

From the Mogao Grottoes to the Margravial Opera House in Bayreuth.

Case Studies on the Impact of Visitors on the Moisture Balance of Historic Rooms

Potential impacts of large number of visitors on artefacts and monuments are often discussed as the most important issue when we try to determine the priority between the accessibility and preservation of historic spaces. However, it is not always easy to determine the scale of the impacts. We need to understand both chemical kinetics of materials and resulting damage processes as a consequence to the amplitude as well as frequency of climatic fluctuations. This paper attempts to present the state of knowledge and discuss this interrelationship for selected case studies.¹

The most significant impact of visitors to works of art in enclosed spaces is linked above all to the role of the human being as a moisture source. Depending on the level of his/her activity, a typical person releases 40–110 gram of water and 7–14 liter of CO₂ per hour to the environment while visiting museums and archeological sites. Further, visitors release not only physiological products such as skin and hair, but also textile fibres from their clothes, to the environment. These will deposit on works of art and historic interior surfaces, if they cannot be promptly vented to the outside or removed by filter devices of HVAC systems.

In spaces where the rate of ventilation is limited, the CO₂ exhalation by visitors becomes of considerable importance, as the safety and comfort of visitors will be compromised. However, the threat diminishes, if the infiltration of the outside air is significant. Therefore, it plays a major role when we deal with artefacts in caves or tombs.

For the moisture generation, the situation is somewhat different. Here walls and architectural surfaces, as a function of their porosity and moisture storage characteristics, decisively influence the humidity balance by adsorption and desorption processes. The buffering potential of modern concrete is for example by far lower than for lime based renderings or wooden surface elements in historic interiors.² Furthermore, the outside environment can not only act as a dissipater for high moisture levels, but also, depending on the meteorological conditions, it can act as an important source of moisture. Finally, capillary water movements through ground and walls often play a significant role for the moisture balance indoors.

As for understanding the impact by visitors, we need to record numbers of visitors, lengths of visits, their activity levels,

and outside weather conditions. It is also important to note whether a mechanical system, such as dehumidifiers or air-conditioning, has been installed in the visited space to isolate its microclimate from the outdoor conditions or other approaches have been taken to control infiltration of the outside air.

Damage processes, kinetics and dependance on cycle frequencies

Excess moisture is the major risk for the microbiological damages, e.g. through fungal and bacterial colonization. Mural paintings in the Marchini-rooms, Castle Weissenstein in Pommersfelden were widely covered by white efflorescences, which were identified as fungal mats and mechanically removed (Fig. 1). Organic materials such as paper, textiles or leather are especially susceptible to microbiological attacks.

An important precondition for mould growth is when the ambient temperature falls below the dew point temperature for at least three days.³ This implies that short term events in connection with persistent higher RH values (> 70%) can cause this kind of damage.

The humidification in winter forms a major condensation risk. 45 years ago wrote Benoist about museum heating, that European visitors are willing to accept a level of 15°C in museums in contrary to visitors in the US – who prefer 21°C.⁴ There is no doubt, that under the central European climatic conditions, a level of 15°C should be more sustainable from the conservation point of view, because it allows for much lower water input in order to stabilize the humidity conditions in winter. Nowadays, however the comfort requirements call for elevated temperatures in Europe as well.

The lower margin of tolerance is set by risk of increased brittleness, the breakage of single fibres and the formation of fissures and cracks. For wood and leather, this margin lays above 40% RH.⁵ This applies as well to protein based binding media in polychrome surfaces.

In general, porous material responds to changes in relative humidity with a volume change. The fact that painting canvases tend to shrink while being exposed to elevated humidity levels is due to the way the horizontal and vertical fibres are intertwined in the textile structure. The dilatational response of adobe to changes of relative humidity between 30 and 90% is shown in Figure 2. During the humidification phase the adobe expands progressively while during the drying/dehumidification phase the adobe shrinks. It is worth noting that shrinkage during the drying phase takes place faster than expansion the humidification.⁶

Clays with a high exchange capacity and inter-layer cations, such as montmorillonite swell in response to an increase in water vapor pressure or water content by hydration of the inter-layer cations.⁷

¹ The collaboration of Ann Bourges, David Carson, Eric Doehne and Tiziana Lombardo at the Getty Conservation Institute, of Matthias Staschull, Sebastian Falcon and Mattei Lazarescu is gratefully acknowledged. The authors also appreciate the support of the Dunhuang Academy, the Egyptian Supreme Council of Antiquities and the Bayerische Verwaltung der Staatlichen Schlösser, Gärten und Seen.

² LEGRUM, 1994.

³ STEINERT – DRAEGER – PAULMANN, 1981.

⁴ BENOIST, 1960.

⁵ THOMSON, 1986.

⁶ BOURGÈS – SIMON – MÜLLER, 2003.

⁷ SPARKS, 1986.

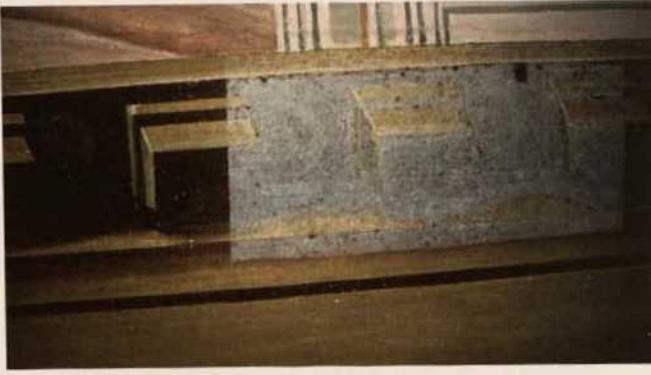


Fig. 1. Pommersfelden, Castle Weissenstein, the Marchini-rooms: Microbiological colonization of mural painting surfaces / Schloss Weissenstein, Marchini-Räume: Mikrobiologische Besiedelung von Wandmaleroberflächen.

Through the cycling experiment expansion and shrinkage amount to a similar magnitude in a reversible way (Fig. 3). Dilatation ranges from 150 to 3100 $\mu\text{m}/\text{m}$, depending on the type of clay. Montmorillonite bound adobe reached 20 times higher dilatation than kaolinite bound, which can be attributed to the different CEC (hydration of interlayer cations) and surface area (osmotic swelling) of montmorillonite and kaolinite.

The apparent reversibility of the process indicates that the stress does not exceed the elastic range of the material and hence does not produce significant damage. The time to reach the equilibrium expansion is depending on the composition of the adobe. Not in all cases the maximum expansion could be reached within a 24-hour cycle.

The situation changes drastically, when the presence of hygroscopic salts comes into play. Concerning a sodium chloride laden adobe, five processes are competing during changes of ambient relative humidity (Fig. 5): With RH values exceeding the point of deliquescence for NaCl at 75%, a preliminary dilatation, typical for non-contaminated materials, can be recorded, which is soon balanced and converted into shrinkage due to the subsequent dissolution of NaCl in pore spaces. Then the expansion due to the swelling of wet clay minerals becomes the decisive process and continues without reaching equilibrium until the end of the wet phase.

During the drying phase, the material first shrinks quickly due to the contraction of the clay minerals. This is then converted into expansion due to the recrystallization of NaCl in the pore network and the resulting pressure. Crystallization and dis-

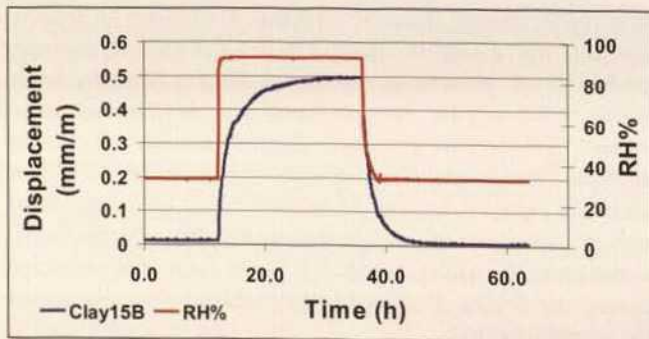


Fig. 2. Unidirectional displacement (hygroscopic dilatation) of adobe as a function of relative humidity and time / Eindimensionale Längenänderung (hygroscopische Dilatation) eines Lehmziegels als Funktion von relativer Feuchte und Zeit.

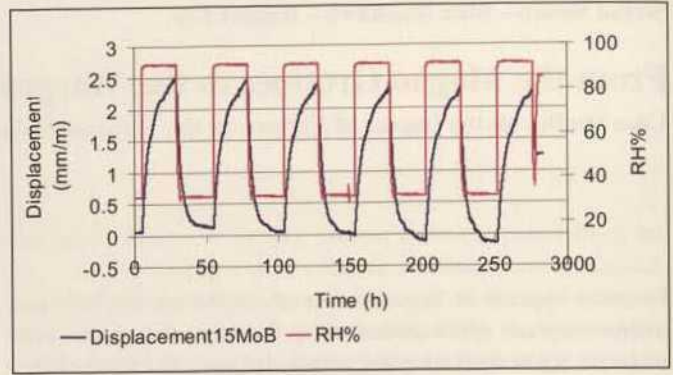


Fig. 3. Unidirectional displacement (hygroscopic dilatation) of montmorillonite rich adobe as a function of relative humidity and time / Eindimensionale Längenänderung eines Montmorillonit-reichen Lehmziegels als Funktion von relativer Feuchte und Zeit.

solution of salts is supposed to take place preferentially in the coarse pores⁸ and lead to a progressive decay of the material. Repetitive humidity cycles produced an irreversible and increasing structural expansion in sodium chloride contaminated brick.⁹

As observed for NaCl-laden sandstone¹⁰ the amplitudes of dilatation increase with the number of cycles underlining the role of NaCl as a damage factor for porous materials (Fig. 7).

Small RH ($\text{RH} \pm 2\%$) changes around the $\text{RH}_{\text{equilibrium}}$, independent of the rate, and the number of cycles, lead to reversible adsorption and desorption of water, and do not change the morphology of NaCl crystals. Rapid and large RH changes result in dramatic changes of crystal morphology and the formation of non-equilibrium crystals. A positive relationship between the extent of non-equilibrium crystal formation and the resulting damage potential is assumed.

The hygroscopic dilatation of wood is more important than the thermal dilatation. It is anisotropic, depending on the fibre direction, highest in tangential fibre direction, significantly lower in radial direction, and lowest with the fibre direction. Figure 4 shows that the moisture content under the $55 \pm 10\%$ RH regime varies between 6–14 mass-%. Knowing the dilatation coefficient (as for pine wood ca. 0.24%/percentage point of variation of wood moisture content, \perp to fibre direction, mean of radial and tangential value),¹¹ the expected hygroscopic dilatation of wood can be calculated as a function of variations in the ambient relative humidity.

Against common understanding, maintaining the relative humidity constant at 55% can not prevent dilatation phenomena of wood under temperature variations (Fig. 6). At 15°C and 55% RH a wooden object is equilibrated to a moisture content of 11%. With an increase in temperature e.g. to 20°C, the RH of the environment would have to increase to 60% RH in order to suppress dilatation phenomena caused by the subsequent variation in the moisture content of the wood.

Changes of 10% RH can cause a dilatation in wood of 0.5% (Fig. 6). For canvas under these conditions dilatations coefficients of 0.05–0.1% were determined.¹² The amount of resulting dilatation increases exponentially with higher variations of RH. The damage progress is expected to increase by the dis-

⁸ HONEYBORNE – HARRIS, 1958.

⁹ WENDLER, 2002.

¹⁰ LOMBARDO – DOEHNE – SIMON, 2004.

¹¹ WENDEHORST, 1975.

¹² CORNELIUS DU PONT, 1967.

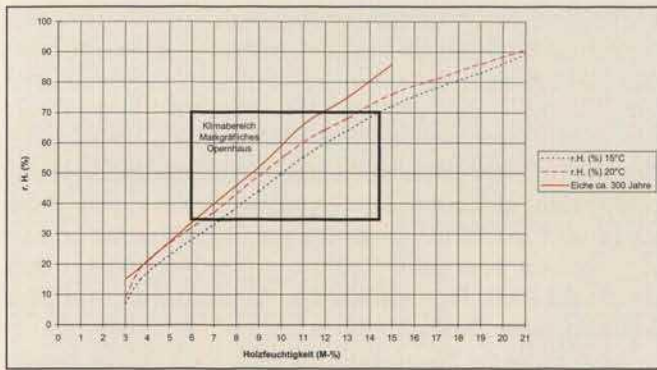


Fig. 4. Moisture equilibrium curves for wood as a function of relative humidity / Ausgleichsfeuchtekurven für Holz als Funktion der relativen Feuchte (nach Wendehorst, 1975 und Legrum, 1994).

cordancy due to the different dilatation behaviour where the material is covered by polychrome surface layers, especially through their binding media. Generally, it can be stated, that although the dilatation behaviour is clear, a correlation with resulting damage still has to be established and should be subject to further investigations.

The cycle frequency is a significant parameter for the assessment of the damage potential of climatic changes. Cycles shorter in duration (e.g. daily cycles) exceed longer cycles (e.g. monthly cycles) in their damage potential. This is due on the one hand to their higher number, on the other hand to the structure of the surrounding interior surfaces. The outermost architectural surfaces (e.g. paint layers, gilding etc.) follow in their sorption and dilatation behaviour changes of the ambient environment much faster than objects with higher volumes (e.g. masonry, sculptures). Seasonal changes of moisture and temperature are hence supposed to cause less stress, because they occur slower than the penetration of moisture or heat into the material and hence do not contribute on the same level to the building up of zones of discordancy between the interior and the exterior of the object.

Case Studies

The Tomb of Queen Nefertari, Valley of the Queens, Egypt

The Tomb of Queen Nefertari is located in the Valley of the Queens in western Thebes (the west bank of the present-day

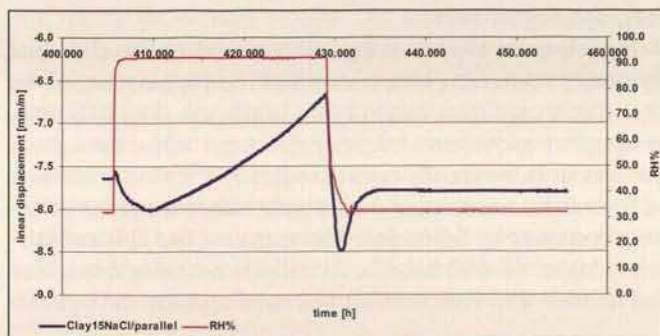


Fig. 5. Displacement of NaCl laden adobe (Clay15NaCl) during one cycle of relative humidity / Hygroskopische Dilatation eines mit Kochsalz befrachteten Lehmziegels während eines Feuchtezyklus (30–90% relative Feuchte).

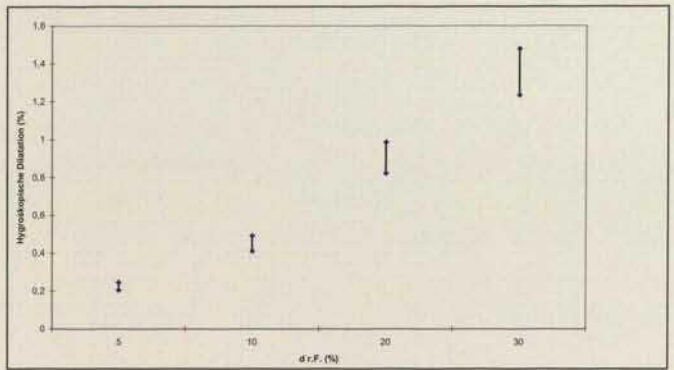


Fig. 6. Hygroscopic dilatation of wood as a function of relative humidity changes / Hygroskopische Dilatation von Holz als Funktion von Schwankungen der relativen Feuchte (nach Wendehorst, 1975).

city of Luxor), Egypt (Fig. 11–12). It is oriented north to south and carved approximately 13 m deep into the limestone bedrock. Figure 8 shows plan and section views of the tomb. A steel entrance door, left opened only during the visiting hours, is attached to a large steel bulkhead on the south wall of the upper chamber. A steep staircase, (A), approximately 4.5 m long, leads to the arched entry gate of the tomb at ground level. The tomb consists of two major chambers: the upper chamber, (C), and the burial chamber, (K). There is a 3.3 m drop between the floors of the two chambers, which are connected by a staircase (I) approximately 7 m long. The estimated total volume of the tomb is approximately 475 m³.

Figure 10 shows changes of the relative humidity and carbon dioxide in the tomb during an experiment conducted with 37 adult Egyptians in the burial chamber in August 1992. Both rates of the moisture and carbon dioxide generations coincided with typical rates that are published by the ASHRAE. The natural infiltration rate of the tomb was evaluated to be 8.9 m³/hr (0.019/hr) from the decay rate of the carbon dioxide. This low rate resulted from the combination of a high outside summer-time temperature (35°C), lower temperature (29°C), and the architectural configuration (the entrance is approximately 13 m above the floor) of the tomb. The warm, therefore, buoyant outside air has no chance of entering the cooler cave located 13 m below the ground. On the contrary, as seen in the same figure, the decay rate of relative humidity was much higher than that of the carbon dioxide. This indicated that a large portion of the moisture released by the visitors was absorbed by surfaces, such

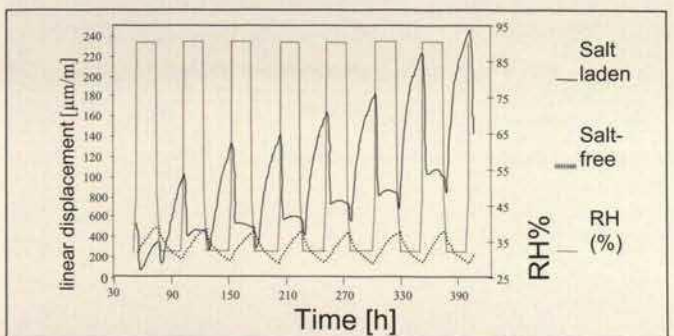


Fig. 7. Dilatation (µm/m) as a function of time and RH for salt-free and salt-laden Umm Ishrin sandstone / Hygroskopische Dilatation als Funktion von Zeit und relativer Feuchte bei salzfreiem und salzbelastetem Umm Ishrin-Sandstein.

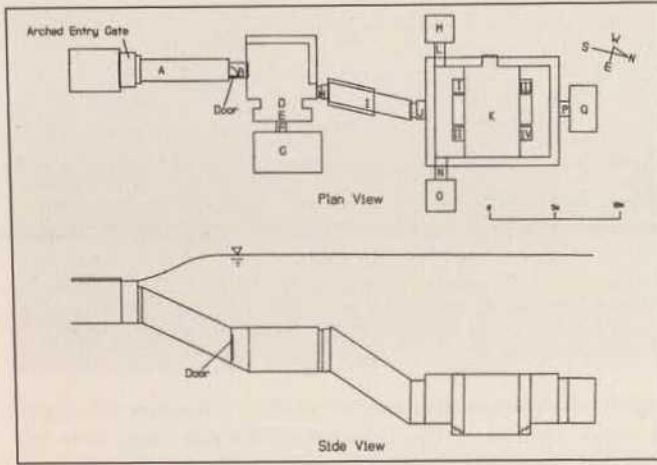


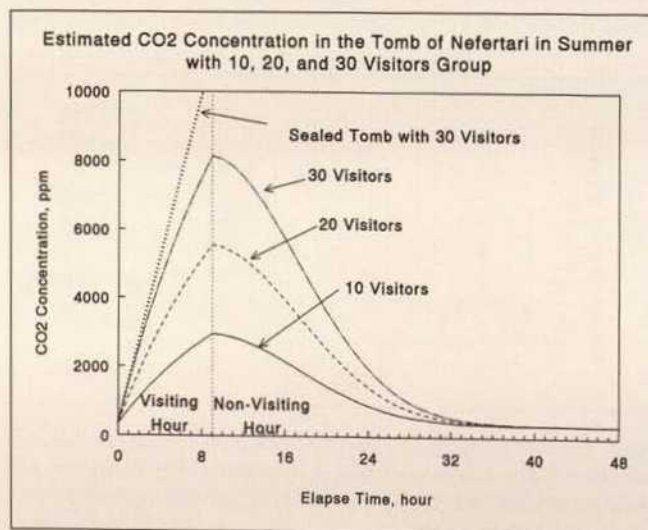
Fig. 8. Valley of the Queens, The Tomb of Queen Nefertari, Floor plan and cross section / Tal der Königinnen, Grab der Königin Nefertari, Grundriss und Längsschnitt.

as wall paintings, floor, and ceiling, of the tomb. It took more than 48 hours before the relative humidity returned to the pre-experiment level.

Based on natural infiltration rates evaluated from the experiments, we estimated a build-up of carbon dioxide in the tomb as well as its residual concentration after 8 hours of continuous visitation by groups of 10, 20, and 30 visitors as shown in Figure 9. Even with only 10 visitors in each group the concentration exceeded 2000 ppm, at which most visitors will feel uncomfortable, in the first 5 hours. And the concentration will not be reduced to the ambient (340 ppm) level by the following morning, indicating a daily build-up of the carbon dioxide.

The Mogao Grottoes, China

The Mogao Grottoes are located some 1,800 kilometers west of Beijing along the ancient Silk Road, at the eastern edge of the Taklimakan Desert and the south-western edge of the Gobi Desert, beside the oasis town of Dunhuang in north-western China. The site is a Buddhist sanctuary and consists of 492 decorated cave temples situated along 1.6 km of cliff face, dating between the fourth and the fourteenth century A.D. A typical architectural feature of the caves is shown in Figure 15. Figures



13 and 16 show wall paintings in one the caves. The caves were cut into a natural cliff face, approximately 50 meters high, running and consisting of a soft, poorly cemented, fine-grained conglomerate. A mud plaster mixed with sand and straw was laid directly on the conglomerate surface, and a white ground was applied prior to the paint layers. Modern threats to the preservation of these unique Buddhist artefacts include the intrusion of tens of thousands of tourists. The number of visitors increased from about 50,000 a year in 1980 to more than 200,000 in 1990. The trend has been continuing to more than 300,000 in early 2000's.

The caves of the Mogao Grottoes were, for centuries, mostly open to the outdoor environment, since their facades have long been decayed or removed as the site was abandoned for centuries. In the 1960's a concrete facade and walkways were built to facilitate access (Fig. 18). All decorated caves were fitted with alumina doors to shelter the caves from the outside climate. The doors are normally closed when the caves are not visited, and opened only during visitation.

The environments of two architecturally similar, medium-sized caves, one open to daily visitations and the other one closed to visitors at all times, were monitored for two years. During that period, several controlled experiments with visitors were conducted in the caves to determine the impact of visitors

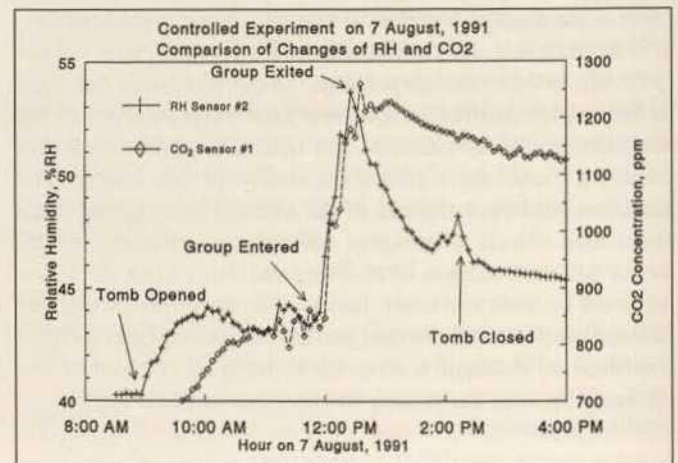


Fig. 10. Relative humidity and CO₂ concentration in the Tomb of Queen Nefertari, recorded before and after the visit of a tourist group / Vergleich von relativer Feuchte und CO₂-Konzentration im Grab der Königin Nefertari vor und nach dem Besuch einer Touristengruppe.

on the caves' microenvironments. Daily between 300 and 800 visitors visited the open cave during summer months, June, July, and August 1991.

The impact of visitors on the microenvironment was assessed by simply subtracting temperature and relative humidity of the non-visited cave from those of the visited cave (Fig. 17). Both, temperature and relative humidity difference varied throughout the period. However, the open cave had a (1°C) lower baseline of (overnight) temperature during early summer, and the difference decreased by September. The open cave had also a consistently higher (4-6%) baseline for relative humidity throughout the summer. The visitors effect was more apparent through two

Fig. 9. Calculation of CO₂ concentration for Nefertari tomb as a function of amount of visitors / Berechnung der CO₂-Konzentration für das Nefertari-Grab als Funktion der Besucherzahl.



Fig. 11. Valley of the Queens, The Tomb of Queen Nefertari / Tal der Königinnen, Grab der Königin Nefertari.

daily positive spikes (one in the morning and the other in the afternoon as caves were closed during the lunch hour) of 2 to 4°C during the summer months. The relative humidity also had two daily spikes, however, the spikes varied in both magnitude and sign (positive and negative). Positive spikes were found on hot, therefore, dry days, while negative spikes occurred on humid days. Monthly averages of the absolute humidity of the visited cave were higher than those of the closed cave and very similar to those of the outside air.

Controlled experiments conducted in the caves with visitors revealed highly variable, however, high infiltration rates, of 2 to 12/hr. These facts, along with the results of the monitoring,

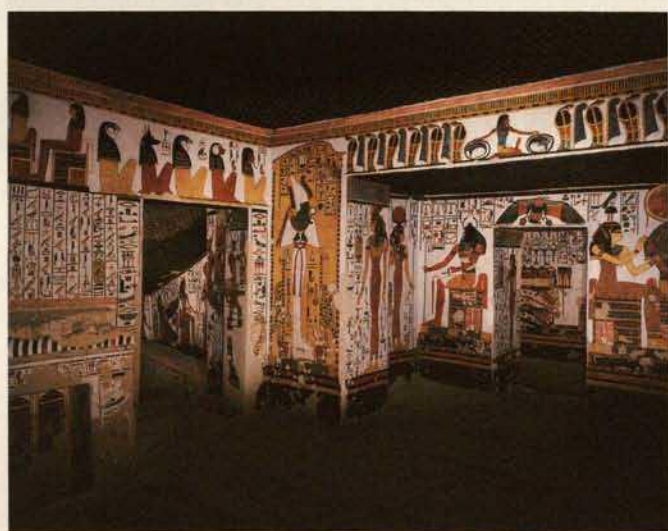


Fig. 12. Valley of the Queens, The Tomb of Queen Nefertari / Tal der Königinnen, Grab der Königin Nefertari.

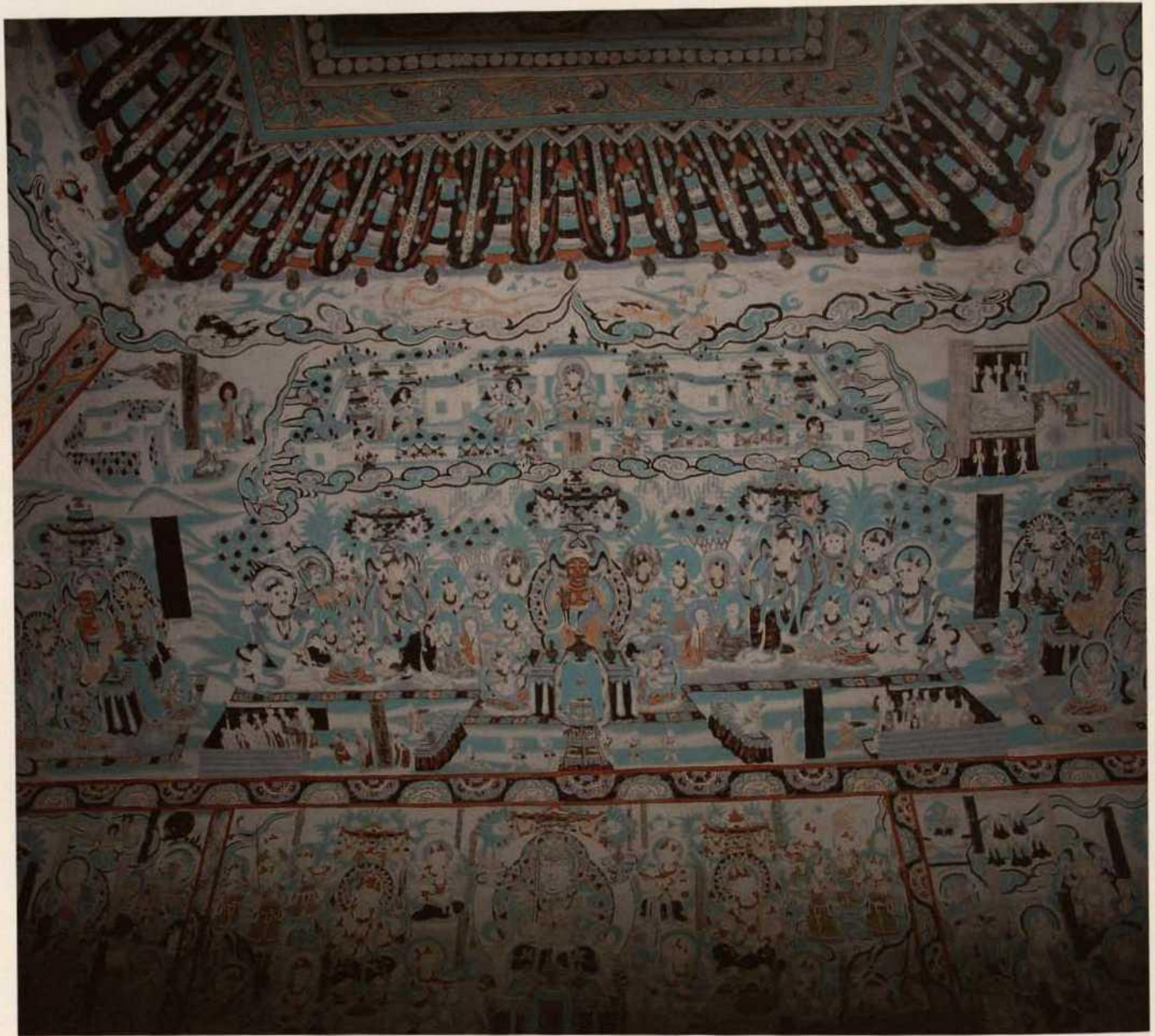


Fig. 13. Mogao Grottoes, Cave 25, Mural paintings on earthen plaster, detail / Mogao Grotten, Höhle 25, Wandmalerei auf Lehmputz, Ausschnitt.

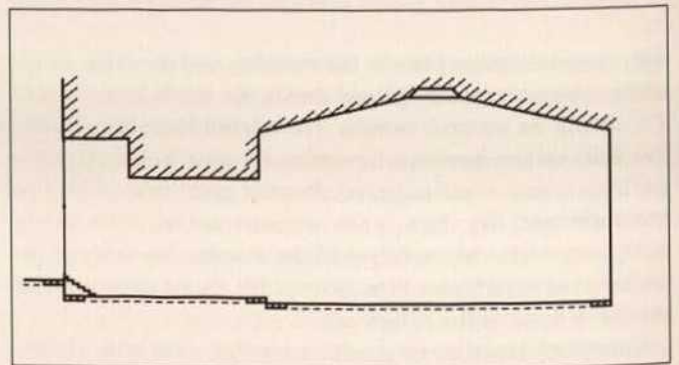


Fig. 15. Mogao Grottoes, cross section of a typical cave / Mogao Grotten, Längsschnitt einer typischen Höhle.

Fig. 14. Mogao Grottoes, the north view / Mogao Grotten, Fassaden, Nordansicht.



Fig. 16. Mogao Grottoes, Cave 25, Mural paintings on earthen plaster and polychrome sculptures / Mogao Grotten, Höhle 25, Wandmalerei auf Lehmputz und polychrome Plastik.

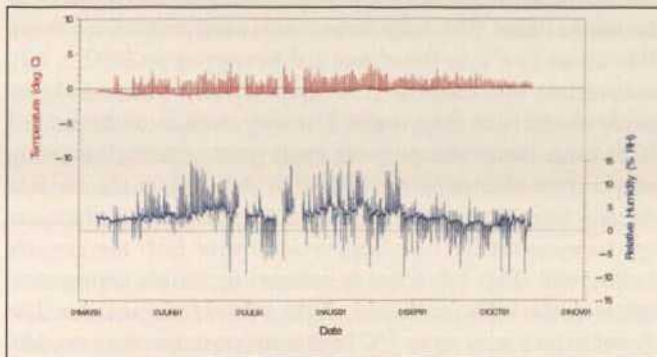


Fig. 17. Mogao Grottoes: Air temperature and relative humidity difference between Cave 323 (visited cave) and Cave 335 (closed cave) / Mogao Grotten: Vergleich von Lufttemperatur und relativer Feuchte zwischen Höhle 323 (Besucherverkehr) und Höhle 335 (geschlossen).



Fig. 18. Mogao Grottoes, Concrete façade and walkways, the north view / Mogao Grotten, Fassaden mit Laufstegen, Nordansicht.

indicated that the impact of visitors on the moisture balance is recorded as an increased infiltration rate of the outside air. Therefore, the combination of rate of visitation and the outside climate determines the humidity conditions in the caves of the Mogao Grottoes.

Saint-Michel d'Aiguilhe, Le Puy, France

The walls of the 10th/11th century chapel Saint-Michel d'Aiguilhe (Le Puy en Velay, France) are mainly built of a basaltic tuff with black basalt or lava components (5–30% of the composition) in a greenish matrix of fine porphyroclasts. The matrix is highly porous (27–38%). The stone is capable to absorb large volumes of water in a short amount of time. The corresponding water uptake coefficient (W-value) ranges from 10–19 kg/m²/h.

Due to its location on top of a volcanic cone, the chapel is extremely exposed to the environment (Fig. 23). Everywhere on the outside walls, on exposed stones the deteriorating effects of the weathering, mainly flaking and scaling, but also surface recession, are obvious. The buildings masonry is hardly protected against wind, rain, sun and ice. There is no plaster, nearly no canopy and there is no roof rail. Therefore, particularly on the south-western side the driving rain, which is transported by wind, and additionally the run-off from the roof percolates regularly on the outside of the unprotected porous stone (Fig. 24).

On the inside the stone is covered by plaster with a thickness of ca. 2–3 cm. On the south-western wall, huge parts of the plaster seem to be detached. The inner plaster on the western

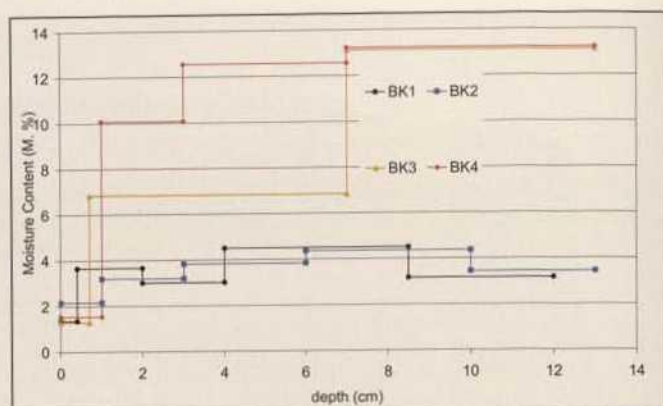


Fig. 21. Saint-Michel d'Aiguilhe: Moisture profile in walls / Feuchte-Tiefenprofil der Wände.

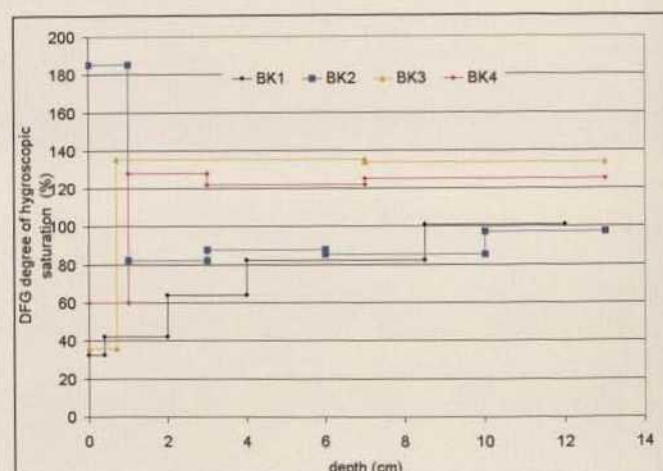


Fig. 22. Saint-Michel d'Aiguilhe: Moisture Degree (DFG) of hygroscopic saturation (%) as a function of depth in the walls / Hygroskopischer Durchfeuchtungsgrad (DFG) als Funktion der Mauertiefe.

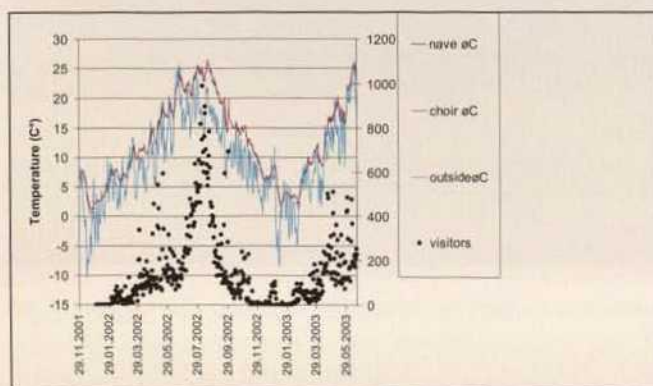


Fig. 19. Saint-Michel d'Aiguilhe: Temperature variation and visitors traffic / Temperaturschwankungen und Besucherverkehr (2001–2003).

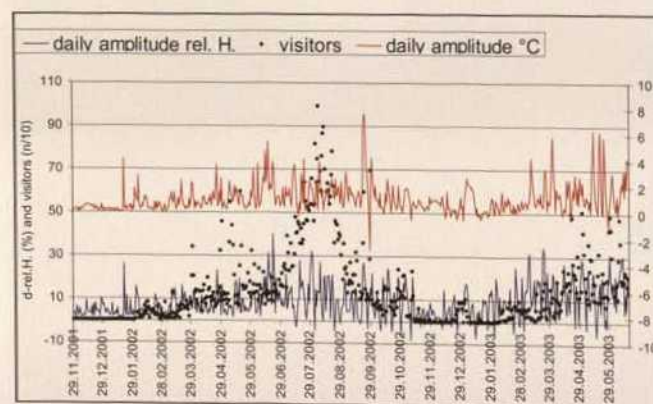


Fig. 20. Saint-Michel d'Aiguilhe: Daily variation of relative humidity and temperature / Tägliche Schwankungsbreiten von relativer Feuchte und Temperatur.

and north-eastern side of the chapel seems to be in better condition. Anamnesis showed, that the interior 12th century mural paintings may have been consolidated by a wax treatment during the 19th century.

Figure 19 shows the relation between the interior and outer air temperatures. The deviation of the air temperature sensors in the room remains within a margin of $\pm 0.5^\circ\text{C}$. Even in winter times, when the chapel is closed for visitors, the inner air convection is sufficient for a well-balanced climatic situation in the whole room. The daily mean room temperatures are rising from about 1–4°C in December and January up to 28°C in July and August. This range of 25°C twice a year is rather wide for an old chapel with thick walls. The wall surfaces undergo this 25°C temperature change twice every year as well. The yearly temperature change in the chapel is induced by the outside climate. But amazingly, in spring and early summer, the average temperature in the chapel rises faster than the outside temperature (Fig. 19). Even in summer the inside temperature keeps on the high peak level of the outside temperature. The chapel experiences up to 5°C higher temperatures than outside.

This effect may have two reasons: In spring, the chapel is heated by sun irradiation. The roof has a low inclination supported directly on the vaults, with almost no buffering air layer between roof and vaults. There is only a 2 cm layer of insulation material in the roof. The masonry of the vaults is rather thin. Therefore the heat of the roof is easily conducted into the room. Besides, the dark color of the masonry enhances the



Fig. 23. Saint-Michel d'Aiguilhe (Le Puy), Chapel Saint-Michel / Ansicht der Michaelskapelle.

absorption of sun irradiation (Fig. 24). Secondly, in case of high tourist activities (up to 1000 visitors a day in August 2002) the visitors could increase the room temperature by their body heat. The peaks of the inner temperature are corresponding with the long term peaks of the outside temperature. It is obvious, that the high amplitudes of the outside temperature are reduced in the inside – especially in winter, when the chapel is closed. But in summer under the influence of the tourist activities, the room has less protection against the outside climatic conditions. As a consequence in summer the amplitudes of the temperature outside are experiencing a faster transfer towards the interior. The daily variations of room temperature and humidity are shown in Figure 20. From the beginning of November until March (when doors remain closed and there are no tourists), the daily variation does not exceed 1 or 2°C. In summer, when the chapel is open to the public, the daily temperature changes in the inside range from 2°C to 6°C. A maximum of 8°C was recorded during a period of rapid cooling in the week of the 22nd of September associated with a high number of visitors (up to 700 visitors a day on September 29).

In winter the relative humidity in the chapel is around 70%. The air in the room is drier than the air outside. At that time also the mean of the absolute humidity in the chapel is lower than the absolute humidity outside. The lower absolute humidity inside points to the option that the “dry conditions” in the chapel are supported by water absorption of the walls during that period of high humidity outside and low tourist activities.

Because of the dramatic temperature increase inside the chapel during the summer months, the relative humidity inside is reduced to a level of 50 to 60%. The value of the relative humidity keeps under the level of the humidity outside, but the absolute humidity is corresponding to the values of the air outside. The low relative humidity inside at that time is caused by the higher temperature-level in the chapel. Due to the open doors and windows in the summer season, the range of the daily change in relative humidity in the chapel is more than twice as high as in winter times (Fig. 20).

The daily amplitude of the relative humidity in the nave (blue) corresponds to the tourist activities. The daily amplitudes are about 5 to 15% in winter and 15–40% in summer (Fig. 20).

During relatively warm days around the new years eve 2002/2003 the chapel was frequently visited (Fig. 20). The visits correlate with an increase of absolute humidity air in the cold church through increased air exchange with the outside environment. Both relative humidity and temperature increase slightly during these periods, due to increased air exchange with the outdoor environment. Because the temperature inside reacts slowly, there are several dangerous approaches to the dew point temperature. On days without visitors (second and ninth day in the diagram) the room climate is not affected by the outer climate. In the case of lower outside temperatures, opening of the chapel could lead to frost effects within the wall. As in the case of Mogao grottoes, the impact of visitors on the moisture balance is recorded as an increased infiltration rate of the outside air. Therefore, the combination of rate of visitation and the outside climate has a large influence on the climatic conditions in St. Michel d'Aiguilhe.

A special feature of St Michel d'Aiguilhe, which influences the climatic conditions is both the degree of exposure to the weather and the open character of a highly absorbent masonry. All of the four moisture profiles within the walls, recorded in July 2002, show increasing water contents from the interior surface towards the core of the masonry. The water contents of the south-west-wall (BK1 and BK2) rise up to 4 Mass-%, the cores of the north-east-wall (BK3 and Bk4) even up to 13 M-% (Fig. 21). These water contents are in a range of 100% to 150% of the hygroscopic capacity (Fig. 22). Therefore, they cannot be adsorbed from the air in the chapel, but are the result of capillary water soaked through the wall. The driving rain and run-off water from the roof percolating over the facade are the most reasonable source. The significant differences between



Fig. 24. Saint-Michel d'Aiguilhe, Joint system of the basaltic tuff masonry / Michaelskapelle, Fugensystem des basaltischen Tuffmauerwerks.

N- and S-exposure can be attributed to faster drying on the South side during summer period. The weather data for Le Puy give an average of 200 degrees for the prevailing wind direction, which corresponds to WSW.¹³

Margrivial Opera House Bayreuth

Inaugurated in 1748 by Margravine Wilhelmine, the sister of Frederic the Great, the Margrivial Opera House in Bayreuth belongs to the outstanding baroque theatres in Europe. Constructed by the Galli Bibiena in the typical Italian classicistic baroque style, its interior decorations survived the centuries and several restoration attempts largely unaffected (Fig. 27).

The continuous use of the Opera House for theatre plays, concerts and other events was subject to a major discussion since the mid nineties of last century, leading to a long-term and systematic assessment of the climatic conditions. A condition survey on the polychrome and gilded wooden elements (Fig. 25) and the decorative paintings (Fig. 26) revealed an increase of damage with height inside the theatre.¹⁴

In the following years from 1997 to 2001 the climatic conditions were recorded in order to assess the stress generated by and through the regularly scheduled events. The aim was to establish better climate conditions for the decorated surfaces, with emphasis on the typical implications during the winter season.

Fig. 25. Bayreuth, The Margrivial Opera House, Interiors, detail: Fame / Markgräfliches Opernhaus, Innenausstattung, Detail: Fama.



Fig. 26. Bayreuth, The Margrivial Opera House, Ceiling paintings on canvas borders fixed by ancient nails / Markgräfliches Opernhaus, Deckengemälde auf Leinwand mit Randbefestigung durch historische Nagelungen.

An HVAC system by Fa. Landis & Gyr was introduced in the eighties, but soon this set-up had to be replaced by a second system. It functions by retrieving air from outside, if necessary mixed with the ambient air inside the Opera House, filtered, warmed or cooled, and reintroduced into the public area of the Opera House after filtering it, from special elements located in the floor.

Two climatic regimes control the opera house. On the one hand the museum regime, under which the HVAC system is started only when the temperature falls below 7°C or the relative humidity exceeds a certain threshold value. Humidity and temperature control is effected through a heater with a supplied air of 55% ± 10%. This is in accordance with generally accepted museum standards.¹⁵ The tolerated margin of ±10% RH however is relatively high. During the museum regime the auditorium and the stage area are separated by a steel curtain, which decouples the climatic conditions in both zones.

The theatre regime prevails 55% RH and constant temperature of 20°C. During the change from museum to theatre regime the temperature increase must not exceed 1 K/d. The relative humidity should be kept constant, while the maximum air supply is fixed to 20,000 m³/d.

The development in the amount of events in the Opera House is shown in Figure 28. Due to the 250th anniversary of the theatre a maximum amount of 72 events was reached in the season 1997/98. Especially in summer and autumn the density of events increased since 1996.

The heating for events during the cold winter season leads to the development of considerable temperature profiles with height as shown in Figure 30. This increase of surface temperatures is accompanied by a dangerous drop of RH below the safety margin of 45% correlating with the observed damage processes.

¹³ Meteonorm V4.0.

¹⁴ SCHWENKENBECHER, 1995.

¹⁵ THOMSON, 1986.

▷ Fig. 27. Bayreuth, The Margrivial Opera House, view on the prince's loge / Markgräfliches Opernhaus, Blick zur Fürstenloge.



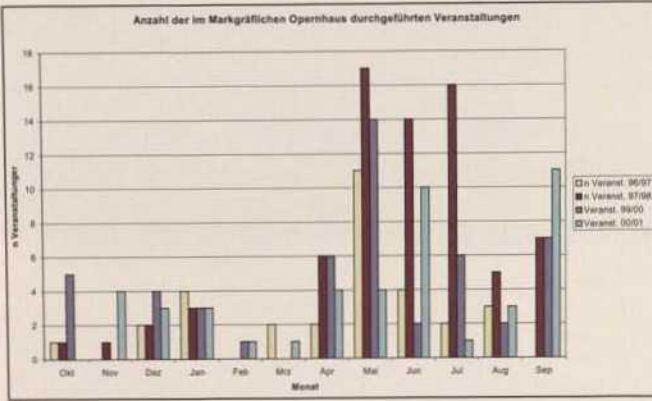


Fig. 28. Bayreuth, The Margravial Opera House: Number of events in the Opera House from 1996–2001 / Markgräfliches Opernhaus: Anzahl der Veranstaltungen zwischen 1996 und 2001.

As an example how single events can cause climatic stress to the interiors of the Opera House, relative and absolute humidity and temperature are shown for the days before and after the concert on the evening of January 23rd, 2000 in Figure 33.

The diagram shows the temperature (straight lines), the relative humidity (dotted thick lines) and the absolute humidity (straight thick lines) for various sensor positions (1: trumpet loge, 5: stage and 10 proscenium arch). In the time leading up to the event, the relative humidity is significantly too low around 40%. In a steep slope of heating the temperature in the theatre is increased within several hours for almost 10K to 20–23°C – in contradiction to the program which obliges to heating rates of max 1 K/day! Simultaneously the relative humidity drops to ca. 25%. It's not before the afternoon of the 24th that the extremely low and damaging humidity starts to normalize, combined with a fast drop of air temperature.

Until noon of the 23rd the absolute humidity in stage and auditorium is on the same level, with a higher temperature in the stage area. Just before noon temperature and absolute humidity drop in the stage area, probably due to an exchange with the outdoor environment (e.g. transport of instruments). At the same the heating in the auditorium takes place accompanied by a considerable height profile. After the concert, the temperature decreases exponentially. On the morning of the 24th, the thermal context between stage and auditorium is re-established

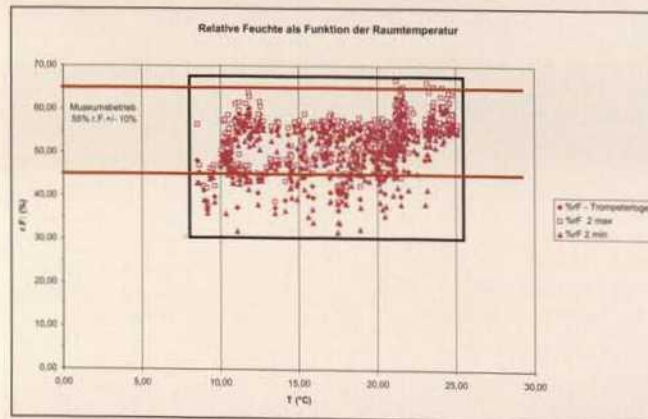


Fig. 29. Bayreuth, The Margravial Opera House: Range of relative humidity as a function of temperature in 1996/97 / Markgräfliches Opernhaus: Relative Feuchte als Funktion der Raumtemperatur während der Saison 1996/97.

lished by the opening of the steel curtain. Consequently, the theatre experiences a drastic cooling, while the stage zone is warmed up. The most obvious consequence is another drop of relative humidity, increasing with the height, by a drain of water vapour towards the dry stage area.

It is worth mentioning that the opening of the steel curtain not only allows for balancing the temperature, but also for a faster exchange of absolute humidity, which in this time of year is usually lower in the stage area. Therefore the drop of temperature in such critical phases may not be accompanied by an expected increase of relative humidity, but in the contrary, by a further detrimental drop.

A humidity release of approximately 40 g per person per hour can be assumed under most of the current usage conditions. During a concert of 2 hours duration and 550 visitors approx. 44 kg of water are introduced into the theatre. In the estimated volume of 6000 m³ the absolute humidity could hence increase

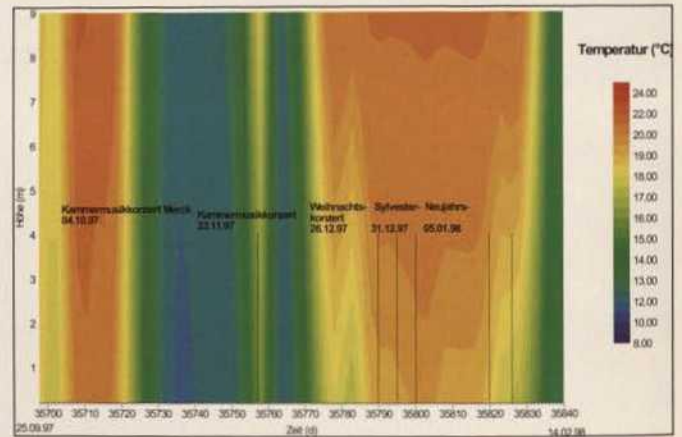


Fig. 30. Bayreuth, The Margravial Opera House: Temperature as a function of height, during winter 1997/98, shown as a function of time with indications for the events / Markgräfliches Opernhaus: Temperaturhöhenprofil während des Winters 1997/98 mit Hinweis auf einzelne Veranstaltungen.

for more than 7g/kg of dry air. However, this is not the case due to the high resorptivity of the surrounding walls and built in structures. The moisture input by the visitors of the concert is only visible in the form of spikes on top of a process which is controlled by other parameters, mainly the fast moisture

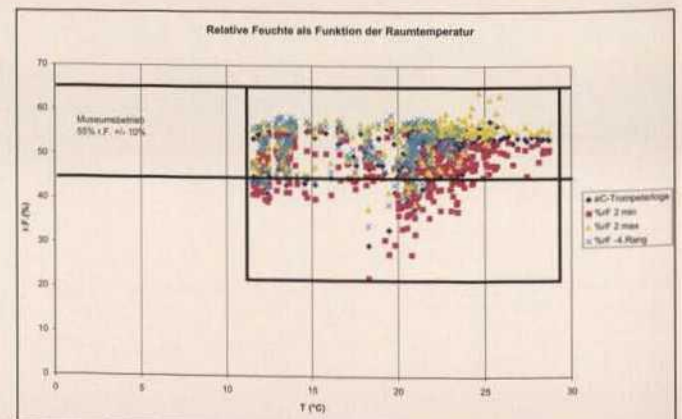


Fig. 31. Bayreuth, The Margravial Opera House: Range of relative humidity as a function of temperature in 1997/98 / Markgräfliches Opernhaus: Relative Feuchte als Funktion der Raumtemperatur während der Saison 1997/98.

exchange with the huge volume in the stage area, in dependency of the opening periods of the steel curtain.

Over the years, the stabilisation of the climatic conditions has been the aim of the project. The range of RH as a function of the air temperature in the Opera House is given for the years 1996–2001 in Figure 29 to Figure 34. The diagrams show that eventually in 2000/2001 (Fig. 34) the relative humidity could be stabilized within the desired corridor of $55 \pm 10\%$ RH. This was accompanied by significantly lower temperatures, which were reaching especially in the season 1997/98 high values of almost 30°C (Fig. 31).

The frequency of days on which the relative humidity fell below the minimal RH of 45% is given for all investigated seasons in Figure 35. During the last season (2000/2001), an important amelioration of the situation could be stated, after problems with the tuning of the HVAC system had led to a serious aggravation and a negative trend in the preceding years, where the RH fell short on 21%, 30%, and 27–58% (in 1999/2000 seasons, depending on the sensor location) of the respective period. The performance increase is attributed to subsequent maintenance of the HVAC system and a better tuning.

Significant daily humidity variations affect especially higher zones as the proscenium arch, more intensively during the winter season, for example in 2000 on more than 60% of the days in January (Fig. 37).

Over the years the climatic situation in the Opera House improved. Events of drastic drying or excessive change in relative humidity could be reduced. Most of the recorded RH values fall into the desired corridor of $55 \pm 10\%$. The proposed decrease in temperature during the theatre regime has shown favourable results. However, the increased humidity in the auditorium during the winter season increased also the condensation risks in surrounding building parts as the stair cases.

Conclusions

While assessing the potential for damage to artefacts or buildings, the frequency of relative humidity fluctuations has to be taken into account. Cycles, shorter in duration may still affect surfaces, where materials of different dilatations coefficients are combined and hence a significant amount of stress is generated at their interface. During relative humidity cycles, the drying of many

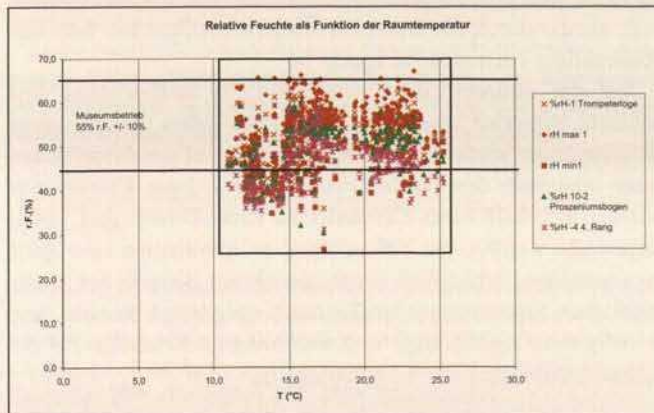


Fig. 32. Bayreuth, The Margravian Opera House: Range of relative humidity as a function of temperature in 1999/2000 / Markgräfliches Opernhaus: Relative Feuchte als Funktion der Raumtemperatur während der Saison 1999/2000.

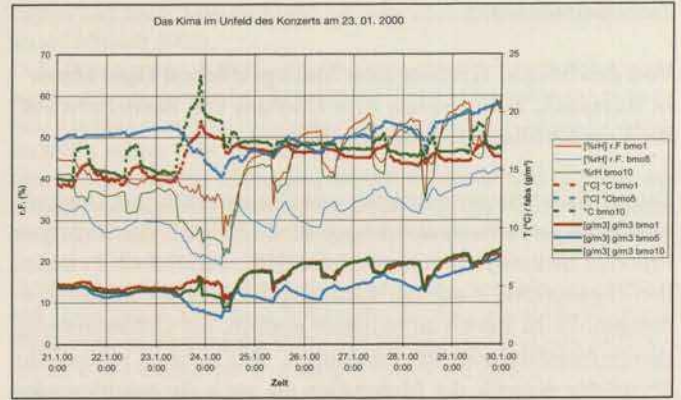


Fig. 33. Bayreuth, The Margravian Opera House: Climatic conditions before and after a concert on January, 23rd, 2000, (hourly recorded values) / Markgräfliches Opernhaus: Klimabedingungen im Umfeld eines Konzerts am 23. Januar 2000 (Stundenwerte).

materials takes place faster than the humidification process due to the mechanism of water transport in and out of the substrate. In the presence of hygroscopic salts in porous materials, quick relative humidity changes favour the non-equilibrium formation of salt crystals. This may have a greater damage potential than the equilibrium formation of salt crystals. Furthermore, the presence of hygroscopic salts in porous materials can counterbalance and even increase hygroscopic dilatation phenomena.

In spaces that are well isolated from the outside environment, impacts of visitors on their microenvironments are not only the accumulation of exhaled and perspired moisture that may be dangerous for objects but also an increased level of carbon dioxide that may compromise the visitors' safety and comfort. Opening of doors and windows, that are parts of a building envelope against the outside climate, may result in a larger infiltration of the outside humid air into the spaces than the moisture exhaled and perspired by visitors, when the outside climate is wet. The humidification of poorly insulated indoor space during dry and cold winter climate may cause a great risk of condensation on surfaces or inside of the building envelope. With these effects being difficult to control within a building, humidification should be minimized or avoided, where possible. Especially the case study of the Margravian Opera House has shown the importance of regular and independent control for the long-term stability of HVAC systems.

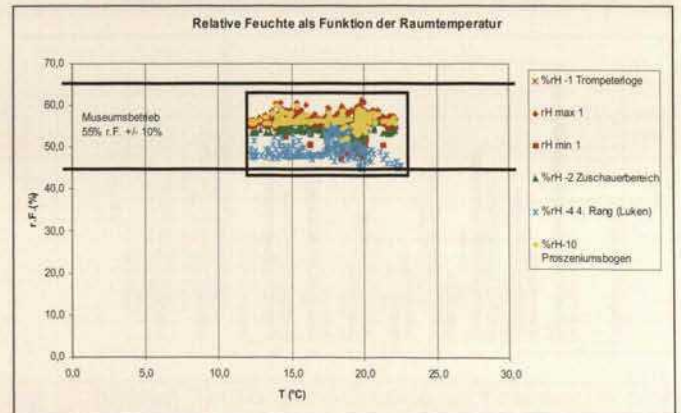


Fig. 34. Bayreuth, The Margravian Opera House: Range of relative humidity as a function of temperature in 2000/01 / Markgräfliches Opernhaus: Relative Feuchte als Funktion der Raumtemperatur während der Saison 2000/01.

Zusammenfassung

Von den Mogao Grotten zum Markgräflichen Opernhaus in Bayreuth. Fallbeispiele zum Einfluss von Besuchern auf die Feuchtebilanz historischer Räume

Die mögliche Beeinträchtigung von Kunstwerken und Denkmälern durch große Besuchermengen wird häufig als das wichtigste Problem diskutiert, wenn es darum geht, Prioritäten zwischen der Zugänglichkeit und der Erhaltung historischer Räume festzulegen. Es ist jedoch nicht immer einfach, die Größenordnung dieser Beeinflussung zu bestimmen. Wir müssen sowohl die chemische Kinetik der Materialien als auch die resultierenden Schadensprozesse in Ihrer Antwort auf Amplituden und Frequenz klimatischer Fluktuationen verstehen.

Die bedeutendste Auswirkung von Besuchern auf Kunstwerke in umgrenzten Räumen ist mit der Rolle des Menschen als Feuchtequelle verbunden. Abhängig von seinem Aktivitätsniveau setzt eine typische Person während des Besuchs in einem Museum oder einer archäologischen Stätte stündlich ca. 40–110 Gramm Wasser sowie 7–14 Liter CO₂ frei. Darüber hinaus bringen Besucher nicht nur weitere physiologische Produkte wie Hautpartikel oder Haare, sondern auch Textilfasern aus ihrer Kleidung in die Umwelt ein. Diese werden auf Kunstwerken und historischen Raumbooberflächen abgelagert, falls sie nicht unmittelbar nach außen entlüftet oder durch Filteranlagen in Klimatisierungssystemen entfernt werden.

In Räumen mit begrenztem Luftaustausch erlangt der CO₂-Ausstoß von Besuchern eine beträchtliche Bedeutung, da Sicherheit und Komfort der Besucher gefährdet sind. Diese Gefahr sinkt, wenn eine Infiltration von Außenluft besteht. Deshalb spielt das CO₂ eine wesentliche Rolle, wenn es um Artefakte in Höhlen oder Gräbern geht.

Was die Entstehung von Feuchte anbelangt, ist die Situation etwas anders. Hier beeinflussen Wände und Architekturoberflächen in Anhängigkeit von ihrer Porosität und Feuchtespeichercharakteristik entscheidend die Feuchtebilanz durch Adsorptions- und Desorptionsprozesse. Das Pufferpotential modernen Betons ist hier beispielsweise wesentlich geringer als das kalkgebundener Putze und Oberflächenelemente aus Holz in historischen Innenräumen. Daneben kann die äußere Umgebung nicht nur zur Abführung von hohen Feuchteniveaus beitragen, sondern auch selbst eine wichtige Feuchtequelle darstellen. Schließlich spielen kapillare Wassertransportprozesse durch Grund und Wände eine wesentliche Rolle für die Feuchtebalance im Innenraum.

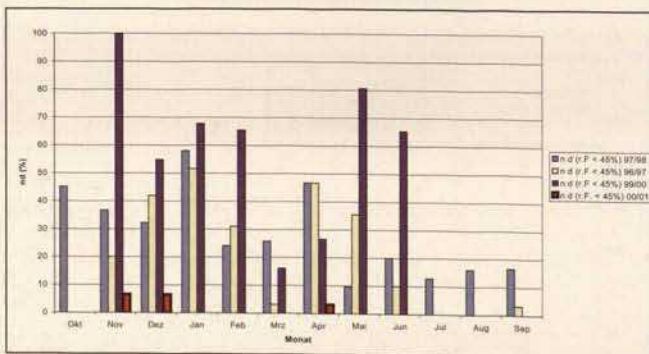


Fig. 35. Bayreuth, The Margravial Opera House: Percentage of days/a on which RH fell below the minimal RH (45%) for the seasons 1996 to 2001 / Markgräfliches Opernhaus: Prozentuale Anzahl von Tagen, an denen eine Unterschreitung der Mindestraumfeuchte von 45% registriert wurde (Saisonvergleich 1996–2001).

Um die Wirkung von Besuchern zu verstehen, müssen wir ihre Anzahl, die Dauer des Besuchs, ihr Aktivitätsniveau und die äußeren Wetterbedingungen aufzeichnen. Ebenso wichtig ist es festzustellen, ob ein mechanisches System wie Entfeuchter oder Air-Conditioner im gegebenen Raum installiert wurden, um dessen Mikroklima von der Umwelt abzukoppeln, oder ob weitere Anstrengungen unternommen wurden, die Infiltration der Außenluft zu kontrollieren.

Zu hohe Feuchte ist ein Hauptrisiko für mikrobiologische Schäden, z.B. durch Pilz- oder Bakterienwachstum. Es wird das mechanische Dilatationsverhalten von Erdmaterialien, Naturstein und Holz mit und ohne Salzbelastung als Funktion von Feuchteschwankungen beschrieben. Besondere Aufmerksamkeit verdienen kinetische Aspekte und die Abhängigkeit von der Zyklenfrequenz. An vier ausgewählten Beispielen, den Mogao-Grotten in China, dem Grabmal der Königin Nefertari in Luxor, Ägypten, der Kapelle Saint-Michel-d'Aiguilhe in Le Puy, Frankreich, sowie des Markgräflichen Opernhauses in Bayreuth wird versucht, den Einfluss der Besucher auf die klimatischen Bedingungen zu quantifizieren.

Für eine Einschätzung des Schadenspotentials von Feuchteschwankungen für Artefakte und Gebäude muss deren Frequenz berücksichtigt werden. Selbst kürzere Zyklen können Oberflächen belasten, in denen Materialien mit verschiedenen hygroskopischen Dilatationskoeffizienten kombiniert sind und an deren Kontaktfläche in der Folge eine bedeutende Belastung eintritt.

Während zyklischer Schwankungen der relativen Feuchte erfolgt aufgrund der unterschiedlichen Wassertransportmechanismen im Substrat die Trocknung vieler Materialien schneller als die Befeuchtung. In Gegenwart hygroskopischer Salze ist deren Kristallisation bei schnellen Wechseln der relativen Feuchte über den Deliqueszenzpunkt hinweg in Nicht-Gleichgewichtsformen favorisiert, denen ein größeres Schadenspotential als den Gleichgewichtsformen zugeschrieben wird. Weiterhin können hygroskopische Salze im Feuchtwechsel die hygroskopischen Dilatationsphänomene in porösen Substraten ausgleichen oder mit umgekehrtem Vorzeichen sogar verstärken.

In von der Umwelt isolierten Räumen beschränkt sich die Beeinträchtigung des Mikroumfelds durch Besucher nicht nur auf die Anreicherung der von ihnen freigesetzten Feuchte, die die Objekte bedroht, sondern auch auf einen Anstieg an Kohlendioxid, der die Sicherheit und das Wohlbefinden der Besucher gefährden kann. Das Öffnen von Türen und Fenstern, die Teile des Gebäudemantels zur Abschirmung des Außenklimas sind, führt zu einer wesentlich stärkeren Infiltration von feuchter Außenluft, als die durch die Besucher freigesetzte Feuchte, falls das Außenklima entsprechend feucht ist.

Auf der anderen Seite verursacht die Befeuchtung von schlecht isolierten Innenräumen während kalter und trockener Wintermonate große Kondensationsrisiken auf den Oberflächen oder innerhalb des Gebäudemantels. Da diese Effekte nur schwer innerhalb eines Gebäudes zu kontrollieren sind, sollte angestrebt werden, die Befeuchtung zu minimieren oder ganz zu vermeiden. Schließlich konnte gerade am Beispiel des Markgräflichen Opernhauses in Bayreuth aufgezeigt werden, wie wichtig eine regelmäßige und unabhängige Kontrolle für die Langzeitstabilität einer Klimaanlage ist.

¹⁶ Die Langzeitstudie begann im März 1998 mit 22 Schadstellen, die analog im Mittelformat (6 x 6 cm Diapositiv) fotografisch dokumentiert wurden (A. Bunz).

¹⁷ Zwischenbericht 2002 (S. Dinkelacker).



Fig. 36. Bayreuth, The Margravian Opera House: upper loge house, tempera painting on pine wood support, detail: wide loss of paint layers due to significant climatic fluctuations (after retouching) and new damage (still without retouching) / Markgräfliches Opernhaus, "Sichtklappe" des oberen Logenhauses, Temperamalerei auf Nadelholz, Detail: umfangreiche Malschichtverluste infolge der erheblichen Klimaschwankungen (mit Retuschen) und neue Schadstellen (noch ohne Retusche; 2005).

Anhang

Matthias Staschull

Überprüfung der Schadensprogression im Markgräflichen Opernhaus Bayreuth durch „Mikromonitoring“

Die Ursachen für zahlreiche Kleinstschäden an den Skulpturen und wandfesten Malereien des barocken Zuschauerraumes konnten mit den erheblichen Schwankungen des Raumklimas in Verbindung gebracht werden. Das relativ häufige Aufheizen und Abkühlen der sensiblen Raumschale wurde dahingehend reduziert, dass während der kritischen Jahreszeit, also von November bis Mai, nur wenige Veranstaltungen in sogenannten Zeitblöcken durch die Bayerische Schlösserverwaltung genehmigt wurden. Zudem wurde die vorhandene Klimaanlage aus den 1970er-Jahren ersetzt.

Trotz der Verbesserung der Klimatechnik um 1998 gelang eine Reduzierung von Schäden an der Raumschale nur in begrenztem Umfang. Zur Überprüfung einer weiteren Schadensprogression wurde ab 1998 ein „Mikromonitoring“ an bestimmten Stellen der Skulpturen und Malereien installiert.¹⁶ Eine Erweiterung bzw. Veränderung einiger Stellen erfolgte bei den Aktionen im November 1999 und im März 2002. Diese weiteren Aufnahmen und Beobachtungen unter gleichen Bedingungen in den folgenden Jahren brachten in Kurzfassung folgendes Resultat. „Auch nach 40 Monaten lässt sich im Zuschauerraum des Opernhauses eine Progression der Schäden eindeutig feststellen, allerdings in weitaus gemäßigerem Tempo als 1998.“¹⁷

Letzte fotografische Aufnahmen im Oktober 2005 (Fig. 36) ergaben, dass der Prozess einer „schleichenden Reduzierung“ des Kunstwerkes nicht aufgehalten, vielleicht jedoch in seiner Menge verringert werden konnte. Eine Weiterführung der Untersuchungen ist geplant.

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Abbildungsnachweis

Abb. 1, 23–26: Konservierung & Denkmalpflege Consulting, Olching (Dr. Stefan Simon); Abb. 11–18: Shin Maekawa, Los Angeles; Abb. 27: Bayerische Verwaltung der staatlichen Schlösser, Gärten und Seen, München (Foto: Klaus Frahm, Börsen); Abb. 36: Bayerische Verwaltung der staatlichen Schlösser, Gärten und Seen, München (Foto: Dr. Matthias Staschull); alle übrigen: S. Simon – S. Maekawa – R. Utz.

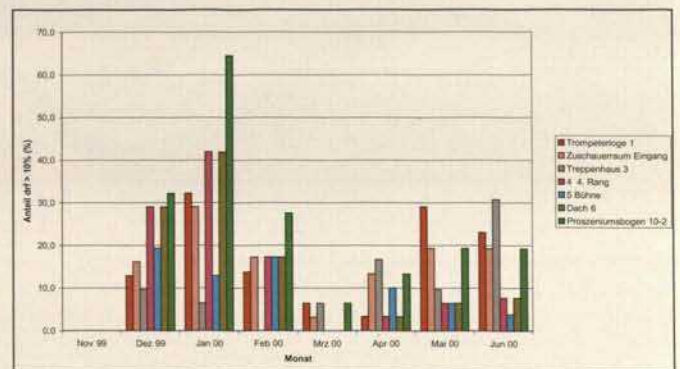


Fig. 37. Bayreuth, The Margravian Opera House: Frequency (% days/month) of humidity variations >10% for different sensor locations within the theatre during the season 1999/2000 / Markgräfliches Opernhaus: Prozentuale Häufigkeit (Tage/Monat) von Schwankungen der relativen Feuchte >10% an verschiedenen Sensorpositionen während der Saison 1999/2000.

