Groupe BIZOT Group

Handbook #1

ADOPTING THE BIZOT GREEN GUIDELINES

Last update: September 2023

This first handbook accompanies the ‘refresh Bizot Green Protocol’. It is intended to provide museum colleagues with evidence, tools and case studies to ease the adoption of the Bizot Green Guidelines and, more broadly, help museums to adopt climate control solutions that are safe for the objects and enable museums to reduce their energy consumption and carbon-emission.

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1. List of museums applying the Bizot guidelines

To be updated

- Art Gallery of New South Wales (since 2014)
- Art Gallery of Ontario
- CSMVS
- Guggenheim
- Louisiana Museum of Modern
- National Galleries of Scotland
- National Gallery Singapore
- National Gallery of Victoria
- Museum of Fine Arts Budapest
- Museum Nacional d'Art de Catalunya
- MoMA
- M+
- Ordrupgaard
- Rijksmuseum (since 2022)
- Tate
- Victoria and Albert Museum

2. The scientific data behind the guidelines

Note: This section of Handbook 1 summarizes the results of scientific research into the impact of environmental conditions on art collections. It is intended to provide substantive grounds for the practical implementation of the environmental guidelines set out in the Bizot Green Protocol.

It is based on the perspective of the Managing Collections Environments Initiative and is not intended to replace more comprehensive standards and guidelines that are well established in the cultural heritage field. Please send your comments to mlukomski@getty.edu and ccwinter@getty.edu

SCOPE

In recent years, there has been a growing emphasis on managing indoor environments in museum buildings to protect vulnerable art objects in a responsible manner, while also reducing energy use and carbon emissions. It is widely recognized that the museum building and its collections should be viewed as one system, and that significant energy savings can be achieved by changing the system operating algorithm and measures such as sealing the structure, improving insulation to reduce heat gain/loss, and optimizing ventilation rates. But interventions in the building are not always possible and it has been demonstrated that relaxing the parameters of temperature and humidity also produces a considerable reduction in energy consumption.

Research conducted since the 1990s has established a range of acceptable climatic conditions for objects. In general, elevated temperatures have been found to accelerate chemical degradation and, when paired with high relative humidity, over time increase the risk of biological attack. In practice, choice of temperature range for exhibition rooms is strongly limited by human comfort. On the other hand, research into the moisture response of materials has shown that museum collections can sustain greater variations in relative humidity than previously thought. This conclusion was reflected in the Bizot Green Protocol (2015), and the joint IIC and ICOM-CC declaration (IIC International Institute for Conservation of Historic and Artistic Works and ICOM-CC International Council of Museums - Committee for Conservation 2014).

Despite the establishment of these guidelines, their implementation has faced obstacles, including a belief that existing scientific knowledge did not fully explain the risks posed by temperature and humidity variations. In fact, this concern was already expressed in an explicit way in the text of joint IIC and ICOM-CC declaration:
‘The issue of collection and material environmental requirements is complex, and conservators/conservation scientists should actively seek to explain and unpack these complexities.’

This document intends to summarize the outcomes of scientific research and monitoring campaigns conducted since, providing general information on how conservation science understands the environmental effects on collections. It also highlights specific results, tools, and methods created to support the development of sustainable climate control strategies in museums. It is not a comprehensive guide. Much of the information presented can be found in ASHRAE Chapter 24, on the GCI website, on the CCI website, and other publicly available resources.

It is also important to highlight that the information and tools outlined in this document should be used within risk management approach. This involves identifying, evaluating, and prioritizing potential risks to cultural objects and heritage collections, and developing strategies to minimize those risks. Risks related to climate must be considered in relation to other risks and frequently do not pose the greatest risk to collections. When considering an environmental management strategy, it is important to take into account its financial, environmental, and access impacts, as well as the lifetime expectancy of the collections and an overall institutional preservation policy aligned with its mission.

ENVIRONMENTAL EFFECTS ON COLLECTIONS

BIOLOGICAL DAMAGE

Mold growth in museum environment can be a major problem for aesthetic and structural integrity of objects in collections. Mold disintegrates and/or discolors skin, leather, textiles, paper, as well as wood, paint, and glass. The germination and growth of mold on the surface of materials are caused by high relative humidity or dampness when the temperature is sufficiently high. The most comprehensive and conservative mold growth data came from the food research. Occurrences of microscopic mold were reported at a relative humidity as low as 60% (Ohtsuki 1990; Strang 2013), defining a conservative limit for preventing mold growth on any material, at any temperature.

A systematic study on materials inoculated with a mixture of mold species resulted in defining combination of humidity, temperature and time needed to observe mold growth. For example, mold growth will become visible on highly susceptible materials after 3 months at 70% RH or after 1 week at 85% RH. A stable RH in a ‘dangerous zone’ is not better than fluctuating one. Periodic drops of humidity may be beneficial since they reset the mold growth clock back to zero.

The conditions mentioned above are very conservative. Experimental investigations, on which they were based, involved highly sensitive materials already contaminated by mold spores. Most museum objects are less vulnerable to mold growth. There are also many examples of collections exposed to high humidity in which mold growth is not observed (Maekawa, Beltran, and Henry 2015).

Conclusions: the limit of 60 RH at room temperature can be considered completely safe from the point of view of the risk of mold growth. In practice, mold growth should not be expected even at much higher humidity, especially when the humidity drops periodically below 60RH, a good air circulation is maintained, and regular inspections and dusting is performed.

Insect infestation is another manifestation of biological attack – material-specific and potentially very damaging to museum collections. There are relatively few experimental data on the relationship between the risk of insect infestation and climate parameters. However, it is well documented that below 15°C, insects that can damage cultural heritage collections become sluggish and do not fly, limiting the risk of infestation spreading. Also, low relative humidity limits pest risk because eggs and larvae are sensitive to dehydration.

Conclusions: there are no studies showing that moderate variation of humidity in the mid-range are increasing risk of insect infestation in museum collections. High temperature (especially at high relative humidity) is problematic since it increases insect's metabolism and speeds up their reproduction cycle.

CHEMICAL DAMAGE

The deterioration of heritage materials that are chemically unstable can cause a loss of mechanical strength and aesthetic quality of museum objects. Certain materials commonly used by artists in the latter half of the 19th century and beyond, such as paper, photographic materials, rubber, and many plastics, are particularly prone to degradation in specific conditions, and can deteriorate within decades. Since the rapid decay of organic materials is driven mostly by acid hydrolysis, relative humidity is an important parameter. However, temperature plays a much more critical role. This damage mechanism is not limited to materials that are acidic from the beginning but also materials such as textiles, paper and leather which become acidic after exposure to certain internal and external pollutants. Also, atmospheric pollutants (such as sulfur and nitrogen oxides, as well as natural agents such as ozone) can accelerate the chemical degradation of materials. Their influence can be evaluated using specific tools, such as a calculator developed within the European project MEMORI (Grøntoft et al. 2016).

The consensus is that the rate of acidic hydrolysis is a product of three factors: acidity factor, a temperature factor, and a relative humidity factor. There are currently three models that calculate the rate of decay, or expected lifetime, for a range of low stability materials as a function of temperature and relative humidity. The first model elaborated by the Image Permanence Institute defines Preservation Index based on the study of chemical degradation of cellulose acetate, a polymer present in most film materials (Reilly 1995). The second model, developed by (Michalski 2000) uses data from degradation of paper, film and dyes and is considered applicable to a broad category of low-stability organic materials. The third model of (Strlič et al. 2015) is derived from a review of data on paper and is applicable to wood pulp-based papers post 1850. These models can be used to predict the expected lifetime of materials relative to the lifetime at room conditions: 20°C and 50 RH. The differences in the results obtained with the three models are negligible between 20%

and 60% RH, so any of these models can be used within this range and will give the same practical answers.

Calculations for the temperature and humidity range of the BIZOT green protocol give the following results: setting the relative humidity at 60% RH and the temperature at 20°C reduces the expected lifetime for chemically unstable objects to 0.75 relative to the lifetime at room conditions 20°C, 50% RH, while setting 40% RH at 20°C increases the expected lifetime to 1.35. The results are much more dramatic for temperature: maintaining 25°C in the gallery at 50% RH halves the expected lifetime (0.5), while maintaining 16°C at 50% RH extends the lifetime to 1.7. For the unstable climatic conditions, including unexpected events and seasonal fluctuations, estimates can assume a simple linear dependence on relative humidity: for instance, if half the year is at 40% RH and half at 60% RH, then the effective annual relative humidity is the average: 50 RH. Temperature dependence, however, is far from linear, and averages cannot be used. For unstable temperature conditions, an accurate calculation should be carried out using the most adequate of the three models described or other tools such as the HERIe (Kozłowski et al. 2019).

Lower temperature reduces the rate of all forms of chemical reactions. For relative humidity, however, there are some critical levels which should not be crossed for certain specimens and artefacts. At specific relative humidity, some minerals may hydrate, dehydrate, or deliquesce. When they are part of porous stone, a corroded metal, or a natural history specimen, these minerals cause disintegration of the object. Specific critical relative humidity values are known for many minerals in natural history collections (Waller 2013). Metals present in museum collections, particularly bronzes, have a complex chemistry of corrosion, with several critical relative humidity values. While there is no universal safe humidity range for metal objects it is beneficial to keep relative humidity at low levels. Studies have shown that above 75 RH rapid acceleration of corrosion and subsequent serious damage should be expected. Glass collections can also be sensitive to moisture, as unstable glass can contain materials prone to deliquescence. For such collections stable 40 RH is recommended (Koob et al. 2018).

Conclusions:

Both temperature and relative humidity play a role in the chemical degradation of museum objects, and generally the values of these parameters are more important than their variability. While increasing temperature accelerates rate of all chemical reactions and the resulting degradation processes, relative humidity plays complex role. There are objects in museum collections that require specific relative humidity conditions. The collection can be organized by identifying the sensitive objects and strategically placing them in rooms with the desired conditions. For smaller objects, it is possible to use microclimatic solutions such as small containers or display cases with controlled relative humidity.

Changes of humidity within 40-60 RH range have much smaller effect on expected lifetime of chemically unstable objects than the temperature variations. Although the temperature range proposed in BIZOT Green protocol is relatively narrow and dictated by human comfort, the choice of temperature in the gallery is not without significance for objects made of chemically unstable materials. A practical rule of thumb for the benefits of lower temperatures is that each 5°C reduction doubles the lifetime of chemically unstable objects.

MECHANICAL DAMAGE

Mechanical damage in museum objects may result from low or fluctuating temperature and relative humidity. The most sensitive to climatic variations are hygroscopic materials such as wood, paper, leather, or parchment as well as components of decorative layers such as animal glue, paints, or cellulose acetate. These materials are present in panel paintings, furniture, sculptures, or decorative objects – valuable and common types of artefacts in museum collections. In most cases, it is the desire to protect these objects from any physical change that leads to very strict climate control in exhibition and storage spaces. Climate-induced damage in objects happens when the dimensional response of material (swelling and shrinking) resulting from the sorption and desorption of water vapor is restrained. Parts of the object can be fully restrained by another, rigid and immobile component (e.g. panel in rigid frame); partially restrained when connected to a component with a different coefficient of expansion (e.g. paint layer on wooden support); or self-restrained when it has different coefficient of expansion in different directions (radial, tangential, or longitudinal directions in wood) or is experiencing a gradient in moisture or temperature over its volume (e.g. bulky wooden sculpture). Restrained swelling and shrinking causes stress to build up in the material, and when the stress exceeds a critical level, the material can permanently deform or crack, and in the case of composites, delamination can occur.

The risk of mechanical damage depends not only on the amplitude of temperature and relative humidity variations, but also on their level. This is because the properties of materials vary at different temperature and humidity levels. At low temperatures and low relative humidity materials exhibit ‘glassy’ behavior with small tolerable strains, whereas at high temperatures and high relative humidity they are in ‘rubbery state’ with large tolerable strains. Very common in museum collections, animal glue based materials (gesso, paper size, gelatin) experience transition from a ‘glassy’ (hard and strong) to a ‘rubbery’ (week and sticky) state in high relative humidity (>75% RH) or higher temperature (>35^{o}C) (Karpowicz 1989; Krzemień et al. 2016; Mecklenburg 1991; Michalski 1991; Bridarolli et al. 2022). In rubbery state these materials easily deform and are far less likely to break than in mid-range relative humidity at room temperature. For most paints, transition to glassy state is happening at lower than room temperatures, in the range of 10 to 0^{o}C (Hartin et al. 2015; Hagan 2017; Mecklenburg and Tumosa 1991). Paints are in ‘rubbery state’ in room temperature (flexible but tough) and become brittle and fragile in low temperatures. Wood, on the other hand, can be more easily deformed over 75% RH and may crack if constrained (e.g. as a part of cabinet joint) during its return to a middle or low humidity.

Another factor to considered when assessing risk of climate induced physical damage is a rate of temperature and humidity change. The dimensional response of a material in interaction with temperature and moisture vapor is not instantaneous. Water diffusion in material depends upon the material’s type, its density/porosity, moisture content, the speed at which the air is moving around the material. It is also strongly influenced by temperature: increasing and decreasing with increases and decreases of temperature, respectively. Also the shape and size of an object is crucial for understanding its time response. A thick, bulky object will respond more slowly to a change of relative humidity in the air than thin object made with the same material. At a given depth from the surface they will respond at the same rate; however, it will take longer for a thicker object to reach moisture equilibrium with surrounding air. Furthermore, objects coated with a layer with lower vapor permeability will exchange moisture vapor with the surrounding air more slowly than uncoated objects and thus will be less effected by RH fluctuations.

Fast changes in RH induce stronger internal moisture gradients, and hence higher stresses, than slow changes. In turn, the slow RH variations of the same magnitude induce a more significant overall dimensional response of an object which - when externally restrained - induces higher damage risk and attain its maximum at the largest 'equilibrium' dimensional response. As a result, worst-case conditions can be achieved regardless of the rate of RH change, and it is the magnitude of the RH change, not the rate of change, that determines the risk of damage.

A further clarification is necessary at this point. It is known that the strain at failure for heritage materials such as acrylic or oil paints decreases with increasing strain rate (see, e.g. (Hagan 2017)). For this reason, larger long-term (seasonal) variations in temperature and humidity can be considered for sensitive collections. On the other side, based on Hagan's work, 'fast' changes of the indoor climate – for example, ± 10% in one hour - bring only a slight reduction i.e. 20% in the strain at failure compared to change occurring in 1 day for lead white oil paint. The change is larger, approximately 40% ?reduction? for more ductile zinc white oil paint, but brittle, not ductile materials are more vulnerable to physical damage, and they dictate climate control in museums.

Finally, no well-documented case studies or collection observations can be found in the conservation literature in which damage from fast RH fluctuations within the BIZOT Green Protocol range was demonstrated. Such demonstrations would possibly facilitate - in future - selection of exceptional objects which according to the BIZOT statement 'require specific and tighter RH control, depending on the materials, condition, and history of the work of art'.

All materials respond also dimensionally to changes in temperature. In most hygroscopic materials, the thermal conductivity is a few orders of magnitude higher than that of water vapor, and the dimensional response caused by temperature variations is much smaller than response caused by relative humidity variations. Therefore, the response to moderate temperature variations occurring in real-world display conditions should be considered instantaneous and the risk related with thermally induced dimensional change - negligible.

The first models assessing the risk of physical damage to susceptible museum objects were developed in the early 1990s. They used realistic mechanical properties of painting materials and assumed that materials were uniformly restrained (Erhardt and Mecklenburg 1994; Erlebacher et al. 1992; Mecklenburg and Tumosa 1991; Mecklenburg 2005; Mecklenburg, Tumosa, and Erhardt 1998; Michalski 1991; 1993). Results show that approximately 15 RH fluctuations around 50 RH are within elastic limit of materials and should be considered safe. Similar range of safe RH was obtained by finite element modeling for bulky wooden objects (wooden sculptures) (Jakieła, Bratasz, and Kozłowski 2008; Soboń and Bratasz 2022), for delamination in paint (Tantideeravit et al. 2013) and for historic textiles (Bratasz et al. 2015) - the last three works analyzed the impact of cyclically recurring environmental loads.

Much research has been done over the past decade to further refine these models and quantify the behavior of the unique composite structure of art objects made of water-sensitive materials. The main criticisms of existing models stemmed from the fact that, because samples of historic materials are too small for mechanical testing, the models are using material properties of mock-ups rather than historic materials themselves. To address this problem systematic research program was initiated at the Getty Conservation Institute, focused on micromechanical characterization of historic paints – materials particularly difficult to mimic in laboratory or conservation studio (Łukomski, Bridarolli, and Fujisawa 2022). In addition, climate-induced damage to wood (Luimes and Suiker 2021; Konopka and Kaliske 2022) and moisture-induced crack initiation in paint layers (Bosco, Suiker, and Fleck 2021) have been analyzed using fracture modeling, the latter also for paints degraded by metal soap formation (Eumelen et al. 2023). Recently, within the frame of European project Collection Care full-scale 3D FEM models of canvas paintings was developed to analyze spatial distribution of stress in paintings under desiccation and possible crack formation among different compositions of material layers (Janas et al. 2022; Lee et al. 2022).

All the models created so far show that the risk of climate-induced damage depends on the state of preservation of the object as well as the residual stresses between the various materials and components of the object, which can be present even under stable climatic conditions. The first problem was recently addressed by (Bratasz and Vaziri Sereshk 2018) - they demonstrated, that in the case of paintings, the fully developped cracquelure reduces sensitivity of paint layers to changes in humidity. The importance of residual stresses in animal-based adhesives (components of sizing canvases, furniture joints, but also paint layers) is well known, but quantifying their effect on the cracking process requires further research and is currently being investigated by various research groups, including the Getty Conservation Institute.

Summarizing, research conducted over the past decade using more detailed material data and more complex models has given us a good understanding of the failure mechanisms and critical conditions leading to physical damage of various types of museum artifacts. There is general agreement that sensitive museum objects can tolerate fluctuations of ±10 RH, whereas variations greater than ±20 RH result in a rapidly increasing risk of fracture.

Mechanical models quantifying the risk of climate-induced damage, have been extensively validated by monitoring adequate types of objects (either historic or mockups). Hover, if there are doubts about their applicability for particular collection or specific materials, the concept of ‘proofed fluctuation’ can be used to further inform the choice of climate control strategy. The concept is based on observation that restrained components that have already fractured because of an excessive fluctuation in the past will not fracture further until a fluctuation exceeds historic (‘proofed’) fluctuation (Michalski 2014; 1993; 2013). Consequently, for objects that have ‘acclimatized’ to the environment within which they have been preserved for a long time, the safe range of humidity is determined by the largest past RH fluctuations. It is generally accepted that the risk of physical damage beyond that already accumulated in the past is extremely low, as long as fluctuations do not exceed the historic climate (Michalski 2014).

The ‘proofed fluctuation’ concept is much more than just theoretical hypothesis. It was confirmed by many observations and studies of historic objects. For example, Acoustic Emission (AE) measuring campaign performed by (Strojecki et al. 2014) showed only microscopic increase of damage in already visibly cracked XVIII wooden wardrobe in unstable climate (20% to 65% RH short term, 30% to 50% RH 30-day average). Similar results were obtained in experimental program, implemented by the Managing Collection Environments Initiative at the Getty Conservation Institute (Łukomski et al. 2018). Observed lack of AE response for objects (kept previously in uncontrolled environment) exposed to increasingly wide humidity variations clearly supported the ‘proofed fluctuation’ concept. The concept was further demonstrated by the permanent deformation of the newly constructed panel when exposed to 20% RH, and the fact that subsequent exposure to 20% RH did not result in increased deformation. An important evidence was collected by researchers and conservators from the Rijksmuseum. (van Duin 2013) reported that humidity in the rage of 20-30 RH resulted in documented damage (new hairlike crack on the surface of seventeenth-century marquetry cabinet door) but also stated that this was an exception: most furniture in the conservation studio did not suffer during these dry conditions and in milder weather they never observed any damage. (Oreszczyn, Cassar, and Fernandez 1994) showed that there was no visible damage differences between collections in historic houses with ‘improved’ climate control and those without any.

The implications of the ‘proven fluctuation’ concept for designing climate control in museums are hard to overestimate. Most of art objects before entering climate-controlled museum buildings were exposed and effected by natural climates. For such objects improving climate control beyond the historic pattern cannot be easily justified based on mechanical risks. The exception are new and recently restored objects, not exposed previously to broader climatic fluctuations, or objects for which damage progress is observed even in very strictly controlled climatic conditions.

Conclusions: Often, the strict control of temperature and humidity fluctuations in museums is dictated by the desire to avoid climate-induced physical damage to art objects. However, scientific research conducted over the last three decades has concluded that sensitive museum objects can tolerate fluctuations of ±10 RH, while variations greater than ±20 RH result in a rapidly increasing risk of damage. The moderate temperature variations occurring in real-world display conditions pose negligible risk of physical damage to collections. Practical decisions about level of climate control for collections can also be informed by ‘proofed fluctuation’ concept. However, this requires knowledge of the historical climate and ensuring that the objects have acclimatized to it. In practice, this may call for monitoring the development of damage for particularly sensitive objects, those with an unknown climatic history or conserved objects that have not been subjected to climate variations

MONITORING CLIMATE-INDUCED PHYSICAL CHANGES OF ART OBJECTS

As discussed above, heritage science has developed two general approaches to inform climate specifications for museum collections at risk of physical damage. First is based on analysis of the physical response of materials and objects to relative humidity and temperature fluctuations, the second on the analysis of historical climates to which the objects have ‘acclimatized’. These two approaches have limited predictive power for objects made of unknown or under-studied materials, or for objects with too short or unknown histories for which it is uncertain whether acclimatization has taken place. Relaxing climatic specification for collections containing such objects can still be achieved if the preservation state of collection is monitored, preferably using highly sensitive, non-invasive techniques allowing caregivers to modify climate control strategy before unacceptable changes of objects are observed.

The most easily available and affordable technique is photography. It allows to compare changes in surface of the object and, if camera is positioned properly, also its global deformation. Macrophotography can be used to focus on details (such as tips of cracks and paint flakes) and time laps photography can help to trace development of cracking or deformation in time. Photography can be routinely taken in gallery and storage. The drawback is the difficulty to reproduce conditions during taking photos (camera position, distance, light). Also, the use of time laps photography requires a permanent camera and light installation, which for many applications may not be acceptable. Photography can be also used for capturing detail shape of the object (photogrammetry) but 3D scanning can be more efficient for such measurements, especially that structural light scanners recently become significantly less expensive, and many museums has access to them. Measurements with handheld scanner can be performed within the minutes (especially that it is not necessary to capture all object but only shape of interest) with accuracy of point measurements better than 1mm. Such measurements repeated in constant intervals can capture permanent deformation of the object or its part. The main disadvantage of both photography and 3D scanners is than results are obtained in intervals and shortening these intervals would make measurements very labor intensive and potentially obtrusive. For monitoring climate induced deformation one can also use strain gauges utilizing resistance foil or Fiber Bragg Gratings. They provide continuous measurement of surface deformation in real time. Strain gauges can be extremely sensitive, and as such able to trace response of the object to climatic fluctuations. However, they need to be attached to the surface and information is coming only from the point of contact. Effective evaluation of permanent deformation would require many such sensors, which may be very difficult to implement practically.

Particularly interesting for monitoring collections are full field measuring techniques capable of detecting structural defects of materials. Thermography is one of such techniques. It is fast, non-invasive, and allows heterogeneity and defects of materials located under the surface to be detected. During the measurements, temperature of the surface is increased using lamp or warm air. Losses in the material structure and surface delamination of the pictorial layer create barriers to the flow of the heat and as a result engender warmer areas on the examined surface. Thermographic images, showing a map of the damage areas, can be collected periodically to monitor changes in object caused by climatic conditions. Thermography is an active method, requiring subtle heating of the surface. Thermographic cameras are widely available, however, it is important to keep in mind that the quality of measurements strongly depends on spatial resolution of used camera, so proper choice of monitoring equipment is of crucial importance. The strength of the signal depends on the degree of surface heating, and depth on which damaged area is located below the surface. In some cases, thermographic maps can be difficult to interpret (less heat conductive layer may be mistaken with delamination) especially when heating of the surface is not uniform.

Very precise information about the state of preservation of the pictorial layer can be obtained by more complex, optical techniques - the most common are Digital Image Correlation (DIC) and Digital Speckle Pattern Interferometry (DSPI). Both can register micrometer dimensional changes of the surface induced by heat, load or vibration and associate them with flaws of decorative layers. DSPI is particularly useful for analysis of surfaces of art objects. It is full-field interferometric technique based on recording and analyzing laser light scattered by examined surface. It can detect and map micro damages (well before they are discernible visually), and when sound-induced excitation is used, delamination of paint layer can be unequivocally distinguished from inhomogeneities of paint layer itself (task inherently difficult for thermography and DSPI with thermal excitation). The method is portable and extremely sensitive, but its operation and data analysis require certain level of technical knowledge and experience.

One of the most promising monitoring methods suitable for the direct and continuous monitoring of physical change in cultural heritage objects is Acoustic Emission (AE). The technique was introduced to the field in the late 1990s and has been consistently used by several research groups to trace micro-fracture in art objects exposed to potentially harmful conditions. It consists in measuring ultrasound waves which are generated during the brittle cracking of the material. These waves propagate through the material and are recorded by piezoelectric sensors positioned on their surfaces. AE technique is robust and highly sensitive, capable of operating in harsh environments and detecting crack initiation and growth at a micrometrical scale. A number of conservation science laboratories have incorporated AE as an analytical method to elucidate and quantify damage in artistic material. Museums have also shown increasing interest in AE due to its ability to support assessments of new, existing, and modified climate control strategies in the context of collection risk, with successful applications at the National Museum in Krakow (Poland), the Getty Museum (Los Angeles, USA), the Victoria & Albert Museum (London, UK), the National Trust (UK) and national

Gallery of Victoria (Australia). One of the obstacles in the widespread application of AE monitoring in cultural heritage is related to the cost of hardware and the need to train staff on the processing and interpreting AE data. However, in recent years, the expanding use of AE in cultural heritage has initiated the development of standard measurement and data analysis protocols that can more efficiently develop the capabilities of non-specialist staff and expand the AE user community.

In summary, there are various, well developed, and extensively tested techniques available for those who would like to monitor physical response of objects in collections to climatic variations. These methods are capable of detecting different damage phenomena, they differ in costs, sensitivity, repeatability and their application may require either high or low level of technical knowledge. Most of those techniques can be effectively used to evaluate risk related with existing climate control strategy, and the most sensitive of them can act as an early warning system. When designing monitoring campaign, one should choose technique (or suite of techniques) most sensitive to anticipated damage phenomena, but also one which can be effectively operated within financial and organizational boundaries of the institution. The choice of objects for monitoring is a critical decision to be made. They need to be representative for the collection, and not necessary the most vulnerable ones. It should be assumed that the most susceptible objects may require special accommodations (sealed or climate-controlled boxes or vitrines) and should not dictate climate requirements for entire collection.

TOOLS SUPPORTING the DEVELOPMENT OF SUSTAINABLE CLIMATE CONTROL STRATEGIES

The use of environmental data analysis tools can support the sustainable management of cultural heritage collections. Such tools can provide users with an improved understanding of the collection environment, quantitatively relate the risk of damage to environmental impacts, and given training, be used by conservation professionals and decision makers for heritage buildings with collections. Science-based degradation models and damage functions become useful for practitioners when they are incorporated into institutional, national, or international guidelines and standards. BS 4971:2017, BS EN 16893:2018, the AICCM Environmental Guidelines (2018), and the 2019 ASHRAE chapter on Museums, Galleries, Archives, and Libraries are examples of recently updated guideline that can be used by collection institutions to help develop climate control strategies for storage and exhibition spaces.

However, in many cases, the direct application of guidelines may not be fully satisfactory. Degradation models offer a high level of detail in defining deterioration processes, selecting materials and construction types of affected objects, and defining the object's preservation state. They also allow one to predict object response for specific interior climate conditions. This level of detail goes beyond what comprehensive guidelines on the museum environment can offer. Therefore, many scientific groups have chosen to focus on the development of data-based predictive tools that reflect the nuances of degradation models and can be applied by practitioners.

A number of data analysis tools focus on improving our understanding of the museum environment. One example is the GCI Excel Tools (2021) that seeks to statistically describe and visualize the climatic conditions in an exhibition or storage space. Humidity ratio and dew point temperature are calculated from concurrent temperature and relative humidity data, and statistics include moving average, moving range, and percentiles. The data is then visualized by time series, probability distribution plots, and psychrometric charts, with each providing a different perspective on the environment. This and other similar tools can be useful for anyone who seeks to compare their environment with those described in standards and guidelines. Additionally, this can help coalesce discussion about the museum environment by the multi-disciplinary stakeholders and decision-makers who have varying levels of expertise on the topic.

Another category of digital tools is dedicated to predicting change in art objects by applying damage functions for specific classes of objects and for given climate histories (as defined by the user). An overview of select available tools analyzing the risk of climate-induced physical damage, light damage, and chemical and biological degradation can be found in (Cosaert et al. 2022), (table 5.1). This publication also presents more general tools dedicated to the risk analysis of museum collections, taking into account the combination of different agents of deterioration. Additional information about existing decision-making digital tools in preventive conservation can be found on webpages of heritage institutions involved in their development, including the GCI’s Managing Collection Environments (MCE) Initiative, Canadian Conservation Institute, University College London’s Institute for Preventive Conservation, Image Permanence Institute, and more.

It is hard to overestimate the potential impact of using digital tools in preventive conservation. At the same time, it is understood that these tools need to be properly introduced to practitioners. Training and didactic material on new and existing tools, as well as forums for data analysis (e.g., ConCode) should be readily available on the internet and presented at conferences. Workshops have also been developed that aim to train users of digital tools, including a workshop series on decision-making digital tools by IPERION HS (Integrating Platforms for the European Research Infrastructure on Heritage Science) or the GCI’s MCE workshops on Facilitating Decision-making Through Analysis of Temperature and Relative Humidity Data. Training opportunities are important for several reasons. Workshops familiarize new users with capabilities of digital tools and update already advanced users with changes and new functionalities introduced by developers. Exposure to multiple tools and increasing familiarity with their capabilities helps users build a "toolbox" from which to select the most appropriate tools for a variety of scenarios. Beyond the tools themselves, training offers participants an opportunity to begin development of a network through which information and experiences can be exchanged between users and tool developers; this allows participants to learn how others have used data analysis to support their environmental aims and may potentially foster more user-oriented tool development.

In summary, there exists a wide range of digital tools supporting decision-making in the management of museum environments. Most are freely available and supported by research groups working on modeling climate-induced damage for collections. Digital tools offer a higher level of detail than general environmental guidelines, but require investment of staff time and effort to use them effectively. However, they provide heritage professionals with a means of improving their understanding of climate-induced risk for collections that, when combined with collection monitoring and use of recent environmental guidance, can support more sustainable museum practice.

CONCLUSIONS

Since the publication of the Bizot Green Protocol in 2015, there has been a growing recognition that the climate crisis is one of the most significant threats facing the world today. Urgent action is required from the cultural heritage sector to lead the way in addressing this issue. At the same time, extensive research has been conducted to unpack the complexities of material behavior and environmental requirements. The current understanding provides ample evidence that adopting broader environmental parameters does not compromise the safety of most collections.

Scientific evidence derived from experiments, observations, and field campaigns demonstrates that museum collections survive exceptionally well in climatic conditions that are much wider than traditionally assumed. Practitioners can use user-friendly models and predictive tools developed for the cultural heritage sector to realistically evaluate the risk of damage posed by temperature and relative humidity for specific collections. These models can also help to identify particularly sensitive objects that can be separated from the general collection and handled with tailored solutions, without the need to apply narrow parameters for the whole collection.

While we argue that the risk posed to collections by temperature and relative humidity variations within the Bizot parameters is minimal for the majority of collections, it is also important to state clearly that the numbers 40-60% relative humidity and 16-25°C temperature range with 10% daily variation do not have any fundamental meaning from a scientific point of view. Rather, they represented numbers that seemed reasonably acceptable ten years ago. We propose that they should be viewed as a starting point for implementing sustainable strategies of environmental management. In other words, we do not advocate for the replacement of one prescriptive solution (50 ± 5% RH, 21±2°C) with another (40-60% RH, 16-25°C). Instead, we advocate for a more nuanced determination of environmental parameters that is based on the preservation needs of the objects, as informed by scientific research and experience, and the sustainability goals of the institution.

For such an endeavor, it is fundamental that institutions adopt a risk management approach, replacing the traditional focus on avoiding minor risks at all costs that normally have great financial and environmental impact. This transition will be easier if a multidisciplinary approach involving all appropriate stakeholders, such as engineers, architects, facility managers, security staff, administrators, archivists, collections managers, conservators, heritage scientists, curators, and registrars, is adopted as well.

Bibliography for guidelines

- Bosco, Emanuela, Akke SJ Suiker, and Norman A Fleck. 2021. Moisture-induced cracking in a flexural bilayer with application to historical paintings. Theoretical and Applied Fracture Mechanics 112: 102779.
- Bratasz, Łukasz, M Łukomski, A Klisińska-Kopacz, Witold Zawadzki, Krzysztof Dzierżęga, Marcin Bartosik, Jan Sobczyk, FJ Lennard, and Roman Kozłowski. 2015. Risk of Climate-Induced Damage in Historic Textiles. Strain 51 (1): 78-88.
- Bratasz, Łukasz, and Mohammad Reza Vaziri Sereshk. 2018. Crack saturation as a mechanism of acclimatization of panel paintings to unstable environments. Studies in Conservation 63 (sup1): 22-27.
- Bridarolli, Alexandra, Ashley Amanda Freeman, Naoki Fujisawa, and Michał Łukomski. 2022. Mechanical properties of mammalian and fish glues over range of temperature and humidity. Journal of Cultural Heritage 53: 226-35.

- Cosaert, Annelies, Vincent Laudato Beltran, Geert Bauwens, Melissa King, Rebecca Napolitano, Bhavesh Shah, and Joelle Wickens. 2022. Tools for the Analysis of Collection Environments: Lessons Learned and Future Development: Research Report. Annelies Cosaert and Vincent Laudato Beltran, eds. Los ….
- Erhardt, David, and Marion Mecklenburg. 1994. Relative humidity re-examined. Studies in conservation 39 (sup2): 32-38.
- Erlebacher, Jonah D, Eric Brown, Marion F Mecklenburg, and Charles S Tumosa. 1992. The effects of temperature and relative humidity on the mechanical properties of modern painting materials. MRS Online Proceedings Library 267: 359-70.
- Eumelen, Gijs JAM, Emanuela Bosco, Akke SJ Suiker, and JJ Hermans. 2023. Chemo-mechanical model for degradation of oil paintings by amorphous and crystalline metal soaps. European Journal of Mechanics-A/Solids 97: 104827.
- Grøntoft, Terje, David Thickett, Paul Lankester, Stephen Hackney, Joyce H Townsend, Kristin Ramsholt, and Monica Garrido. 2016. Assessment of indoor air quality and the risk of damage to cultural heritage objects using MEMORI® dosimetry. Studies in Conservation 61 (sup1): 70-82.
- Hagan, Eric WS. 2017. Thermo-mechanical properties of white oil and acrylic artist paints. Progress in Organic Coatings 104: 28-33.
- Hartin, DEBRA DALY, STEFAN MICHALSKI, ERIC HAGAN, and MYLÈNE CHOQUETTE. 2015. Overview of the CCI lining project: do linings prevent cracking and cupping in paintings. American Institute for Conservation of Historic and Artistic Works Paintings Specialty Group Postprints 28: 137-50.
- Jakieła, Sławomir, Ł Bratasz, and R Kozłowski. 2008. Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions. Wood Science and Technology 42: 21-37.
- Janas, Arkadiusz, Laura Fuster-López, Cecil Krarup Andersen, Angel Vicente Escuder, Roman Kozłowski, Katarzyna Poznańska, Aleksandra Gajda, Mikkel Scharff, and Łukasz Bratasz. 2022. Mechanical properties and moisture-related dimensional change of canvas paintings–canvas and glue sizing. Heritage Science 10 (1): 160.
- Karpowicz, Adam. 1989. In-plane deformations of films of size on paintings in the glass transition region. Studies in Conservation 34 (2): 67-74.
- Konopka, Daniel, and Michael Kaliske. 2022. Inside the icon: experimental and numerical analysis of climate impacts on the damage potential of panel paintings. Paper read at VirtEx: Virtual Experiments for Wooden Artwork, at Dresden: Institut für Statik und Dynamik der Tragwerke.
- Koob, Stephen P, N Astrid R Van Giffen, Jerzy J Kunicki-Goldfinger, and Robert H Brill. 2018. Caring for glass collections: the importance of maintaining environmental controls. Studies in Conservation 63 (sup1): 146-50.

- Kozłowski, Roman, Arkadiusz Kupczak, Artur Działo, Łukasz Bratasz, and Michał Łukomski. 2019. HERIe: A Decision-Supporting Tool Based on Quantitative Assessment of Damage Risk. The Mechanics of Art Materials and Its Future in Heritage Science: 21.
- Krzemień, Leszek, Michał Łukomski, Łukasz Bratasz, Roman Kozłowski, and Marion F Mecklenburg. 2016. Mechanism of craquelure pattern formation on panel paintings. Studies in Conservation 61 (6): 324-30.
- Lee, DS-H, N-S Kim, Mikkel Scharff, Astrid Valbjørn Nielsen, M Mecklenburg, Laura Fuster-López, Lukasz Bratasz, and Cecil Krarup Andersen. 2022. Numerical modelling of mechanical degradation of canvas paintings under desiccation. Heritage Science 10 (1): 130.
- Luimes, Rianne A, and Akke SJ Suiker. 2021. Numerical modelling of climate-induced fracture and deformation in wood: Application to historical museum objects. International Journal of Solids and Structures 210: 237-54.
- Łukomski, Michal, Vincent Beltran, Foekje Boersma, James Druzik, Ashley Freeman, Marcin Strojecki, Thomas Learner, and Joel Taylor. 2018. Monitoring acoustic emission in an epidemiological pilot study of a collection of wooden objects. Studies in Conservation 63 (sup1): 181-86.
- Łukomski, Michał, Alexandra Bridarolli, and Naoki Fujisawa. 2022. Nanoindentation of historic and artists' paints. Applied Sciences 12 (3): 1018.
- Maekawa, Shin, Vincent L Beltran, and Michael C Henry. 2015. Environmental Management for Collections: Alternative Conservation Strategies for Hot and Humid Climates (): Getty Publications.
- Mecklenburg, Marion F. 1991. Some mechanical and physical properties of gilding gesso. Gilded Wood Conservation and History.
- ———. 2005. The structure of canvas supported paintings. Paper read at Preprints: Interim Meeting: International Conference on Painting Conservation: Canvases: behaviour, deterioration & treatment.
- Mecklenburg, Marion F, and Charles S Tumosa. 1991. An introduction into the mechanical behavior of paintings under rapid loading conditions. Art in transit: Studies in the transport of paintings.
- Mecklenburg, Marion F, Charles S Tumosa, and W David Erhardt. 1998. Structural response of painted wood surfaces to changes in ambient relative humidity. Painted wood: history and conservation.
- Michalski, Stefan. 1991. Paintings: Their response to temperature, relative humidity, shock, and vibration. Art in transit: Studies in the transport of paintings: 223-48.
- ———. 1993. Relative humidity: a discussion of correct/incorrect values. mh 500 (3): 1oo.
- ———. 2000. Guidelines for humidity and temperature in Canadian archives.
- ———. 2013. Agent of Deterioration: Incorrect Relative Humidity. Canadian Conservation Institute, Available: https://www. canada.

ca/en/conservationinstitute/services/agents-deterioration/humidity.html.

- ———. 2014. The power of history in the analysis of collection risks from climate fluctuations and light. Paper read at Proceedings of the ICOM Committee for Conservation 17th Triennial Meeting, Melbourne, Australia.
- Ohtsuki, Torao. 1990. Studies on Eurotium tonophilum Ohtsuki: Minimum Humidity for Germination and Characterization of Yellow Pigments Produced by this Fungus. Scientific Papers on Japanese Antiquities and Art Crafts 35: 28-34.
- Oreszczyn, Tadj, May Cassar, and Keith Fernandez. 1994. Comparative study of air-conditioned and non air-conditioned museums. Studies in Conservation 39 (sup2): 144-48.
- Reilly, James M. 1995. New Tools for Preservation: Assessing Long-Term Environmental Effects on Library and Archives Collections: ERIC.
- Soboń, Magdalena, and Łukasz Bratasz. 2022. A method for risk of fracture analysis in massive wooden cultural heritage objects due to dynamic environmental variations. European Journal of Wood and Wood Products 80 (5): 1201-13.
- Strang, Tom. 2013. Mould risk to cultural property-on the problem of defining adverse environmental conditions and potential for harm. Paper read at Microbial Biodeterioration of cultural property: recent topics on the investigation of and countermeasures for biodeterioration of outdoor/indoor properties and disaster-affected objects: International Symposium on the Conservation and Restoration of Cultural Property (36th: 2012: Tokyo, Japan).
- Strlič, Matija, Carlota M Grossi, Catherine Dillon, Nancy Bell, Kalliopi Fouseki, Peter Brimblecombe, Eva Menart, Kostas Ntanos, William Lindsay, and David Thickett. 2015. Damage function for historic paper. Part III: Isochrones and demography of collections. Heritage Science 3: 1-11.
- Strojecki, Marcin, Michał Łukomski, Leszek Krzemień, Joanna Sobczyk, and Łukasz Bratasz. 2014. Acoustic emission monitoring of an eighteenth-century wardrobe to support a strategy for indoor climate management. Studies in conservation 59 (4): 225-32.
- Tantideeravit, S, MN Charalambides, DS Balint, and CRT Young. 2013. Prediction of delamination in multilayer artist paints under low amplitude fatigue loading. Engineering fracture mechanics 112: 41-57.
- van Duin, Paul. 2013. What real museum objects can teach us about the influence of climate conditions. Climate for Collections–Standards and Uncertainties. Climate for Culture. Postprints: 271-82.
- Waller, Robert. 2013. Temperature-and humidity-sensitive mineralogical and petrological specimens. In Care and Conservation of Geological Material, 25-50. Routledge.

3. Introduction to microclimate

Cultural heritage collections, the building envelopes in which they are displayed and stored, and climate conditions of their geographic location provide an almost infinite number of variables, which need to be compiled, analyzed, and interpreted to develop appropriate conditions for the long-term preservation of diverse artifacts.   Research in recent decades has provided new insights into suggested temperature and RH parameters to prevent deterioration and damage to museum objects. Based on the data obtained by GCI/ Museum Collections Environment and others (see Appendix I) broader ranges of environmental guidelines can now be proposed for certain types of collections.

Many other materials, however, such as ancient and archaeological objects (more so if impregnated with soluble salts), metals, composite materials *(and more…)* may require tighter or particular values of RH to prevent chemical and mechanical agents of degradation to become active or pacify ongoing deterioration.

Display cases that hold microclimates provide alternatives to tighter gallery climate control and offer customized, safe, and sustainable solutions in these instances. Different approaches to the design and maintenance of microclimate vitrines are available, from low cost and relatively simple solutions to state-of-the-art cases with active control systems.   The information provided below is intended as a broad overview of options and resources to be considered when developing microenvironments for objects with specific requirements.

Microclimates
- Passive
- Active
- Choice of buffers and desiccants

Case materials and design
- Different choices of construction
  - Freestanding, shadow boxes, wall cases etc.
  - Access to compartments
  - Air exchange
- Safe case materials
  - Building materials
  - Paint
  - Fabric
  - Gaskets
- Vapor barriers
- Material testing

Monitoring
- Review of different types of loggers

Areas for further research
- Need for more active testing and data collection
- Need for more detailed research of specific materials and behavior to changes in RH and temperature (such as archaeological materials already degraded, salts, metals, corrosion products, glass, composite materials, modern and synthetic materials, other)

Literature and resources
- American Institute for Conservation Wiki
- https://www.conservation-wiki.com/wiki/Environmental_Guidelines

- Canadian Conservation Institute
- https://www.canada.ca/en/conservation-institute/services/preventive-conservation/guidelines-collections/metal-objects.html

- Hatchfield, Pamela. 2002. *Pollutants in the Museum Environment : Practical Strategies for Problem Solving in Design, Exhibition, Storage.* London: Archetype Publications.

- Harrison, Lynne. 2018. “Variations on a theme: re-evaluating the performance of modified microclimates for the protection of old master paintings.” *The Picture Restorer* Spring (52), 23–31.

- Kupczak, Arkadiusz, Mariusz Jędrychowski, Marcin Strojecki, Leszek Krzemień, Łukasz Bratasz, Michał Łukomski, and Roman Kozłowski. 2018. "HERIe: A Web-Based Decision-Supporting Tool for Assessing Risk of Physical Damage Using Various Failure Criteria." *Studies in Conservation* 63, no. S1: 151-55.

- Padfield, Timothy, Borchersen, Karen, Christensen, Mads Chr, and Nationalmuseet. 2007. *Museum Microclimates : Contributions to the Copenhagen Conference 19-23 November 2007. Edited by Tim Padfield and Karen Borchersen; Scientific Committee Mads Christian Christensen, et al.* Copenhagen: National Museum of Denmark.

- Paterakis, Alice Boccia. 2016. *Volatile Organic Compounds and the Conservation of Inorganic Materials.* London: Archetype Publications.

- Paterakis, A. Boccia, M. Mariano, Hyslop. 2013. “Oxygen Absorbers and Desiccants in the Protection of Archaeological Iron: Maintaining Some Control.” In *Metal 2013 Edinburgh, Scotland 16th – 20th September 2013, Interim Meeting of the ICOM-CC Metal Working Group, Conference Proceedings*, Ewan Hyslop, Vanesa Gonzalez, Lore Troalen, Lyn Wilson, eds. (Edinburgh: Historic Scotland and ICOM-CC), 185-191.

- Schieweck, A., and Krüger, Markus. 2011. *Mitigation Strategies for the Sustainable Improvement of Microclimates within Cultural Heritage Objects and Museum Institutions.* Stuttgart: Fraunhofer IRB Verlag, 40-44.

- Shashoua, Yvonne, and Bridgland, Janet. 1999. “Ageless Oxygen Absorber: From Theory to Practice.” *12th triennial meeting, Lyon, 29 August-3 September 1999: preprints (ICOM Committee for Conservation).* London: Earthscan Ltd., 881-887.

- Tétreault, Jean. 1999. *Coatings for Display and Storage in Museums.* Technical Bulletin (Canadian Conservation Institute) No. 21. Ottawa: Canadian Conservation Institute.

- Tétreault, Jean. 2003. *Airborne Pollutants in Museums, Galleries and Archive: Risk Assessment, Control Strategies and Preservation.* Ottawa: Canadian Conservation Institute.

- Tétreault, Jean. 2021. *Control of Pollutants in Museums and Archives.* Technical Bulletin (Canadian Conservation Institute) No. 37. Ottawa: Canadian Conservation Institute.

- Tétreault, Jean. 2022. *Airtightness Measurement of Display Cases and Other Enclosures.* Technical Bulletin (Canadian Conservation Institute) No. 38. Ottawa: Canadian Conservation Institute.

- Tetreault, Jean, and Paul Bégin. 2018. *Silica Gel: Passive Control of Relative Humidity*. Technical Bulletin (Canadian Conservation Institute) No. 33. Ottawa: Canadian Conservation Institute.

- Thickett, David, David Saunders, Joyce H Townsend, and Sally Woodcock. 2008. "Presentation in Original Contexts via Microclimates." *Conservation and Access: Contributions to the London Congress 15-19 September 2008*. London: International Institute for Conservation of Historic and Artistic Works, 98-103.

- Johanna C. Thunberg, David E. Watkinson & Nicola J. Emmerson. 2021. "Desiccated Microclimates for Heritage Metals: Creation and Management." *Studies in Conservation*, 66:3, 127-153. DOI: 10.1080/00393630.2020.1799599

4. Energy efficiencies

ENERGY EFFICIENCY ALTERNATIVES

Passive
- Building orientation
- Wall to window ratio
- Building envelope (R value)
- Exposure to sun (max PV potential)

ECM ECM = energy conservation measures are tools or best management practices which are implemented in order to save energy)
- Minimize size of mechanical Equipment
- Energy efficient chillers/pumps – i.e. frictionless, magnetic bearings, oil free, centrifugal, heat recovery, ~20 degrees ^T

VFDs on all pumps and motors VFD = variable frequency drive. Enables a pump or motor to operate at most efficient energy level to satisfy load requirement

Well insulated CHW[1] piping, HHW[2] piping

Optimize use of natural light

LED lighting

Remove vampire loads at night

Set back environmental conditions at night or times of non-occupancy

Energy storage (battery or thermal)

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[1] CHW = chilled water

[2] HHW = heating hot water

Optimize control systems to minimize number of ACH[3]s based on code compliance and air quality requirements, eliminate inefficiencies of cooling/heating simultaneously, optimize outside air exchange rates

Select MERV[4] filtration to lowest acceptable and code compliant standards for use of the space (reduce pressure drop across filters and lower fan motor requirements)

Develop demand reduction programme for implementation with low employee/visitors numbers or utility overload (i.e. blackout)

Eliminate steam use – replace with hot water for heating or high pressure (adiabatic) atomizers for RH
Utilize BMS[5] analytics and FDD [6]software

CRM[7]:

- Electrify mechanical equipment – reduce gas consumption
- Renewable Energy on prem or PPA/VPPA[8]
- Raise/lower set HVAC points to reduce energy consumption
- Alternate fuels i.e. hydrogen fuel cells
- Utilize low GWP[9] refrigerant *

LESSONS LEARNED

1. **Managing building environments passively:** ensure sufficient energy metering is in place so that the consumption can be tracked across day/week/year cycles and can be linked to local areas.

2. **Passive delivery with some added plant:** monitored not simply through resultant RH/T tracked in the room but through energy consumption linked to areas - to ensure plant interventions are kept to a minimum. We found when we moved to a passive first approach that past Air Con thinking quickly overtook passive control protocols and that energy consumption crept up although the conditions RH/T were stable. There was a learning curve to be climbed. Looking at energy consumption was essential to see if plant control was going awry.

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[3] ACH – air changes per hour, minimizing the number of air changes saves energy

[4] MERV = Minimum efficiency reporting value – a measure of level of air filtration, larger number requires more energy to push air through

[5] BMS = building management system

[6] FDD – fault detection diagnostics – analytical tool which detects inefficiencies in a mechanical system

[7] CRM = carbon reduction measures

[8] PPA = power purchase agreement; Virtual power purchase agreement. A contractual agreement with a utility provider in which renewable energy certificates (RECs) are obtained in addition to energy provided.

[9] GWP – global warming potential – measurement of how climate "friendly" a refrigerant gas is to the atmosphere

5. Bibliography on environmental control

- AIC (American Institute for Conservation) "Environmental Guidelines." *AIC Wiki: A Collaborative Knowledge Resource.* 2020. https://www.conservation-wiki.com/wiki/Environmental_Guidelines
- Dardes, Kathleen, Erica C. Avrami, Marta De la Torre, Samuel Y. Harris, Michael Henry, and Wendy Claire Jessup. 1999. *The Conservation Assessment: A Proposed Model for Evaluating Museum Environmental Management Needs*. Los Angeles, CA: Getty Conservation Institute. http://hdl.handle.net/10020/gci_pubs/evaluating_museum_environmental_mngmnt_english
- Henderson, Jane. "Managing Uncertainty for Preventive Conservation." *Studies in Conservation* 63, no. sup1 (August 2018): 108–12. https://doi.org/10.1080/00393630.2018.1479936.
- Maekawa, Shin, Vincent L. Beltran, and Michael C. Henry. *Environmental Management for Collections: Alternative Conservation Strategies for Hot and Humid Climates*. Tools for Conservation. Los Angeles, California: Getty Conservation Institute, 2015.
- *Museums, Galleries, Archives and Libraries*. 2019 ASHRAE Handbook—HVAC Applications, edited by Heather Kennedy, ASHRAE (American Society of Heating Refrigerating and Air-Conditioning Engineers), 2019, p.1-41.https://www.ashrae.org/technical-resources/ashrae-handbook
- IPI's Guide to: Sustainable Preservation Practices for Managing Storage Environments. Image Permanence Institute, Rochester Institute of Technology, 2012. https://s3.cad.rit.edu/ipi-assets/publications/sustainable_preservation_practices/sustainable_preservation_practices_all.pdf
- IPI's Methodology for Implementing Sustainable Energy-Saving Strategies in Collections Environments. Image Permanence Institute, Rochester Institute of Technology, 2019. https://s3.cad.rit.edu/ipi-assets/publications/methodology_guidebook/methodology_guidebook_all.pdf
- Padfield, T, Morten, Ryhl-Svendsen, Larsen, Poul Klenz, and Jensen, Lars Asbjerg. "A Review of the Physics and the Building Science which Underpins Methods of Low Energy Storage of Museum and Archive Collections." *Studies in Conservation* 63, no. sup1 (August 2018): 209–215. https://doi.org/10.1080/00393630.2018.1481324.
- "Reflections on the Psychological Basis for Suboptimal Environmental Practices in Conservation." *Journal of the Institute of Conservation* 41, no. 1 (January 2, 2018): 32–45. https://doi.org/10.1080/19455224.2017.1422777.
- Staniforth, Sarah. "Environmental Conditions for the Safeguarding of Collections: Future Trends." *Studies in Conservation* 59, no. 4 (July 2014): 213–17. https://doi.org/10.1179/2047058414Y.0000000142.
- Sterrett, Jill, and Roberta Piantavigna. "Building an Environmentally Sustainable San Francisco Museum of Modern Art." *Studies in Conservation* 63, no. sup1 (August 2018): 242–50. https://doi.org/10.1080/00393630.2018.1481324.
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6. Sharing experiences

4. 14.1 Testimonies

1	Rijksmuseum, Amsterdam	Since two and a half years we have a climate working group consisting of engineers and conservators. This multi-disciplinary approach is proving very effective. We are pleased that we finally broadened the specifications, and are also very active in exploring ways to run the air-conditioning systems more efficiently. Both actions are important and should go hand in hand, we believe. We are also involved in research, such as the Climate4Wood-project, which, like research carried out by other groups suggests that most objects can safely withstand considerable fluctuations in RH. Because our objects are made of many (combinations of) different materials in, and the condition of objects can vary so much, research takes much time and the results do not always convince all of those who are responsible for the care of the objects. Pending the outcome of research, our climate working group has managed to obtain widespread support from the staff at the museum for the BIZOT-guidelines. Report of the Rijksmuseum Working Group on Sustainable climate conditions v1.pdf

6.2. Case studies

On Bizot Guidelines

- **Case study 1** | Adoption of the Bizot Protocol and Guidelines at the NGV (Australia) [here]
- **Case study 2** | Sustainable models of collection care and museum operations at CSMVS (India) [here]
- **Case study 3** | Adoption of Bizot Green Protocol and guidelines at the Rijksmuseum (The Netherlands) [here]

On alternative solutions to climate control and energy efficiency measures

- **Case study 4** | Energy efficiencies and environmental control at the Rijksmuseum (The Netherlands) [here]
- **Case study 5** | Developing an Adaptive Climate Control Strategy and Programme Monitoring Micro-change in Wooden Heritage Objects at the NGV (Australia) [here]
- **Case study 6** | BAS – HVAC System Nightly Shutdown at NGV (Australia) [here]
- **Case study 7** | NGS Case study of a low energy building solution for housing collections National Galleries of Scotland: National Portrait Gallery (United Kingdom) [here]
- **Case study 8** | NGS Case study – Collection care through building design at the National Galleries of Scotland (United Kingdom) [here]
- **Case study 9** | Use of Microclimates within Frames at Tate (United Kingdom) [here]

7. Practical tools

7.1 Wording for loan agreement

MoMA's Borrower's Agreement states: "The Borrower will maintain constant and adequate protection of the Loaned Work from the hazards of fire, theft, exposure to extreme or deteriorating light, extremes of temperature and relative humidity, insects, dirt, handling by unauthorized or inexperienced persons, or touching by the public. While on view, the Loaned Work must be visible to a trained security guard at all times. Fire detection/prevention, temperature/humidity control, and security systems must operate on a 24 hour per day, 7 day per week basis. In accordance with the guidelines established at the November, 2014 Bizot Group Meeting, the Loaned Work shall only be unpacked, repacked, temporarily stored, and installed in areas where temperature is maintained at a stable 61-77 degrees Fahrenheit (16-25 degrees Celsius) and stable relative humidity of 40-60%. Within these ranges, temperature will not vary by more than +/- 4 degrees Fahrenheit and humidity will not vary by more than +/- 10% within a 24-hour period. MoMA's Registrar must be notified immediately of any fluctuations in temperature or humidity greater than those specified above."

MoMA's Exhibition Agreement states: "The Exhibition shall only be unpacked, repacked, temporarily stored, and installed in areas where the average temperature is maintained at stable 61 - 77 degrees Fahrenheit (16 - 25 degrees Celsius), and stable relative humidity of 40-60%. Within these ranges, temperature will not vary by more than +/- 4 degrees Fahrenheit and humidity will not vary by more than +/- 10% within a 24-hour period. MoMA's Registrar must be notified immediately of any fluctuations in temperature or relative humidity greater than those specified (in accordance with the guidelines established at the November, 2014 Bizot Group Meeting: Achieving Sustainability for Galleries and Museums)."

Guggenheim Museum NYC wording for Borrower agreement (with exceptions for certain more fragile materials):

The Artwork shall only be unpacked/repacked, temporarily stored and installed in areas where temperature is maintained at a stable relative humidity in the range of 40-60% with fluctuations of no more than ±10% in a 24-hour period and a stable temperature in the range 16–25°C.

Tate wording for loan out agreement:

Climate
Tate endorses the Guiding Principles and Guidelines of the International Bizot Group Green Protocol, 2015.

Temperature control: the range is 18-24 degrees Celsius, 21 degrees Celsius +/-3.
Relative humidity: the range of 40-60 per cent, 50 per cent +/-10 with a maximum cumulative fluctuation of 10 per cent in any 24-hour period.

Atmospheric pollution: works of art should not be exposed to concentrations of sulphur dioxide in excess of ten micrograms per cubi metre, of nitrogen oxides in excess of ten micrograms per cubic metre, or ozone in excess of two micrograms per cubic metre. In areas of heavy pollution, active measures must be taken to exclude or reduce levels of gaseous pollution. A high standard of dust filtration is required when a mechanical ventilation system is employed.
General: works of art must never be placed in close proximity to sources of heat, cold or strong air-currents (radiators, fireplaces, deshumidifiers, air conditioning outlets or intakes)

7.2. Climate emergency declaration

A number of cultural organisations have recently declared climate emergency:

In the Netherlands, Belgium, Germany the United Kingdom:

- *Klimaatverklaring voor erfgoedorganisaties | Publicatie | Rijksdienst voor het Cultureel Erfgoed*
- *Energiekrise: Museumsbund empfiehlt neue Richtlinien für die Museumsklimatisierung – Deutscher Museumsbund e.V.*
- *Tate (press release) on Climate Emergency Declaration* and Tate policy about climate change

Lastly, KiCulture organized an Climate Conference in December 2022 and is currently circulating a declaration, asking museums to commit to changing their climate conditions and loan agreements (Getting Climate Control Under Control Declaration (google.com)).

7.3. Methodology to implement Sustainable Energy-Savings in Collections environment

IPI's produced a useful guide to help with implementing Sustainable Energy-Saving Strategies in Collection Environments. The guide can be accessed here.

7.4. Local environment control: object level

Action	display	storage	In transit	Comment
well sealed, back boarded frames (right across frame reverse) with glazing significantly irons out fluctuations in RH, and to a minor degree T	y	y	Y	supports greater leniency and seasonal variation and flexibility for energy lead controls for plant
Fully eco plastic wrapping and sealing (RH)	n	Y – but open access storage is hindered via this route	Y (in or aside from crate)	
Use of sealed and glazed shadow boxes for artworks	y	y	Y	Will also provide protection for vulnerable framing
Addition of buffering material within framing sets ups	y	y	Y	Requires monitoring
Climate control display cases	y	n	y/n	Vast range of options

				here for local control -

Managing building environments passively: ensure sufficient energy metering is in place so that the consumption can be tracked across day/week/year cycles and can be linked to local areas.

Passive delivery with some added plant: monitored not simply through resultant RH/T tracked in the room but through energy consumption linked to areas - to ensure plant interventions are kept to a minimum. We found when we moved to a passive first approach that past Air Con thinking quickly overtook passive control protocols and that energy consumption crept up although the conditions RH/T were stable. There was learning curve to be climbed. Looking at energy consumption was essential to see if plant control was going awry.

7.5. Decarbonisation action plan for non-profit and institutions

GCC published in March 2023 a new tool to help non-profit organisations to develop a decarbonisation action plan. You can access this tool here.