Value and heat distribution

The various types of air heating, with their localized 3-D heating surfaces (radiator/convectors or duct outlets) create undirected air streams that circulate throughout the room. These streams primarily reach the ceiling area, whereas the wall surfaces are heated only accidentally (mainly higher up), with less warm air reaching the window niches, outside wall corners, and the lower parts of the wall surfaces. Thus, these systems can guarantee physiologically sufficient surface temperatures of outer walls and windows only when large amounts of heating air are circulated and the temperature of this air is considerably higher than the desired wall surface temperature. So, besides physiological inconveniences, such as drafts and the worsening of the inhaled air by "pollution" with dust and heat, they produce disadvantages for the building substance and for energy consumption (see next paragraph), because, with both methods, the primary goal is raising the room air temperature.

In fact, air heating systems do not attempt to maintain the thermal state of the inside surface of the building envelope (disregarding earth-contacted building parts), which in summer is an almost equally high temperature on the whole inner surface of the outer walls, with that of the surfaces of the interior walls being just as high (when there is no air cooling). Thus, during the heating period, large parts of the building envelope are insufficiently heated, as is explained in the next paragraph. In dwelling rooms, this provokes higher equilibrium humidity in the walls and objects near them, with the consequences being better dust adhesion, possible mold growth, and higher heat transmission through the outer walls, not to mention the danger of condensation. In the official interpretation, however, all of the above "is caused by the inhabitants," rather than poor building design, through their water vapor production combined with "improper ventilation." This interpretation is absurd; the reason why it is so can easily be understood by comparing winter with summer.

In summer, the outside absolute humidity is several times higher than in winter, because higher temperature means greater molecular vibration in solids, allowing more water to remain in the gaseous state ("in the air") since less hydrogen bonding is taking place. At the same time, the natural air exchange of rooms is low, because the temperature gradient between inside and outside air is low, while the behavior of the inhabitants and their water vapor production are the same. All of this leads to absolute room air humidity that is higher than in winter, but not to moist wall surfaces and mold growth, due to the homogeneous temperature of inner wall surfaces being as high as the room air temperature.

The fact that, with "air heating," wall surfaces in winter are colder in many places than the room air results in a potential for damage that is rarely correctly assessed. For example, in the case of dwellings, damage to window frames is usually blamed on the weather and mold growth on the dwellers (see above) rather than on constant condensation in winter. In addition, increased heat losses due to higher heat transmission through damp building parts are seldom openly discussed. Indeed, the U-value in the formula for transmission heat loss, which is actually a function of the wall's humidity, is taken as a constant of the given material in the official DIN formula for heat demand in the heating period, based on a certain humidity content considered typical for the material's porosity, without considering the form of heat distribution ("air heating"/"wall heating") which also affects the wall's humidity. Capillary condensation, for example (see 4.2), is actually caused by "air heating."

The modern concept of museum heating – "air heating" with humidification, either by air conditioning or by locally heating the air with radiator/convectors plus humidifiers – results in the above mentioned higher equilibrium humidity, whereas the "wall heating" concept of the ancient Romans, the hypocaust heating system, allowed bathing water temperatures of about 45 °C in their public baths, even for the lowest outside temperatures, without danger of condensation (see Figs. 4 and 5). Comparison of Figs. 1 and 5 and Figs. 6 and 4 makes it obvious that with the heat distribution concept presented here, tempering of the building envelope, condensation is excluded for physical reasons, as it was 2000 years ago with its Roman predecessor. Here again our experience with wall-base heating becomes understandable, that no vapor barriers or thermal insulation need to be installed for walls or floors with earth contact, which also allows the protective screed under floor coverings to be omitted.

4.2 Relative room air humidity and heat distribution

In museums, the problem of condensation is intensified if, during frost periods, higher room temperatures ("18 °C") are desired. During the heating season the amount of water vapor in the outside air (the absolute air humidity) is low. Thus, any kind of room heating leads to a need for humidification in order to maintain a given relative humidity when maintaining the room temperature against a falling outside temperature (which also means falling outside absolute humidity). Heating the bulk of the room air, however, leads to an additional need for

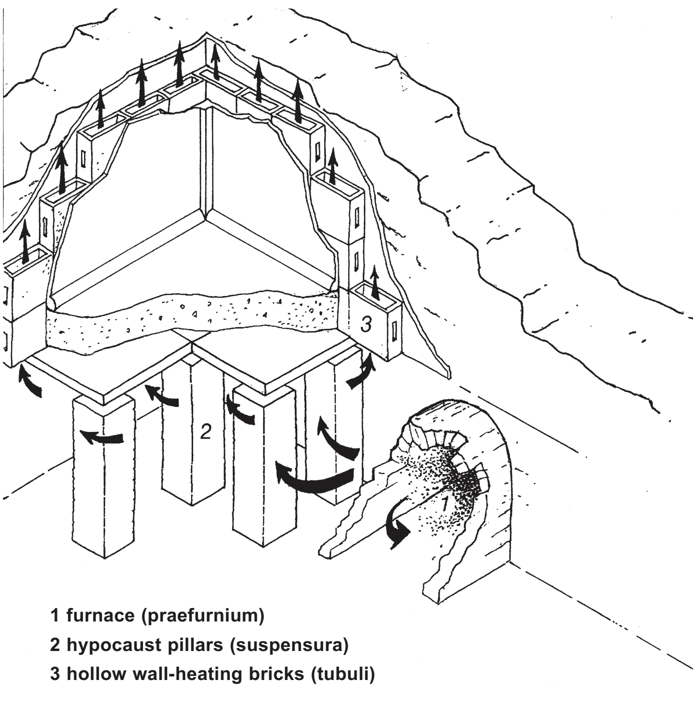


Figure 5:
Hypocaust heating, functional scheme.

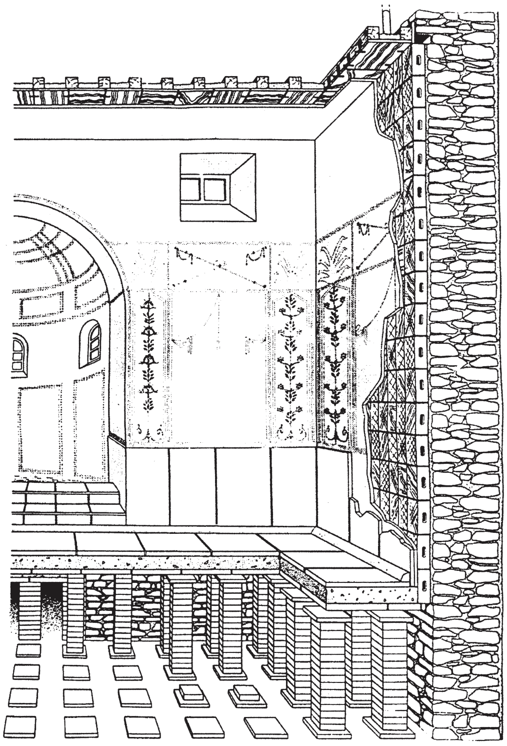


Figure 4:
Roman baths in Weißenburg, reconstructed cross-section of the northwest corner of the caldarium.

Figures 4 and 5: Moisture protection and room heating 2000 years ago: tempering of the building envelope using hypocaust heating — no plaster or wall-base damage due to moisture. From: Führer zu archäologischen Denkmälern in Bayern, Franken 1, Stuttgart 1984, p. 71.

humidification, because the pressure of the room air is higher than that of unheated room air (radiation heating) or that of the air in summer (when the outer absolute air humidity is high). With air heating, the air – since it is the heating medium – has a temperature of 30 to 40 °C in the upper part of the room. This causes higher air exchange (higher ventilation heat losses) and, thus, (compared to radiation heating) a greater amount of water vapor is carried away with the warm air lost to the outside through building joints and openings. This vicious circle is aggravated further, when higher values of RH ("55%") are aimed at, as the higher absolute humidity achieved by humidification means that colder locations and artifacts near them are made even damper by (invisible) capillary condensation in joints and material pores. At considerably lower surface temperatures – given the same absolute humidity – (visible) condensation occurs on the surface (for microclimatic measurement examples, see the article by Ranacher).

For the case of unheated room air (radiation heating), the interdependence of the demand for artificial humidification, room temperature, and desired RH can be illustrated by the following examples (see Fig. 7): A climate value pair of 18 °C and 55% RH corresponds to a humidity ratio of 7.1 g of water per kg of air, whereas at 18 °C and 40% it is only 5.2 g/kg. If, during the short periods with the lowest outside temperatures, 15 °C were allowed, the humidity ratio would be only 4.2 g/kg at 40%. If one takes the outside humidity ratio to be 0.8 g/kg, which would be the case for -15 °C and 90% RH, in the first case 6.3 g of water per kg of air would have to be added by humidification but only 3.4 g/kg in the latter case.

With wall-base heating tubes, due to the planar vertical (2-D) geometry of the heating surface (strip of plaster), there is only a slow one-dimensional (upwards) convective flow in the boundary layer (Coanda effect), which covers the whole wall surface since the heating tubes run the entire length of the bottom of the wall, and thus heats the complete wall surface. Furthermore, the physiological inconvenience of drafts and the constant manipulation of the breathed-in air are eliminated.

4.3 *Hydrogen bonding*

The invisible wetting of the "inner surface" of hygroscopic materials, capillary condensation, occurs even "on surfaces" (at boundary layers – which means also the inner surfaces of the capillaries) which are only a few K colder than the room air, due to the adhesive force resulting from the bipolar form of the water molecule (hydrogen bonding, see Fig. 8). But, for the case when the "inner" surfaces of walls and artifacts attached to them are equally warm or slightly warmer than

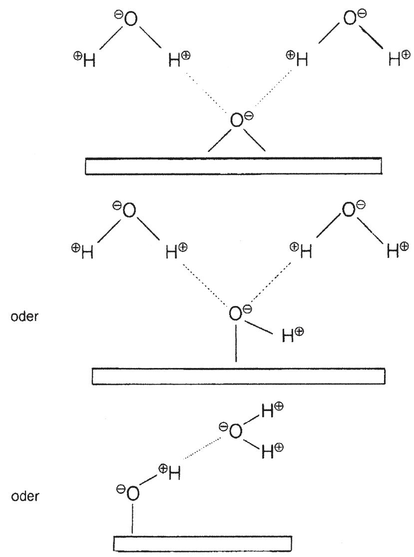


Figure 8:
Hydrogen bonds on hydrophilic surfaces
The rectangles represent three examples of the "inner surface" (capillary wall) of porous mineral materials (masonry, plaster, etc.) with possible forms of the adsorption of water molecules through formation of a hydrogen bond.

Through a slight temperature rise, i.e. due to a slight increase in the vibration of the molecules of the material including the bonding partner on the capillary wall, these weak bonds can be broken (start of the drying out of the material due to slow expulsion of the water molecules along the temperature gradient) or their formation can be hindered (elimination of rising and condensing moisture).

Drawing from Torraca, G.: Porous Building Materials. Vienna 1986, p. 13f the room air ("wall heating"), the wetting effect of hydrogen bonding is greatly weakened or even eliminated. So, when – instead of heating the room air – the inner sides of the exterior walls of a room are heated ("wall heating" in winter) the kinetic energy of the bonding partners (atoms and molecules of the "inner surface" of the materials) is higher than the bonding force. This, in fact, is a weak force that can be broken even by the small rise in temperature of walls heated by the Coanda effect.

5. Climate guidelines based on experience

Based on long-term observations by the Landesstelle, which are increasingly being confirmed by the literature in the field, the following guidelines for climate planning can be given. These guidelines, which also apply to museums without specially trained personnel, hold up in everyday operation. They are summarized under the premise of a tempered building envelope with sealed joints, aiming at the goals of "meeting conservational requirements," "lowest possible energy use," and "minimizing the use of equipment."

5.1 Rooms without extended occupancy

For open air museum buildings and museums which are closed in winter, the guidelines for rooms without regular or extended occupancy are that, in the course of the year, the room temperature and the RH may vary slowly between the freezing point and 27 °C as well as between 40% and 70%. In particular, the values for RH are valid only for "wall heated" rooms, where the wall temperature is higher than the air temperature so that at no point is the temperature lower than the room (air) temperature (measured in the middle of the room), so that the relative humidity measured at that one point is not exceeded at any other point. Furthermore, considering already existing mold or rust, the relative humidity should only rarely reach the upper boundary and should not remain there for several weeks. During the majority of the time with high outside absolute humidity (i.e., summer), the room RH should be kept under 65% through moderate heating, which by itself prevents new mold formation as well as the growth of existing mold and enormously slows down the build-up of rust. This summer heating is usually only necessary in ground-contact rooms and in buildings with very thick walls, where a need for summer heating also exists from a physiological point of view.

5.2 Continuously occupied rooms

For storerooms with work areas that cannot be separated from the storeroom area and for "normal" museums, which are open during winter, the guideline is that (for physiological reasons), at the lowest outside temperatures, the room (air) temperature should only rarely fall below 15 °C. With "wall heating," such room conditions should be suitable for "walking" persons since the stagnant or only slightly moving room air reduces heat loss from the body's surface. Additionally, the perceived temperature is higher than the room (air) temperature because of the greater amount of heat radiated from the walls (particularly the bases). As with other kinds of room heating, when it is freezing outside or when room use requires higher air exchange rates, "wall heating" also creates a demand for humidification, but it is considerably lower than with "air heating." For large buildings, which have maintenance staffs for humidifiers or air conditioners, 16 °C should be allowed as the low temperature limit, in order to minimize the humidification demand and reduce energy costs. The humidity limits and restrictions given in Section 5.1 are equally valid here.

Following these guidelines enables energy-cost-intensive air dehumidifiers to be avoided and eliminates most of the need for air humidification. The upper temperature limit valid for summer should be reached as seldom as possible and should not be surpassed at all. This, however, should not be achieved through energy-cost-intensive cooling but rather, independent of mechanical equipment, through improving the buffering effect of the building envelope, including external sun protection, and through reducing the heat dissipated by artificial lighting. If these guidelines are realized in connection with the minimal climate technology described below, a narrow short-term fluctuation band (max. 0.5 K and 2% RH per hour) can be maintained under everyday conditions. This was impressively shown by measurements in the Kunstforum Ostdeutsche Galerie in Regensburg, which were conducted as part of the PREVENT Project (see the article by Kotterer).

6. Minimal climate control technology

Given a building envelope that follows the guidelines presented in Section 3.1, the equipment for storerooms and museums required for low-cost climate control can usually be limited to three simple types: light protection (6.1), control of air exchange (6.2) and tempering (6.3). Section 6.3 also shows how to meet higher temperature requirements, i.e. how to heat assembly rooms, dwellings, and office buildings using tempering.

6.1 Protection from light

Only three key points with regard to protection from damages due to light will be mentioned. In storerooms and exhibition rooms, the highest possible reduction of the annual exposure to light must be strived for, particularly for uncovered freestanding objects made of organic material. This can be achieved through two simple measures: by excluding daylight completely outside of times of use and by maintaining light intensity, measured at a level of 2.5 m, below 300 Lux (paper and textiles below 100 Lux) during times of use. The radiation emitted by the room lighting should have as low a proportion of short wavelengths as possible, especially UV radiation. This can be achieved with existing lighting, which emits too much short wavelength radiation, if only reflected light is allowed into the exhibition level (no metallic reflecting surfaces). Finally, the heat load from artificial lighting and from daylight should be kept as low as possible. Simple measures for this have already been discussed in Section 3.1. To avoid the need for cooling, which is physiologically unfavorable and causes high installation, maintenance, and energy costs, the installed power of the artificial lighting must not exceed 20 W/m^2 (!) and measures for attenuating the impact of solar radiation through the transparent parts of the building envelope are indispensable. If outer shading is not possible, more complex measures, e.g. between the panes of the double-glazed windows, are indispensable (see the article by Huber).

6.2 Control of air exchange

A fundamental prerequisite for controlled air exchange is sealing the joints of outer doors and windows and installing an airlock entry. If this is done and if the above mentioned measures against inner and outer heat loads are also realized, ventilation can be performed with one or more low peak capacity (e.g. ca. 400 m^3/hr) exhaust fans, depending on the size of the building, whose task is to assure a minimum air exchange rate of between 0.1 and 1 ACH. The fans can be mounted in a chimney, window, or the ceiling (with roof access) and should be operated only when needed, regulated by the user via a speed controller (see next paragraph and Section 6.2.1). The RH in the building changes only slowly under these circumstances. The small return flow of outside air needed for these low air exchange rates can flow through window and door seals, whose locations have been carefully chosen: The fans should be located opposite to where the replacement air enters, so that a "flushing" of the whole room (or a sequence of several rooms) occurs. Thus, windows close to the fan must be sealed. Furthermore, the joints through which the incoming air flows should be located so as to produce as low as possible dust and pollutant loads on the room air, e.g. facing away from the street to an inner court or park (for more on the theme of "natural ventilation" see the article by Käferhaus on Schönbrunn Palace).

As a rule, the ventilating fans will be operated continuously only in the beginning. For example, if before storing artifacts or mounting an exhibition it is necessary to remove building moisture or if the material humidity of objects to be stored must be reduced to a normal value, which is possible in a gentle way with the aid of the radiation from the warm walls (see Section 8). Later operation of the ventilating fans, instead of window ventilation, can be limited to strictly occupancy dependent needs, i.e., the actual need when people are present (the fresh air requirement for light activity is ca. 1 m^3 per person per hour). Thus, sudden change of the relative room air humidity can be avoided while air replacement at a rate sufficient for a small number of people takes place. Experience also shows that in summer, by limiting the air exchange rate to a maximum of 1 ACH, ventilation can be used for natural cooling during the night without sudden climate changes occurring.

These statements as to the amount of time the ventilating system must be operated are valid for all kinds of buildings and use, including buildings with central ventilating systems, if the building envelope is optimized according to Sections 3.1 and 6.1 and if the building is heated with tempering.

6.2.1. Air humidification and dehumidification

The second element of "minimal climate control technology" is a small air humidification capacity in the form of one or a few air humidifiers. These should work on the principle of evaporation because of the lower potential for damage: In contrast to other processes, if the regulating system fails, there is no fear of exceeding the upper humidity limit. Since during the heating season the need for humidification is fundamentally lower with wall heating than with other kinds of heat distribution, because it avoids heating the air, simple low-capacity humidifiers are sufficient, if cleaned regularly, particularly if water vapor losses can be further reduced by carefully tracking down and sealing leaky building joints. Thus, humidifiers that are clearly under-sized by usual standards should be purchased. If the humidifiers are already on hand, they should be operated at a low output setting. Then they operate more continuously and thus short-term fluctuations in humidity are lower.

During times of high outside absolute humidity (summer), "summer tempering" keeps the temperature of critical parts of the building, such as the cellar or ground floor, equal to that of the uncritical upper floors, which follow the mean outside temperature "without heating," simply by accumulating solar radiation. With summer tempering the temperatures in the whole building follow the mean outside absolute air humidity, so that equipment for air dehumidification is not necessary anywhere. This also goes for a cellar in a hill or a housed excavation. Based on the premise that the slowly varying climate changes during the course of a day (see Section 3.2.2.) are conservationally harmless, dehumidifiers are also not needed in buildings with high occupancies, e.g. museums with high numbers of visitors. The as-needed operation of a minimal ventilation system can remove a sufficient amount of the water vapor given off by people, preventing the upper air humidity limit from being exceeded.

6. 3 Tempering

The third element of "minimal climate control technology" or the simplest way to profit from the advantages of the 2000-year-old principle of Roman hypocaust heating tempering. Depending on the planned capacity, a wide range of goals can be achieved:

- protection of historic buildings, open air museum buildings, or housed excavations from damages due to humidity, in general, and to salts from the ground, with advantages for the historic furnishings also
- sensible heating of huge volumes like churches, with advantages for their murals, altar pieces, and organs

- stabilization of the room climate of museums and storerooms in the simplest possible way without the need for climate zones (the museum as a "giant showcase")
- heating of dwelling or office buildings, including the stairwells, so that all rooms on all floors are comfortable (see Fig. 6).

In all cases, the goal must be a clearly raised temperature at the base of the wall. This may be due to the high temperature of two surface-mounted painted tubes in contact with the wall and the lower temperature of the strip of wall behind them, or to the medium-high temperature of the strip of plaster covering a plastered-over pair of tubes (plaster thickness in front of the forward-most edge of the tubes: 15 mm ± 5 mm). Only so, in addition to earth-contacting wall bases being dried out, is the main phenomenon necessary for heating of the whole wall surface strong enough: limited but continuous convection in the wall-air boundary layer. Convection strong enough to heat the whole wall surface occurs only with a surface temperature at the wall-base that is clearly higher than that of the rest of the wall and the room air (e.g. 25 K higher for plaster over the tubes or 35 K higher for bare tubes on the plaster) depending on the goals described above and on the outer temperature, see Fig. 9). For the situation represented in Fig. 9, with the 10 cm high strip of plaster over the tubes having a mean surface temperature of 40 °C, 40 W/m is "transferred into the room" (see Fig. 10).

Under these conditions, this alternative type of wall heating offers important advantages compared to other modern forms of wall heating: the installation can be restricted to one or two tube loops at the wall base, without additional thermal insulation and without any restriction on the placement of furnishings (other than a gap of 15 mm to the wall). Other better-known forms of wall heating, which ignore both boundary layer convection and the improvement of the U-value, are based either on a layer of thermal insulation and a grid of many

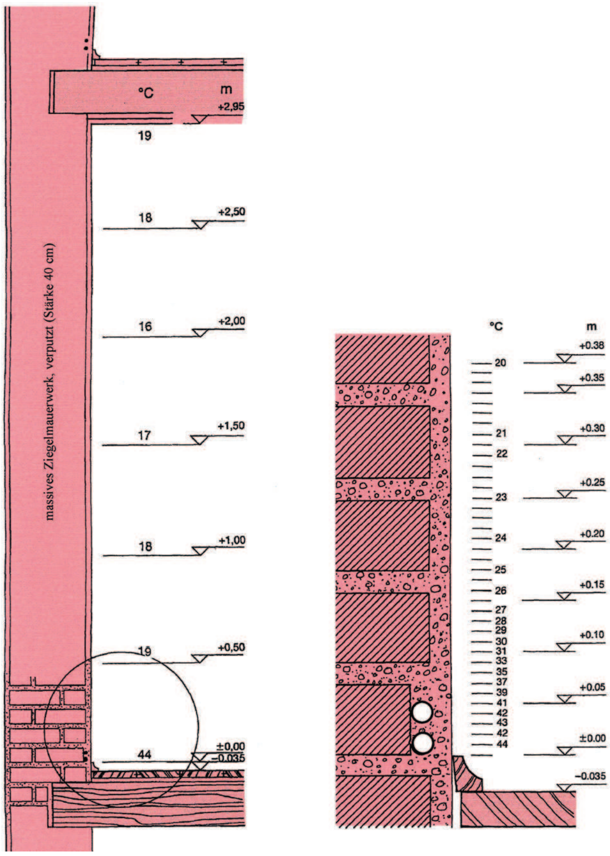


Figure 9:
Temperatures on the inner surface of a tempered outside wall
Measurements using an infrared thermometer.

Outside temperature – 10°C (tree at height of 1.8 m), room temperature 20.5°C (table top in middle of the room), Massive masonry outside walls (~1800 kg/m3, 40 cm thick), pipes under plaster of ~20 mm thickness, average hot water temperature 60°C (at the manifold for the given floor 63/57°C).

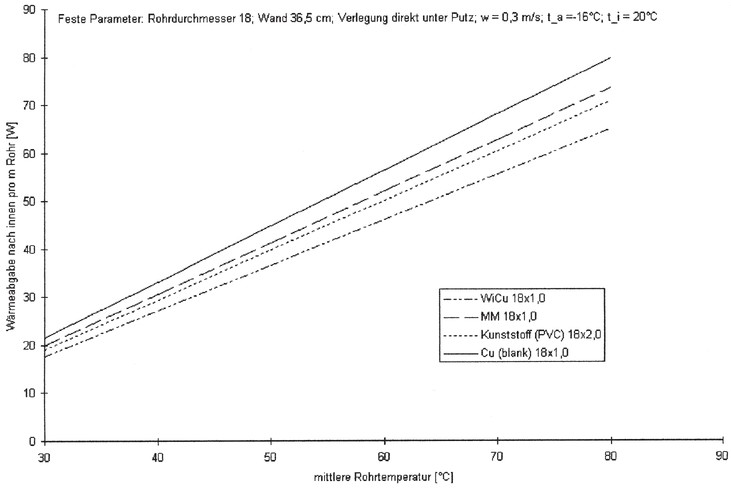
-The surface temperatures above the wall base (drawing on the left) are the result of continuously rising warm air, whose amount depends on the surface temperature of the pipe covering.

-The surface temperature of the strip of plaster in front of the pipes (drawing on the right) is ~20 K lower than the average water temperature, due to the poor thermal conduction of the material (typical for dry mineral materials!) for only 2 cm thickness despite continuous operation. Thus: "plaster thickness maximum 15 mm!"

-Thermography of the outsides of walls with heating pipes on the room side does not show the location of the pipes, despite high heating water temperature. This confirms the high thermal insulation capability of dry mineral materials (see Figs. 15 – 20 in the German version).

Drawing Rudolf Werner, Landesstelle für die nichtstaatlichen Museen in Bayern, Munich

Figure 10:
Heat transfer of various heating pipes installed directly under the plaster. From [4]
-Bare copper has the best heat transfer for the smallest external diameter.
-According to calculations based on unchanged wall moisture content, for a mean temperature of 60°C, the Cu tube (Ø 18 mm) emits 56 W/m.
-Thanks to the high thermal insulation of the dried-out wall, the performances are higher than calculated so that for a smaller pipe diameter, a similar performance will be achieved (e.g. 50 W/m for bare Cu (15 mm) and a minimum mean temperature of 60°C.



tubes per m², which is not allowed to be "shaded" by furnishings, or – as at the beginning of the "tempering age" – consist of double-wall shells, formed by adding a thin inner wall to the outside wall, the gap being heated by a band convector (location of furnishings not restricted).

The heat from the uniformly heated surface(s) of the exterior wall(s) is radiated toward the rest of the room, i.e. in the direction of the other portions of the room envelope and its furnishings. If this heating is performed at the exterior walls of all rooms of the building, the complete building envelope is heated, which results in a uniformly heated building. Combined with controlled, occupancy-dependant, low-level air exchange and external solar radiation protection for the windows, the whole building's relative humidity is also nearly uniform so that it functions as a "giant display case."

6.3.1 Planning of tempering systems

6.3.1.1 Thermal emissivity

To create functional security for tempering systems, in which both heating tubes under plaster and routed in the open (example on rafters in a roof) occur and for clarifying the question whether the thermal insulation of feed lines routed in the open is necessary, it is helpful to compare the thermal emissivity of various materials, with which the different strength of their thermal radiation will vary. Among crystalline materials, polished nonferrous metals are "bad" radiators. Mineral materials and materials with an amorphous structure, however, radiate more strongly. In the following the thermal emissivities of three important materials for "radiation heating" will be compared to a black body, which will make apparent the great difference in their thermal radiation:.

- black body..1.0
- bare Cu (depending on how dirty).......................................0.05 – 0.15
- plaster, paint or clear lacquer on the same tube ....0.93 – 0.96

The practical importance of these values for "everyday heating" is only visible through measurements with a "passive" infrared thermometer, which is available for € 130. Contrary to the many times more expensive professional instruments, these do not measure the temperature of a surface with a measuring beam but rather measure the thermal radiation emitted by the surface, which depends on the emissivity of the surface, and displays a temperature in °C. This instrument makes possible two important basic statements: For distant measurements it shows the combined effect of the various radiation heat sources on a single point in the room (e.g. where a person is sitting), while through exact orientation with the laser pointer the individual sources can be distinguished (plaster strips in front of tubes as well as painted tubes, wall surfaces above these, windows, lamps, etc.). For close up measurements, the actual heat radiation of the individual surfaces depending on surface material will be displayed. In the latter case one learns:

- For the same surface temperature a bare copper tube is "insulated” while nonmetallic surfaces "heat.”
- The radiation from pipe insulation with a plastic jacket or a painted sheet metal jacket is the same as that from an uninsulated bare copper tube.

While stainless steel like copper belongs to the "bad” radiators (full power only after painting or under plaster), the radiation from iron pipe increases in the first weeks after installation due to patina formation. Thus not only the heating tubes but also the feed lines should be bare copper, starting at the heat source. The extra price for copper will be compensated by being able to do without the pipe insulation that the usual iron pipes require.

6.3.1.2 Transmission heat loss

With radiation heating, the heat loss due to the thermal transmission of the building shell can be estimated with a simple formula, previously used for sizing tile stoves, which gives the loss per m² of outside wall. One observes that the heat loss with radiation heating (= dry evenly-heated wall surface) decreases with increasing wall thickness or that a wall made of a nonporous material loses less heat than a wall of the same thickness made of a porous material. The formula is:

$$Q_T = (\lambda_{dry}/d)\ \Delta T_{max}\ ,$$

where λ_{dry} is the thermal conductivity of the wall material when dry, d is the wall thickness in m, and ΔT_{max} is the maximum temperature difference between inside and outside. If one supplements this formula with an additional factor, the room height h (in m), one gets the heat loss per meter of wall, W_{loss}:

$$W_{loss}\ [\text{W/m}] = h\ (\lambda_{dry}/d)\ \Delta T_{max}\ .$$

The comparison of this result with the heat given off per meter of heating loop, according to Fig. 10, allows one to answer the question, "How much heating performance per meter of outside wall is required?” Or put another way, "How many loops operating at what foreline temperature are required?” The result is sufficiently accurate for high-density walls (above 1400 kg/m³). The capacity required for the heat source is estimated as the product of the total pipe length (pipe length per m of wall x inside circumference of floor x number of floors) times the required heating capacity per meter of wall. In dwellings the result is rounded up so that, with boilers for combined space and hot water heating, enough capacity exists for rapidly heating the hot water.

As an example, the heat loss per meter outside wall of a rental building typical of 1900, with 50 cm thick outside walls of stuccoed solid brick (2000 kg/m³), sealed kastenfensters up to 1.2 m wide, and a room height of 3 m will be assessed. Maximum temperature difference (ΔT_{max}) is 35 K (outside: -15 °C, room: +20 °C); 0.4 W/m-K will be assumed for the thermal conductivity of the dry wall material (λ_{dry}):

$$W_{loss} = (0.4\ /\ 0.5) \times 35 \times 3 = 84\ \text{W/m (per m wall!)}.$$

Experience shows that this heat loss can be compensated by a single standard heating loop (two tubes, foreline and return line, return above foreline), which can produce 100 W/m. With such a minimal installation, it is recommended to detour the return line up to the underside of the windowsill under each window or to install it at this height in the whole room (see Fig. 6d). One can reduce the ca. 65 °C foreline temperature required to obtaining 100 W/m from one meter of loop (= 2 m of tubes) by mounting extensions of the return line in the sides of the widow openings (see Fig. 6d). If one loop at the wall base and another at windowsill height (with return line detours into the sides of window openings) are used, a foreline temperature of 50 °C will scarcely ever be reached. For direct heating of high-density outside walls, a more exact differentiation between porous massive building materials, such as brick, and pore-free materials, such as granite, is not necessary because a similarly large reduction of the heat loss results for both. In the first case due to the water being driven out of the pores by tempering and in the second case due to the raising of the "AC thermal resistance" thanks to the high average wall temperature that results from long-term tempering.

6.3.2 Installation of wall-base tempering

Heating loops are normally installed at the bases of the inner sides of all exterior walls, consisting of a "foreline" tube (going away from the source) and a "return line" tube (returning to the source), mounted with the return line above the foreline (Ø = 12 – 22 mm), while a single tube is installed at the base of both sides of partition walls standing on soil. The single tube traverses from one side of the partition wall to the other through a hole drilled through the wall near to an outside wall and thus runs along both sides of several inside walls (see Fig. 6).

The best material for "active" heating tubes, i.e. for tubes which heat the surrounding material, is bare copper, due to its extraordinarily high thermal conductivity, its easy handling, and its comparatively small bending radius. Furthermore, copper tubes (with soldering fittings, see below) need only narrow grooves for installation under plaster because of their minimal wall thickness (1 to 1.5 mm for diameters of 12 to 22 mm). The use of copper in modern heating systems does not create the danger of corrosion in contrast to its use in water supply systems. There are two distinctive differences. First, the tubing of modern heating systems is sealed against the atmosphere and – except after (re-) filling – do not contain fresh water with new oxygen and new salts from the ground. Thus, the water in heating systems is "dead" water and inner corrosion for all materials is suppressed, even with the usual combination of ferrous and nonferrous metals. Second, a heating tube not in use cannot get colder than the material in contact with it. So, the plaster around heating tubes does not become wet due to condensation as it does with uninsulated fresh water tubes. Thus, corrosion of the outer surface of bare copper heating tubes in houses is also impossible, whether plastered over or free on the wall's surface. This does not apply to iron pipes, whose surface has to be protected. The corrosion resistance of copper heating tubes applies even under the plaster of earth-contacted walls, where no damage could be found after long nonfunctional periods, e.g. after one year.

In large halls and churches, a roll of soft copper tubing is advantageous for mounting under plaster, since it can be easily mounted using a tubing bender. In rooms of houses, one prefers straight pieces of tubing (5-m lengths). For best contact, for wall-surface installation, and to avoid an unnecessary plaster thickness for under-plaster installation, the connections (fittings) have to be solder fittings because their diameter only slightly exceeds that of the tubing, whereas the diameter at both ends of press fittings is about 8 mm greater than that of the tubing. The fittings are soft-soldered with electric soldering pliers, thus avoiding material embrittlement and the danger of smoke and fire, disadvantages of hard soldering with a flame.

AFigures 11 – 14:
Optimal pipe locations for thin walls or for foreline temperatures <50°C (compare to Fig. 6d). With this arrangement a tubing diameter of 15 mm is sufficient, so that with the use of solder fittings no slits need be made in the wall, rather for tubes installed on the unplastered wall a plaster thickness of 15 mm is satisfactory (see Section 6.3.2, p 23). Drawings Heiko Folkerts, Bernried

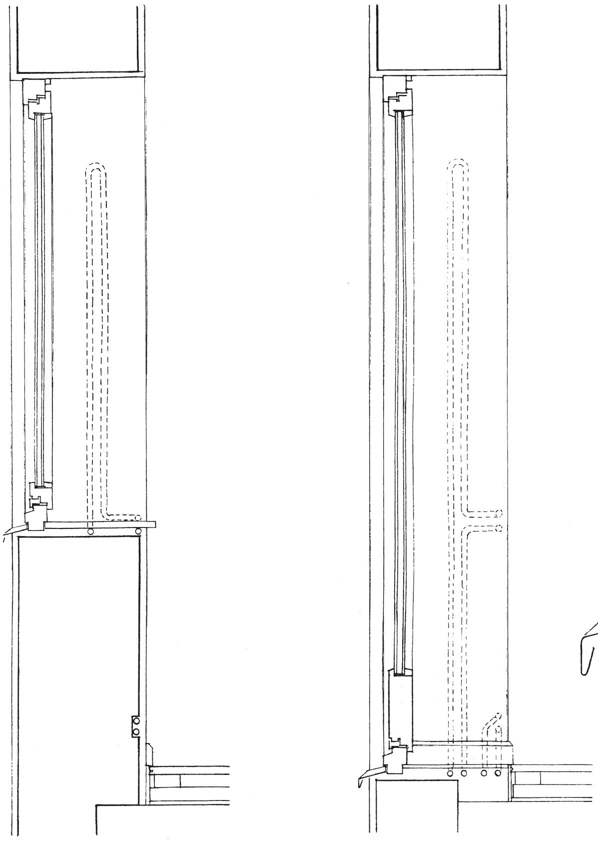
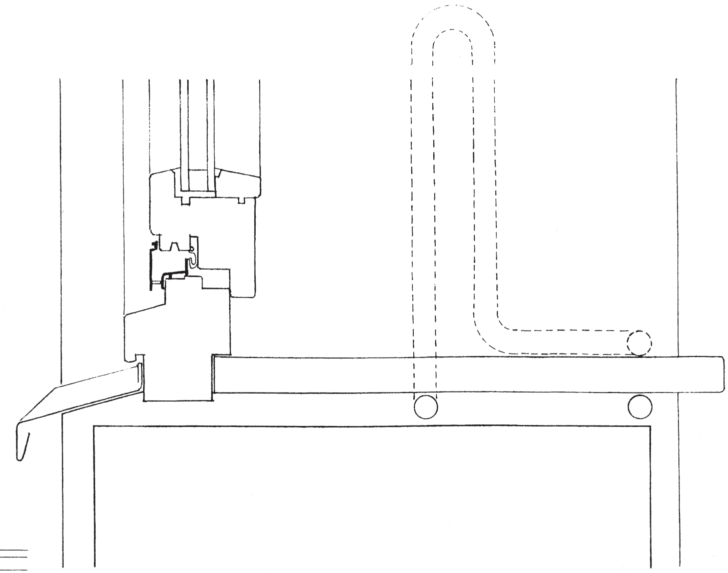
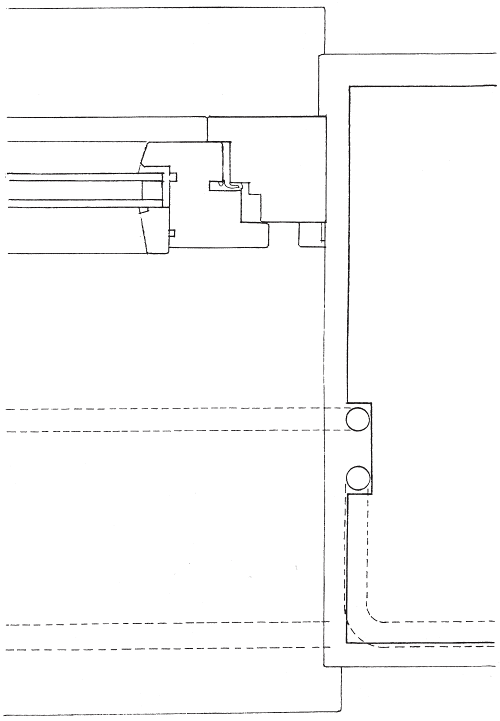


Figure 11:
Window and door axis (section) with wall-base and windowsill-level loops under plaster. M 1:20

Figure 12:
Windowsill (section) with windowsill-level loop (return line detours in the plaster of the sides of the window openings). M 1:5





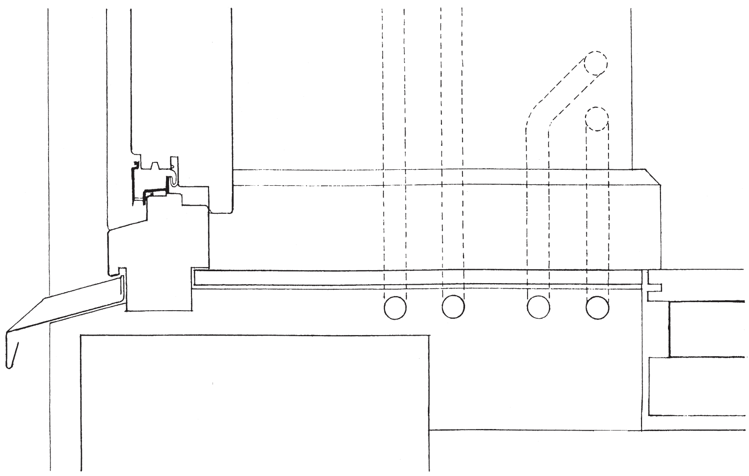


Figure 13:
Windowsill (top view), underneath the windowsill-level loop in contact with it (section of return line detours in the plaster of the sides of the window openings). M 1:5

Figure 14:
Door threshold (section) with the detours from wall-base and windowsill-level loops in the plaster of the sides of the window openings. The loops cross the threshold under a tile cover. Wall thickness 40 cm, stone windowsill 25 mm thick; floorboards on crossed joists. M 1:5

For installation both on the wall surface and under plaster, the tubing is mounted using pipe hangers (for single tubes) or double-tube clamps (for a pair of tubes). To avoid an unfinished appearance (open mounting) or unnecessary "buckles" (under plaster mounting), both mounts consist of galvanized steel without the usual elastic inserts. Three reasons allow direct contact of the mounts with the tubing:

- Without moisture, there is no risk of the development of a galvanic cell. In contrast to a coldwater tube, which is colder than either the wall material or the room air, a heating tube cannot get colder than its surroundings. Thus, (capillary) condensation occurs neither on the surface of the bare tube nor on its plaster covering.
- The temperature change, and thus movement, of a copper heating tube in contact with a massive (high heat capacity) material with temperature changes of the heating water is minimal due to the high thermal conductivity of the tubing and the buffering effect of the massive material-
- Contact with a massive material suppresses vibrations and thus noise due to the streaming medium.

For installation on the wall surface, the tubing needs to be forced into contact with the wall, so that as much heat transfer as possible occurs through conduction, except for smaller irregularities of the wall surface, which get heated by radiation. For adequate radiation intensity, surface-mounted tubing must be painted (e.g. with wall paint), since this raises its thermal emissivity, and thus the amount of heat radiated, by a factor of eight! On the other hand, copper tubing without a heating task (e.g. hanging from the ceiling in the boiler room without physical contact) needs no thermal insulation if left bare. (The heat emission from the surface of 60 °C bare copper tubing is the same as that from the surface of normal thermal insulation of the same tubes, when this surface is not a reflecting metal sheet or foil.) Both the function and the appearance of tubes mounted on the wall surface can be improved if the cavities between tube and wall are filled with normal fillers (aiming for a straight groove) before the tubing is painted.

For installation under plaster, the same mounting devices are used as mentioned above, again without elastic inserts, here to avoid the need for a thicker layer of plaster. Given solder fittings, the heating tubes are covered with a maximum of 20 mm of plaster (15 ± 5 mm) after being installed in a groove either in the plaster or the wall material (for a loop with two 15-mm diameter tubes, the groove is about 7 cm high, and 3 cm deep). For mounting on top of masonry that afterwards will be plastered, a total plaster thickness of 20 mm (for a 15-mm tube) or 25 mm (for an 18-mm tube) is sufficient, (e.g. a first layer with the thickness of the tube diameter followed by a thin second layer). For historic buildings where no groove in the wall material is possible, out of respect for the wall decoration, and the tubes are to be mounted at the wall-base only, they can be covered with plaster or concrete that tapers outward toward the bottom or is rectangular so that it forms a "plaster baseboard," which can be painted to resist wet cleaning, or covered with a thin tile.

The temperatures occurring in conventional heating or tempering systems do not affect plaster materials. Even gypsum plaster in contact with tempering tubes with a water temperature of 70 °C does not decompose [3], whereas until now it was assumed that dehydration is unavoidable at temperatures over 60 °C (for lime plaster see below). The risk of cracking of plaster in contact with heating tubes is not due to the temperature of the tubes but to their elongation with increasing temperature, which must not be hindered. Since the thermal expansion for copper is only 0.017 mm/(m-K) – so that the elongation of a 10-m tube for a temperature increase of 60 K is only 10 mm – cracking can easily be excluded if small cavities to accommodate the expansion are created in the wet plaster at the outer sides of all bends. This is possible if some simple advice is followed:

- The first step is a preheating period of several hours with the whole system at ca. 70 °C. This shows whether the connections are tight and all loops are functioning properly (no air enclosures). Further, a first drying effect on the wall's surface is achieved. The latter is more intense if the tubing is washed over with mortar water ("slurry"), increasing its thermal emissivity similar to painting, for in this transitional phase the tubing transfers heat only by radiation.
- Then follows the forming of the cavities in the plaster, room-by-room, beginning by closing the thermostats of the loops in a room. When the temperature of these tubes has dropped to human skin temperature (about 30 °C), over each bend of the tubing a batch of plaster is applied and smoothed until it is as thick as the lateral edge of the tube. Then each loop is heated for some minutes (inlet temperature at least 65 °C) by opening the valve until the return temperature is at least 50 °C. Thus, the sides of the bends are pressed into the soft plaster. In this simple way, cavities are formed which allow the elongation of each section of tubing during operation. After reaching the 50 °C return temperature, the valve is closed again so the plaster batches do not dry too fast.
- Immediately after the plaster at the bends is dry, the plastering of the grooves or the wall can begin, with the inlet temperature to the tubes set at about 30 °C. Due to the above mentioned points, there is no need for special plaster material or for any fabric to hold the plaster over the tubes, either because of corrosion, which occurs only with cold water tubes (due to condensation), or tubing temperatures or temperature changes, since space for elongation of the tubes has already been created and the plaster is not affected by the temperatures used.
- Whenever plastering over cold tubes (e.g. when the heat source is not yet available) a 15 mm wide by 20 cm long strip of insulation material (height according to tube diameter) has to be added before plastering at each change of direction on the outer side of the bend.

In rooms without temperature requirements, the heating tubes can also be mounted in the joint between the wall and floor covering or – one besides the other – directly under the floor covering (if it is mineral and not thicker than 3 cm!), with the first tube in contact with the wall. This applies to rooms with a height of up to 4 m and is independent of the outside wall thickness. For this case, where the emphasis is on conservation of architecture and stabilization of the RH at mean values, outside wall loops can be very long: Because of heat accumulation in the drying wall material around the tubes, one loop can supply several rooms on one side of a building.

In rooms with higher temperature requirements, the loop must be mounted above the floor covering, potentially covered by a strip of ceramic material (max. 2 cm thick), and the length of the loop should not exceed the length of the outside walls of 3 rooms. In the case of wooden baseboards, the loop must be mounted above the upper edge of the wood. In earth-contact rooms with wooden floor coverings, installation of an additional single-tube loop beneath the floorboards, at all wall bases at the height of the outside ground, guaranties a thermal barrier against rising dampness, independent of the height of the wooden floor and baseboard above the ground level.

In office buildings and dwellings, every room usually gets its own loop. Here, it is preferable to mount the tubes at two levels. For an exterior wall thickness of 40 cm or more, one loop is sufficient, if the return is mounted at the height of the lower edge of the windowsill, with detours along both sides of the windows (if possible in the sides of the window openings). For a wall thickness less than 40 cm, two separate loops should be installed, one at the wall base and one at the windowsill level (see Figs. 11 – 14). The above-mentioned detours along the windows, now made by the return tube of the second loop, are indispensable in half-timbered houses (or buildings with less than 20 cm wall thickness). This

Figure 6:
Examples of pipe placement

F Foreline
R Return line
OW Outside-wall loop
PW Partition-wall loop (in basements: for high-value applications; in ground floor rooms: for floors in contact with earth or outside air, or over unheated basement)

Foreline temperatures are given for routine operation over the course of a year, after the drying out phase which is performed at maximum foreline temperature

Lower foreline temperatures (< 50°C) and smaller pipe diameters (15 mm) are possible with a doubling of the pipes shown in 6d (loops at both wall-base and windowsill levels, with detours of the windowsill-level return line into the sides of the window openings)

Visible installation: tubing in contact with wall, painted

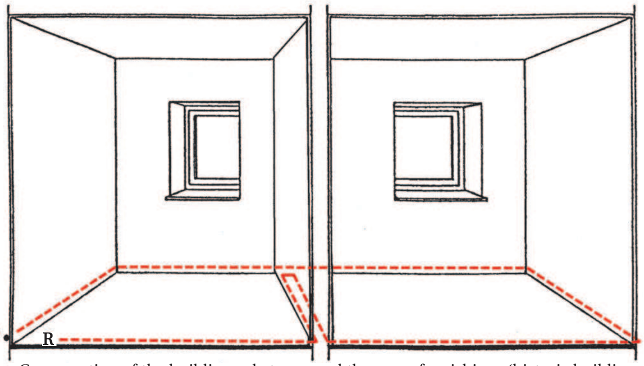
Invisible installation: only for mineral coverings (max. 1.5 cm plaster or equally thick stone chair rail molding; for wooden chair rail moldings, locate tubes above)

Separation of the pipes in loops = closest placement allowed by the solder fittings (soft soldering)

Tubing material: optimum performance with bare copper (for Cu heating tubes corrosion protection is not necessary)

Drawings Rainer Köhnlein, Landesstelle für die nichtstaatlichen Museen in Bayern, Munich and Michael Kotterer, Regensburg.

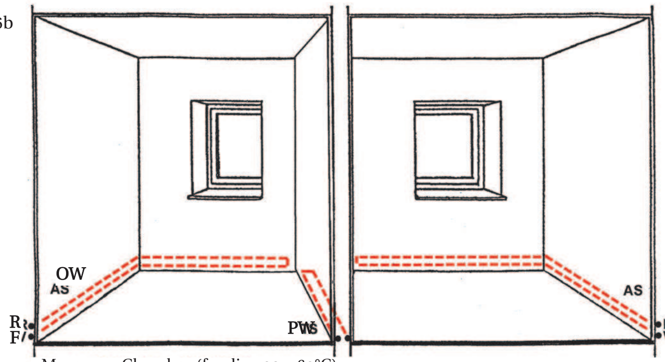
6a



- Conservation of the building substance and the room furnishings (historic buildings, exhibited buildings in open air museums, housed excavations; foreline ~ 30°C)
- Elimination of dampness and heating of cellars (foreline 30 – 40°C)

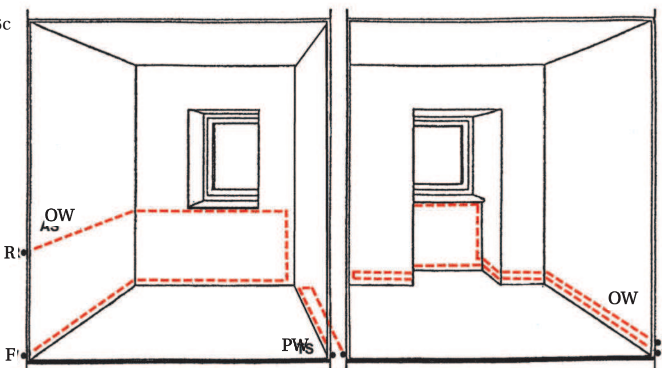
Ring layout shown is sufficient for half of the cellar of a single family house

6b



- Museums, Churches (foreline 30 – 60°C)
- Dwellings (wall thickness above 60 cm; foreline 30 – 65°C)

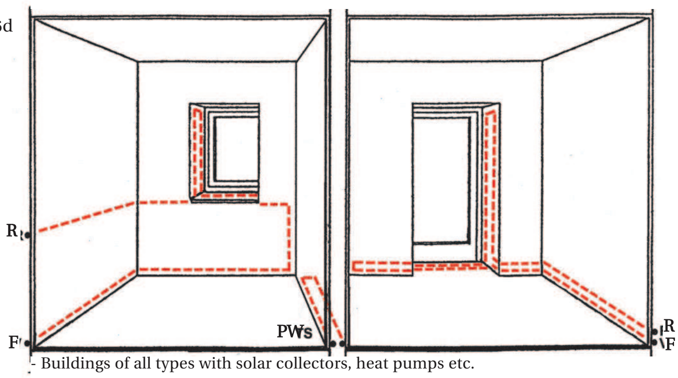
6c



- Museums with higher temperature requirements (foreline 30 – 55°C)
- Dwellings (wall thickness between 30 and 60 cm; foreline 30 – 65°C)

Windowsill level tubing in contact with the underside of the windowsill

6d



- Buildings of all types with solar collectors, heat pumps etc.
- Dwellings (light construction: porous wall materials, half-timbered, glass facades, foreline 30 – 65°C)

optimal installation (4 tubes plus detours on both sides of the windows) allows maximum foreline temperatures under 50 °C, which means return line temperatures under or about 40 °C. Thus, the advantages of new boiler designs can be realized and the contribution of solar collectors over the heating period can be considerable.

With ceiling-high wall paneling, if there is at least a 15-mm gap between it and the wall (allowing the warm air to rise behind the paneling so that a convection cell can form), for conservational purposes it is sufficient to mount a painted heating tube loop on the wall behind the baseboard of the paneling. This is because, by heating the whole shell, the protected warm air rising in the hollow space compensates for the radiation absorbing effect of the wooden baseboard. In living rooms, a second loop at the level of the windowsills should be added, if the paneling can be removed without damaging it. In any case, the tubes have to be in contact with the wall, with the wood kept at least at a distance of 5 mm. For walls without plaster, the tubes then have to be mounted in the joints of the masonry).

With only chest-high paneling, it is recommended to install the return line tube either on top of its upper edge, in contact with the plaster and painted, or in the plaster directly above or behind the horizontal wooden strip at the top of the paneling, so that from this second area of heat accumulation additional convection can occur, which heats the remaining portion of the wall. In order to prevent damage due to excessive dryness on the backs of paneling, showcases, or cupboards positioned close to the wall, 6-cm high strips of reflecting foil can be mounted on them, centered on the height of the heating tube runs. This dryness can occur because, when it is freezing outside, the surface temperature of the tubing, or its plaster covering, is much higher than the temperature of the air rising along the wall surface. This applies particularly if the tubing is installed on top of the plaster.

6.3.3 *"Radiators"*

In general, for dwelling or office room conditions in rooms with a continuously operated wall-base heating loop, "radiators" can be connected directly to the loop piping, because of the low additional heat demand, but only in the form of a single and purely radiating plate, without additional structure for enhancing convection. When radiating plates are installed, the functioning of the heating loop must remain independent of the setting of the radiator control valves. This "minimal heating system" (a pair of continuously heated, uninsulated, wall-base heating tubes whose temperature can vary only slowly and which extend the complete length of the outside walls of a room, with additional radiating plates beneath every window that can be switched on or off) is sufficient for producing, in a short time and in the simplest way, temperatures high enough for dwelling and office rooms.

An additional loop for supplying these radiating plates is not necessary since, shortly after running the wall-base tubes for the first time, the thermal conductivity of the wall material in their vicinity is reduced considerably due to drying out. After a period of 10 to 20 hours, through heat storage, the temperature spread (the difference between fore- and return lines) is reduced so much that enough reserve remains for additional radiating plates to be switched on. With loops of up to 30 m in length, a spread of less than 10 K occurs. Thus, if during continuous conservational operation (such as controlling the climate of a room) the heating tubes were at temperatures of, e.g., 38/30 °C, due to its "mean radiation temperature" of about 34 °C, the radiation plate would supplement the existing radiation from the wall base, so that the already "tempered" room would feel more comfortable. When it is freezing outside, by raising the water temperature, the loop can give higher performance within some minutes, thanks to the existing stored heat, so that at the wall base as well as at the radiator an increase of the surface temperature can occur rapidly.

6.3.4 *Regulation*

The hardware required for tempering is, due to the physics of the tempering process, very simple. This also applies to regulation of the temperature. If one builds a temperature limiter into the return line of each loop, at the return manifold or another location close to the end of the loop, then one gets self-regulation of the "wall/heating-tube system" at the set temperature, at a cost of about € 40 per loop. Since the heating water is cooled less if the heated area absorbs "external heat," the thermostat reduces the water flow accordingly. Since the heat flow to the area heated by a heating tube drops immediately when external heating occurs, heat starts to accumulate and thus the temperature starts to rise quickly in the vicinity of the heating tube. This applies in reverse if the outside temperature drops suddenly. Thus, contrary to common opinion, the regulation of tempering reacts in the short-term. However, because of the heat storage capability of the wall (its thermal inertia), room temperature does not change rapidly, so that sudden large increases or decreases of the heating water temperature are not required.

In this context, the generally bad experience with cost intensive electronic regulation technology ("control boxes"), which has become standard today, must be pointed out. On the one hand, optimum functioning of tempering technology for the lowest energy consumption is guaranteed only if energy can be stored from performance overshoots, which are prevented by continuous regulation. On the other hand, the self-regulating effects discussed above, in connection with slowly varying boiler regulation through an outside temperature sensor located under (!) the outside stucco of the north facing wall, lead to only gradu-ally varying room temperatures, with a maximum variation of 2 K during the course of a day. Such variations are irrelevant both conservationally and physiologically. But only this method of operation, through use of physical effects, leads to an energy consumption which is usually lower than with conventional heating processes and which cannot be reduced any more through complicated regulating processes.The often assumed delayed reaction of tempering is thus restricted to those situations where, as is the case when the heating is turned off temporarily or reduced nights and weekends, discontinuous operation aimed at saving energy gives up the advantage of stored heat.

6.3.5 *Energy consumption*

That the "reduced heating" in buildings with massive construction is not energetically sensible was shown in the Waldstraße School in Hattingen (built 1880 with 50 cm brick walls, Ú = 2000 kg/m³). Two-thirds of the building (all classrooms) is tempered with heating tubes. During the years 1996-1997, the city could not determine any energy savings with reduced heating nights and weekends, compared to the recommended slowly varying continuous operation. Further, the average energy consumption of the years since 2000 lies at about 18 kWh per m³ per year (see Table above), which means, that the requirements of the energy saving regulations are met by tempering alone (without thermal insulation of the heavy masonry walls or the old double windows – "kastenfenster" – having been repaired).

	1st heating period 9/96–9/97	1997 – 2000 (average of 4 years)	2001
Radiators/Convectors kWh/m³·a	35,97	24,61	20,58
Tempering kWh/m³·a	21,39	18,21	18,05
Heating Degree-Days	4.093	3.296	3.410

Source: City of Hattingen 3/2003

Table
Energy consumption in a school (building envelope with heavy masonry)

6.3.6 *Thermography*

In the above-mentioned textbook can be found a sentence regarding the calculation of the ceiling temperature for ceiling heating under flat roofs that is astounding for the usual heat loss calculations based on U-values. "In consideration of the relatively low number of very cold days and the storage capability of concrete ceilings, it is sufficient to use a (lowest) outside air temperature of -5 °C for the calculation." This is in agreement with the observations that could be made during the thermography of the outer surface of the outside walls of a tempered single-family house in Lengdorf, Bavaria, which was performed from 5:45 to 6:30 on 5 March 2002 at an outside temperature of -4.5 °C (Figs. 15 – 20). For only 26 cm thick uninsulated concrete walls that were heated with two heating tube loops with 60 °C foreline temperatures from early evening on, with the infrared camera one could indeed observe strong radiation from the outer surface but no variation in the amount of radiation that would indicate the location of the heating tubes on the inner surface.

The suspicion that thermographs, taken before dawn, of monolithic external walls with heating tubes on the inner surface do not show transmission losses but rather the re-radiation of the solar radiation absorbed during the previous day became firmer when the same wall, continued on unheated as a courtyard wall, in the same thermograph, was colored-coded yellow rather blue or black (Fig. 17: West wall of the courtyard, continued as west wall of the atelier, before sunrise). Also to see in the thermograph, a blue color-coded porous brick wall (heated in the same way) shows no lighter stripes in the tube area, but one can make out the joint network around the block surfaces. The plaster on the mortar of the horizontal joints and the massive perpendicular edges of the stones radiated lighter than those on the porous brick surfaces. More dimly, these details could also be seen on the north side (Fig. 20). Such color differences, which appear regularly on thermographs of tempered buildings, can only be explained by the fact that high-density (thus poor U-value!) mineral building materials, whose pore humidity is maintained under their "practical moisture content", store substantially more of the solar radiation energy and after the radiation ends re-radiate it much more slowly than less dense materials. Historical building and heating technology (high density materials with hypocaust wall heating or tile stoves) always result in direct solar energy use. This statement applies also to massive wood construction (log houses).

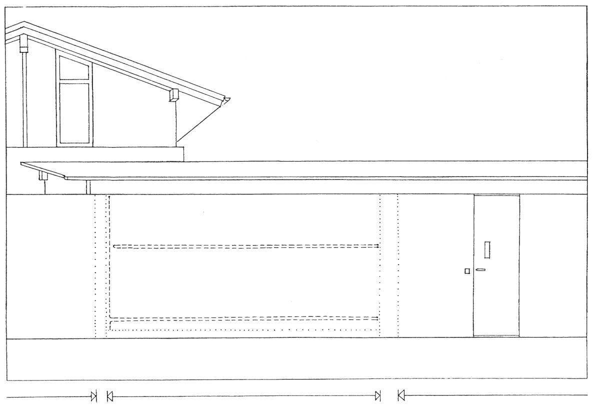
Thermographs of monolithic external walls with heating tubes on the inner surface, taken before dawn, do not show the positions of the heating tubes, which one would expect based on the high U-values of masonry walls or concrete. Comparison of the heating water temperature and the surface temperature of the plaster layer covering the tubes (see Fig. 9, right) shows that this is impossible (20 K lower temperature on the surface of a 20 mm thick plaster layer). Instead of seeing heatloss from the room's heating system, one sees the re-radiation of the solar radiation absorbed on the day before, which is of various intensities depending on the density of the (inthe heated case dry) walls and their average temperature (heated/unheated). This was confirmed by heat flux measurements (see Mauerbach), there: a) no higher heat transmission was seen at the heating tube level than at 30 cm higher; b) the solar energy gain of the directly heated outside walls was higher than that of an identical outside wall of a room heated with radiators!

Photos author; drawings Heiko Folkerts, Bernried; Thermography Thomas Böttler, Miesbach.

Figure 15:
Single-family house in Lengdorf, Bavaria, with courtyard and service buildings (atelier and garage) from the west. Courtyard, atelier, and garage walls of 26 cm concrete; atelier wall with 2 tube loops and without thermal insulation.

Figure 18:
Single-family house in Lengdorf, Bavaria from the north Courtyard and ground floor entry walls of concrete (26 cm thick); entry wall with 4 individual tubes and without thermal insulation.

Figure 16:
Schematic diagram of the routing of the heating tubes on the inside of the west wall of the atelier
(painted tubes in plastic clips with 1 cm gap to painted concrete wall surface)



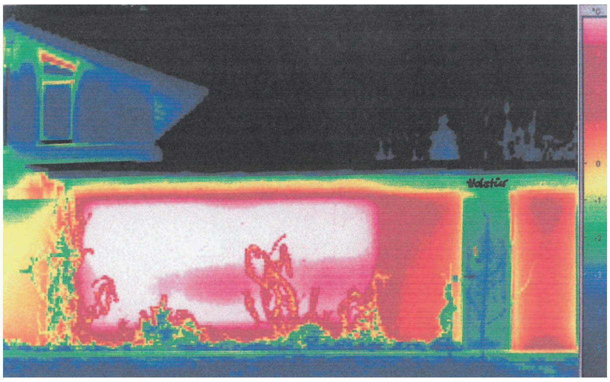
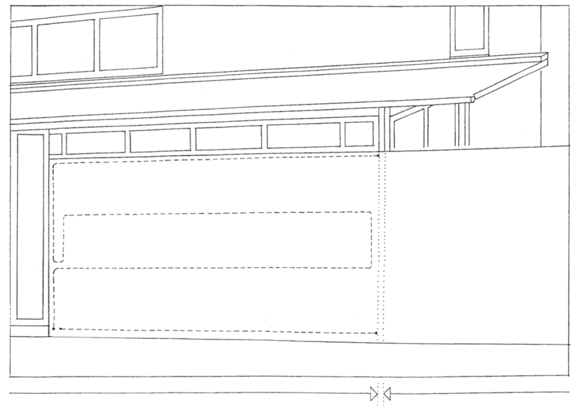


Figure 17:
Thermograph of the outside of the west wall of the courtyard, atelier, and garage (5-03-2002, 5:55, -4.4 °C; clear night after a sunny day, heating tubes operated since 18:00 of the previous day with Tm = 60 °C). The atelier wall appears a nearly homogenous white thanks to a long period of radiation. There are no lighter stripes discernable at the two tube levels. The colors of the remaining walls correspond to their mass density. Thus the courtyard wall (freezing cold air on both sides) is yellow, the wall of the unheated garage red, the light construction wall (above the windowsill level of the upper story) dark blue, the porous brick wall supporting it light blue, and its top green (higher storage mass due to mortar filling of hole ends). The upper loop is mounted 20 cm below the windowsill under plaster.

Figure 19:
Schematic diagram of the routing of the heating tubes on the inside of the north wall of the ground floor entry
(painted tubes in plastic clips with 1 cm gap to bare concrete wall surface behind the wardrobe).



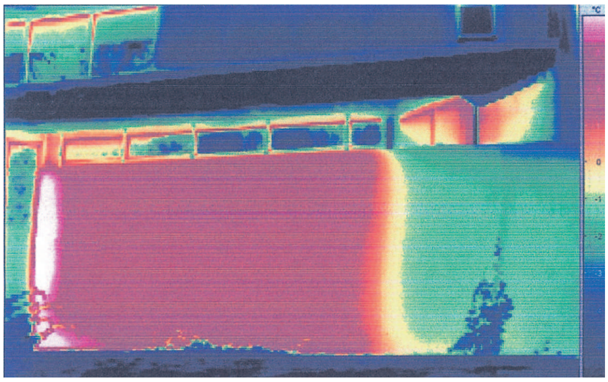


Figure 20:
Thermograph of the outside of the north wall of the courtyard and ground floor entry (5-03-2002, 6:30, -4.3 °C; dawn after a sunny day with clear night, heating tubes operated since 18:00 of the previous day with Tm = 60 °C). No lighter stripes discernable at the 4 heating tube levels of the ground floor wall. The dry concrete wall of the entry appears a homogeneous red. The courtyard wall (surrounded by freezing air) is green, the light construction wall on the upper floor is dark blue, analog to the west side.

Thermography of the remaining north wall, where the heating tubes are under plaster, shows similar results.

6.3.7 Extreme example of "minimal tempering"

An extreme answer to the question of "how long – for conservational purposes – can a tube loop be" is the museum in Ratibor Palace in Roth near Nuremberg. On the third floor, which has wood paneling reaching to the level of the windowsills, box windows (original lead glass windows outside and newer windows inside, both without seals) and a loam-filled ceiling under an uninsulated roof, a 75-m-long outside-wall loop of bare copper tubes with a diameter of 18 mm (foreline and return line each 37.5 m long) supplies all seven rooms on the north side, including the tower, and a further 70-m loop the six rooms on the south side. For an outside temperature of -15 °C, a room temperature of 8 °C can be maintained. This result is amazing not only because of the building characteristics and the length of the tubes, but also because the conditions for heat transmission from the tubes are bad: All tubes are bare and simply lie between the edge of the

Figure 21:
Alf Lechner Museum, Ingolstadt (northwest side). The space between the added glass façade (with entry) and the preexisting structure connects the air volumes of the ground and upper floors (12,590 m^3).

Figure 22:
Alf Lechner Museum, Ingolstadt (southwest side)
The rear-ventilated cladding has a gap of 25 cm to the outside wall.

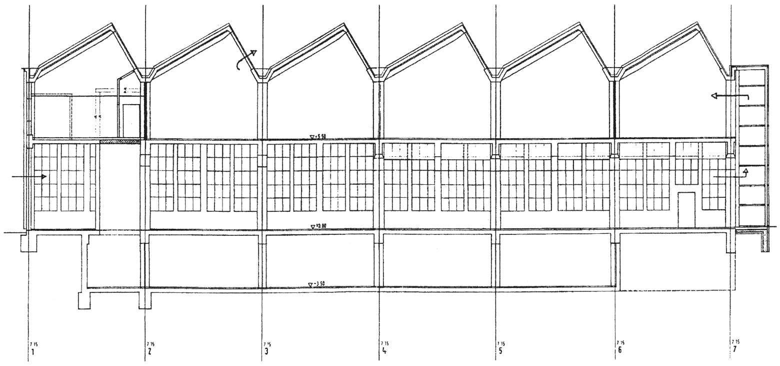


Figure 23:
Alf Lechner Museum, Ingolstadt (cross-section). The basement (1/3 of the floor area) lies northeast of the ground floor central row of columns. The flow of ventilating air is shown by the arrows.

Figure 24:
Alf Lechner Museum, Ingolstadt (inside view of the glass façade looking southwest). The gap between the glass façade and the preexisting structure forms a 10 m high shaft that is without hot-air currents in the heating season.

Photos of Figs. 21, 22, 24 und 20 by Michael Heinrich, Munich, the rest by the author.

wooden floor covering and the outside wall, below the level of the lower edge of the paneling. Thus, there is almost no physical contact so that the conduction path to the bulk of the wall is minimal, and internal radiation behind the paneling is severely reduced because the emission of bare tubes is 8 times lower than with painted tubes.

A further reduction in performance is caused by the surface temperature of the base of the paneling being low, which reduces both radiation into the room from the base and convection at the surface of the paneling. So, for hard frost, the temperatures at the distribution manifold are 70 °C (foreline) and 50 °C (return). The foreline temperatures could be lower or the room temperature higher if the foreline tube were in contact with the wall, plastered over or painted, and the return line tube were mounted above the upper edge of the pane-

Figure 25:
Alf Lechner Museum, Ingolstadt, Ground Floor.
Part of the central pillar loop (Ø 18 mm): the foreline (painted) is in physical contact with the joist and the north and south sides of the pillars, in each case changing from one to the other side at the pillar base in the screed. The return line (unpainted) was shoved into the cavity of the joist.

Figure 26:
Alf Lechner Museum, Ingolstadt, Upper Floor.
Wall pillars with sample for the sawtooth roof beam heating loop; at the wall base 2 heating tube loops before the "baseboards" are concreted in place: below the wall base loop (Ø = 18 mm), above the feed lines (Ø 22 mm) for the sawtooth roof beam loops.

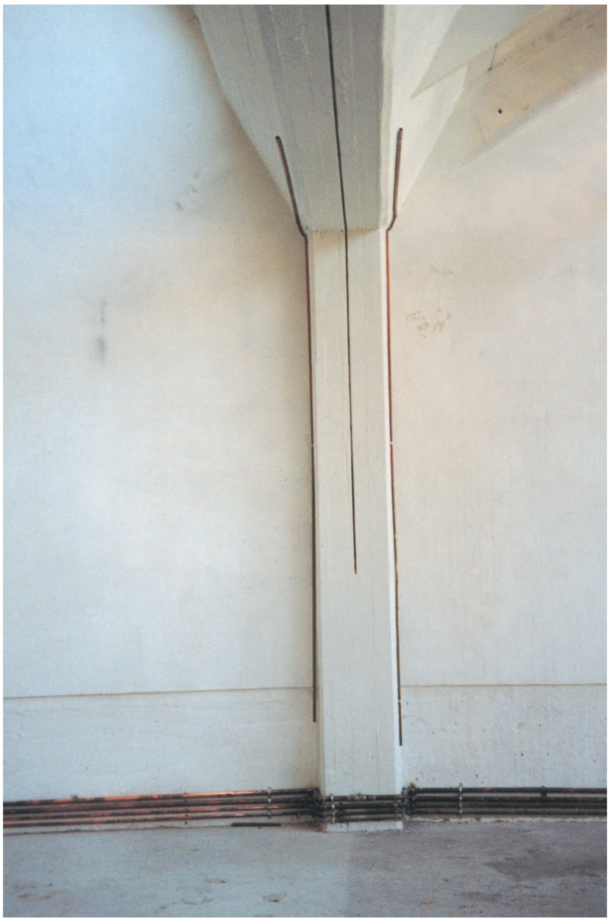


Figure 27:
Alf Lechner Museum, Ingolstadt, Upper Floor, View to West. .Part of one of the two heating loops on the beams supporting the sawtooth roof (Ø = 18 mm, in physical contact, painted): The single heating tubes above the lower edge of the concrete beam change at the central pillars to the other side of the beam.

Figure 28:
Alf Lechner Museum, Ingolstadt, Northeast Corner of Glass Façade , from inside. In the corner post are the feed lines to the two tube loops of the façade (Ø = 18 mm) at the heights of the floors (ground floor: 3rd and 4th horizontal steel U-beams, upper floor: 6th and 7th horizontal steel U-beams of the framework for supporting the glass. All tubes are painted and held in place by plastic clips. Left: ground floor loop foreline (in lower U-beam) and return line (in upper U-beam).

Figure 29:
Alf Lechner Museum, Ingolstadt, Ground Floor. Southwest wall, with wall-base and windowsill-height heating tubes (Ø = 18 mm), before the window niches were plastered and the concrete "baseboards" were poured.

ling, visible but painted or under the plaster. Due to physical principles, however, and despite all of the flaws, the main goal is achieved, namely the storage of heat in the masonry of the outer walls, which prevents the floor from getting cold. The case is an exemplary demonstration of how little the field of heating is oriented towards the phenomenon of heat storage, which small but continuously operated heating systems can produce.

7. An Important Example of a Minimal Facility

Alf Lechner Museum, Ingolstadt – Renovation and remodeling of an industrial building as a low-budget project with minimal moisture control and thermal insulation measures and minimally invasive housing systems technology (opened 2/2000).

The former automobile assembly building is a two-story 1950s concrete-skeleton industrial building with 24 cm thick aerated concrete infill, a basement under about one third, single-pane steel-framed glazing on the ground floor (3/4 room height), and an aerated concrete sawtooth roof on the upper floor with single-pane glazing. A new glass façade, supported by a post-and-beam steel frame, was built about three meters in front of the old northwest wall, which was removed from both stories, combining them into one gallery space. The gaps between the façade and the roof and the ends of the old walls were also filled with the glass-steel construction. Rear-ventilated metal cladding was installed on the three remaining outside walls, for hiding the windows and the rain gutters (distance from wall, 25 cm). (Figs. 21 - 24).

With a total heated volume of 13,600 m^3, the museum includes, in addition to the two-story gallery for exhibitions (12,560 m^3), a multi-function area on the upper floor (875 m^3), with 2 offices, bath, and large workroom, as well as functional rooms in the basement (1280 m^3), with a workshop, restroom facility, technical room (10 m^2), and side rooms. Of the total cost of € 1.02 million, the most expensive items were the glass façade and the ventilated metal cladding.

Thanks to the building physics effects of the wall heating, thermal insulation and moisture control measures could be minimized. These were completely omitted in the earth-contacted areas of the building (2/3 of the ground floor area and the entire shell of the basement, normal concrete without a moisture barrier or thermal insulation). At the wish of the architect, the concrete outside walls each received a 1 meter high, 10 cm thick strip of thermal insulation where ground floor and first floor begin, the sides of the sawtooth roof received 2 cm, and the opaque roof areas and the retained ground floor glazing 10 cm. The window openings of the 2nd floor were filled with brick (1200 kg/m^3). The glazing of the sawtooth roof was replaced with insulating glass (k = 1.5 W/m^2·K), which was also used for the glass façade.

The ventilation system (€ 2556) consists of 2 exhaust fans with multi-leaf dampers in the glazing of the sawtooth roof at the southern end of the upper floor hall (max. air flow volume 2 x 3000 m3/h) and 2 fresh air multi-leaf dampers in the southern ground floor outer wall (air flow between the floors is through the broad gap to the glass façade, see flow arrows in Fig 23).

The heating system (net cost of € 36,046) consists of an area heating connection (€ 7055), a substation with regulation (€ 9561), and the tempering system (€ 19,429), whose heating tubes (uncoated copper, 18 and 22 mm diameter) have a total length of 1124 m, including manifold tubing. At the massive exterior building elements the tubing loops are mounted with physical contact, both under plaster: at the base of the massive outside walls (ground floor: return tube detours into the niches with windowsill contact, Fig. 29), as well as on plaster and painted: on the second floor, on both sides of the wall pillars and the beams supporting the sawtooth roof (Figs. 26 and 27), and on the ground floor, a single tube on both sides of the 6 pillars and under the hollow joist returning in its cavity (Fig. 25). In the glass façade, the tubing loops are mounted thermally separated, one loop for each floor, with each tube located in a separate horizontal U–beam of the glass façade (Fig 28). For an average tube temperature of 70 °C, the maximum specific heating capacity is ca.65 W/m (see Fig. 10). With 1124 m of tubing, this is equivalent to 73 kW or 5.4 W/m^3 of finished volume.

Since November 2000, a minimum room temperature of 19 °C has been maintained in the heating season with this low maximum heating capacity with unusually low energy consumption. Thus the project, with its total heated volume of 13,600 m^3, of which 12,590 m^3 extends over two stories, is an impressive example for how far both heating and plumbing costs can be reduced with realization of all of the physical effects of the heating-tube tempering method and proper planning of the tube locations. As in this example, thermal insulation of earth-contacted walls and floors, including floating screed, is also not needed for new construction. For at least 19 °C, the yearly specific heating energy consumption was 20.4 kWh/m^3 in the 2nd year of operation, for 3956 heating degree days (HDD), and 18.2 kWh/m^3 for the 3rd year (3,723 HDD), thus showing the energetic importance of physically sensible heat distribution. A further tested example over two winters is the Kulturspeicher in Würzburg, which has a heated volume of 50,000 m3, of which ca. 40,000 m^3 is continuous over three floors during the day because the doors of the exhibition rooms are open to the staircase (160 m long!). The minimum temperature of the building is 18 °C. There a minimal tempering system (2 heating tubes on all wall bases) was also sufficient and insulation of the basement floor (160 m long!) was not necessary.

8. Compact storage units and wall-base tempering

The optimal furniture for storerooms are roller shelves or compact storage units. In conventionally heated or air-conditioned storerooms in basements, however, these devices turn out to be "critical" pieces of furniture, whereas in wall-base heated basement rooms a closed compact unit can be positioned even in close vicinity to the exterior walls. This is not possible with "normal air conditioning," because the air that is conditioned by the "air machine" neither reaches into the closed roller-shelf unit nor is it able to heat the walls surrounding it. Thus, the walls stay cold and the disadvantage of cool room envelope surfaces is not compensated. For this reason, compact storage units are usually placed at great distances from the walls in rooms of heavy wall construction or in basements, so that expensive space remains unused. One often even hesitates to close the units in such rooms; the seals are removed or the individual compartments are kept at a distance from each other so that "the air is able to circulate." Only so, however, can the danger of mold growth be reduced – by giving up the dust protection. The confusion that results from considering only the symptoms is demonstrated by the fact that manufacturers often offer units with large holes in the sides, the "seals" now functioning only as shock absorbers.

If, however, the surfaces of the walls which surround such roller shelves or any other piece of furniture are heated directly and are kept warm, heat will be radiated from the walls to the furniture (without detouring through the bulk of the room air). Thus, no matter how big the storage unit might be, even if it filled the whole room, after some time there would be a uniform temperature, equal to the room temperature, whose direct result would be uniformly reduced RH inside the units, corresponding to that of the room air. Accordingly, the humidity of the material would also be reduced gradually and gently, throughout the whole cross-section, without the need for air constantly circulating between the stored goods (see Section 8.1). Thus, the material is gradually dried out, so that after a while the process continues with less energy consumption.

It must be emphasized again that, with tempering systems, the distance from the wall of furniture, roller shelves, and other objects is determined only by the fact that, for the wall surfaces to be tempered, small amounts of warm air must be able to rise continuously within the gaps, since there are no wall registers, rather only one or two heating tube loops installed in the wall base. Room for these warm air currents, however, is guaranteed if the gap is in no case less than 2 cm. In exceptional cases, that which was mentioned with regard to "paneling" in Section 6.3.2 (p 26) applies here also: in order to avoid the more intensive impact of radiation from the warm strip in the area of the tubes at maximum mean water temperature, it is sufficient to mount a strip of cardboard or of radiator reflection foil on the side of the piece of furniture or object at the appropriate height.

8.1. Normalization of the equilibrium humidity of stored artifacts by means of tempering

If one, on the one hand, wants to avoid cost intensive "climate control systems" while, on the other hand, normalize the material humidity of stored artifacts in a conservationally convenient way, it is actually only a question of slowly raising the temperature of the surfaces of the walls surroundings the inventory, because the material achieves this temperature equally slowly. Thus, the equilibrium humidity in the material gradually decreases without stress occurring at the surfaces of the objects.

In the long run, a lower but at the same time homogenous material humidity, throughout the whole cross-section of the stored artifacts is achieved so that, in the total collection, not only the activity of microorganisms and biological growth comes to a halt, but new occurrence of any forms of growth is also impossible. Furthermore even the conditions for insects ("wood worms") become less favorable: on one hand due to the lower material humidity, on the other hand due to the lack of cold periods between fall and the beginning of the heating season, during which the formation of pupae necessary for reproduction would take place. During such a phase of "humidity normalization," the collection should be loosely placed. The compartments of compact storage units should be kept separated. While monitoring the RH, the continuous transport of the moisture emitted from the material must be guaranteed by ventilation. A low cost and at the same time safe solution is maintaining a constant, minimal air exchange rate (between 0.1 and 1 ACH) by means of an exhaust fan with speed control, as described in Section 6.2.

These findings show clearly the general importance of a "radiation climate," not only for the storerooms and for permanent exhibition areas in museums but also for buildings and uses of any kind.

9. Ignorance of the facts of physics by theory and state of the art

What has been said so far explains the fact that, for the time being, in the areas of room heating, air conditioning, and restoration/prevention of damage due to humidity or salt, standard theory and practice do not sufficiently take into account the facts of physics – in particular the effects of heat radiation. For that reason "all encompassing" and thus low cost concepts, as shown here, are rare.

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