CHAPTER 24

MUSEUMS, GALLERIES, ARCHIVES, AND LIBRARIES

THIS chapter presents best practices and advice on planning, designing, and implementing environmental strategies for long-term preservation of cultural heritage that also support access in an economically and environmentally responsible way. It aims to support a holistic approach, taking into consideration the types of collections, buildings, and environmental control systems that can sustain appropriate conditions for specific collections with their own climate histories. It acknowledges that any strategy will have to be an integral part of heritage preservation as a whole. The chapter is applicable to museums, galleries, nonresidential historic buildings, reference libraries, and archives, as well as to both new and existing structures. It is not designed for buildings with public access that only hold collections not intended for preservation, such as school libraries.

This chapter is primarily directed at HVAC engineers and facility managers involved with indoor climate control projects in cultural heritage institutions, including new construction and extensions, renovations and upgrades of existing systems, and the adjustment of climate control strategies towards sustainability. Because this chapter has been widely used by allied professionals in a much broader context, it informs all stakeholders involved in the decision-making process on designing and implementing environmental strategies for cultural heritage collections. These include, but are not limited to, engineers, architects, collection owners, cultural heritage administrators, collection managers, conservators, conservation scientists, curators and registrars.

The information in this chapter focuses on mechanical and, to a limited extent, nonmechanical approaches to the control of temperature, relative humidity, and indoor air quality. Tables and graphs are used to provide clear and easy access to specific information, but the underlying text is necessary to understand the full context.

1. TERMINOLOGY

The terminology used in this chapter derives from the professional conservation field and, except where noted, is taken from the website of the American Institute for Conservation of Historic and Artistic Works (AIC 2018).

Cultural property includes objects, collections, specimens, structures, or sites that have artistic, historic, scientific, religious, or social significance.

Tangible heritage includes buildings, historic places, and monuments, as well as objects and collections significant to the archaeology, architecture, science, or technology of a specific culture.

Intangible heritage, according to the United Nations Educational, Scientific and Cultural Organization (UNESCO), includes traditions or living expressions inherited and passed on within a culture, such as oral traditions, performing arts, social practices, rituals, festive events, knowledge, and practices concerning nature and the universe or the knowledge and skills to produce traditional crafts (UNESCO 2017a).

Digital heritage includes valued knowledge or expressions that have been created digitally, or converted into digital form from existing analogue resources (UNESCO 2017b).

Preservation is protection of cultural property through activities that minimize chemical and physical deterioration and damage and that prevent loss of informational content. The primary goal of preservation is to prolong the existence of cultural property.

Conservation is the profession devoted to preservation of cultural property for the future. Conservation activities include examination, documentation, treatment, and preventive care, supported by research and education.

Preventive care (also called **preventive conservation**) is mitigation of deterioration and damage to cultural property through the formulation and implementation of policies and procedures for the following: appropriate environmental conditions; handling and maintenance procedures for storage, exhibition, packing, transport, and use; integrated pest management; emergency preparedness and response; and reformatting/duplication.

2. KEY CONSIDERATIONS

2.1 HERITAGE

“Heritage is our legacy from the past, what we live with today, and what we pass on to future generations. Our cultural and natural heritage are both irreplaceable sources of life and inspiration” (UNESCO 2018).

Cultural heritage (tangible, intangible, and digital) is considered essential to the understanding and appreciation of humanity’s diverse cultures and history. The importance of cultural heritage may be national, regional, or local, and it may have symbolic, aesthetic, cultural, social, historical, scientific, and monetary values that are frequently impossible to estimate. Thus, access to and preservation of cultural heritage is important and may even be legally mandated.

This chapter addresses preservation of tangible heritage: physical objects such as books and documents, works of art, historic tools and utilities, archaeological artifacts, specimens of natural history, examples of popular culture, products of various technologies, and historic buildings.

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2.2 CONTEXT

Objects are often held by various collecting institutions such as museums, galleries, historic buildings, libraries, and archives. These collections have different uses, depending on the institution's mission, and require specific management policies: in museums, the majority of a collection may be kept in storage with limited access, with a smaller portion on temporary or semipermanent display, often in showcases; in archives and libraries, almost all of the collections are in storage, from which they are pulled for research or exhibition; historic houses have most of their collections on permanent open display. Individual objects from collections may be on short- or long-term loan to another organization.

Collections may be housed in purpose-built buildings or existing buildings of historic significance; sometimes, the building may be as (or more) important than the collection it houses. Most collections have been housed in existing buildings with climate control ranging from nonmechanical strategies (e.g., thermal insulation, window shutters) to mechanical systems (e.g., localized dehumidifiers, full HVAC). As a result, collections have a specific climate history that should be taken into consideration when reviewing environmental strategies.

2.3 INTERNATIONAL STANDARDS

To facilitate loans, cultural heritage organizations often look to follow international guidelines on environmental control. It is therefore important to be aware of the shift in thinking about sustainable collection management that is having a major impact on standards and guidelines. The U.K. National Museum Directors' Conference (NMDC 2008) focused on a long-term, broad plan for minimizing excessive energy use in the care of collections, reducing museums' overall carbon footprint. In turn, the International Group of Organizers of Large-Scale Exhibitions (Bizot Group 2015) proposed a broader set of interim temperature and relative humidity guidelines for hygroscopic materials on loan, based on the NMDC proposal; their goal was to simplify international loans, reduce costs, and decrease the carbon footprint. This prompted the Association of Art Museum Directors (AAMD) to request input from the conservation community.

As a response, the international professional organizations International Institute for Conservation of Historic and Artistic Works (IIC) and International Council of Museums—Committee for Conservation (ICOM-CC) published a declaration on environmental guidelines (IIC/ICOM-CC 2014). It states

- "The issue of museum sustainability is much broader than the discussion on environmental standards, and needs to be a key underlying criterion of future principles.
- "Museums and collecting institutions should seek to reduce their carbon footprint and environmental impact to mitigate climate change, by reducing their energy use and examining alternative renewable energy sources.
- "Care of collections should be achieved in a way that does not assume air conditioning (HVAC). Passive methods, simple technology that is easy to maintain, air circulation and lower energy solutions should be considered.
- "Risk management should be embedded in museum management processes."

2.4 PRESERVATION AND RISK MANAGEMENT

Preservation of cultural heritage involves mitigating the impact of agents of deterioration (CCI 2018). It requires a trade-off among many factors and there is no single golden rule. Instead, risk management approaches are used to arrive at an appropriate solution (see the section on Overview of Risks). For example, creating an environment for preserving the collection that causes problems for the building in which it is housed is not acceptable.

It is possible to substantially slow deterioration caused by environmental agents of deterioration, thus fulfilling a major function of the collecting institution. However, doing so may conflict with another important function of cultural institutions: allowing public and scholarly access. Additionally, extremely tight control over all environmental parameters comes at a price few cultural institutions can justify or afford. Managing risk, not avoiding it altogether, is the objective.

Climate-induced risks should be seen in context and relation to other risks to the preservation of cultural heritage, such as natural and human-caused disasters. Frequently, it is not the greatest risk to a collection, and available funds may be spent more effectively elsewhere. Therefore, it is fundamental that an institution develops an overall preservation strategy, of which its climate control is an integral part, based on a comprehensive risk assessment. A climate-control strategy should complement mitigation plans for other risks and should not in itself create a greater hazard. Consequently, greater risk reduction can come from ensuring the reliability of the system, rather than controlling minor excursions from defined climatic ranges. Most threats to collection preservation, in fact, can be addressed by properly maintained housing and professional support.

2.5 SUSTAINABILITY

This chapter advocates environmental strategies and solutions for cultural heritage collections that support their access and preservation in a responsible way (i.e., that are sustainable economically, socially, and environmentally). It aims to inform strategies that sustain feasible climatic conditions for the foreseeable future and takes into consideration

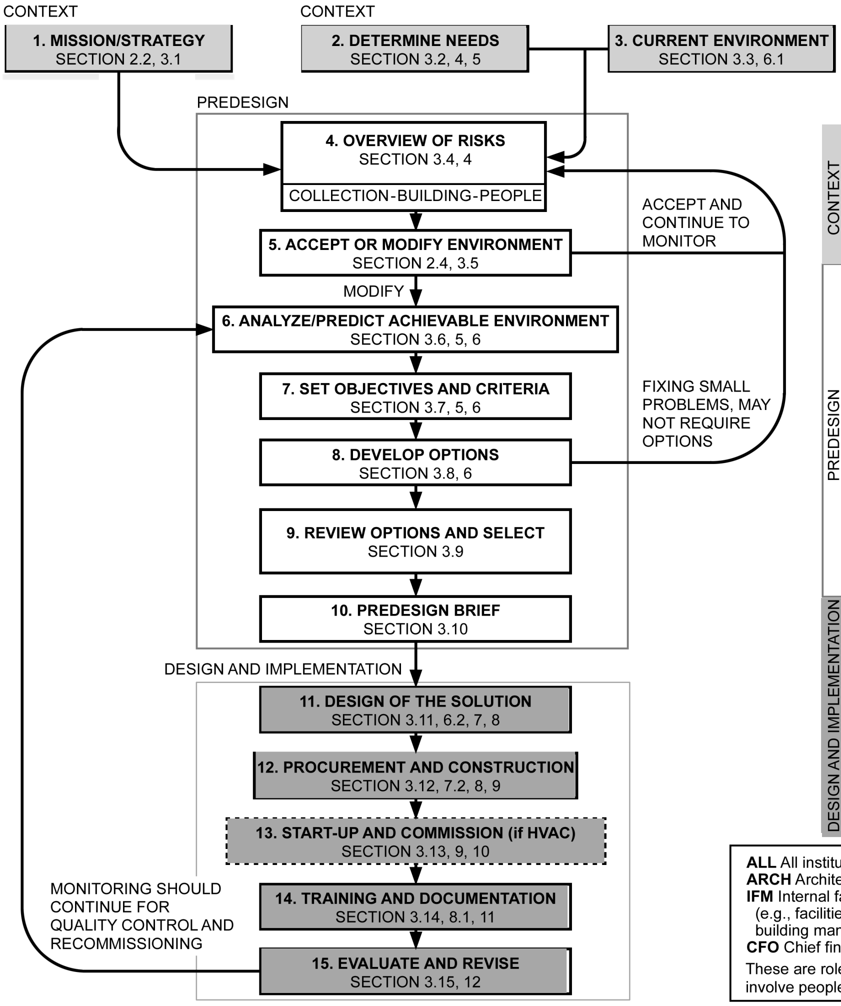
- An organization's mission and resources
- The needs of the collection and its users
- Building type
- Local, regional, national, or international policies
- Suitable environmental systems

To design and implement appropriate climate control for a specific collection, it is important to involve all appropriate stakeholders, which can vary by institution but may include engineers, architects, facility managers, security staff, cultural heritage administrators, archivists, collection managers, conservators, conservation scientists, curators, and registrars. Administrators are responsible for fiscal and political decisions, whereas collection managers and conservators are responsible for providing access and care of the collection. Curators build the collection and design exhibitions. Registrars oversee the legal paperwork and administration related to collection management. Security staff is critical to safekeeping of the collection.

Therefore, a multidisciplinary approach is required to obtain a comprehensive overview of all aspects that impact an environmental management strategy, and some of this work should be carried out before an engineer is engaged in a project.

Cultural institutions frequently operate as nonprofit organizations on tight budgets with limited human and/or technical resources. Insisting on best-available technology for extraordinary humidity control or comprehensive pollutant filtration may endanger long-term fulfillment of the institutional mission.

From project inception, both the design objective and realistically available operation and maintenance resources must be considered. Having reliable monitoring data is crucial in the decision-making process. Before embarking on full mechanical control solutions, efforts should be made to use or integrate strategies that do not rely on mechanical control, including passive building solutions and non-



STAKEHOLDERS

		LEAD	CONSULT	INFORM
CONTEXT	1.	DIR/CUR	COLL, IFM	ARCH, ENG, EXT
	2.	COLL, IFM	CUR	ENG
	3.	EXT/COLL, IFM	CUR/EXT, SEC	ARCH, ENG
PREDESIGN	4.	EXT/COLL, IFM	ENG, ARCH, CUR, EXT, SEC	DIR
	5.	DIR/CUR/COLL	ARCH, ENG, IFM	DIR
	6.	IFM, ENG, ARCH	COLL, CUR, EXT, ARCH	DIR, ALL
	7.	COLL, IFM, ENG	EXT, CUR, ARCH	EXT
	8.	ARCH/ENG/EXT	CUR, COLL, SEC, IFM	ALL
	9.	ALL	EXT, ALL	ALL
	10.	DIR/CUR, COLL, IFM	SEC, EXT, CFO	ENG, ARCH, COMM
DESIGN AND IMPLEMENTATION	11.	ENG/ARCH	IFM, COLL, SEC, EXT	CUR/DIR COMM
	12.	ENG/ARCH, IFM, CFO	COLL, SEC, COMM	CUR/DIR
	13.	COMM, ENG	IFM, EXT, CFO	SEC, COLL, CUR
	14.	IFM, ENG	COLL, SEC, COMM	ALL
	15.	ENG/EXT, IFM	COLL, SEC	CUR/DIR

ALL All institution staff
ARCH Architect
IFM Internal facilities staff (e.g., facilities manager, building manager)
CFO Chief financial officer
COLL Collections staff (include collections manager, conservator, registrar)
COMM Commissioning agent
CUR Curatorial
DIR Director
ENG Engineer
EXT External experts
SEC Security

These are roles, rather than job titles, and some may overlap. It is best to involve people early in the process rather than later. Not exhaustive.

Fig. 1 Decision Diagram for Environmental Management Strategies in Museums, Galleries, Archives, and Libraries
(based on Taylor, forthcoming)

mechanical adjustments, which can successfully provide appropriate environmental control for the collection.

In accordance with the international call for reducing energy use and examining alternative renewable energy sources, solutions that can complement the local external climate should be explored first. These include building envelope improvements; integrated strategies that address preservation, access, and human comfort needs; hybrid systems (alternative energy sources); seasonal and diurnal adjustments; and enclosures providing microenvironments for individual or multiple objects.

3. CONTEXT AND PREDESIGN

Before an appropriate environmental management strategy can be developed, many contextual factors need to be considered. Cultural institutions vary not only in their geographic location and building morphology, but also in their purpose, mission, and the materials, condition, and needs of their collections. The values placed on different collections, their uses, and their expected lifetimes all influence an environmental management strategy.

This section addresses the process of developing sustainable environmental management strategies for different types of projects, from installing new or upgraded mechanical systems in new purpose-built or renovated structures, to more energy-efficient climate control strategies in existing situations. Although there are significant differences between new purpose-built museums and historic houses, the decision points are similar.

A schematic decision-making flowchart can be used to define the necessary, broad steps from strategic plan to evaluation (Figure 1). It is intended for both new and existing buildings with a range of environmental solutions. The diagram also accounts for situations where there may be no collection preservation problems or the environment is deemed appropriate, but there is a desire to reduce energy consumption. The components/steps in the diagram are described in the following text. Although the later steps outlined in Figure 1 are not within the scope of predesign, these sections describe considerations that can be addressed during the predesign phase.

Different projects require different amounts of time and resources for individual steps. For many cultural institutions, particularly those that have been operating for some time, relevant information such as collection surveys or significance assessments may already exist, reducing the time required for predesign. In all instances, however, decision making is a multidisciplinary activity involving a variety of stakeholders, whose role and level of involvement can change throughout the project. The list on the right-hand side of Figure 1 shows the expected level of participation for stakeholders at each step: if they are making decisions, if they should be consulted or be informed. If there is doubt, it is usually advisable to engage the stakeholders earlier in the process.

Table 1 Examples of Space Types in Museums, Galleries, Archives, and Libraries

	Collection	Noncollection
Public space	Changing exhibition galleries Permanent collection galleries Reserve/scholar collections Open storage Most reading/collection study rooms	Entrances/vestibules Atria Cafeteria Restaurants Shops Auditoria Education spaces Restrooms Coat/baggage rooms
Nonpublic space	Conservation laboratories Collection storage Workshops and mount-making areas Archive stacks Library stacks Quarantine areas Photography studios Digitization areas	Offices Crate storage (controlled relative humidity may be required) Mechanical/electrical rooms Data centers/IT rooms Food preparation areas Loading bays
Low-occupancy space*	Cool and cold storage Low oxygen storage Low-relative-humidity rooms Off-site storage (e.g., high-density library stacks)	General storage areas (sales shop inventory, event equipment, etc.)

*Occupancy in these spaces is for short periods, and meeting human comfort standards may not be required.

Notes:

(1) Collection spaces and adjacent noncollection spaces often require substantially different types of control. Providing barriers (e.g., doors, air curtains) to limit airflow and moisture vapor exchange between these spaces is usually necessary for successful control.

(2) As exhibition needs change and collections grow, it is common for noncollection areas to be repurposed for collection exhibition. It is important to keep this in mind when planning HVAC systems. A café or atrium may not require relative humidity control or special filtration, but if the space is repurposed to exhibit objects that require specialized environments (relative humidity control, etc.), retrofitting a system to provide the appropriate environment can be costly and disruptive.

(3) Objects may be displayed in noncollection spaces through careful object selection (e.g., statues in vestibules) or use of display cases with the necessary microclimate performance. Offices that display collection items, such as paintings, should apply the same preservation requirements as collection spaces. Classrooms or other education spaces may be used to house some collection objects for extended periods; if so, collection-appropriate environmental control may be required.

A design engineer may not be involved in the early stages of this process. All these steps, however, influence the choice and delivery of the environmental management strategy and include important information for considering appropriate goals and solutions. A new building may involve developing a strategic plan and mission before a building project is started, whereas an operating museum may engage an engineer to provide a solution to an identified problem or undesirable situation.

3.1 MISSION AND STRATEGY

The purpose of any cultural institution is central to all decisions, even if its influence is implicit. Almost all cultural institutions have a mission statement, even those where the building is yet to be constructed. An operating museum often has statements of significance for collections, which describe the reasons for their importance. The mission of the institution and how its heritage assets are valued determines how the assets should be preserved and what is understood as a risk. The values of a collection directly inform the impact of a hazard, and even how different kinds of damage are regarded. An archive values the informational assets of its collection, often allowing access to individual items by researchers, increasing the risks of damage caused by handling. A fine arts museum may value aesthetic appearances that are affected by minor damage. A library and a contemporary art museum will have different expectations of the lifetimes of their objects and how their values are embodied by the material. This concept is also addressed in the section on Context, under Key Considerations.

3.2 DETERMINE NEEDS

Although the collections are usually the principal focus for managing the environment in a cultural institution, the needs of occupants and of the building itself must be balanced (along with capital and operating costs). Historic buildings can often be more significant than the collections that they contain. The respective importance of these needs varies among institutions and even among spaces, and their requirements can conflict.

The differing needs of spaces in cultural institutions can be broken down into broad categories of use by considering whether they contain collections, people, or both. This also helps identify spaces that can often be more flexible in terms of control, because there are many areas in cultural institutions that do not house collections, are not open to the public, and have occupancy for short and limited periods. Table 1 shows the kinds of spaces found in cultural institutions and what their use could imply through a matrix of occupancy levels for collections (columns) and people (rows). Spaces that house both often require the most consideration. Given that needs often differ between people and collections, the matrix presents opportunities to emphasize certain needs. Although specifics may vary over time (e.g., long-term uses, short-term management of spaces that are unoccupied at night), Table 1 provides some guidance of where resources are best applied. The specific collection needs must further be addressed in context.

Collection needs vary considerably with the kinds of materials, combinations of materials in a single object, and how the objects were made. Even library collections comprise a mix of materials to consider. Information about different materials can require specialist knowledge from conservation or science experts, some of whom may be external to the institution.

Relevant information to determine collection needs includes

- Materials
- Construction/assembly
- Condition and vulnerability (see Tables 2 and 13)
- Current and intended uses of the collection

- Frequency and kinds of access
- Specific climate history (and movement of objects over time)

Relevant information to determine building needs includes

- Materials and construction
- Condition and vulnerability
- Current and intended uses of the building
- History and changes to the building

Relevant information to determine human needs includes

- Numbers of staff and visitors and their current and/or intended activities
- Current and intended uses of spaces
- Expected kinds of clothing (which can vary in historic properties)

For a new institution, data gathering may involve plans and blueprints, and collection policies, rather than assessments of specific collections, but information that can help determine needs can be found in a range of sources. In operating cultural institutions, a collection risk assessment and/or condition survey may have been carried out for the collection, which would include most of this information. Collection needs are described more comprehensively in the sections on Overview of Risks and Environmental Effects on Collections.

3.3 CURRENT ENVIRONMENT

Analyzing and understanding the past and current environmental conditions in and surrounding the buildings, and the interactions among climates, buildings, people, and collections, is essential to developing appropriate environmental management, even if no intervention is carried out in the cultural heritage institution. Information relevant to understanding the influence of the environment on the building, collection, and people includes climate zone and predicted climate change, site macrocontext and morphology, the building and its orientation, existing methods of environmental control, and monitoring data on each hazard (temperature, relative humidity, pollutants, and light) both indoors and outdoors. This often requires a year of data collection, particularly for seasonally affected parameters such as temperature and relative humidity. These data are collected regularly in cultural institutions, but the points of measurement, sampling interval, and reasons for monitoring should be reviewed. A building management system (BMS) may provide useful information about existing environmental management, particularly with respect to human comfort, but in general, climate monitoring should be independent from the system that is used to control climate, and it may be necessary for data to be gathered close to objects.

Other contextual factors to consider include staff, their roles, institutional policies, operating costs, and energy use, as well as an institution's budget. Each institution should seek to understand its pattern of energy consumption and recognize the most energy-intensive activities, which usually include lighting; appliance use; and mechanical ventilation, heating, and cooling. The sampling interval for monitoring energy use should be short enough (typically 1 h or less) to evaluate daily energy consumption patterns. Energy consumption should be evaluated according to existing national or international regulations, and compared with existing benchmarking systems or, if no benchmarks are available, with energy consumption in similar cultural institutions. For further discussion on environmental context, see the section on Climate Loads.

3.4 OVERVIEW OF RISKS

The impact of the environment on materials can only be understood when both the environmental conditions and material properties are known. By connecting preservation needs to materials' responses to environmental conditions, expected changes can be understood. Considering information about the institution's values and assets along with material change clarifies decisions about future risk and priorities. Synthesizing the impact requires an overview of which factors are most important and how the collections are affected by the building and people, and vice versa; mitigating risk to one aspect may increase risk to another. Integrating the information allows a comprehensive definition of the situation, because criteria vary between institutions: for example, historic houses may place more emphasis on preserving the building than a new museum might.

Understanding this impact allows comparison to other general risks (see Table 2). Developing this overview allows an institution to prioritize needs, allocate resources, and develop goals for the development of a strategy. Much of this information may already exist in the form of a risk assessment. For further discussion of collection risks, see the section on Overview of Risks.

3.5 ACCEPT OR MODIFY ENVIRONMENT

Once information has been gathered and synthesized, modifications to the environment may be considered. If the current environment is appropriate for the institution's identified needs, goals, and resources, the most appropriate decision can be to do nothing at the present time and continue monitoring. Other priorities in the institution may take precedence.

For an operating institution, changes to existing building management and/or modifications to the building envelope may be appropriate ways to address the identified risks or high energy consumption. Problems can be addressed without directly modifying the environment, by adjusting locations and activities such as changes in circulation patterns, use of selected spaces, and exhibition policies. Dividing collections by material type is a common measure, particularly in storage locations. When planning a new building, managing the risks most relevant to the institution's mission should be addressed early, with careful consideration of building morphology, envelope characteristics, and expected energy use, as recommended by the International Institute for Conservation of Historic and Artistic Works and the International Council of Museums Committee for Conservation (IIC/ICOM-CC 2014).

Environmental modification may involve direct intervention, either mechanical or nonmechanical; passive design measures are also available. There is no risk-free scenario, and any decision must take into account available resources and the impact on the institution as a whole, as well as overall environmental impact. Even after the initial diagnosis of risks, it is likely that this consideration may require further investment and expertise before a final plan can be developed.

Regardless of how big or small the expected changes to the environment or management, monitoring should be carried out to further investigate problems or check for simple solutions.

For related information, see the section on Preservation and Risk Management.

3.6 ANALYZE/PREDICT ACHIEVABLE ENVIRONMENTS AND IMPEDIMENTS

If it is decided that a comprehensive solution is required, further analysis (e.g., diagnostic monitoring, hygrothermal modelling of indoor spaces, deeper investigation of existing control methods) will be necessary. Assessing information already gathered indicates what environments can realistically be achieved in a given climate zone with existing control methods, or the expected impact of proposed changes in the building envelope or type of environmental control.

Comparing what environment can be achieved in the current or planned space with what is identified as necessary for collection preservation indicates the kind and level of intervention that is appropriate. This could include energy-saving options where a collection's sensitivity is lower than the tightest level of control that can be managed (see Tables 13A and 13B), or a new approach to environmental management in the institution. For new buildings, this step presents an opportunity to consider appropriate parameters and objectives for different needs in the proposed spaces based on their (potentially mixed) use.

The sections on Environmental Effects on Collections and on Design Parameters for Performance Target Specifications contain further discussion of environment and impediments.

3.7 SET PARAMETERS AND OBJECTIVES

Understanding what is required to sustain the collection over time, and to ensure access to and use of the collection, is essential. Knowing the resources necessary to accomplish this, as well as what is achievable with the building envelope, the environmental parameters can be agreed upon. The expected lifetime of a collection, or its desired rate of deterioration, can be reviewed at this point, which may require input from a conservation scientist. Many collections comprise a mix of materials with differing preservation qualities. If a collection largely comprises a limited range of materials, or if materials can be easily separated from one another, specific information about the responses of those materials to environmental conditions can be directly applied. If the collection has been in the same environment for a long time (usually longer than 10 years), it will have had time to acclimatize to those conditions. Tables 13A and 13B provide information on the expected implications (outcomes) of different kinds of climatic control for mixed collections.

These parameters also must take into account human comfort (see ASHRAE *Standard* 55-2017) and cost implications.

The sections on Environmental Effects on Collections and on Design Parameters for Performance Target Specifications contain further discussion of parameters and objectives.

3.8 DEVELOP OPTIONS

How the environment is managed (according to agreed-upon parameters and objectives) has multiple implications, not just for the collection and costs (financial and energy consumption), but also on facility operations. Even in small interventions, staff should have access to the information because simple measures can affect other activities, such as security or audience engagement events. A clear understanding of the resources available, including budget, staff roles, time, training, and space, is needed for control options to be developed and evaluated.

For a new building, the solution may be part of a larger, integrated approach. HVAC design options should first consider the building as a means of control (see Tables 12, 13A, and 13B).

For more details, see the section on Design Parameters for Performance Target Specifications, and ASHRAE *Guideline* 34-2018.

3.9 REVIEW OPTIONS AND SELECT

Many criteria may be involved in selecting the most appropriate approaches to environmental management. A method to determine consensus should be decided upon, and the key stakeholders for the project identified. All staff affected by environmental management should be consulted (or represented) in terms of how the options meet the chosen criteria. This is often best carried out through facilitated, recorded meetings where criteria are addressed systematically and transparently (Cassar 1995). Such processes present the opportunity to examine different perspectives and resolve apparent conflict through discussion. Results should be archived for future reference.

Criteria for evaluating approaches to environmental management may well go beyond collection preservation and cost, to include issues such as impact on historic building fabric and human comfort. For example, historic houses can be adversely affected by installation of mechanical systems. A cultural institution's mission statement can be a useful reference point to weigh the importance of criteria. This stage distills much of the information gathered earlier in a clear, digestible form for all stakeholders, so informed decisions can be reached collaboratively.

3.10 PREDESIGN PROGRAM BRIEF

This is an opportunity for owner's requirements to be defined before the solution is designed, including approach, scope, design team, and timeline. In some cases, a design engineer might not be engaged until after creation of the program brief.

While setting criteria for the design team, solutions outside the scope of the design team (e.g., housing objects in display cases or archival boxes) should be part of the overall project effort. This again allows project goals to be aligned with the institution's wider mission and other goals. A range of stakeholders already engaged in the process will be involved in planning and construction, so a clear shared vision helps the cultural institution work through the development.

3.11 DESIGN OF SOLUTION

Although design of the solution is discussed more comprehensively later in the chapter, some considerations can be addressed during predesign. All needs identified while developing the predesign program brief should be communicated, and a liaison with collection and building staff should be identified. The solution may not yet be designed, but if the general approach is known, decisions can be made about whether to move collections before work begins. Rehousing a collection requires considerable time, including measures for documentation (e.g., database, photography, radiofrequency identification [RFID]) and security, as well as environmental management. If the collections are not being moved, preparation for extra protection may be needed during an implementation phase. Depending on the approach, projected growth of the collection may also be a consideration during predesign.

3.12 PROCUREMENT AND CONSTRUCTION

Procurement and construction are discussed in more detail later in the chapter, but there are opportunities to prepare for this stage. A risk assessment may be required for the designed solution (especially if the collection is moving). Information from the context and predesign phases about the values of the collection and building is relevant and should be accessible. For larger projects, a dedicated collections professional responsible for oversight of collections preservation issues during construction may be engaged.

Cultural institutions often have historic buildings that are intended to last for a long time. The life cycle of materials, and any impact of the solution on historic values, should be understood by all parties.

3.13 START-UP AND COMMISSIONING

Commissioning and start-up are discussed later in the chapter. A commissioning agent should be identified and engaged during final predesign and early design stages, so they understand the underlying design goals and can be present through the process.

3.14 TRAINING AND DOCUMENTATION

Training and documentation are discussed later in the chapter, but the data gathering that has already occurred should be instructive to this process. Understanding and documenting current management and maintenance practices can help communicate in-house skills and expertise to the design team. Time during a project may need to be put aside for training, and a realistic understanding of institutional and staff capacity is required before implementing a design option. Staff changes over the time horizon of larger projects may also need to be considered.

Table 2 Agents of Deterioration: Potential Hazards in Managing Collection Environments

Agent	Comments
Physical forces	Handling, shock, and vibration can cause immediate or accumulative long-term damage to fragile objects. Risks often increase during construction work, when collections may have to be relocated or secured in situ. Mechanical systems may present a risk if vibration is transmitted through ductwork to works hung on adjacent walls or in particularly active air drafts. Vibration transmitted to objects may cause them to move, and to fall off of exhibit and/or storage shelves.
Thieves and vandals	Can be addressed by limiting access to mechanical systems to improve security.
Fire*	Fire (and its related methods of extinction) can result in serious damage or even total loss of building(s), collections, operations, and services. Fire prevention and control, aimed at reducing the risk of a fire occurring and minimizing its effects, should be given the highest priority possible. It is recommended that each HVAC system be integrated with a fire detection system, ensuring that the system is shut down in a fire alarm to limit the spread of fire, smoke, and soot.
Water*	Liquid water (including rain, flood water, or water from broken pipes) is often related to incidents and disasters, but also includes dampness resulting from condensation and rising damp in buildings. Liquid water is very destructive to collections: it can stain, deform, or even dissolve materials. Wet conditions can quickly germinate mold, fungi, and bacteria, creating hazardous conditions for human health.
Pests	Infestations primarily include insects devouring collections; mold, fungi, and bacteria also qualify as pests. Limitation measures include avoiding high relative humidity and warm conditions, maintaining overall cleanliness, and controlling indoor air quality and ventilation (which helps reduce temperature gradients and thus relative humidity).
Pollutants (or contaminants)	Includes outdoor-generated gaseous and particulate contaminants that infiltrate the building and indoor-generated gaseous pollutants. Sources and effects of pollutants are detailed in the section on Airborne Pollutants/Contaminants. Particulate filtration to control both coarse and fine particles and gaseous filtration is discussed in the section on Airborne Pollutant Control Strategies.
Light (or radiation)	Most materials undergo some form of permanent photochemical or photophysical change from exposure to radiation (i.e., visible, infrared [IR], and ultraviolet [UV] light), which is an inevitable consequence of display. Light damage is cumulative but relatively easy to control if addressed at architectural, design, and operational levels by eliminating ultraviolet radiation, minimizing infrared radiation, and limiting light exposure by decreasing illumination intensity or its duration.
Temperature	When temperature increases, damaging chemical processes accelerate. Any temperature change affects the absolute humidity in the air, resulting in changes in relative humidity. Relative humidity and temperature are often considered together when deciding on a climate control strategy, especially for susceptible classes of materials such as early synthetics (plastics), paper, and photography.* See the section on Temperature and Humidity for details.
Relative humidity	Each organic/hygroscopic material has a specific level of moisture content consistent with maximum chemical, physical, or biological stability. Relative humidity becomes a risk factor when it causes the moisture content in a material to be significantly too low or too high. Fluctuating relative humidity with large and prolonged variation in levels can also be damaging, specifically to objects of composite materials and/or restrained constructions. Inorganic (nonhygroscopic) materials can also be adversely affected by moisture in the air (e.g., corrosion of metals, salt efflorescence in porous materials). See the section on Temperature and Humidity for details.

*Fire and water are often associated with building and mechanical (design) malfunctions, such as power outages, electrical short circuits or water pipe failure (especially over spaces containing collections). These failures are infrequent but do happen, and it is important to remember that a single failure could ruin a significant portion of a collection. Every effort should be made to route water lines and other utilities away from areas that house collections. Building systems also rely on the infrastructure to provide utilities and communications. Where the infrastructure is not reliable or is of inadequate capacity, provisions should be made for temporary or alternative supply.

3.15 EVALUATE AND REVISE

This step is addressed later in the chapter, but data gathered at any early stage can help serve as a baseline for evaluating the solution, and should be documented and archived for future reference. This includes data on climate and pollution as well as energy costs. How environmental monitoring is carried out during predesign should inform continued monitoring beyond implementation of the solution.

4. OVERVIEW OF RISKS

A collection's longevity is directly influenced by the building's architecture, any climate control systems (nonmechanical or mechanical), and existing preservation procedures and protocols. These may positively mitigate the impact of risks or, alternatively, exacerbate them. Mechanical engineers need to consider the risks for collections even if they do not appear to relate directly to a building's mechanical systems. The hazards listed in Table 2 are called **agents of deterioration** in the conservation field and may affect collections. Note that there can be interactions between different agents of deterioration, and many hazards are created by several agents in conjunction with one another (CCI 2018). Assessments are often used to identify the potential impact or magnitude of a risk occurring.

Any climate control strategy should complement mitigation strategies for other risks and should not in itself create a greater hazard (e.g., when an energy supply fails, or when an active HVAC system spreads fire or soot if no automatic HVAC shutdown is provided).

Table 2 does not cover natural emergencies, which are often devastating and have effects beyond the institution. Institutions (should) have emergency response policies in place to deal with incidents, emergencies and disasters.

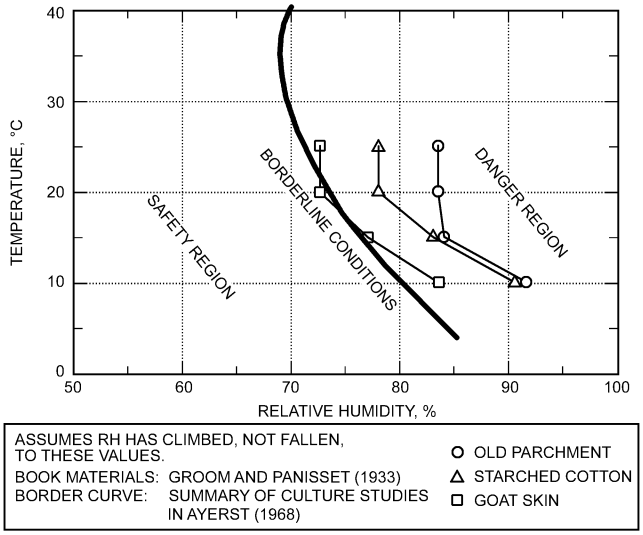


Fig. 2 Temperature and Humidity for Visible Mold in 100 to 200 days

5. ENVIRONMENTAL EFFECTS ON COLLECTIONS

Providing specialized temperature and relative humidity control has been central to museum, gallery, archive, and library design since the nineteenth century, and numerous architectural and HVAC solutions have been explored. Luciani (2013) provides a detailed history of these engineering and architectural solutions throughout the twentieth century in North America and Europe. Until recently, temperature and relative humidity specifications were based on cautiously applied qualitative understanding (Michalski 2016), rather than quantitative understanding applied to decisions influenced by sustainability. This section summarizes the technical knowledge available to support current decisions, particularly when selecting or modifying targets.

5.1 BIOLOGICAL DAMAGE

High relative humidity levels and dampness accelerate mold growth on most surfaces. Of all HVAC-controllable environmental parameters, high humidity is the most important factor.

The most comprehensive mold data are from the feed and food literature. Fortunately, this provides a conservative outer limit to dangerous conditions. Mold on museum objects occurs first on surfaces contaminated with dust, sugars, starch, oils, etc., but can also occur on objects made of grass, skin, bone, and other feed- or food-like materials. Water activity is identical to and always measured as the equilibrium relative humidity of air adjacent to the material. This provides a better measure than the equilibrium moisture content (emc) for mold germination and growth on a wide variety of materials (Beuchat 1987). Figure 2 shows the combined role of temperature and relative humidity. A study by Groom and Panisset (1933) of the most vulnerable book materials concurs with the general trend of culture studies from Ayerst (1968) and comprehensive data on mold growth in buildings obtained by Sedlbauer (2001). Ohtsuki (1990) reported microscopic mold occurring on clean metal surfaces at 60% rh. The fungal DNA helix is known to collapse near 55% rh (Beuchat 1987), so a conservative limit for no mold ever, on anything, at any temperature, is below 60% rh. Chapter 26 suggests a similar lower boundary to avoid mold in food crops.

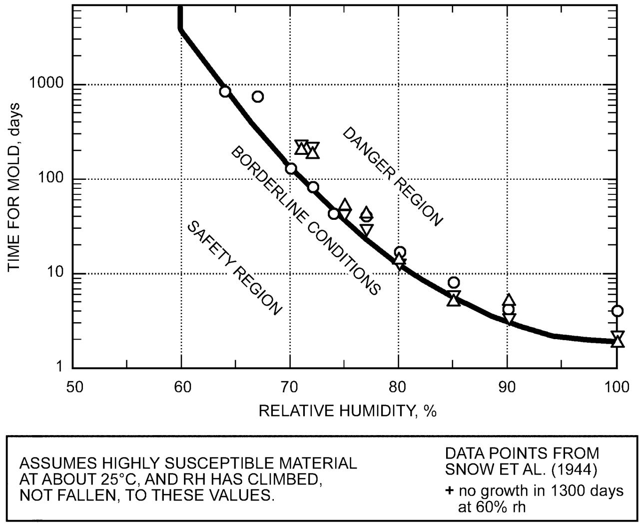


Fig. 3 Time Required for Visible Mold Growth

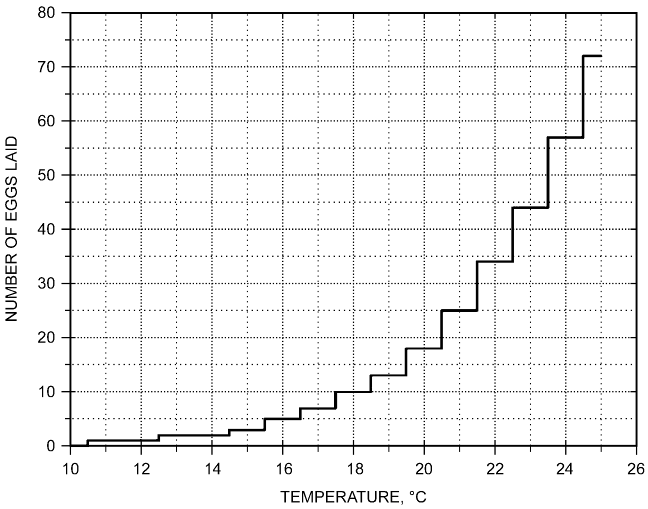


Fig. 4 Number of Eggs Laid by Webbing Cloth Moth (*Tieneola bisselliella*) as Function of Temperature

Snow et al. (1944) looked for visible mold growth on materials inoculated with a mixture of mold species. These are plotted in Figure 3, and follow the same trend reported by Hens (1993) for the European building industry for wall mold.

Figures 2 and 3 show practical dangers: growth in less than a summer season requires over 70% rh, and growth in less than a week requires over 85% rh. Care must be taken to avoid cold surfaces where condensation might occur, such as on windows and ductwork.

There are relatively few experimental data on the relationship between the risk of insect infestation and climate parameters (Strang 2012). Child (2007) and Pinniger (2001) suggest that, below 15°C, pests that can damage cultural heritage collections start to be sluggish and do not fly. Also, low relative humidity further limits pest risk because eggs and young larvae are sensitive to dehydration. Child (2007) reported that the furniture beetle (*Anobium punctatum*) require relative humidity levels above 60% to reproduce. A risk index quantifying the threat of pest infestation was proposed by Brimblecombe and Lankester (2013). As shown in Figure 4, the number of eggs laid by the webbing cloth moth depends on T according to the following relationship:

$$E = \int \left\{ 130 \exp \left[-\left(\frac{T^2}{30} - 30 \right) / 12 \right]^2 \right\}$$

5.2 MECHANICAL DAMAGE

Very low or fluctuating relative humidity or temperature can lead to mechanical damage of objects. The fundamental cause is the expansion and contraction of materials, combined with some form of internal or external restraint. Hygroscopic materials absorb moisture when relative humidity rises and desorb moisture when relative humidity falls, causing change in dimensions. Dimensional change caused by temperature change is more rapid, but much smaller than that caused by relative humidity in hygroscopic materials. When the dimensional change of a component in an object is restrained, the component is strained and stressed. Components can be fully restrained by another, stronger, immobile component; partially restrained when connected to a component with a different coefficient of expansion; or restrained within themselves when experiencing a gradient in moisture or temperature. Beyond a critical stress or strain point, irreversible deformation or fracture occurs.

Concerns about mechanical damage from temperature and relative humidity fluctuations have led to extremely narrow specifications, such as 21 ± 1°C and 50 ± 3% rh (LaFontaine 1979). These "best-available technology" specifications were based on the assumption that, because very large fluctuations could be seen to cause obvious damage, any size of fluctuation must bring some degree of damage. Revisions to this assumption, based on limited quantitative research, drove the first (1999) edition of this chapter. Recent research has further strengthened the need for a more flexible approach to climate control for museum collections.

The materials most sensitive to temperature and relative humidity fluctuations are all hygroscopic polymers, whether complex natural mixtures such as wood, paper, leather, or parchment, or processed products such as animal glue, oil paints, acrylic paints, or cellulose acetate. The stress or strain that causes fracture depends on the amplitude and rate of any temperature or relative humidity change. Low temperatures, fast rates of strain, and low relative humidity lead to brittle "glassy" behavior with small tolerable strains, whereas high temperatures, slow rates of strain, and high relative humidity lead to more "rubbery" behavior and large tolerable strains. The transition between these two behaviors occurs at the polymer's **glass transition temperature**, which is a gradual change over a range that is typically10 to 20 K wide (Hagan 2017; Michalski 1991).

Some materials, such as paints, are in their flexible but tough state at room temperature. When temperature drops, these materials become increasingly brittle and fragile: artists' acrylic and oil paints enter their glassy states in the range of 10 to 0°C (Daly Hartin et al. 2018; Hagan 2017; Mecklenburg and Tumosa 1991). In this temperature range, risk of fracture from small errors in handling greatly increases.

Other materials, such as animal glue, paper size, and photographic gelatin, are in their hard but strong state at room temperature. High relative humidity (>75% rh), however, pushes them into their rubbery state (sticky and weak) because of the plasticizing effect of moisture (Karpowicz 1989; Krzemien et al. 2016; Mecklenburg 1991; Michalski 1991). Wood can be more easily deformed over 75% rh; if constrained in a cabinetry joint, a wood component will be permanently deformed by high relative humidity. This leads to tensile fracture of the component if it is restrained during its return to a middle (or low) humidity.

Simple models of uniformly constrained material, combined with data on the mechanical properties of painting materials in particular, suggested that a fluctuation of approximately 15% rh was tolerable within the elastic limits of such materials (Erhardt and Mecklenburg 1994; Erlebacher et al. 1992; Mecklenburg and Tumosa 1991, 2005; Mecklenburg et al. 1998; Michalski 1991, 1993). More detailed research has since emerged: Jakieła et al. (2008) used numerical modelling of large pieces of wood, as used in sculptures, to show a tolerable fluctuation of 15% rh (in the 25 to 75% rh range). Tantideeravit et al. (2013) showed similar tolerance using finite element modelling for delamination in paint, as did Bratasz et al. (2015) for historic textiles. Overall, the last decade of work with more detailed material data and more complex models has confirmed that, for materials found in collections, uniformly constrained components tolerate fluctuations of at least ±10% rh, whereas fluctuations beyond 20% rh cause rapidly increasing risk of fracture.

Three large practical factors must be added to any simple model based on uniform restraint: stress relaxation, stress concentration, and proofed fluctuation.

Stress relaxation results from the shift over time from glassy to rubbery behavior. Wood will stretch more than twice as much across the grain before fracturing if the strain is applied slowly over 3 months rather than over the course of one day (Madsen 1975). Even highly pigmented oil paint (ground), which has only very gradual relaxation, experiences only half the stress of a 10 min event if that same strain is applied gradually over 3 months (Daly Hartin et al. 2018). This general tendency to relax to about half the stress when comparing cycles lasting hours to those lasting months is the justification for equating the risk from a seasonal adjustment of 10% rh to a short-term increment of 5% rh for Types A1 and A2 in Table 13A.

Stress concentration is well known to engineers, and can be described as the increase in local stress because of a flaw, groove, hole, or narrowing of the component. The fracture pattern (cracks starting at these weak points) is familiar to conservators. Stress concentration was used to help construct categories in Table 3. Objects that fit uniform restraint models are in the category of medium sensitivity (i.e., stress concentration of ~1); values around 2 indicate high sensitivity, and 3 and above are very high sensitivity. These include assemblies where a weak layer bridges a joint in strong components that either diverge or shear during relative humidity change. Low-sensitivity assemblies do not restrain any components (e.g., sheets of paper or thin wood free to expand and contract).

Proofed fluctuation is the phenomenon whereby restrained components that have already fractured because of an excessive fluctuation in the past will not fracture further until a fluctuation exceeds that historic "proofed" fluctuation (Michalski 1993, 2014). Consequently, higher-sensitivity objects in Table 3 move to lower sensitivity categories, and a collection's sensitivity both diminishes and becomes less varied. Proofed fluctuation has become part of some standards (e.g., Ente Italiano di Normazione [UNI] *Standard* 10969) and has been refined to include **fatigue**: repetitive fluctuations must accumulate as many cycles as have already occurred before there is significant risk of new fracture (i.e., when partway along an *S-N* fatigue plot depicting stress *S* against the number of cycles *N* to failure, one must move significantly along the *N* scale to grow the fracture). Michalski (2014) created a graphic tool using *S-N* plots for estimating tolerable fluctuations, given a known history of fluctuations.

Proofed fluctuation implies that improved climate control beyond the historic pattern for a collection cannot be justified easily on the basis of mechanical risks, unless there is an active program of restoration of fractured objects, which erases proofed fluctuations. (Chemical and biological deterioration have no such limiting concept: they accumulate up to the point of total destruction.) Proofed fluctuation also clarifies the type of climate control risk that does warrant careful mitigation: the probability of extreme fluctuations beyond the proofed fluctuations (e.g., during HVAC system malfunction). The time span for judging reliability in museums is 100

Table 3 Sensitivity of Unproofed Objects to Relative Humidity Fluctuations[a]

Objects and Effects of Fluctuations	Low Sensitivity	Medium Sensitivity	High Sensitivity	Very High Sensitivity[b]
Flat sheets of paper, film, tape, leather, parchment, metal, with image or data layer. May delaminate, fracture, or distort permanently.	**Support layer with finely dispersed image/data layers.** Includes most single sheets of paper with print, halftones, line drawings, inks, washes. **Laminates with low differences in expansion.** Includes most case-bound books (not leather or parchment book covers). Most CDs. Commercial signs painted on metal.	**Layered structures with moderate strength, moderate differences in expansion.** Includes most photographs, negatives, and film. Most magnetic records. Thin, well adhered inks on parchment, such as deeds. Gouache on paper. Book bindings of vellum and/or wood. Gilded parchment, leather.	**Layered structures with poor strength, moderate to high differences in expansion.** Includes thick images on parchment. Globes. Thick oil-resin images on paper or cloth. Objects listed as medium vulnerability that have weakened substantially because of UV exposure, or aging already causing flaking.	**Large reactive (to fluctuations) sheets restrained at periphery**. Includes large paper sheets adhered to stretchers, 19th-century photos on fabric and stretchers. Large prints adhered at all four corners (usually tear near the point of restraint).
Wood or wood assemblies. May crack, split, delaminate, or distort permanently.	**Single wood components, or assemblies designed to eliminate stresses.** Includes floating panels in furniture or room paneling; tongue-and-groove planking nailed or bolted on edge only (e.g., wainscoting), wood boxes on farm machinery (unless jammed because of painting, warping), hollowed-out totem poles, wooden tool handles. **Assemblies with prior damage that allows stress release.** Includes most old tables where all screws and joints are loose, any panels already split.	**Wood assemblies with uniformly distributed stresses during fluctuations.** Includes most plain wood furniture with tight joints, no prior splits, most veneers and marquetry that cover a continuous piece below, such as most 18th- and 19th-century chests of drawers. Furniture made with plywoods, such as Victorian catalog pieces. Fluctuation to higher relative humidity may not always cause visible damage, because many joints/panels are invisibly crushed, but this makes them more likely to split during lower relative humidity. **Large wooden objects.** Outer layers are constrained uniformly by the inner core because of gradient in response to relative humidity change.	**Wood assemblies with concentration of stresses during fluctuations.** Includes veneer over corner joints, such as many wardrobe doors, Art Deco furniture. Fretwork applied wooden ornaments. Assemblies with bolts, nails, screws that hold both sides of a single plank. Many musical instruments.	**Wood assemblies with attached or inlaid metal, horn, shell, etc., that spans more than 10 mm across the wood grain.** Attachment or inlays may delaminate or buckle. Includes masks with adhered shell, 18th- and 19th-century fine furniture, clocks with inlays.
Pigmented coatings on a support: paintings, gilding, lacquer. May crack, delaminate, flake.	**Acrylic paintings on canvas.** Includes many paintings since 1960 (may move to medium sensitivity if a heavy glue size was used, or if adhesion between layers is poor).	**Rigid paint layers on canvas, in moderate to good condition.** Includes most oil paintings on canvas (may move to high sensitivity if weakened by water damage or great age). Definitely move to high sensitivity if stretched too tight, or tightened during high relative humidity. Note: fluctuation from low relative humidity is a much higher risk to paintings on fabric than from high relative humidity; however, over 85% rh may cause canvas shrinkage and flaking of the ground plus paint layers Includes oil paint, gilding on narrow spans of wood, gilt furniture, picture frames.	**Oil paint, gilding, on wide spans of wood, or paint on other organic rigid supports with weak adhesion.** Includes most panel paintings, wide gilded panels. If seams are flawed, with rigid fills, etc., then may become very high sensitivity. Miniatures on ivory, because of poor adhesion and undulations of some ivories. Heavy modern paintings on smooth side of fiber-board may delaminate because of weak adhesion.	**Paint layers bridging seams or flaws that concentrate stress**. Includes polychromes, painted furniture, painted architectural wood elements. Note that hairline cracks over joints of doors or painting frames are usually considered normal, but not those in heavily lacquered furniture.
Other organic objects.	**Woven organic materials without edge restraints.** Includes most basketry. Textiles such as blankets, flags, simple costumes.	**High crimp woven organic materials with edge restraints.** May tear during fluctuation to high relative humidity. Includes needlepoint fixed to a stretcher.	N/A	N/A
Organic materials with zero stress level at 100% rh.			Includes teeth, boats made from stretched leather on rigid construction. Crack when relative humidity drops below critical level (e.g., teeth below 50% rh).	
Other objects where ratcheting mechanism may exist.			Objects where small parts continuously dislocate and block expansion of object. Elephant tusk positioned downwards: small parts fall down gravitationally during low relative humidity period and block material expansion during rises of relative humidity.	

[a] Vulnerability assumes objects can fully respond to fluctuation. Objects in enclosures take many days or weeks to respond. See Table 8 for response time of objects.

[b] These objects are very rare: they break rules of craftsmanship and will have already failed unless relative humidity has never fluctuated since fabrication. Alternatively, these are objects that underwent overly interventive and inflexible restoration.

years. Catastrophes of mechanical damage to collections are usually caused by a system failure that causes novel conditions, compounded by a failure of rapid response (monitoring failure).

Two types of observational studies of historic objects in uncontrolled spaces are confirming these models: acoustic emission and visual evidence. Strojecki et al. (2014) applied acoustic emission to a 1785 wardrobe that was high sensitivity when new (veneer bridging many seams in structural wood components, some of which have fractured). It is on permanent display in a type D (see Table 13A) controlled museum (20 to 65% rh short term, 30 to 50% 30 day average), so it has been proofed to the building's historic climate pattern. A year of acoustic emission established that fracture because of fatigue is growing only very slowly, on the order of 13 mm/century. Given that the existing crack is at least 100 times longer, growth is decelerating. Bratasz and Vaziri Sereshk (2018) demonstrated an upper limit to craquelure growth as well, which they call "crack saturation". Ekelund et al. (2018) compared the current state of cracks in similar pieces of furniture to old photographs and established that current variations of at least ±20% rh and ±10 K did not increase visible damage. Oreszczyn et al. (1994) compared visible damage differences between collections in historic houses with "improved" climate control and those without, and saw none. Highly sensitive techniques for measuring distortions are giving similar evidence (Lasyk et al. 2012).

Overall, it is new (unproofed) or restored objects with erased proofed fluctuations that are more likely to be sensitive, not old (proofed) objects. The rare large fluctuations are the greatest risks, not the frequent and small ones. Very-long-term reliability and ease of rapid repair (before collections fully respond) are more important than trimming ripples in hourly climate data. The section on Temperature and Relative Humidity defines different levels of control of fluctuations (AA, A1, A2, B, C, and D). The most stringent level, AA control within ±5% rh, can only be justified if there are unproofed objects of very high sensitivity, if the small risk of fatigue fracture is unacceptable, and if all larger risks have been controlled. For many collections, either A1, A2, B, C, or D will provide suitable control of the remaining risks of fracture.

5.3 CHEMICAL DAMAGE

This section is not intended to replace the use of standards available for cold storage of collections, listed in Table 4. Standards consider not just the benefits of low temperature and low relative humidity, but also their side effects, their management, and critical procedures that are beyond the scope of this chapter. The ranges in Table 4 are not specific recommendations; rather, they only show the maximum range of conditions cited as various recommendations in each standard.

Both ISO *Standard* 18934 and the Image Permanence Institute (IPI; Adelstein 2009) provide definitions for four temperature terms: room, cool, cold, and either subzero (ISO) or frozen (IPI). This chapter uses *frozen* (although it unfortunately could imply that equilibrium moisture in hygroscopic materials goes through a phase transition and freezes like bulk water, which it does not.) IPI (Adelstein 2009) defines the first three terms by "anchor points" rather than ranges: 20°C, 12°C, and 4°C. These anchor points are used in Table 5.

Relative Humidity

The National Archives and Records Administration (NARA 2013) changed relative humidity control from a steady 45% rh to a permissible seasonal swing between 30% and 50% rh. They estimated a savings of $650 000 per year in utility costs as well as an increase of 20% in collection lifetime. This section enables quantitative answers to very common questions about sustainable variations on fixed standards: how much do benefits change with adjustments in temperature and relative humidity? How much does risk climb during high temperature and high humidity? Are seasonal adjustments possible for energy saving? What are the risks during retrieval? This section is also a reminder that not only archives, but all collections with low-stability objects listed in Table 5, can benefit from low temperature.

Table 4 ISO Storage Standards for Collections that Use Cold Storage

ISO Number	Collections Covered	Range of Relative Humidity	Range of *T*
18911:2010	Photographic films (except nitrate)	20 to 50%	0 to 7°C
18920:2011	Photographic prints	30 to 50%	2 to 16°C
18923:2000	Magnetic tape	15 to 50%	2 to 16°C
18934:2011	Multiple media	30 to 50%	Room: 16 to 23°C Cool: 8 to 16°C Cold: 0 to 8°C Frozen –20 to 0°C

Lower temperature reduces the rate of all forms of chemical decay. For the most rapidly decaying organic materials (right-hand columns of Table 5), the dominant mechanism is acid hydrolysis, which increases strongly with the acidity of the material, and increases with moisture content (Zou et al. 1996). Moisture content, in turn, depends on relative humidity. The consensus is that the rate of decay (or its reciprocal, lifetime) is a product of an acidity factor, a temperature factor, and a relative humidity factor (which sometimes includes a correction dependent on temperature).

$$L = f(\mathrm{pH})\, f(T)\, f[\mathrm{rh}(T)] \qquad (1)$$

where L is lifetime, in years.

For our purposes, acidity is a given, and only temperature and relative humidity can be controlled. The temperature function is an Arrhenius equation:

$$f(T) = C\exp\left(-\frac{E_a}{RT}\right) \qquad (2)$$

where

C = constant, units of time
R = gas (Boltzmann) constant, 8.134E-3 kJ /mol·K
E_a = activation energy, kJ /mol
T = temperature, K

Michalski (2002) compiled data from reviews of activation energies (notably reviews by Nishimura [1996]) for paper, film, and photographic dyes, as well as further individual studies of magnetic media and the yellowing of varnish. More than three-quarters of all the studies of paper degradation, acetate film degradation, and dark fading of dyes fit within an E_a range of 80 to 120 kJ/mol. In Figure 5, this range is shown by the shaded area. Michalski (2002) further showed that this range of E_a can be derived with no consideration of a specific material, but simply by examining the kinetics of a chemical process that requires several decades to proceed at room temperatures. Thus, both data and theory suggest that this E_a range can be used to estimate the benefits of cold storage, and the risks from high temperature, for all organic materials suspected of being low or very low stability (Table 5). Michalski (2000, 2002) selected a middle value for mixed collections at 100 kJ/mol, shown by the heavy black line in Figure 5. For decay of polyester polyurethane (the weak link in magnetic media, and a popular material with artists in the late twentieth century) and for yellowing of natural resins, the activation energies fall slightly lower, 60 to 80 kJ/mol (between the shaded area and the dashed line in Figure 5.)

Data on the influence of relative humidity are much less extensive than those for temperature, and insufficient to select between differing models. Some authors assume that the true variable is moisture content (Strlic et al. 2015; Zou et al. 1996) and use a

Table 5 Classes of Chemical Stability

High Stability	Medium Stability	Low Stability	Very Low Stability
Wood, glue, linen, cotton, leather, rag paper, parchment, oil paint, egg tempera, watercolor media, gesso. Serviceable examples up to 3 millennia old exist, from dry burial or dry enclosures at ~20°C. These examples were protected from any acid exposure (e.g., air pollution from Industrial Revolution), and have never been damp. Skin, bone, and ivory of the woolly mammoth have survived intact for over 40 000 years while frozen.	Current best estimate for stable photographic materials (e.g., 19th century black-and-white negatives on glass, 20th century black-and-white negatives on polyester film) to remain usable as images with little or no change.	Acidic paper (e.g., newsprint, low-quality books, papers post-1850) and some film become brittle and brown, difficult to access. Acetate film shrinks, image layer cracks. Celluloid and many early plastics become yellow, crack, distort. Natural materials acidified by pollution (textiles, leather) weaken, may disintegrate.	So-called unstable materials. Typical magnetic media (e.g., video/audio/data tapes, floppy disks) begins to be unplayable. Least-stable photographic materials decay (e.g. color prints fade in the dark; poorly processed items yellow, disintegrate; cellulose nitrate yellows, disintegrates, faster when packaged in large amounts). Many elastic polymers, from rubber to polyurethane foams, become brittle, or sticky, or disintegrate. Some acrylic paints on some canvas supports yellow rapidly.

Lifetimes at Various Temperatures*

	High Stability	Medium Stability	Low Stability	Very Low Stability
60°C, heat treat, sun	~4 years +	~1 year	~6 months	2 months
30°C, hot room	~250 years +	~75 years	~25 years	~7 years
25°C, warm room	~500 years +	~150 years	~50 years	~15 years
20°C, room	**Millennia ~1000 years**	**A few centuries ~300 years**	**One human lifetime ~100 years**	**One human generation ~30 years**
12°C, cool	~3200 years +	~1000 years	~320 years	~100 years
4°C, cold	11 000 years +	~3300 years	~1100 years	~330 years
–20°C, frozen	750 000 years +	~225 000 years	~75 000 years	~22 500 years

Source: Modified from the tables "Chemical sensitivity of materials to room temperature" and "Approximate lifetimes of the materials at various temperatures" (Michalski 2018)

**Lifetime* defined here in terms of effects or utility described for each material listed in the top row. Lifetimes expressed in each row have considerable uncertainty, but relative improvement from top to bottom rows is certain.

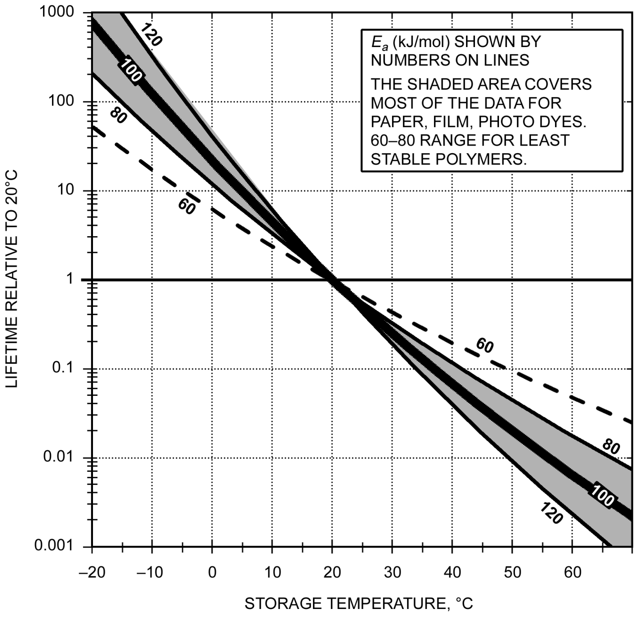


Fig. 5 Effect of Temperature on Lifetime for Various E_a

complex function of relative humidity that includes a temperature correction.

Three advisory tools are currently available: the preservation index (Reilly 1995), Michalski (2000), and Strlic et al. (2015). These tools can be used to derive equations for a lifetime (L_r) relative to the lifetime at room conditions 20°C, 50% rh. These equations have been used to plot lines of constant relative lifetime (also called **isoperms**) on the psychrometric chart in Figure 6. The following equations are all arranged with the temperature and relative humidity components separated for clarity, and with R separated so that E_a becomes explicit as the numerator above RT.

1. Preservation Index, derived principally from acetate film data, but considered applicable to all organic objects as listed in Table 5 (the equation derived from Table 1 in Reilly (1995) fits within 5%); available as a wheel calculator, and as a software tool, from Image Permanence Institute (IPI 2018).

$$L_r = 4.69 \times 10^{-17} \left\{ \exp\left[\frac{94.9}{RT}\right] \exp[\mathrm{rh}(0.02087T - 8.79)] \right\} \tag{3}$$

2. Michalski (2000) derived from a review of data on paper, film, dyes; considered applicable to all organic objects. (Equation (4) was used for a similar figure in previous editions of this chapter.)

$$L_r = 6.17 \times 10^{-19}\ \exp\left(\frac{100}{RT}\right)\left(\frac{1}{\mathrm{rh}}\right)^{1.3} \tag{4}$$

3. Strlic et al. (2015), derived from a review of data on paper; applicable primarily to paper and other cellulosic materials listed in Table 5.

$$L_r = 9.468\times10^{-21}\exp\left(\frac{119}{RT}\right) \exp\left\{-36.72\left[\frac{\ln(1-\mathrm{rh})}{1.67T-741.82}\right]^{\frac{1}{5.7688-0.012T}}\right\} \tag{5}$$

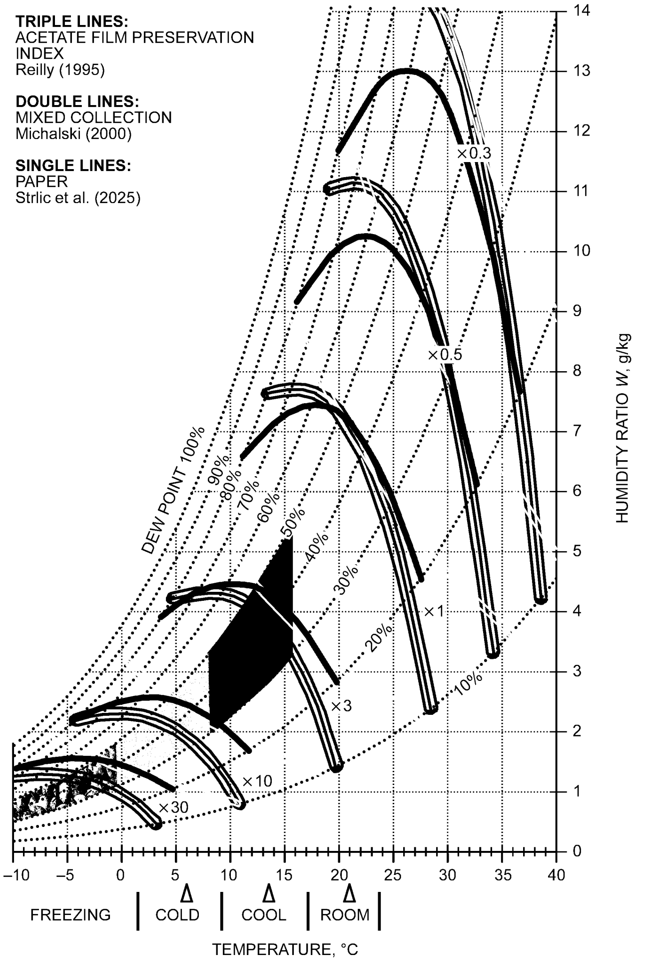


Fig. 6 Lines of Constant Lifetime (Isoperms) for Three Models

Between 20 and 60% rh, differences in the three models are negligible for practical purposes (Figure 6). Beyond this humidity range, the models diverge because of the different functions selected (exponential versus power law), but this is largely irrelevant because relative humidity extremes are usually avoided (mold risk at very high values, and mechanical risks at very low values). The small differences between models on the effect of very low temperature are not because of any differences in opinion about the function (Arrhenius), but on the value of E_a selected, which depends on the particular data set that each author emphasized: acetate film, mixed collections, or acidic paper. The E_as of all three models fit within the shaded area of Figure 5. Essentially, in the range of 20 to 60% rh and for high and low temperatures, any of the three models can be used and will provide the same practical answers.

Temperature

A common technical question beyond the scope of fixed standards is the impact on lifetime of out-of-spec events, or seasonal fluctuations. Estimates can assume a simple linear dependence on relative humidity: for instance, if half the year is at 30% rh and half at 60% rh, then the effective annual relative humidity is the average: 45% rh. Temperature dependence, however, is far from linear, and averages cannot be used. The derived equations are general and users can select a preferred E_a, but the graphs and worked examples assume the middle E_a value of 100 kJ/mol (the small differences of E_a of the three models do not make practical differences).

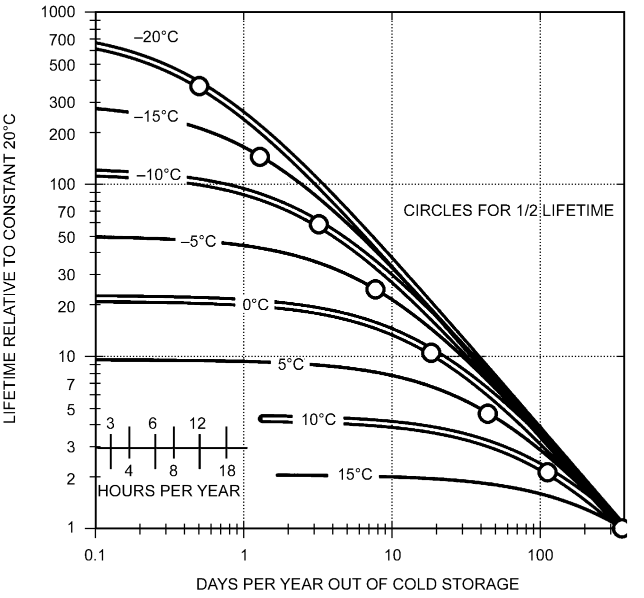


Fig. 7 Effect of Time Out of Cold Storage
(Based on Michalski [2000])

A common query concerns the effect of short periods at higher temperature. The reciprocal of Equation (2) can be used to find the average rate of decay of an object that is normally at a cooler temperature (T_c) but which is at a higher temperature (T_h) for a fraction f of the time. The result for net lifetime is

$$L_r(T_c) = \left\{ f + [(1-f)]\exp\left[\frac{E_a}{R}\left(\frac{1}{T_h} - \frac{1}{T_c}\right)\right]\right\}^{-1} \qquad (6)$$

where

$L_r(T_c)$ = lifetime relative to a lifetime of 1 at T_c
f = fraction of time at hotter temperature
T_c = temperature in colder condition, K
T_h = temperature in hotter condition, K

There are two situations of interest: objects in cold storage that are occasionally retrieved to room temperature, and collections at room temperature that are occasionally exposed to high temperature. Figure 7 plots the relationship for retrieval from cold storage, and Table 6 provides worked examples.

There is no advantage to very low temperature cold storage if the object is retrieved frequently to room temperatures. Cold storage does not reverse the decay that progresses during warm periods. Temperatures for cold storage should be designed considering the expected retrieval pattern. Examples in Table 6 can be considered the break-even point, where the retrieval pattern has cut the potential of the cold temperature by one-half. Lower-temperature storage will not significantly improve remaining lifetime, unless retrieval time also diminishes.

Figure 8 plots the loss of lifetime from chemical risk during periods of high temperatures as compared to room temperature (20°C). An annual accumulation of about 30 days at 40°C cuts lifetimes at 20°C in half. Using high temperatures (e.g., 60°C for pest control should not exceed a total of 6 hours per year (or 60 hours each 10 years) to maintain 90% of normal lifetime; this is a reasonable tradeoff for reducing the risk of massive insect damage.

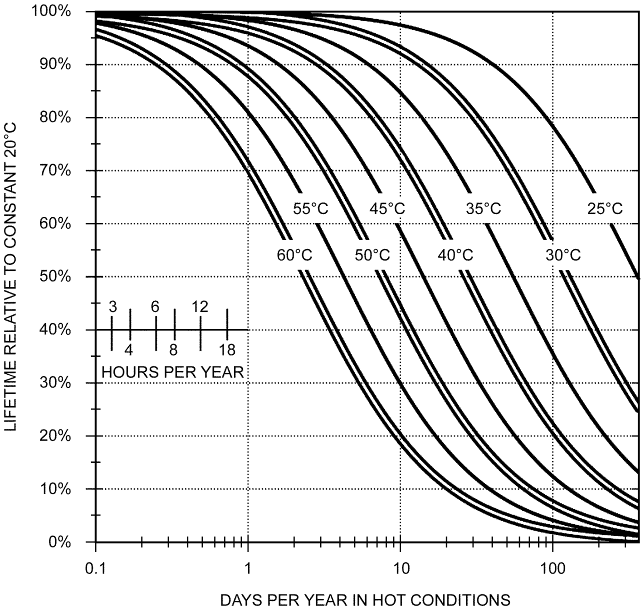


Fig. 8 Reduced Lifetime Caused by Occasional Hot Conditions
(Based on Michalski [2000])

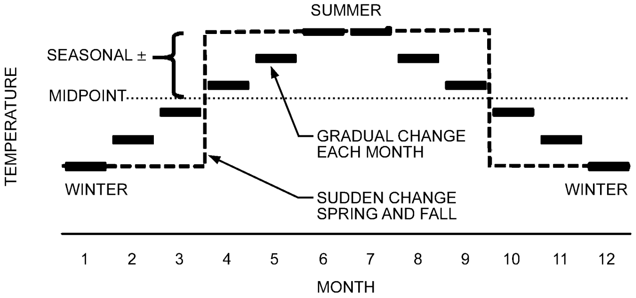


Fig. 9 Seasonal Patterns Used for Sudden and Gradual Changes

Table 6 Object Lifetime and Effects of Time Out of Storage

	20°C	10°C	5°C	0°C	–5°C	–10°C
Relative lifetime compared to 20°C	1	4.4	9.6	21.6	50	120
Lifetime for very low stability objects, years	30	132	298	650	1500	3600
Time out of storage causing 50% loss		107 days/y	42 days/y	18 days/y	7.5 days/y	3.1 days/y
Lifetime remaining		66 y	150 y	325 y	750 y	1800 y

A seasonal swing in temperature can allow energy savings, especially in climates with cold winters. Its benefit to collections with low chemical stability is much more important than the smaller risks from annual temperature fluctuation. Because of the exponential dependence of lifetime on temperature, summer adjustments must be balanced by even larger winter adjustments. If one assumes a typical annual schedule (Figure 9) of two winter months at the lowest temperature, two summer months at the highest temperature, and four months of adjustments through the two swing seasons, then the correction between the midpoint temperature and the effective annual temperature for calculating lifetime is given by Figure 10.

Table 7 Examples of Corrections to Temperature Midpoint

Seasonal ±	Correction	Equal to Constant 10°C	Equal to Constant 20°C
5 K gradual	–1 K	9 ± 5°C	19 ± 5°C
8 K gradual	–2 K	8 ± 10°C	18 ± 10°C
5 K sudden	–2 K	8 ± 5°C	18 ± 5°C
8 K sudden	–4 K	6 ± 10°C	16 ± 10°C

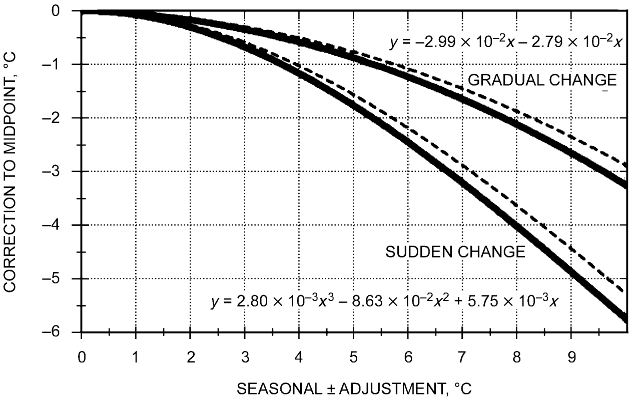


Fig. 10 Correction to Temperature Midpoint Caused by Seasonal Adjustment

The correction alters slightly with the midpoint temperature (the solid lines are for near 0°C, and the dashed lines for near 20°C), but for cautious estimates at any temperature, use the solid lines. Table 7 provides several worked scenarios. For example, when the seasonal adjustment reaches ±5 K or more, almost all aging occurs during the summer months, and winter simply becomes a dormant period in comparison.

Retrieval from cold storage raises the question of whether to build a transition space, and what procedures to use for acclimatization. Two risks are mitigated by a transition space: condensation during retrieval (the major risk) and direct mechanical effects of the temperature change (usually minor). A transition space adds complexity to cold storage construction and operation. In smaller installations, it also represents a large fraction of “lost” storage. The greatest risk of condensation is during reentry to warm conditions or during failure of the cooling system, so it is essential that objects in cold storage always be inside moisture proof packaging or bags, and that these packages not be opened until the object has reached room temperature. This packaging reduces the need for tight control of relative humidity fluctuations in cold storage, because response times are many days or weeks (see Table 8). When moving from extreme cold storage (–20°C), small amounts of condensation can still form inside packages, such as film cans (Padfield 2002) and larger wrapped plastic objects, causing irreversible blanching of some plastics (Shashoua 2004, 2005, 2008) Despite these side effects, cold storage remains the only option for preserving low-chemical-stability materials (Shashoua 2014). Detailed advice for retrieval of paper, film, and magnetic media is available in the ISO standards listed in Table 4.

5.4 CRITICAL RELATIVE HUMIDITY

At a specific critical relative humidity, minerals may hydrate, dehydrate, or deliquesce. When part of a salt-containing porous stone, a corroded metal, or a natural history specimen, these minerals cause disintegration of the object. Distinct critical relative humidity values are known for dozens of minerals in natural history collections (Waller 1992). Pyrites, which are contaminants of most

Table 8 Hygric Half-Times (near 20°C)

Time Range	Objects or Enclosed Objects	Design Implications
A year or more $>10^8$ s	Wooden objects at least 12 mm thick if wrapped in heavy-gage polyethylene (200 μm), with perfect seams. **Enclosures:** Paintings on canvas, paper, or photographs with several layers of matboard (or buffer) framed with glass front and impermeable backing board, perfect seals except for single pressure equalization pinhole, ~15 years. If acrylic sheet, 4 mm, ~11 months (Michalski 2005).	Risk only emerges if annual average space relative humidity is unacceptable to enclosed object.
~10^7 s Weeks to months	Large uncoated wood objects, 100 mm across the grain, 760 mm along end grain, 100 days. Books, exposed only on fore edge, tightly compressed ~25 days, if loosely compressed ~ 11 days (Derluyn et al. 2007). Bigourdan (2012) gives ~18 days, unspecified hardcover book, exposed all sides. **Enclosures:** Spools of 35 mm film inside metal can, 60 days (Adelstein et al. 1997). Paintings on canvas, paper or photographs with several layers of matboard (or buffer) framed with glass front and impermeable backing board, but gaps of 0.1 mm at top and bottom, 30 days. (Michalski 2005).	Hourly and daily relative humidity fluctuations create negligible risk. Seasonal space adjustments smoothed out. System loss lasting less than a week creates little risk.
~10^6 s Days to a week	Old panel painting, back "waterproofed," ~15 days (Stilwell and Knight 1934). Spools of 35 mm film, no can, 4 days (Adelstein et al. 1997). Uncoated wood slab, 22 mm across grain, 160 mm along end grain. Most wooden cabinetry when empty. Ivory, uncoated, handheld **~**25 mm cylindrical (Lafontaine and Wood 1982). **Enclosures:** Paintings on canvas, paper, or photographs with several layers of matboard (or buffer) framed with glass front and impermeable backing board, but gaps of 0.5 mm at top and bottom (Michalski 2005). Hackney (1990) measured at most 6 days with glass frame and coated backing board; gaps must have determined performance. Archive box, paperboard or polypropylene, no holes, full, ~2 days (Batterham and Wignell [2008], estimated from measured damping of external daily fluctuation of ×4.)	Hourly and daily relative humidity fluctuations create little risk. System loss lasting several days can create high risk.
~10^5 s A day	Uncoated wood slab, 8 mm across the grain, 130 mm along end grain. Ivory, uncoated, handheld **~**25 mm cylindrical (Lafontaine and Wood 1982). **Partial enclosures:** Paintings on canvas with continuous paint layer and impermeable backing board applied to frame (Di Pietro and Ligterink 1999).	Hourly relative humidity fluctuations create little risk. System loss lasting all day can create high risk.
~10^4 s Hours	Bare acrylic paint, medium-thick layer. Bare oil paint, alkyd paint, thin layers. Uncoated wood, wood fiber boards, leather, skin, 3 mm thick.	Hourly relative humidity fluctuations or system loss can create risk.
$<10^3$ s Few minutes or less	Single sheet of paper, 4 min (Kupczak et al. 2018b). Includes book pages that are fanned open. Thin sheet of parchment, ivory. Thin layers of watercolor paint, gouache. Feathers, fur, hair. Lightweight textiles, costumes. Gelatin layer of photographic print or film. Sized canvas used for paintings.	Relative humidity fluctuation or system loss of only a few minutes can create risk. (Museums rarely display these objects unenclosed.)

Note. All plates considered exposed both sides unless noted otherwise. Adelstein et al. (1997) and Bigourdan (2012) reported 90% response times, converted here to halftimes by ×0.3 assuming exponential decay. Derluyn et al. (2007) measured a 50 mm square experimental book, closed on all sides but fore edge. Their times have been adjusted to a more realistic 100 mm depth, so ×4 (square law) is applied. Estimates from Michalski (2005) based on material data plus enclosure leakage equations. Wood objects and furniture based on Figures 11 and 12. Others are based on calculations using Equation (7) for a plate and diffusion coefficients from the literature.

fossils, disintegrate if held above 60% rh (Howie 1992). Bronze, one of the most important archaeological metals, has a complex chemistry of corrosion, with several critical relative humidity values. This variety means there is no universal safe relative humidity; particular conditions should be achieved for specific artifacts with local cabinets or small relative-humidity-controlled packages (Waller 1992). The only generalization is that any relative humidity above 75% is dangerous.

Rapid corrosion above 75% rh occurs for two reasons: increased surface adsorption of water, and contamination by salts. Water adsorption on clean metal surfaces climbs rapidly from 3 molecules or less below 75% rh to bulk liquid layers above 75% rh (Graedel 1984). This phenomenon is aggravated by most surface contaminants, as shown in studies of the role of dust on clean steel corrosion. The most common contaminant of museum metals, sodium chloride, dissolves and liquefies (deliquesces) above 76% rh.

Glass collections, objects with glass bead decoration, and stained glass may contain a type of historic glass that is very sensitive to incorrect relative humidity because of deliquescence of unstable constituents. A stable 40% rh is recommended. See van Giffen et al. (2018) for detailed recommendations on climate control for various types of historic glass.

Response Times of Artifacts

Approximate thermal response times of objects are familiar from common experience, and their calculation is described in Chapter 25 of the 2017 *ASHRAE Handbook—Fundamentals*. This section focuses on the response time that is much less familiar to most engineers, but much more important to preservation science: hygric response times.

Table 8 provides hygric half-times for common objects and enclosed objects in cultural institutions. Where direct measurements are available, these have been cited; other estimates are based on calculations. Lower temperatures greatly increase all these times (Adelstein et al. 1997); conversely, higher temperatures shorten them. Response times at least double for each drop of 10 K: for example, ×2 for cool conditions, ×4 for cold, ×8 or more for freezing storage.

The hygric half time of a plate (a shape that applies to many cultural objects, or that provides an upper bound to cylinders, cubes, spheres, etc) is given by Crank (1979) as

$$T_{1/2} = 0.049\frac{L^2}{D} \tag{7}$$

where

$T_{1/2}$ = half-time of enclosure system, s
L = thickness of plate (or sheet), m
D = diffusion coefficient, $\mathrm{m^2/s}$

Some estimates in Table 8 are based on Equation (7) and diffusion coefficients found in the literature on polymers. An object with a surrounding moisture barrier (coating or enclosure) can be simplified as a series of two resistances to moisture flow. Figure 11 was generated using this approach, with wood data from Siau (2012) for medium-density wood near 50% rh. When barriers provide useful resistance (upper lines in each plot in Figure 11), the plots have a slope of 1 (linear). When coatings provide negligible resistance (e.g., the boundary layer of air in a calm room), the slope changes to the square law of Equation (7). There is only a slight curve as thickness drops to 1 mm across the grain. As Kupczak et al. (2018b) show, the contribution of the boundary layer of air, though measurable, is far from rate determining even for a single sheet of paper. In practical terms, although thinner objects (e.g., a violin, ivory miniature, paper sheet) respond more quickly, they benefit greatly from even simple coatings or enclosures, whereas massive objects do not.

Figure 12 was generated using the same series resistances model, but using leakage equations for an enclosure found in Michalski (1994). The horizontal plateaus are in the region where crack leakage is insignificant, and the wood coating dominates halftime. The slopes are the region where leakage (infiltration) dominates, and the knees indicate which size cracks are worth blocking.

The humidity half-time of a leaky enclosure with a hygroscopic material (objects or additional buffers) can be expressed in terms of the fraction of the enclosure volume filled with the buffering material (Michalski 1994):

$$T_{1/2} = 0.69\frac{V_h \alpha \rho}{V_e N C_{ws}} \tag{8}$$

where

$T_{1/2}$ = half-time of enclosure system, s, h, or days (depends on leakage units)
V_h = volume of hygroscopic material, $\mathrm{m^3}$
V_e = volume of enclosure, $\mathrm{m^3}$
α = hygric capacity (slope of moisture isotherm) kg/kg
ρ = bulk density of hygroscopic material, $\mathrm{kg/m^3}$
N = leakage, air changes per s, per h, or per day
C_{ws} = concentration of water in air at saturation, $\mathrm{kg/m^3}$

The critical role of leakage N for enclosed objects can be seen in Table 8 for paintings or works on paper in a sealed glass frame (increasingly used by major galleries, especially for loaned paintings.) Depending on tiny differences in crack width, performance can change by orders of magnitude. This is because of the key role of infiltration in determining N, and the fact that infiltration varies with the cube of crack width (laminar flow) (Michalski 1994).

Equation (8) can be reduced to an estimate for materials such as paper, wood, leather, and dense fabrics near room temperature (20°C), where $C_{ws} = 0.0173\ \mathrm{kg/m^3}$. Using a conservative density of $\rho \approx 600\ \mathrm{kg/m^3}$ and a conservative hygric capacity of $\alpha \approx 0.05$, then

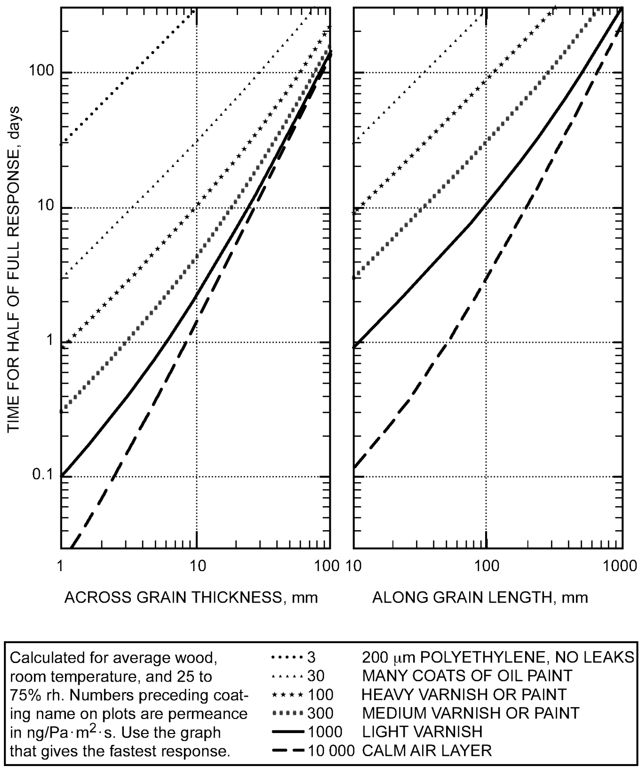


Fig. 11 Calculated Humidity Response Times of Wooden Artifacts

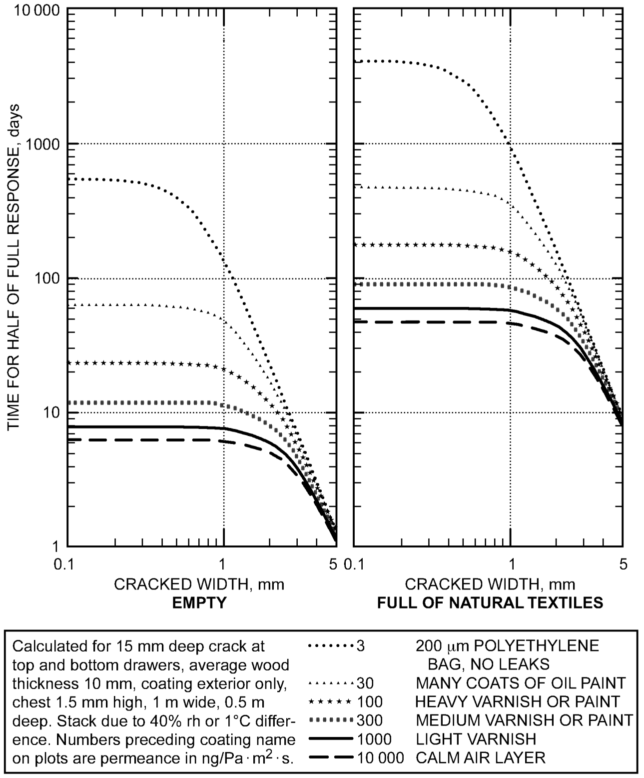


Fig. 12 Interaction of Air Leakage, Wood Coating, and Textile Buffering on Response of Wooden Chest of Drawers

$$T_{1/2} \sim 0.69 \frac{V_h \alpha \rho}{V_e N} \quad (9)$$

A leakage rate of 1 air change per day (acd) is considered a suitable design target for airtight museum display cases (Thickett et al. 2007), so an enclosure half full of wood or paper ($V_h/V_e = 1/2$) would give a half-time of 600 days. In practical terms, very tight enclosures are rarely very full enclosures (although wrapping large wooden objects in heavy-gage, perfectly sealed polyethylene can achieve this). Half-full enclosures are generally cabinets or crates, and they leak closer to 1 air change per hour (ach), which still provides a 25 day half-time. A tight display case of 1 ach rarely has more than 10% of its volume filled with hygroscopic material, resulting in half-times up to 120 days. In practice, it is difficult but not impossible to design and maintain very low infiltration.

An inevitable concern with enclosures is the humidity fluctuation driven by a thermal fluctuation. This worry first emerged in the 1960s for works of art in shipping crates, but Toishi (1959) showed that if a sealed crate contained hygroscopic material, it would stabilize its relative humidity despite drops from room temperature to freezing and back. Stolow (1966) provided complete data and equations for the counter-intuitive finding that, with natural hygroscopic materials, case humidity even drops slightly when temperature drops (the opposite of empty enclosures) because of the slight downward shift of moisture isotherms at lower temperature. Thomson (1964) showed that the transition point between relative-humidity-controlled enclosures and empty-enclosure behavior for hygroscopic materials such as wood occurred at about 1 kg/m^3, and humidity control was fully in place by 10 kg/m^3 (about 2% full by volume). Later authors examined further side effects such as mixed thermal/hygric dimensional response in wood (Richard 2007) and condensation in air pockets during cold storage retrieval (Padfield 2002; Shashoua, 2005, 2008) but the general consensus is that such occasional side effects do not outweigh the benefits (Richard 2007; Shashoua 2014).

5.5 AIRBORNE POLLUTANTS/ CONTAMINANTS

Sources

From the outdoors, different-sized particles can infiltrate museums. Gaseous outdoor pollutants such as nitrogen dioxide and ozone can also penetrate buildings, including modern HVAC-equipped construction, when gas filtration is not present to remove them. Within buildings, sources of airborne pollutants include institutional activities such as food preparation, service vehicles in the loading dock, and renovation (e.g., preparation of new exhibitions). Construction products such as wood, paints, adhesives, and sealants, especially by-products formed by chemical curing or solvent release, can be important sources of gaseous pollutants. Collections themselves can be sources of pollutants that can affect other objects nearby; examples include archival materials such as cellulose nitrate and acetate films, as well as acidic papers. Collections made of natural organic materials such as leathers, fur, and wood elements can also release harmful volatile compounds. The metabolism of staff and visitors further contributes to airborne pollutants, and introduces coarse particles from skin cell shedding and clothing. It is important to understand that the impact of gaseous pollutants varies according to the sensitivity of each material (i.e., acetic acid corrodes lead but is harmless to silver; silver is very sensitive to hydrogen sulfide, but lead is minimally affected). In other words, the potential damage is very specific to each pollutant/material system and the damage caused to objects by pollutants is usually cumulative, irreversible, and disfiguring. Table 9 presents a list of objects sensitive to various pollutants and pollutant sources.

Impact

Dust deposition is a general problem for all collections. More precisely, dust deposition impacts objects' aesthetic appearance and affects conservation considerations (e.g., cleaning frequency, risk involved during treatments). Coarse dust is relatively easy to remove from robust surfaces such as flat glasses or metals, but difficult to remove from fragile surfaces such as feathers. Particles generated by people are not usually removed by HVAC filters. Fine particles such as black soot pose a particular challenge. This is a typical problem for museums in the vicinity of high-volume diesel vehicle traffic. Special conservation skills are needed to remedy this situation, but there are cases where the soot cannot be removed (e.g., soot entrenched in the cracks of an ivory sculpture, soot in fragile textiles that may be significantly physically damaged by cleaning treatment).

The deterioration process caused by airborne pollutants can be enhanced in the presence of water vapor. This has a relevant impact on objects both in a direct and indirect way. In the presence of high relative humidity, many processes of deterioration accelerate. An example of an indirect effect that is greatly affected by high relative humidity, especially above 75% rh, is the increase in corrosion rates of many metals by pollutants. For example, formaldehyde does not corrode lead at 75% rh, but corrosion can occur at higher humidities (Thickett 1997). Water vapor can directly affect some materials (e.g., cellulose papers, cellulose acetate, nitrate plastic films) by hydrolysis. With just moisture in the cellulose, deterioration is slow, but increases when acids are present. This reaction is called **acid catalyzed hydrolysis**. Over time, the acids present as by-products of cellulose degradation increase, which further speeds up the reaction (Dupont et al. 2007; Zou et al. 1996). To maximize preservation of objects affected by pollutants, it is usually better to keep relative humidity low, particularly for metal objects. However, the environment must be compatible with the appropriate humidity range established for preservation of organic or composite collections. Oxygen in the indoor environment also may react with objects. Natural rubber is particularly known to degrade by oxidation, and many colorants are vulnerable to fading in the presence of oxygen and light.

Some work has been done to quantify the impact of pollutants on various materials, based on the concept of the **lowest observable adverse effect dose (LOAED)**. This dose is derived using the reciprocity principle: if a critical adverse effect is observed on an object after 1 month at 1000 parts per billion (ppb) of a pollutant, the same damage could occur after 10 months at 100 ppb. When extensive data exist for a pollutant/material system, a **no observable adverse effect level (NOAEL)** can be determined with some confidence. After studying the effect of acetic acid on (untarnished and pure) lead at different concentrations and relative humidity levels for a year, Tétreault et al. (1998) established a NOAEL for the acetic acid/lead system at 430 μg/m^3 or 170 ppb. Extensive sets of LOAED and some NOAEL data have been compiled by Tétreault (2003).

Note that concentrations of gaseous pollutants can be reported in either volumetric units (ppb), which are temperature and pressure dependent, or in gravimetric units (μg/m^3), which are temperature and pressure independent. To standardize reporting for volumetric units, the Compressed Air and Gas Institute (CAGI 2012) recommends using standard conditions of 20°C and 100.0 kPa. IAQ in Museums and Archives (IAQ 2016) provides an online concentration converter for major pollutants.

In general, there are three scenarios where objects can be at risk in museums:

- **Outdoor pollutant infiltration** is a problem in polluted areas where unprotected objects in rooms are exposed to outdoor pollutants that were not adequately blocked at the building level (envelope and filtration). Soot deposition and tarnishing of silver and copper by reduced sulfur compounds are common damage

Table 9 Airborne Pollutants: Sources and High-Vulnerability Materials

Airborne Pollutants	Indoor and Outdoor Sources	Effects on Materials
Aldehydes (RCHO)	Formaldehyde: formaldehyde-based resin in wood products, solid wood, paints and adhesives, natural history wet specimen collections, permanent press fabrics. Acetaldehyde: paints, adhesives, solid woods. Low-molecular-weight aldehydes can be transformed into their respective carboxylic acids in presence of strong oxidant such as peroxides released by oil-based paints or any paint films formed by oxidative polymerization.	Formaldehyde: Corrosion of lead at high relative humidity (>75%).
Amines (RNR)	Ammonia (NH3): alkaline-type silicone sealants, concrete, emulsion adhesives and paints, household cleaning products, visitors, animal excrement, fertilizer and inorganic process industries, underground bacterial activities. If combined with sulfate or nitrate compounds, it can form ammonium salts. Cyclohexylamine (CHA), diethylamino ethanol (DEAE), and octadecylamine (ODA): corrosion inhibitor in humidification systems, some vapor corrosion inhibitors.	Ammonia: blemishes on ebonite and efflorescence on cellulose nitrate. Other amines: thought to be responsible for blemishes on paintings and corrosion of bronze, copper, and silver.
Carboxylic acids (RCOOH)	Acetic acid (CH3COOH): acid-type silicone sealants (acetoxy cure), degradation of organic materials and objects such as cellulose acetate-based objects (vinegar syndrome) and wood products, most paints, flooring adhesives, human metabolism, linoleum, microbiological contamination of air-conditioning filters, oil-based paints, photographic developing products, some "green" cleaning solutions. Formic acid (HCOOH): degradation of organic materials, oil-based paints, wood products. Fatty acids (RCOOH): burning candles, cooking, flooring adhesives, human metabolism, linoleum, lubricant in HVAC systems, microbiological activities from air-conditioning or on objects, objects made of animal parts (including skins, furs, insect collections), oil-based paints, papers, paper and wood products, vehicle exhaust.	Acetic and formic acids: corrosion of copper alloys, cadmium, lead, magnesium, and zinc; efflorescence on calcareous materials (e.g., shells, corals, limestones, calcium-based fossils); fading of some colorants; efflorescence on soda-rich glass objects; lowering degree of polymerization of cellulose. Fatty acids: blemishes on paintings; corrosion of bronze, cadmium, and lead; ghost images on glass; yellowing of papers and photographic documents.
Nitrogen oxide compounds (NO_x)	Nitric oxide (NO): agricultural fertilizers, fuel combustion from vehicle exhaust and thermal power plants, gas heaters, and photochemical smog. Nitrogen dioxide (NO_2): degradation of cellulose nitrate and same sources as for NO, but mainly from oxidation of atmospheric NO. Nitric acid (HNO_3) and nitrous acid (HNO_2): oxidation of NO_2 in the atmosphere or on a material's surface, and the degradation of cellulose nitrate.	Deterioration of paper, fading of some artists' colorants, enhance the deterioration effect of SO_2 on leather and on metals.
Oxidized sulfur gases (SO_2 and H_2SO_4)	Sulfur dioxide (SO_2): degradation of sulfur-containing materials and objects such as proteinaceous fibers, pure pyrite or mineral specimens containing pyrite sulfur dyes, sulfur-vulcanized rubbers, petroleum refineries, pulp and paper industries, combustion of sulfur-containing fossil fuels. Sulfuric acid (H_2SO_4): oxidation of SO_2 in the atmosphere or on a material's surface.	Acidification of paper, corrosion of copper, fading of some artists' colorants, weakening of leather.
Ozone (O_3)	Electronic arcing, electronic air cleaners, electrostatic filtered systems, insect electrocuters, laser printers, photocopy machines, UV light sources, photochemical smog.	Fading of some artists' colorants, dyes, and pigments; oxidation of organic objects with conjugated double bonds such as rubber; oxidation of volatile compounds into aldehydes and carboxylic acids.
Particles (fine and coarse)	General: aerosol humidifier; burning candles; concrete; cooking; laser printers; renovations; spray cans; shedding from clothing, carpets, packing crates, etc. (due to abrasion, vibration, or wear); industrial activities; outdoor building construction; soil. Ammonium salts: reaction of ammonia with SO_2 or NO_2 in indoor or outdoor environments or on solid surfaces. Biological and organic compounds: microorganisms, degradation of materials and objects, visitor and animal danders, construction activities. Chlorides: sea salt aerosol, fossil combustion. Soot (organic carbon): burning candles, fires, coal combustion, vehicle exhaust.	General: abrasion of surfaces (critical for magnetic media), discoloration of objects (especially critical for those with surfaces with interstices [pores, cracks, or micro-irregularities] that entrap dust), may initiate or increase corrosion processes due to their hygroscopic nature. Ammonium salts: corrosion of copper, nickel, silver, and zinc; blemishes on varnished painting and furniture with natural resins and on ebonite; white deposit on object surface; lowering of the degree of polymerization of cellulose. Chlorine compounds: increase of rate of metal corrosion. Soot: discoloration of porous surfaces (painting, frescoes, statues, books, textiles, etc.), increased rate of metal corrosion. Carbon and metallic elements such as iron and magnesium can lower the degree of polymerization of cellulose.
Reduced sulfur gases (S^-)	Carbon disulfide (CS_2): polysulfide-based sealants; fungal growth; rotting organic matter in oceans, soils, and marshes. Carbonyl sulfide (OCS): degradation of wool, coal combustion, coastal ocean, soils, and wetlands, oxidation of carbonyl disulfide. Hydrogen sulfide (H_2S): arc-welding activities, mineral specimens containing pyrite, sulfate-reducing bacteria in impregnated objects excavated from waterlogged sites, polysulfide sealants, vulcanized rubbers, visitors, fuel and coal combustion, marshes, ocean, petroleum and pulp industries (kraft process), vehicle exhaust, volcanoes.	Corrosion of bronze, copper, and silver; discoloration of silver photographic images; darkening of lead pigments.

Source: Adapted from Tétreault (2003).

observed under those conditions. An assessment must be done to decide if better control should be carried out at the building level or if some objects should be placed in enclosures such as display cases, glazed frames, or storage containers. For protection against pollution and for security reasons, many small objects are placed in display cases, and paintings can be placed in glazed frames, but not all items on exhibition or in storage can be enclosed.

- With **pollutants generated in small enclosures**, products used to build the enclosure and the objects themselves can release volatile compounds (typically carboxylic acids and reduced sulfur gases), which can react with the objects housed within. Their concentrations can remain high for a long period if they cannot be exfiltrated or sorbed adequately. The best preventive solution is to carefully select construction products and to evaluate objects' potential emissions. If problematic products or objects cannot be removed from the enclosure, the second-best approach is usually to reduce the pollutant concentration in the enclosure by increasing the air exchange rate. However, an assessment is needed to determine which degree of airtightness is most suitable. The assessment must consider the concentration of pollutants in the room and in the enclosure, as well as the nature of both the pollutants and objects in the enclosure.
- **Indoor-generated pollutants** are similar to off-gassing in enclosures, but at a room scale. Objects displayed in a room with insufficient ventilation and with a high load of emissive materials can be at risk if pollutant concentrations become significant. Sources in the room can be products such as wood and paint, collections made of natural organic materials, and emissions from human activities such as cooking, renovation, or burning incense in religious buildings. Indoor pollutants can also affect people in the space, and the relation between air pollution and the health and comfort of building occupants is the focus of indoor air quality (IAQ) guidance, such as ASHRAE *Standard* 62.1. Possible solutions for minimizing the impact of indoor pollutants are to increase the ventilation, and to consider gas filtration systems or enclosures.

More information on the issue of pollutants in museums and historical buildings can be found in Anaf et al. (2015), Bellan et al. (2000), Bonacina et al. (2015), Grau-Bové and Strlic (2013), Grzywacz (2006), Hatchfield (2002), Lloyd et al. (2007), Mleczkowska et al. (2016, 2017), Nazaroff et al. (1993), Paterakis (2016), Pretzel (2003), and Tétreault (2003, 2017, 2018).

6. DESIGN PARAMETERS FOR PERFORMANCE TARGET SPECIFICATIONS

6.1 CLIMATE LOADS

Climate loads include above- and below-grade liquid water loads from rainfall; thermal loads from conduction, convection, and radiation; thermal and moisture vapor loads from infiltration (especially when driven by stack effect); and vapor transport through permeable envelope assemblies.

ASHRAE *Standard* 169-2013 provides a methodology for defining climatic regions based on thermal and moisture characteristics using nine thermal zones (0 to 8: extremely hot to subarctic), based on heating and cooling degree days, and three moisture zones (A, B, or C: humid, dry, or marine) calculated using precipitation and temperature data. The climate zone classification is useful for differentiating climate regions when considering envelope performance. Table 10 and Figure 13 indicate climate zones for typical cities and geographic locations throughout the world. Figure 14 provides a higher-resolution map of climate zones in the United States. ASHRAE *Standard* 169-2013 provides an extensive list of locations and their climate zone classification.

ASHRAE *Standard* 169-2013 also provides comprehensive location-specific climate data for calculations of loads for system and envelope design. *Engineering Weather Data*, published by the National Climate Data Center of the National Oceanic and Atmospheric Administration (NOAA 1997), includes informative graphics for visualizing seasonal variations in data, but the dataset is older. When using statistical climate data for design, consider not only maximum and minimum design conditions, but also the potential variability of thermal and moisture conditions in a given season; for example, in zones 3A, 4A, and 5A, thermal and moisture loads may change rapidly during spring and autumn. In some climate zones, seasonal dehumidification may not be coincident with large sensible cooling loads; thus, systems may have to be designed for dehumidification independent of cooling.

Bulk moisture from precipitation, especially wind-driven rain, can be a significant moisture load on envelopes above grade. Depending on soil type and site management of stormwater runoff from roofs and at-grade surfaces, rain can also affect moisture loads on subgrade portions of the building. However, even in climate zones classified as dry (B), infrequent but high-intensity rain events can result in significant short-term moisture loads on the building and soil.

The design service life and envelope durability of purpose-built museum buildings may be as long as 100 years. Design for climate loads on building envelopes should consider projections for climate change and their impact on future thermal, moisture, and bulk moisture loads on the building, consistent with the design service life of a building, its envelope assemblies, and environmental management systems.

6.2 BUILDING ENVELOPE

The building envelope mediates exchange of thermal energy and moisture between the interior and the exterior environments, both above and below grade. Above grade, the building envelope typically consists of wall assemblies, wall closure assemblies such as windows and doors, and roof assemblies. Below grade, the building envelope consists of foundation wall assemblies and floor assemblies in contact with soils.

The envelope mediates movement or transport of water, air, water vapor, and thermal energy. Flows that are not effectively mediated by the envelope result in thermal and moisture loads that must be addressed by mechanical systems; unmediated loads have implications for energy efficiency.

Performance Requirements. Envelope performance needed to effectively and efficiently perform the four control functions (water [bulk moisture], air, water vapor, and thermal energy) depends on the exterior climate and desired interior conditions. Table 11 lists the types of climate control recommended for collections preservation and identifies the envelope performance needed to achieve that control in different climate zones. For a given combination of control type and climate zone, the necessary envelope performance for each function is identified as *controlled*, *moderated*, or *optional*. Table 12 provides examples of typical envelope features or assemblies that correspond to these terms. Table 11 also includes considerations that should be addressed in design and for some combinations of exterior climate and interior type of control, and identifies whether hygrothermal analysis of the envelope is needed, recommended, or optional for the different combinations of type of control and climate zone. Hygrothermal analysis using dynamic transient modelling is preferred, but static-equilibrium analysis may be sufficient in some instances.

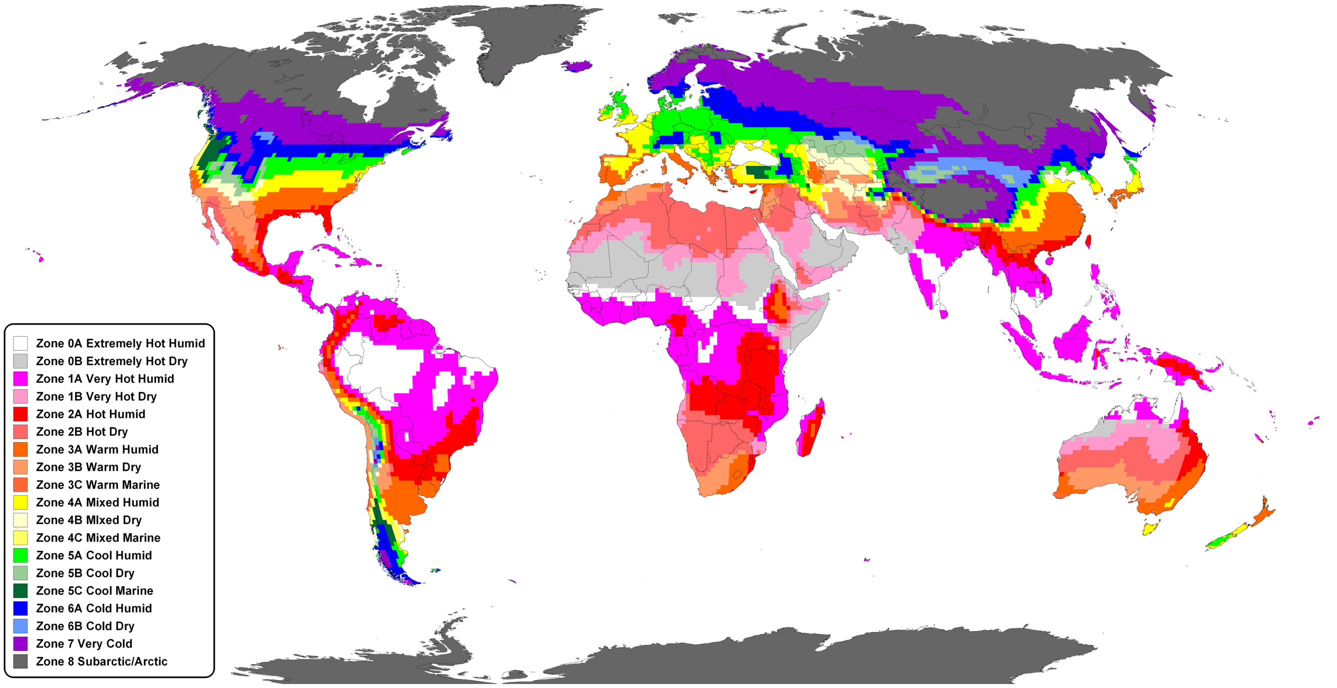


Fig. 13 World Map of Climate Zones
(ASHRAE *Standard* 169-2013)

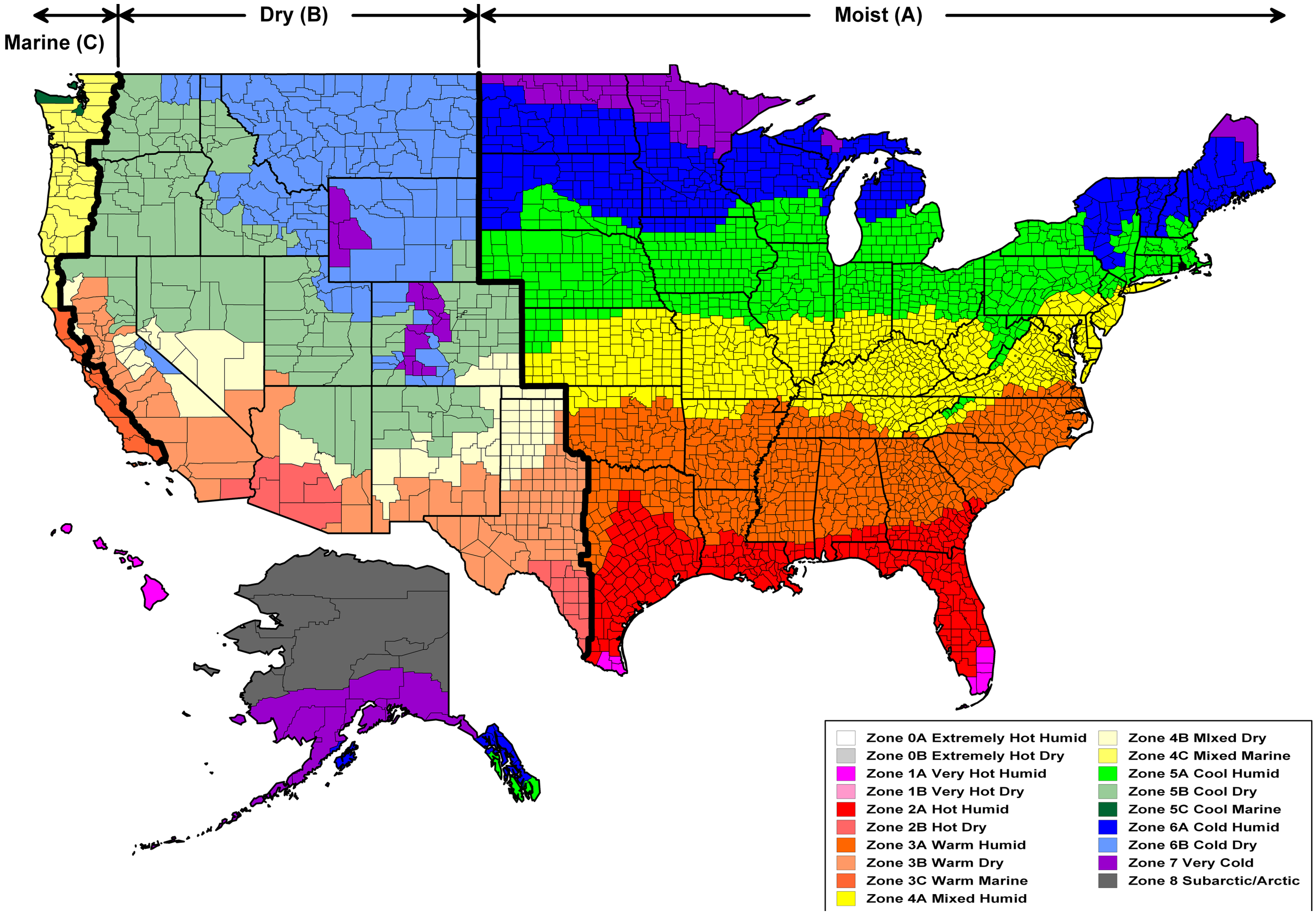


Fig. 14 Climate Zones in United States
(ASHRAE *Standard* 169-2013)

Table 10 Climate Zone Classifications for Select World Cities

Climate Zone	Type	Location	Climate Zone	Type	Location	Climate Zone	Type	Location
0A	Extremely hot, humid	Recife (Brazil)	3A	Warm, humid	Sydney (Australia)	5A	Cool, humid	Toronto (Canada)
		Bombay (India)			Shanghai (China)			Berlin (Germany)
		Manila (Philippines)			Atlanta (United States)			Chicago (United States)
0B	Extremely hot, dry	Ahmedabad (India)	3B	Warm, dry	Athens (Greece)	5B	Cool, dry	Rio Gallegos (Argentina)
		Niamey (Niger)			Tehran (Iran)			Taiyuan (China)
		Riyadh (Saudi Arabia)			Los Angeles (United States)			Denver (United States)
1A	Very hot, humid	Hanoi (Vietnam)	3C	Warm, marine	Nairobi (Kenya)	5C	Cool, marine	Esquel (Argentina)
		Mombasa (Kenya)			Cape Town (S. Africa)			Corum (Turkey)
		Miami (United States)			San Francisco (United States)			Bremerton (United States)
1B	Very hot, dry	Luxor (Egypt)	4A	Mixed, humid	Beijing (China)	6A	Cold, humid	Oslo (Norway)
		Lahore (Pakistan)			Paris (France)			St. Petersburg (Russia)
		Dakar (Senegal)			Philadelphia (United States)			Minneapolis (United States)
2A	Hot, humid	Sao Paulo (Brazil)	4B	Mixed, dry	Kabul (Afghanistan)	6B	Cold, dry	Chifeng (China)
		Haifa (Israel)			Adelaide (Australia)			Bozeman (United States)
		Dallas (United States)			Albuquerque (United States)	7	Very cold	Ulaanbaatar (Mongolia)
2B	Hot, dry	Cairo (Egypt)						Anchorage (United States)
		Lima (Peru)	4C	Mixed, marine	Brussels (Belgium)			
		Phoenix (United States)			Santiago (Chile)	8	Subarctic	Yellowknife (Canada)
					Portland (United States)			Fairbanks (United States)

Source: ASHRAE *Standard* 169-2013.

Design Considerations. Interior environmental requirements for buildings containing collections are typically more stringent than those for human health and thermal comfort, particularly for relative humidity. Depending on the differences between the exterior and interior conditions, there may be large differences in temperature and moisture vapor across the building envelope. The resultant thermal, pressure, and moisture gradients between the exterior climate and the collections spaces have implications for envelope performance.

In new buildings, high-performance building envelopes address thermal and moisture gradients with layered sequences of functionally specific materials such as air barriers, thermal insulation, and vapor retarders/barriers. Older building envelopes typically used thick assemblies of fewer materials, consistent with contemporary expectations for envelope performance, building occupancy, and use. Many existing museum buildings constructed in the mid to late 20th century may have envelope assemblies similar to current high-performance envelopes, but the quality of materials, design details, or construction/installation may compromise their performance.

Furthermore, many collections are housed in existing buildings that are considered significant cultural heritage in their own right; these are not limited to historic buildings, and can include architecturally significant buildings of the late 20th century. The building envelope of historic or architecturally significant buildings is likely to be considered character defining, and changes or alterations to the envelope may be subject to preservation criteria. ASHRAE *Guideline* 34-2018 provides useful information on improving the energy performance of historic building envelopes.

An existing building envelope's performance possesses both strengths and liabilities for environmental management for collections. It may have high thermal mass and moisture capacity that can buffer interior and exterior fluctuations of thermal energy and moisture; these passive, or nonmechanical, aspects of envelope performance can be beneficial during extreme weather events or when mechanical systems are disabled.

Many older building envelopes have poor air control performance, especially at envelope penetrations around windows and doors, as well as the windows and doors and their operable elements. In older buildings originally designed for natural ventilation, intentional stack effect in large stair halls and through skylights above galleries may exacerbate high exchange rates through windows and doors, even when the assemblies have been upgraded.

Vapor control performance of existing wall and roof assemblies is typically inadequate for the differences between exterior and interior moisture vapor that must be maintained for some collections. Steep moisture gradients across envelope assemblies can drive moisture transport, with consequential damage to the building. Examples of damage in masonry or concrete wall assemblies include migration of soluble salts, freeze-thaw cycling, coatings failures or condensation. In wall assemblies with wood, damage may occur from moisture saturation and microorganism activity. Vapor control performance can be difficult to incorporate in an existing building envelope. As a result, depending on the climate zone, vapor control performance of an existing envelope may define the interior relative humidity level that can be safely maintained without risk of damage to the envelope.

When improved vapor control is necessary in an existing building, it may be appropriate to enclose the collections space with a new vapor-controlled interior partition, separated from the interior face of the exterior wall by a substantial air space. This approach, often called **box-in-box**, effectively cascades the total moisture gradient across multiple assemblies, decreasing the moisture gradient across the exterior wall assembly, and can effectively resolve air control issues. This approach may be applied to roof and ceiling assemblies when necessary.

In any case, identification of effective performance improvements for existing building envelopes must be based on evidence

Table 11 Type of Control, Climate Zone, and Typical Envelope Performance Necessary

	Liquid Water Loads (Table 12)		Hygrothermal Loads (Table 12)	Necessary Envelope Performance (Table 12)				Design Considerations
Type of Control	Rain Exposure (Moisture Zone)	Source Moisture	International Climate Zone(s)	Thermal Flows	Air Leakage and Stack Effect	Moisture Vapor	Hygrothermal Analysis	Comments
AA Precision control	All	●	All	●	●	●	■	Building envelope should be separated from interior enclosure of collections space.
A1, A2 Precision control with seasonal changes	All	●	5A, 5B, 5C and colder	●	●	●	■	Building envelope should be separated from interior enclosure of collections space.
	All	●	4A, 4B, 4C	◉	◉	◉	❖	
	All	●	3A, 3B, 3C and warmer	●	●	●	■	Building envelope should be separated from interior enclosure of collections space.
	All	●	6A, 6B, and colder	●	●	●	■	
B Limited control with seasonal changes	All	●	5A, 5B, 4A, 4B, 3A, 3B	◉	◉	◉	□	
	All	●	5C, 4C, 3C	◉	○	○	□	
	All	●	2A, 2B and warmer	◉	●	◉	❖	
	All	●	All B	◉	◉	○	□	Where diurnal temperature differences are large, insulation may be needed to prevent high relative humidity at night caused by cooling.
C Prevent relative humidity extremes	All	●	5C, 4C, 3C	◉	○	○	□	
	All	●	All other zones	◉	◉	◉	□	Moderated or controlled envelopes can eliminate or substantially reduce size of HVAC equipment.
D Prevent very high relative humidity	All	●	All B	◉	○	○	□	Where diurnal temperature differences are large, insulation may be needed to prevent high relative humidity at night caused by cooling.
	All	●	5C, 4C, 3C	○	○	○	□	
	All	●	All other zones	◉	◉	◉	□	Moderated or controlled envelopes can eliminate or substantially reduce size of HVAC equipment.
Cool store	All	●	All	●	●	●	❖	Specialized collections enclosures separate from the exterior building envelope are typically used. Where cooling loads are low (e.g., climate zone 6 and colder) and in some subgrade locations, specially designed exterior envelopes can achieve this performance without a separate interior enclosure.
Cold or “frozen” store	All	●	All	●	●	●	❖	Specialized collections enclosures separate from the exterior building envelope are typically used.
Relative humidity controlled below critical value	All	●	All	●	●	●	❖	Vapor control is a priority in moisture zones A and C, and thermal control is typically needed to maintain relative humidity stability below critical values.

Legend:

Moisture and hygrothermal loads	● Controlled	◉ Moderated	○ Optional
Hygrothermal analysis	□ Necessary	❖ Recommended	☐ Optional

Table 12 Examples of Typical Envelope Assemblies or Features

Loads	Minimum Performance	Examples
Liquid water loads	●	**Source moisture control** is typically achieved by intercepting and diverting rain and surface and subgrade water away from above- and below-grade parts of building envelope. Examples: roof drainage systems; surface water drainage systems, including swales and piped systems; drainage planes in above-grade walls; subgrade drainage systems consisting of waterproofing, drainage planes on subgrade walls and under slabs, and subgrade piping.
Thermal flows	●	**Controlled thermal flows** are typically achieved by building envelopes that meet current ASHRAE *Standard* 90.1 requirements for building envelopes.
	◎	**Moderated thermal flows** are typically satisfied by • *Climate zones 4 and higher*: building envelopes with robust wall construction and thermal mass, retrofitted insulation, storm windows, or insulated glazing and insulated ceiling planes in the uppermost story attics in climates zones 4 and higher. • *Climate zones 3 and lower*: radiant barriers in attics or a double roof with a ventilated cavity. • *Climate zones 5 and lower*: summer solar gain through glazing may be moderated by low window-to-wall ratios, or by fixed or operable features such as *brise soleil*, roller shades, shutters, or blinds.
	○	Controlled or moderated thermal flow measures provide benefits but may not be necessary.
Air leakage and stack effect	●	**Controlled air leakage** is typically achieved by building envelopes that meet current ASHRAE *Standard* 90.1 requirements for building envelopes. **Controlled stack effect** is typically achieved by minimizing number of open communicating stories or by mechanical destratification among floors. **Moderated air leakage** is typically satisfied by limiting overall air intrusion. Examples include: air barriers in walls and in the ceiling plane of uppermost stories, weather-stripping of door and window openings, vestibules or buffer spaces at heavily used entry points.
	◎	**Moderated stack effect** is typically limited by not more than two open communicating stories plus air leakage improvements. If building pressurization is used, interior pressure should be slightly negative during heating and humidification and slightly positive during cooling and dehumidification.
	○	Controlled or moderated measures provide benefits but may not be necessary.
Moisture vapor	●	**Controlled moisture vapor flows** are typically achieved by building envelopes that meet current ASHRAE *Standard* 90.1 requirements for building envelopes.
	◎	**Moderated moisture vapor flows** are typically satisfied by building envelopes with robust envelope construction and limited vapor permeability, such as thick masonry walls. For less robust envelope construction, such as stud-framed walls or wood-framed ceilings in the uppermost stories and wood-framed floors over crawlspaces and basements, a vapor retarder may be needed.
	○	Any controlled or moderated measures provide benefits but may not be necessary.

Note: See also Chapter 64 for moisture management in buildings.

from documentary research and physical investigation of the envelope, and can be often informed by environmental monitoring and hygrothermal analysis.

6.3 TEMPERATURE AND RELATIVE HUMIDITY

This section explains the structure and use of Tables 13A and 13B, which list a set of options (rows) and their characteristics (columns). The tables are not meant to be a simple recipe box. They quantify and codify many options that will be judged by the criteria in Figure 1: the preservation needs of the collection, occupants' needs, capability of the current building envelope, feasibility of a new envelope, and long-term costs and sustainability of HVAC systems. It is an iterative process, exploring and reconciling inevitable conflicts.

Firstly, climate loads and envelope performance, as discussed previously, must be understood. A very common error in cultural institution HVAC specifications is a disconnect between the design specifications and what the envelope (and budget) can support over time.

With awareness of envelope limitations, select the Type of Collection and Building (column 1) that most closely matches the current project. Table 13A applies to general requirements of mixed permanent collections, and Table 13B applies to specialized spaces for specific materials: loans, low-temperature storage, and collections with critical relative humidity requirements.

Within the Type of Collection and Building selected (column 1), examine the Collection Benefits and Risks summarized in the far-right column. For Table 13B, this is usually a straightforward decision: only one option (or various degrees of cold) either is or is not feasible with the project budget in terms of high-performance envelope and HVAC.

Table 13A concerns more common situations, but is more complex.

For the type of collection and building selected (column 1) examine the collection benefits and risks summarized in the various options of the far-right column (only one option is described for the simplest type of building, control type D). If the collection contains only one type of object, or if the most important objects are of one type, then a more precise analysis of benefits and risks can be made using information in the section on the Environmental Effects on Collections.

For each option considered, analyze as well as possible the (1) benefits to the collections, (2) remaining risks to the collections, and (3) costs in terms of the building and HVAC system required. For the latter, it is necessary to understand columns 3 to 6. There are four components to a specification: long-term outer limits, annual averages, seasonal adjustments, and short-term fluctuations and space

Table 13A Temperature and Relative Humidity Specifications for Collections in Buildings or Special Rooms

Type of Collection and Building	Type of Control	Long-Term Outer Limits[a]	Annual Averages	Seasonal Adjustments from Annual Average[b]	Short-Term Fluctuations plus Space Gradients[c]	Collection Benefits and Risks[d]
Museums, Galleries, Archives and Libraries in modern purpose-built buildings or purpose-built rooms **Temperature at or near human comfort**	**AA** Precision control, no seasonal changes to relative humidity	≥35% rh ≤65% rh ≥10°C ≤25°C	For permanent collections: historic annual average of relative humidity and temperature. In public display areas, human comfort temperatures can apply.	No change to relative humidity Increase by 5 K; Decrease by 5 K	±5% rh, ±2 K	Mold germination and growth, and rapid corrosion avoided. No risk of mechanical damage to most artifacts and paintings. Some metals, glasses, and minerals may degrade if rh exceeds a critical value. Chemically unstable objects deteriorate significantly within decades at 20°C, twice as fast each 5 K higher.
	A1 Precision control, seasonal changes in temperature and relative humidity	≥35% rh ≤65% rh ≥10°C ≤25°C		Increase by 10% rh. Decrease by 10% rh. Increase by 5 K; Decrease by 10 K	±5% rh, ±2 K	Mold germination and growth, and rapid corrosion avoided. No mechanical risk to most artifacts, paintings, photographs, and books; small risk of mechanical damage to high-vulnerability artifact. (Current knowledge considers the specifications A1 and A2 as causing the same low risk of mechanical damage to vulnerable collections. Slow seasonal adjustment of 10% rh is estimated to cause the same mechanical risk as rapid fluctuations of 5% rh, because of significant stress relaxation occurring within three months of a slow transition.)
	A2 Precision control, seasonal changes in temperature only	≥35% rh ≤65% rh ≥10°C ≤25°C		No change to relative humidity. Increase by 5 K; Decrease by 10 K	±10% rh, ±2 K	Chemically unstable objects deteriorate significantly within decades at 20°C, twice as fast each 5 K higher.
Museums, galleries, archives, and libraries needing to reduce stress on their building (e.g., historic house museums), depending on climate zone[e]	**B** Limited control, seasonal changes in relative humidity and large seasonal changes in temperature.[f]	≥30% rh ≤70% rh ≤30°C	For permanent collection: historic annual average of relative humidity and temperature.	Increase by 10% rh Decrease by 10% rh Increase by 10 K Decrease by up to 20 K	±10% rh, ±5 K	Mold germination and growth, and rapid corrosion avoided. Chemical deterioration halts during cool winter periods No risk of mechanical damage to many artifacts and most books. Tiny risk to most paintings, most photographs, some artifacts, some books. Moderate risk to high-vulnerability artifacts. Objects made with flexible paints and plastics that become brittle when cold, such as paintings on canvas, need special care when handling in cold temperatures. Chemically unstable objects deteriorate significantly within decades at 20°C, twice as fast each 5 K higher.
	C Prevent relative humidity extremes (damp or desiccation) and prevent high temperature extremes.	≥25% rh ≤75% rh ≤40°C[g]	Within 25% to 75% rh year-round. Temperature usually below 25°C		Not continually above 65% rh for longer than *X* days.[h] Temperature rarely over 30°C	Chemical deterioration halts during cool winter periods. Mold germination and growth, and rapid corrosion avoided. Tiny risk of mechanical damage to many artifacts and most books; moderate risk to most paintings, most photographs, some artifacts, some books; high risk to high-vulnerability artifacts Even greater care is needed than provided in B when handling objects made with flexible paints and plastics that become brittle when cold, such as paintings on canvas. Chemically unstable objects deteriorate significantly within decades at 20°C, twice as fast each 5 K higher.
Collections in open structured buildings, historic houses	**D** Prevent very high relative humidity (dampness)	≤75% rh	Relative humidity reliably below 75% rh		Not continually above 65% rh for longer than *X* days.[h]	Chemically unstable objects deteriorate significantly within decades at 20°C, and twice as fast each 5 K higher. Conversely, cool winter season can extend their life. Mold germination and growth, and rapid corrosion avoided. High risk of sudden or cumulative mechanical damage to most artifacts and paintings because of low-humidity fracture; but avoids high-humidity delamination and deformations, especially in veneers, paintings, paper, and photographs.

Table 13B Temperature and Relative Humidity Specifications for Collections in Buildings or Special Rooms

Type of Collection and Building	Type of Control	Specifications	Collection Benefits and Risks
Temporary exhibit space and unpacking space for loaned objects	Conditions will be stipulated in loan agreements[i]	Conditions will be agreed between lender and borrower. Based on the historic climate to which the object is accustomed, and a risk assessment of the borrower's environment and that of the transit process. Solutions to protect objects from climate shock should first be found in the creation of microclimates (showcases, glazing, etc., potentially using buffering).[e,i]	Benefits and risks are assessed by the lender, and contractual specifications based on this assessment. Often, assessment is highly risk averse, precautionary. For the borrowing institution, the benefits are increased access to popular objects by visitors; risks are monetary and reputational damage if climate control does not meet conditions outlined in the loan contract.
Chemically unstable organic materials in modern purpose-built buildings or purpose-built rooms[j]	**Cool**	8 to 16°C, 30 to 50% rh As defined in ISO *Standard* 18934:2011. IPI (Adelstein 2009) uses an anchor of 12°C.	The benefit of low temperature storage is extended lifetime of objects that will be lost within a generation or two at room temperature. See the section Chemical Damage for details on quantifying the benefits. Biological damage is also much reduced. The risks are the many side-effects of such systems: high humidity or condensation during malfunctions, water exposure. Objects must be packaged appropriately to reduce risk of condensation during retrieval, and a transition space with intermediate climate may be required. Hourly, daily, and even longer humidity fluctuations do not affect most properly packaged objects at low temperatures.[e]
	Cold	0 to 8°C, 30 to 50% rh As defined in ISO-18934:2011. IPI (Adelstein 2009) uses an anchor of 4°C.	
	Frozen	–20 to 0°C, 30 to 50% rh As defined in ISO *Standard* 18934:2011 and Adelstein (2009)	
Unstable metal or glass in modern purpose-built buildings or purpose-built rooms	**Relative humidity controlled to avoid a critical relative humidity of a salt or hydrate**	Many different critical relative humidities for various materials. See the section on Critical Relative Humidity for details and sources of information.	

Notes for Tables 13A and 13B:

[a] Long-term limits apply to combination of selected annual average plus selected seasonal adjustments. See Figure 15 for examples on a psychrometric chart.

[b] Rate of seasonal adjustments in relative humidity set point should not exceed the short-term fluctuation limit each 30 days, and the rate for temperature adjustment should not exceed the short-term fluctuation limit each 7 days (e.g., for A1, a seasonal adjustment can be no faster than 5% rh change per 30 days and 2 K change per 30 days.

[c] Short-term fluctuation means any fluctuation shorter than the times specified in footnote b for rate of seasonal adjustment (i.e., 30 days for relative humidity fluctuations, 7 days for temperature fluctuations). Space gradient refers to the differential in relative humidity or temperature between any two locations where objects are permitted to be placed in the controlled space (designers can specify out-of-limit locations, such as a specific distance to exterior walls and supply vents).

[d] See Table 3 for examples of objects in each sensitivity category, and Table 5 for lifetimes of objects at various temperatures.

[e] Microclimates (enclosures, packaging) can achieve the same relative humidity control as type AA or A in a much less controlled space (e.g., B, C, or D), and with much greater long-term reliability. See the section on Response Times of Artifacts.

[f] Long-term risk (≥10 years) of mechanical damage because of relative humidity fluctuations is dominated by the probability of extreme events such as system overload or failure in winter. Control type B with high reliability is less risk to collections than AA or A with poor reliability.

[g] An upper temperature limit is provided for a mixed collection that may contain objects with waxy materials that deform irreversibly beginning at ~40°C. This limit is set more cautiously for type B control, 30°C than type C control.

[h] From Figure 3, mold germination becomes very slow, but not impossible, in the range of 75 to 65% rh.

[i] In general, professional guidance currently refers to Bizot, which stipulates outer limits of 40 to 60% rh, and 16 to 25°C throughout the year. Ratified as of 2016 by ICOM-CC, IIC, AIC, AAMD, NMD, BM, and Bizo. See Michalski (2016) for details.

[j] See Table 5.

gradients. Rather than defining a specification and then estimating the benefits and risks, Tables 13A and 13B consider practical categories of benefit and risk, and then define the range of specifications consistent with those benefits and risks.

Column 3 (long-term outer limits) specifies the boundaries beyond which risk climbs unacceptably for many mixed collections (in broad agreement with recent guidelines such as BSI PAS *Standard* 198:2012). The upper limit of relative humidity is based on mold risk (see the section on Biological Damage). The lower limits of relative humidity and temperature are based on mechanical risk, such as the probability of fracture of organic materials (see the section on Mechanical Deterioration). The upper limit of temperature is based on the risk of chemical decay, which climbs exponentially with increase in temperature (see the section on Chemical Deterioration). These generalized limits for mixed collections do not replace a thorough determination of the specific vulnerabilities of specific collections based on information in the section on the Environmental Effects on Collections, alongside consultation with conservators and scientists. For example, a (clean) stone sculpture collection is not at risk from high summer relative humidity or high temperature (pollution and vandalism are more likely risks).

Column 4 (annual averages) assumes design for permanent collections, not loans. To minimize mechanical risk, and to reduce energy costs and building stress, annual averages can be set at local historic annual averages, to which the collection has mechanically acclimatized. In public display areas, a range of human comfort temperatures can apply, but cannot be set beyond the long-term outer limits.

Columns 5 (seasonal adjustments) and 6 (short-term fluctuations) are similar to older versions of this table, although some ranges are now wider. Seasonal adjustments are constrained by the long-term outer limit, although short-term fluctuations are allowed to extend beyond this limit. For a discussion of dual set-point control as a means to achieve these parameters, see the section on Controls Design.

Figure 15 shows the interrelation of the four specification components and the role of long-term outer limits for an example of control type A1. The long-term outer limit (35 to 65% rh, 10 to 25°C is defined by the solid-line box. For this project, the annual average is 21°C and 42% rh, shown by the black dot; seasonal adjustments are ±10% rh, +5 K, and –10 K, although application of these seasonal adjustments is constrained by the upper temperature and lower humidity limits of the long-term outer limit. This combination of annual average and seasonal adjustment is shown by the dashed-line box. Short-term fluctuations of ±5% rh and ±2 K are added, and the

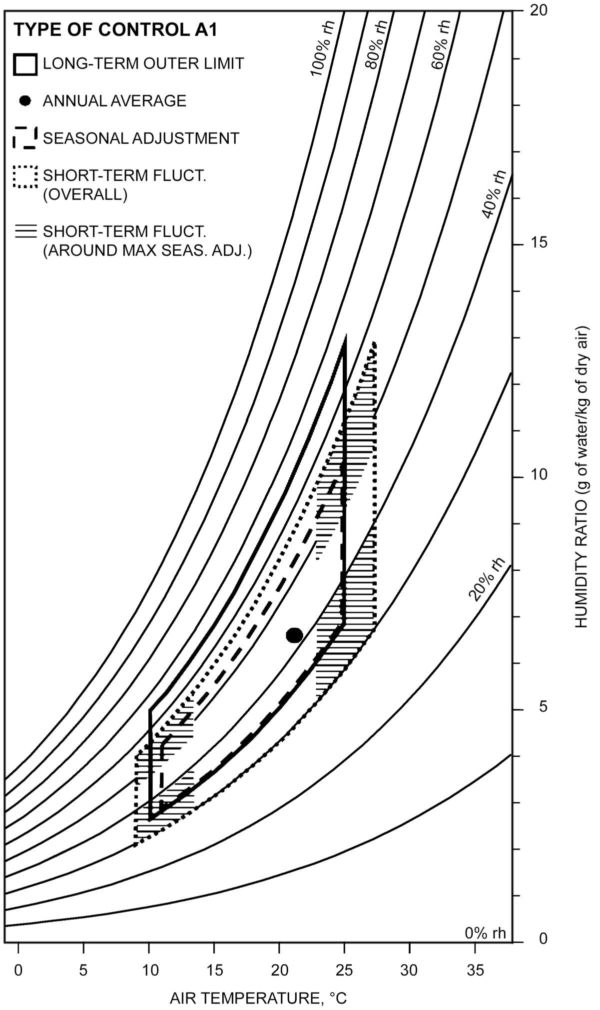


Fig. 15 Psychrometric Depiction of Control Type A1

total range is defined by the dotted-line box. The sections of the dashed-line box that go beyond the long-term outer limits are permissible because they represent short-term fluctuations.

To remain within the bounds of mechanical risk defined for each type of control, it is essential that the annual average be both historically accurate and consistent into the indefinite future. The example in Figure 15, for example, allows short-term relative humidity to drop to 30% because the historic annual average was claimed to be an unusually low 42% rh. At the same time, however, selecting this annual average does not allow short-term humidity to go above 57% rh in summer. Estimates of mechanical risk for each type of control are based on the total range of relative humidity values over many years. If, next year, the annual average setting is changed to 50% rh to justify a summer high of 65% rh, A1 control can no longer be claimed. In a project where historic averages are unknown, select annual averages that are consistent with future needs (e.g., sustainability) or a known critical relative humidity for part of the collection. Given the fixed boundary of the long-term outer limits, the maximum seasonal adjustments are available only for annual averages near the middle of this bounded area.

6.4 AIRBORNE POLLUTANT CONTROL STRATEGIES

In the past, recommendations for maximum pollutant concentrations allowed in museums and archives were based on levels that only limited numbers of major institutions could achieve, and that were measurable with commercial monitors or with sensitive analytical methods (Mathey et al. 1983; NARA 2002; NRC 1986). In the 1980s, little information existed on the impact of some pollutants, such as acetic acid and nitrogen dioxide. As a precaution, "use best available technology' was the stated advice for those pollutants. This expression became popular and, consequently, many institutions requested it as specification, or requested very low limits of pollutant concentrations without justification. Those low limits were often hard to achieve and maintain. Apart from the cost, it also raised the issue of sustainability. In practice, target levels for pollutants were often simply neglected or ignored.

A common analytic method for measuring specific gaseous pollutants uses **diffusive samplers**. A chemical compound in a diffusion tube absorbs a specific pollutant for a fixed amount of time, typically 3 weeks. After the sampling, collected pollutants are sent to a laboratory for analysis. This method can detect most pollutants of interest for museums with good limits of detection (Grzywacz 2006). Particulate matter of different aerodynamic diameters can be measured with precision using a cascade impactor (Krupinska et al. 2013). However, unlike monitoring of temperature and relative humidity, measuring different pollutants is expensive and many museums will avoid doing it unless there is serious doubt about the actual concentration of some pollutants or damage is reported on an object. Qualitative and semiquantitative tests include pH testing, which gives an indication of the acidity level (Tétreault 1992); coarse particle deposition on glass or sticky slides (Lloyd et al. 2007); and metal corrosion electronic sensors or metal coupons, which give information on the corrosiveness of the environment (Coughlin 2011; Thickett et al. 2013). Detection limits of some of these tests can be an issue, as can the fact that they may fail to detect the most harmful compounds for the collection. Test results cannot easily be transposed to specific pollutant concentrations. Even with quantitative measurements, monitoring has some limitations. Not all rooms and enclosures are usually tested, and measurements at a specific location and time may provide limited information: pollutant concentrations can vary based on parameters such as changing seasons, crowd density, space gradients, product aging, and HVAC system adjustments. Measuring pollutant concentrations in a new building before its official opening will not give the same results as a building filled with collections, visitors, and older enclosures. It is best to consider a global preventive strategy before starting a monitoring campaign without being sure the results will provide the proper answer.

Table 14 offers a control strategy for pollutants based on a cost benefit scale and on the reduction of uncertainties of the risk evaluation. The table has three levels of control, and makes recommendations based on the building and enclosure; additional considerations are discussed for each level of control.

- **Basic level:** recommended dust filter performance at least equal to that recommended for office spaces (typically minimum efficiency reporting value [MERV] 11) or as specified by an accreditation program such as the U.S. Green Building Council's (USGBC) LEED Indoor Environmental Quality credit (EQc) 5.1 (MERV 13) (ASHRAE *Standard* 52.2-2017). If appropriate, enclosures should be well sealed to prevent infiltration of pollutants present in the room. Consultation with conservation professionals can provide information on the global strategy for pollutant control, advise on which objects are typically at risk in museums, and provide guidelines for proper selection of products when building enclosures. The goal of the basic level is to avoid or minimize the most common short- and medium-term damage caused by pollutants in museums and archives, at reasonably low costs.
- **Intermediate level**: dust filtration efficiency should be higher than for the basic level (Tétreault 2003). Qualitative or semiquantitative monitoring is suitable in the new installation (rooms and enclosures), as well as some testing of products before use. Some deeper

Table 14 Strategies for the Control of Airborne Pollutants

Level of Control	Building with HVAC system	Display Cases and Storage Cabinets/Boxes	Considerations
Basic			
Basic control of fine particles and avoiding common problems in enclosures.	- Provide basic fine-particulate filtration such as that recommended for office space regulation or for LEED certification (EQc 5.1). - Locate HVAC fresh air intake away from pollutant sources and keep windows closed.	- In closed spaces containing objects, select and use materials recommended by conservation professionals.[a, b] - Ensure airtightness of enclosure (to prevent external pollutant infiltration) if there are no significant amounts of pollutants generated by objects or materials (see Table 9).	- Identify objects (e.g., lead, silver, soda-rich glasses, cellulose papers, calcareous objects) that may be at high or moderate risk from pollutants (see Table 9). - Address pollutants by using a systematic approach: avoid, block, dilute, and sorb.[c]
Intermediate			
Improved control of fine particles and reduced uncertainty and risk of damage in enclosures.	- Use medium-efficiency fine-particulate filtration or select filter performance based on outdoor concentration provided by local authority. - Seal concrete and wooden surfaces (walls, floor, shelves, etc.).	- Test or investigate materials and objects to identify those that contain harmful compounds.[b,c] - Monitor enclosed environment with low-cost monitoring techniques (risk of low sensitivity).[c,d]	- Consider adjusting relative humidity and temperature levels, which often affect pollutants' reactions on objects.
Advanced and special cases			
Optimal control of airborne pollutants in room; better quantification of preservation performance, which allows optimal strategies for improvement.	- Use high-efficiency fine-particulate filtration or select filter performance based on risk analysis result. - Use gas-phase filtration media if outdoor pollutants in surrounding environment or indoor-generated pollutants are an issue.	- Estimate or measure airtightness of enclosure.[e] - Options for special needs: positive air pressure,[c] gas sorbent,[c] anoxia system.[f]	- Maximal average pollutant concentrations for a general collection (excluding moderate- and high-risk objects) should stay below 1000 $\mu g/m^3$ (400 ppb) for acetic acid; 1 $\mu g/m^3$ (0.7 ppb) for hydrogen sulfide; and 10 $\mu g/m^3$ for nitrogen dioxide (5 ppb), ozone (5 ppb), and fine particles. These limits should prevent low-level damage to objects for at least 1 year.[c] Controlling these key pollutants makes it very likely that other pollutants will be controlled as well.
	- Quantitatively monitor[d] concentration of key pollutants and compare against suggested limits or with institutional targets. - Do risk analysis of outdoor, room, and enclosure pollutant concentrations and determine most efficient solutions for minimizing impact of pollutants on specific objects or on collection in general. Adjust institutional target if necessary.		

[a]Tétreault (2017), [b]Hatchfield (2002), [c]Tétreault (2003), [d]Grzywacz (2006), [e]Calver et al. (2005), [f]Maekawa (1998).

investigation can be done to identify vulnerable objects and to determine whether emissions from the collections themselves can be a risk to other objects. This will not necessarily improve conservation of the collection from pollutants, but it reduces uncertainties related to the conservation strategies in place. The strategy can be adjusted, if needed, in the light of the results.

- **Advanced level:** quantitative measurements should be taken of the airborne pollutants (gases and fine particles) outside the institution as well as in some rooms and enclosures containing very significant and vulnerable objects. This can be done for a new installation, during renovations, or as needed. The maximum pollutant concentrations allowed can be based either on the limits in Table 14 for a general collection, or on the target for the general collection and/or for some objects established by the institution. Conservation professionals can help assign pollutant target concentrations aligned with the institution's preservation policy. Quantitative measurement of the air exchange rate for enclosures that need a high airtightness is also recommended. Knowing the airtightness also helps determine the quantity of silica gel or any sorbent needed for an optimal climate control in the enclosure.

Measuring particle and gaseous pollutant concentrations and airtightness of enclosures can provide better confidence on the strategy in place, and can support a proper risk analysis for the overall collection or for specific objects (Krupinska et al. 2013). Local environmental data, obtained from different levels of government agencies, can provide useful information on the outdoor climate. This analysis can help determine the filtration performance needed for rooms and for enclosures holding specific objects or collections. If the room is well controlled, leakage from enclosures may not be an issue. However, if it is difficult to achieve adequate control in the room, then the collection can be better protected inside enclosures. Unfortunately, not all objects can be placed in enclosures (e.g., because of size or access). The length of exhibition/exposure allowed can also be adjusted based on the results of the risk analysis.

For very vulnerable or/and significant objects, some special features can be considered for optimal preservation: positive-air-pressure enclosures (preventing dust infiltration in leaky cases), enclosures with gas sorbents (to reduce the amount of undesired gases generated inside or infiltrated), and low-oxygen enclosures (to minimize oxidative reactions, including photo oxidation). See Table 14 for references.

6.5 CONTROL STRATEGIES FOR OBJECTS WITH HIGH VULNERABILITY TO POLLUTANTS

Some objects tend to be more vulnerable to inadequately controlled environments. Those objects need special considerations that HVAC professionals should be aware of. A conservation professional can also assist with developing preservation strategies.

Silver

Silver is very sensitive to reduced sulfide compounds, mainly hydrogen sulfide (H_2S) and, to some extent, carbonyl sulfide (COS). Sulfur sources are many: the outdoors, from people in the room, and from products and collections inside enclosures. It is usually best to keep silver objects in airtight enclosures with no sulfur-emitting products. Consult the combustion section in the safety material sheet (SMS) for specific products to see if they contain sulfur compounds; products that contain sulfur compounds should be avoided. It is also wise to confirm the absence of sulfur compounds in the product by running a spot test, such as the lead acetate test, Oddy test, or equivalent (Robinet and Thickett 2003; Tétreault 2003). The same strategy can be applied for the preservation of copper. The LOAED for H_2S for silver is 0.10 $\mu g/(m^3 \cdot yr)$ (0.071 ppb/yr) and 1.0 $\mu g/(m^3 \cdot yr)$ (0.71 ppb/yr) for copper (Tétreault 2003). Complete dryness will not stop tarnishing, but will minimize it.

Lead

The most harmful vapor to lead is acetic acid. Lead is not usually at risk of corrosion in a room but may be in enclosures. Any organic-acid-emitting products or objects should be avoided. Lead may never be safe in the presence of wood, painted wood products, or freshly applied sealants or adhesives. The worst situation would be having lead present in a freshly painted enclosure with paint formed by oxidative polymerization (e.g., oil based paint). Polymerization releases aldehydes, organic acids, and peroxides. Those peroxides can convert aldehydes into organic acids (Raychaudhuri and Brimblecombe 2000; Tétreault 2011). Enclosing lead objects in a display case freshly sealed with acetoxy-cured silicone also puts the lead at high risk of corrosion. A relative humidity kept below 35% prevents corrosion by organic acids above the NOAEL (170 ppb).

Calcareous Objects

Calcareous objects (e.g., limestone, ceramics, shells) can react with organic acid vapors, especially when contaminated by chloride or nitrate salts (Halsberghe et al. 2005) in highly humid environments. No data exist to quantitatively assess these objects' vulnerability. As a precaution, it is best to minimize the presence of acid-emitting products or objects in the enclosure as well as relative humidity and temperature fluctuations, and if possible, lower the relative humidity to prevent salt dissolution, reaction, and migration.

Sodium- and Potassium-Rich Glasses

Some historical glasses degrade slowly in the presence of water vapor, resulting in alkali leaching, which can form crystalline corrosion compounds on the surface or modify the structure of the glass. The presence of formic and acetic acids accelerate the leaching (Robinet 2006). These types of glass should be displayed or stored near 40% rh with very little fluctuation (Koob 2006). See van Giffen et al. (2018) for detailed recommendations on climate control for glass. **Enclosures should not contain products that can emit organic acids.**

Colorants

Many colorants (organic pigments and dyes) are known to be sensitive to photooxidation and/or to hydrolysis (Reilly 1998). In addition, some colorants are affected by gaseous pollutants. The most sensitive colorants to nitrogen dioxide, sulfur dioxide, and ozone are curcumin, dragon's blood, aigani, realgar, iron ink, enju, basic fuschin, Brilliant green, pararosaniline, indigo, madder lake, Persian lake, and saffron (Cass et al. 1989; Whitmore and Cass 1989; Williams et al. 1993). Yellow dyes from photographic prints have been found to be affected by acetic acid (Fenech et al. 2010). Artworks with vulnerable colorants should not be displayed long term without protective enclosures, and photograph prints should not be enclosed with products that may release organic acids.

Cellulose Papers

For many decades, sulfur dioxide was thought to be the most damaging pollutant for paper. As its concentration in the environment decreased over the years, it was found that nitrogen dioxide was the main problem for paper. Fine particles and ozone also affect unprotected paper (Bartl et al. 2015; Gurnagul and Zou 1994). At the room level, displaying art on paper without protection (e.g., glazed framing, display cases) is not recommended. However, formic and acetic acid emitted by various organic materials can affect cellulose, but in the presence of aldehydes, the damage is found to be reduced (Tétreault et al. 2013). As a precaution, however, avoid acid-emitting products.

For paper in books, most damage (yellowing, embrittlement) by outdoor and indoor pollutants tends to remain on the margins of the paper sheets, with very slow diffusion into the book. Many archivists will accept some limited deterioration of the pages' edges. If stack or single-sheet papers are framed or protected in airtight boxes, gas filtration in archives and libraries may not be required. The cellulose is best preserved against acid-catalyzed hydrolysis by keeping the relative humidity and temperature as low as possible.

Cellulose Acetate Films

Cellulose acetate films degrade by acid-catalyzed hydrolysis, and acetic acid is the by-product released (Reilly 1993). It is best to preserve films from the 1950s and 1960s in cool or cold rooms (see Table 13B). In ambient conditions, degraded films should ideally be stored in special ventilated cabinets to avoid the risk of damage to other collections. Otherwise, consider enclosing the films in airtight enclosures with moisture sorbents to prevent the ingress of high humidity in the storage area (Nishimura 2015).

Cellulose Nitrate Films

As with any cellulosic material, cellulose nitrate (CN) films degrade by acid-catalyzed hydrolysis, releasing nitrogen oxides. Old CN films, produced mainly from 1896 to 1952, are unstable and must be kept absolutely below 38°C, above which there is a high risk of self-ignition. CN films should be removed from the collection and properly stored according to NFPA *Standard* 40, which provides detailed information on the ventilation requirements. However, it is best to preserve these films in cold rooms (see Table 13B).

Other CN objects (such as faux tortoise shell) do not degrade to the same magnitude as films, but to avoid the risk of damage from nitrogen oxide emissions to other collections, CN objects should be stored either in well-ventilated rooms or in special ventilated cabinets (Coughlin and Seeger 2008). A room with a high load of CN items must also comply with local regulations for explosive and combustible substances.

Difficult-to-Clean Objects

All objects are susceptible to particle deposition, but cleaning of particles is difficult or even impossible for some objects. During handling and cleaning, there is also a risk of physical damage. Example objects include those with powdery pigments or surfaces (e.g., some painted ethnographic objects, butterfly wings); physically fragile objects (e.g., insect collections, filamentous mineral specimens); objects in which fine particles could become lodged in microcracks or interstices (e.g., ivories, painted objects with cracks); and objects with sticky surfaces (e.g., some deteriorated plastics, some polyethylene-glycol-treated wooden waterlogged objects). For these objects, it is best to display and store them in airtight enclosures or in cases with a positive-pressure system. If enclosure is not an option, it is recommended to maintain a minimum distance between visitors and fragile objects: for example, a distance of 1.5 to 2 m reduces dust deposition by 50 to 75% (Lloyd et al. 2007). This distance prevents deposition of coarse particles on objects, but has limited effect on fine particles because of their longer suspension time.

7. CONTROLS DESIGN

Although control technologies for mechanical systems in cultural heritage institutions are similar to those used in the rest of the HVAC field, the control philosophies and logic that determine daily operation of systems that condition collections areas can, and typically should, be quite different. A common criticism of collections environments is the amount of energy required to maintain preservation standards and narrow environmental requirements, especially in structures (historic or otherwise) not designed for that level of control. Updated standards (see the section on Key Considerations) paired with an increased understanding of heritage risk (see the section on Overview of Risks) and how collections materials respond to changes in air conditions (see the section on Environmental Effects on Collections) allow for improved approaches to control and operation (see the section on Design Parameters for Performance Target Specifications) that better achieve sustainability goals while providing appropriate preservation conditions for a variety of materials. Applicable standards as well as preservation and sustainability expectations will have been identified during predesign (see the section on Context and Predesign); outcomes of this process may include selecting a nonmechanical solution to manage the collection environment. If a mechanical solution is required or selected, the control and mechanical design must apply the predesign outcomes, including any design parameters for preservation and sustainability. As mechanical systems move from design and construction into a commissioning/continuous commissioning phase, control and operation should be revisited to assess both achievement of the appropriate environmental conditions as well as energy consumption at individual stages of operation; this combination of appropriate environmental preservation conditions while only using the minimum energy consumption necessary is key to long-term optimal, sustainable operation.

In any cultural heritage application, moisture management and control are almost universally the most critical, difficult, and potentially costly processes to achieve. Moisture's role in determining the overall psychrometric properties of any environment, as well as its central role in most forms of collection degradation, make dehumidification and humidification control primary aspects of the holistic building and system operation. Temperature control, though important for both comfort and preservation, is generally the easier control process, and must be managed to maintain appropriate relative humidity at a given moisture content. To facilitate communication with collections professionals, designers and technicians should be prepared to discuss moisture control in the terms with which the client is most familiar and that map well with collections preservation metrics. Relative humidity is typically the best variable for analyzing risk from deterioration processes that depend on sorbed moisture in objects (see the section on Environmental Effects on Collections). Dew point can also be a useful representation of moisture content, especially for discussions of building envelope performance and deterioration (e.g., window and wall condensation), risks during retrieval of objects from cold storage, or entry of loaned objects during winter. Humidity ratio and enthalpy should be clearly defined when used in communication among the broader design team.

Any controls design should clearly define both the control ranges for temperature and relative humidity and the logical process that governs the operation of the relevant equipment. The sequence of operation should be available as a plain-language document that serves as a master reference for institutional staff (collections and facilities) and guidance to outside contractors (designers, programmers, etc.) for controls or equipment upgrades. This master document should be updated as optimization or other changes in operation dictate.

7.1 PHILOSOPHY

As noted previously, environmental tolerances for cultural heritage collections have largely been redefined through updated science, field observations of environmental impacts on collections, and greater awareness of sustainability considerations. Most collections environments can operate safely within a broader range of temperature and relative humidity conditions than previously understood, leading to new methods and approaches for equipment control and operation to achieve preservation and sustainability goals. Certain environments (e.g., exhibitions with loaned materials governed by an agreement) may still require a narrow band of control, but many collections environments can safely include seasonal adjustments and allow short-term fluctuations without causing damage.

The result is a more complex discussion from the controls design perspective. Information shared and developed during predesign should form the basis of the control philosophy, which should be formalized in a written sequence of operation that provides the logical relationships for how equipment achieves the intended operation. It is critical to recognize that the design sequence of operation is only a model of what is expected to happen: it is likely, even preferable, that the sequence of control will be adjusted during commissioning and optimization. Actual energy loads in the space may be different from models, and it is difficult to predict the effects of collections materials, which may effectively function as heat and moisture sinks in the room environment. Where ratios of hygroscopic material volume to air volume are significant enough, collections may actually buffer environmental changes. Kupczak et al. (2018a) show that, at high ratios, paper collections can reduce fluctuations and energy costs.

Design of temperature and relative humidity controls in cultural heritage settings have traditionally identified a single set point with a dead-band range, and the system works to achieve those set points year-round. With expanded humidity ranges and the use of seasonal temperature control in collections environments, single-point control is no longer the most efficient method. For temperature, occupied collection spaces (where human comfort needs may dictate a narrow range of temperatures throughout the year) are still appropriate candidates for single set-point control. However, low-occupancy collections spaces (e.g., storage) may see both preservation and energy benefits from seasonal temperature adjustments; designs should consider using dual heating/cooling set points or minimum/maximum conditions for seasonal control. Any collections environment, occupied or unoccupied, may benefit from dual relative humidity set points defining where humidification and dehumidification are enabled.

Controls design has two goals:

- Achieving appropriate equipment operation and process management to create and maintain the collection preservation environment defined during predesign
- Using only as much energy as necessary to achieve the desired conditions

Though many cultural heritage institutions or buildings may appear similar on the surface, individual factors such as the following usually require highly individualized controls and equipment designs to match the unique situation (see the section on Context and Predesign):

- Collection type and preservation needs
- Outdoor climate
- Building envelope performance
- Degree of mechanical intervention intended
- Occupancy of collections spaces
- Prioritization of preservation and energy usage
- Institutional capital, operational, and utilities budgets

These factors also heavily influence optimization: similarly constructed buildings and preservation environments (e.g., many offsite library/museum storage facilities) commonly optimize differently for preservation and energy based solely on geographic location and exterior environments, even when many other variables are the same.

7.2 ZONING

An air-handling zone refers to the group of spaces that an air-handling unit (AHU) serves in a building. Zoning in cultural heritage facilities can be broken down into four simple groups, each with different requirements for control. Generally, regardless of zoning, system control should be based on some combination of sensors placed in the collection space; return air sensors can be used as a reference point, but should not be used as the control point in cultural heritage applications. The four typical zoning configurations are as follows.

One AHU to One Space. Desirable for fine environmental control. Control should be based on a temperature/relative humidity (T/RH) sensor in the collection space. Control from return air sensors may not accurately represent what occurs in the space.

One AHU to Many Spaces. Best when spaces are used for the same purpose, have similar criteria for interior space conditions, and have similar interior and exterior thermal and moisture loads. Mixed zones (i.e., collections and noncollections) generally lead to suboptimal preservation conditions or energy use. In collections or mixed occupied collections zones, each individual space should have a T/RH sensor. Control can be based on either high/low readings from individual spaces that will enable a process, or on a zone average of readings from all space sensors. Using a zone average for control can lead to parts of the zone being out of the defined operational parameters, especially in rooms with an external wall or roof exposure. These areas may require either mitigation of the load or air rebalancing for correction. If high/low readings are used, conditions in other subzones must be monitored to ensure that they do not go out of specification. Using a blended return air sensor may lead to inaccuracy or control issues, depending on where return air is being pulled from within the zone.

Many AHUs to One Space. Used in large footprints, most commonly in storage, large galleries, or reading rooms. This strategy is especially useful if different parts of the space are exposed to different loads over a 24 h period (e.g., solar exposure). Control should be based on subzones in the space with individual T/RH sensors: control from return air sensors may not accurately represent what occurs in the space. In this configuration, control and sensor placement should be considered carefully to limit the potential for units to operate suboptimally; for example, the average room condition may register as acceptable, though individual units are performing dissimilar operations (e.g., one system is cooling and the other heating).

Many AHUs to Many Spaces. Typically found in large, multilevel footprints (e.g., multilevel library/archives storage); especially useful if different parts of the space are exposed to different loads over a 24 h period (e.g., solar exposure). Control should be based on subzones in the spaces with individual T/RH sensors, because control from return air sensors may not accurately represent what occurs in the space. For this configuration, carefully consider control and sensor placement to limit the potential for units to operate suboptimally; for example, the average room condition may register as acceptable, though individual units are performing dissimilar operations (e.g., one system is cooling and the other heating).

Zone design, adjacencies, and other aspects of functional organization should be part of early predesign discussions to optimize design for preservation and energy usage, as well as to rightsize systems for efficient initial capital investment.

Table 1 describes building space types in typical cultural heritage facilities, and should inform decisions of physical zoning and control. Ideally, an HVAC zone should consist of physical spaces that require similar environmental control. For many cultural heritage institutions, there are three general environmental zones to consider:

- **Occupied noncollection spaces** where human comfort is typically the priority. They require outdoor air and temperature control, but little moisture control (only for human comfort). These concerns may not be as pertinent for noncollection spaces that are typically unoccupied.
- **Occupied collection spaces** require outdoor air during occupied periods, human comfort temperatures, and moisture control for collection preservation. Systems may dehumidify and humidify based on climate zone (see Table 10 and Figures 12 and 13). Examples include galleries, reading rooms, and collection workspaces, and may constitute a large percentage of the building footprint. *Note*: a common issue is whether to treat certain offices as collection spaces. This should be considered carefully, not only for the added capital and operating cost, but also for risks to the collection if offices are not so treated and are nonetheless used for collections display or storage.
- **Storage environments** (typically unoccupied collection spaces) require temperature and moisture control that is optimized for long-term preservation. Outdoor air may be reduced or eliminated entirely, based on occupancy or other requirements. Depending on the institution, examples include typical low-occupancy storage environments (e.g., library and archives stacks), or truly unoccupied collection spaces (e.g., cold or low-oxygen storage).

Mechanical systems and buildings function best when AHUs and zones are logically divided according to purpose. System and controls designs should avoid mixing collection and noncollection spaces wherever possible and resist the tendency to accept downstream sub-zone controls (e.g., VAV/reheat designs) as immediate solutions to zoning issues. Such designs will invariably be less energy efficient over time, and commonly lead to problems maintaining conditions for the preservation environment as human comfort will take priority.

7.3 BASIC PROCESSES

Cultural heritage facilities perform four basic psychrometric processes on a moving airstream to control internal environments using mechanical intervention (Figure 15):

- **Heating:** raising sensible or dry-bulb temperature, as preheat, reheat, or heating for downstream temperature control. May be accomplished by various equipment, ranging from direct and indirect fired heaters to electric, hot-water, or steam coils. In certain settings, heating may be by nonforced-air systems, using other convection or radiant technologies.
- **Cooling:** decreasing sensible or dry-bulb temperature, commonly for downstream temperature control but occasionally as precooling ahead of some components (e.g., energy wheels) for increased efficiency. Typically accomplished either by direct-expansion (refrigerant-based) cooling or by chilled-water or glycol coils.
- **Dehumidification:** reducing moisture content for the specific purpose of maintaining a safe range of relative humidity at a given temperature condition. Equipment varies from common subcool/reheat coil designs, to various configurations of desiccant or energy wheels, whether as components in a larger air handler design or as a stand-alone package unit.
- **Humidification:** increasing moisture content to attain a minimum relative humidity condition in a downstream space, typically in arid or seasonally dry or cold climates. Humidification can be performed by isothermal (steam) or adiabatic (evaporative) systems, and may be located at the primary unit or in downstream ductwork.

The sequence of operation should clearly identify the logic of when each process occurs; for example, that humidification begins once the space drops below 35% rh, or that sensible cooling and sensible heating cannot be engaged at the same time.

7.4 OUTDOOR AIR AND VENTILATION

Outdoor Air

Introducing outdoor air into interior environments typically increases sensible and latent system loads and serves as the primary source of particulate and gaseous filtration loads. In collections spaces, where the primary goal is maintaining the appropriate interior temperature and relative humidity conditions, outdoor air quantities should be restricted to the minimum necessary for occupancy based on local code. For nonoccupied collections spaces and spaces with periods of zero and nonpeak occupancy (e.g., galleries, reading rooms, workspaces during closed periods), designs should incorporate means of further reducing outdoor air volumes, even to fully closed, based on actual need. CO_2 sensors and modulating dampers can help automate this process, and may allow for flexibility with certain code requirements. Particular consideration of outdoor air requirements should be given to spaces housing materials that may emit hazardous substances (e.g., radon) or require specific outdoor air volumes because of fire code.

Air-Side Economizers

Economizer controls, typically intended for energy-savings/free-cooling of interior environments, should generally be avoided in cultural heritage applications. Dry-bulb temperature and enthalpy controls may allow inappropriate levels of moisture (either too wet or too dry) into the airstream, increasing latent loads for dehumidification and humidification compared to the return airstream. Although dry-bulb temperature and dew-point controls can be programmed to allowable conditions, they generally offer reduced energy benefit compared to other energy-reduction strategies because, generally, most outdoor environments align with both temperature and dew-point requirements only for short periods. Economizers also increase risks to interior environment maintenance: control failure or mechanical failure of outdoor air dampers on ductwork sized to allow for 100% of the system volume can quickly create significant environmental issues. Air-side economizers should not be used unless (1) bin analysis or other study shows outdoor air moisture content to be favorable for an economical number of hours, and (2) favorable outdoor air can be reliably selected by the control system by combined dry-bulb temperature and dew point comparisons.

Pressurization

Positive air pressurization has been frequently used in cultural heritage facilities to minimize incursion of external loads into controlled collections environments. However, this practice often increases energy consumption, and in some cases increases the risk to the building envelope, particularly in historic structures. With improved envelope design and appropriate zoning and adjacency design, positive air pressurization is no longer an absolute requirement in cultural heritage settings. Neutral pressurization is typically an appropriate goal; avoid negative air pressurization. In multiple-story buildings, stack effect (discussed later) creates unavoidable pressurization in upper floors; airflow design should not exacerbate this problem. Positive pressurization is typically created through a combination of outdoor air and duct design, with supply air ducts sized for greater volumes than the return air. Designs for pressurization in cultural heritage facilities should allow for equal volumes of supply and return air to the downstream zone to facilitate recirculation modes (no outdoor air) without pressurization consequences because of duct sizing. Modulating dampers on the outdoor and return airstreams as well as using adjustable return and supply air grilles can allow for balancing adjustments.

Natural Ventilation for Preservation

In some circumstances, natural ventilation may be necessary for interior moisture control and/or inhibition of mold growth. Historic structures with limited mechanical intervention may benefit from controlled natural ventilation on a scheduled basis (e.g., diurnal or seasonal operation) or may require either mechanized or passive ventilation for emergency situations or disaster recovery. The goal of ventilation is one of the following:

- Move out moisture that has originated inside the building (e.g., rising damp)
- Raise temperature of spaces containing a cold surface causing high relative humidity (e.g., a slab floor) or a high-mass wall without solar exposure
- Reduce stratification of spaces containing a small, localized cold surface

These operations may be enabled by a high-limit relative humidity sensor in the space, time scheduled, or (for disaster recovery or power outages) manually activated.

Air Change Rates

Air change rates in cultural heritage institutions are not constant values, and should vary based on zone usage and occupancy, with other specific factors (e.g., events spaces, fabrication or paint shops, conservation labs, off-gassing collections materials) accounted for as necessary. The operational goal after optimization is to run the system with the minimum air volume/change rates necessary to maintain the desired environmental conditions while providing for occupancy and protecting against microenvironments. Proper envelope, airflow design, and duct layout should minimize potential microenvironments; environmental data logging in conjunction with control sensors can alert staff to potential issues. Initial design may use air change rates recommended for particular zone types (office, laboratory, classrooms, etc.) but should include variable-frequency drives (VFDs) or variable speed drives (VSDs) that can control air volume/change rates based on occupancy patterns, established needs, and other factors. Collections storage zones generally require lower air change rates unless extenuating factors (e.g., off-gassing materials, issues with microenvironments) dictate otherwise.

Stack Effect

Stack effect can have significant implications for control in cultural heritage settings, particularly in multistory structures and high-ceilinged spaces (ranging from modern high-bay storage environments to historic structures that may incorporate historic frescoes and murals). Differences in temperature (and, to a lesser extent, moisture) between interior and exterior environments can result in density gradients that induce air movement and exchange, drawing unconditioned outdoor air into the building and often causing issues with airflow, microenvironments, and overall system operation. Stack effect may reverse depending on the exterior and interior conditions: when cooling indoors, upper areas may be negatively pressurized relative to outdoors, drawing warm air into the structure, while lower parts of the building may be positively pressurized. The reverse is true when heating indoors. This is particularly problematic in structures with limited envelope integrity and limited or poor zone design. Where this effect is noted, if envelope improvements are not an option, pay particular attention to airflow design and balancing to combat preservation risks (typically from high-temperature and high-relative-humidity microenvironments).

Stratification

Interior thermal stratification can occur even in buildings with excellent envelope integrity. It is caused by the displacement of warm air by more dense cool air. This can occur independently of interior/exterior pressure differentials and, like stack effect, can create issues in preservation environments because of microenvironments and poor environmental controls throughout multistory or high-ceilinged spaces. Common problems include high temperatures (which can increase rates of chemical decay) near ceilings and on upper levels, and issues with high relative humidity and potential mold risk because of cooler temperatures near floor level, especially in areas with poor air circulation. Proper zoning, airflow design, duct layout, and balancing can reduce stratification. For storage and cool environments, overhead diffusers and floor-level returns generally are preferable; occupied spaces (offices, galleries, etc.) may use floor-level or overhead diffusers. Ceiling or circulation fans may be used as low-impact solutions for improved air mixing and reduced stratification.

7.5 SPECIAL CLIMATIC CONSIDERATION

Humidistatically Controlled Heating

This specialized approach has limited application and must include safety controls, but is sometimes the only option that can handle envelope limitations in cold climates. In this approach, the heating system is controlled by a humidistat rather than a thermostat (LaFontaine and Michalski 1984); cold, damp air is heated until the relative humidity drops to a predetermined safe range, typically below mold germination conditions. Where interior temperatures drop consistently below 10°C, it solves the problem of humidity in a building that does not have an adequate envelope. Humidity-controlled heating does not provide human comfort in winter, but many small museums, historic buildings, and reserve collection buildings may be largely unoccupied during this period. A high-limit thermostat is necessary to stop overheating during warm weather, and a low-limit thermostat may be used if water pipe freezing is a concern. This approach has been used in Canada (LaFontaine 1982; Marcon 1987), the United States (Conrad 1994; Kerschner 1992, 2006), and in many historic buildings in Britain. Maekawa and Toledo (2001) successfully applied humidistatic control in hot, humid climates to minimize mold growth.

Some cautions apply. Foundations in a previously heated building may heave if the ground is waterlogged before freezing. Improving drainage, insulating the ground near the footings, and heating the basement reduce this risk. Problems have occurred in buildings with dense object storage and a very low infiltration rate, such as a specially sealed storage space (Padfield and Jensen 1996); a very slow supply of dehumidified air to the space can be helpful.

This approach is cost effective in seasonal museums (especially for low-mass wood-frame buildings) in colder climates such as the northern United States and Canada, and in maritime regions. Application in hot and humid environments should be judiciously considered, typically where mechanical dehumidification is impractical. Humidistatically controlled heating may be applied where the imminent risk of mold growth outweighs other degradation risks, and should be balanced with the increased risk of chemical decay because of elevated temperatures. In many circumstances, improved air circulation or natural ventilation for air circulation may be a preferred first step for mold avoidance.

Note: humidistatically controlled heating may be used in place of stand-alone dehumidifiers. As described in the following section on Dehumidification, stand-alone dehumidifiers and air conditioners pose a particular threat to cultural heritage collections because of the inherent risk of flooding and electrical fire in the local collections zone; their use should be judicious, and only when the building/space is occupied.

Hot and Humid Environments

Control of mechanical operations in hot and humid environments (whether constant or seasonal) depends largely on the level of mechanical intervention selected. From a control perspective, moisture management (both relative humidity and moisture content/humidity ratio) is the critical process, and may be achieved through various mechanical means, including dehumidification, cooling with secondary dehumidification (as in typical direct expansion/refrigerant-based window, residential, and package air conditioners), ventilation, and, less commonly, humidistatically controlled heating. In most applications, the primary preservation goal is to restrict mold growth and other biological risks, with mechanical damage (particularly in seasonally humid/dry climates) and chemical decay typically secondary concerns.

Envelope capability heavily influences both control design and equipment selection. Where the structure has a modern, purpose-built envelope that can limit sensible and latent loads, temperature control and the limitation of chemical decay may be the first design priority. For most historic, renovated, and/or repurposed structures, control design for collections zones should primarily be based on space relative humidity. Designs should consider a specific ventilation control (whether integrated into the primary system, or as a separate system) that can also be manually enabled in the event of limited power availability or long-term power outages, where generator capacity may only be capable of providing circulation without temperature or humidity control. In mechanical designs where redundancy or back-up power may not be available, control and system designers should also consider advocating for passive strategies, including single-side, cross, or stack ventilation, as a way to provide airflow and limit mold growth during equipment failures or power outages.

Additional information on environmental management in hot and humid climates is presented by Harriman (2009) and Maekawa et al. (2015).

7.6 INTERIOR CONSTRUCTION

Interior construction decisions in multizone buildings can significantly affect the ability to successfully control interior environments. Early during predesign and design, it is essential to share information about partitioning, solar load, and spaces in which collections will be exhibited or stored. Beyond exterior envelope performance, architects and engineers must consider interior zone separations, which may include thermal and vapor barriers between collections and non-collections zones. Zone design should strive to keep spaces on the same mechanical zone contiguous to one another, with interior construction designed to minimize air and vapor flow between the zone and adjacent spaces. Beyond thermal and vapor barriers in interior walls, ceilings, and floors, strategies should include

- Insulated, fire-rated doors
- Door seals, gaskets, and sweeps
- Sealing any penetrations, with overall penetrations kept to a minimum
- Ducted return rather than plenum design

These practices are also commonly required for any environmental zone/space using clean-agent fire suppression systems.

8. CONTROL EQUIPMENT

Hardware and software choices in control design should be based on the best application for the institution/building in question, and vary from basic, direct single-point thermostat/humidistat control of a residential-style heating and air conditioning system to larger building automation (BAS) or building management systems (BMSs) intended to manage multiple air and water systems throughout a building or site. Rather than detailing the structure of the control system, the following factors should be considered in the design of any controls system for a cultural heritage setting.

8.1 HARDWARE

Sensors

Selection. Selection of temperature and relative humidity sensors (thermostats, humidistats) should consider accuracy, initial calibration, and response time. Sensors for cultural heritage applications generally trend toward the more accurate, with ranges of ±0.2 K and ±2% rh or better. As a guideline, response time should be within 1 min for temperature, and less than 2 min for relative humidity (BSI 2010). Reducing project costs by reducing relative humidity sensor reliability and accuracy is a false economy that will compromise operational accuracy and place the collection at risk. Dew-point sensors, though initially expensive, are much less likely to suffer from calibration drift.

Calibration. Design and initial commissioning typically assume newly purchased hardware and represent the best-case operational accuracy for the system. Institutional staff should be provided with guidance for eventual replacement or recalibration to provide continued accuracy in operation. Note that field recalibration rarely achieves the same level of accuracy as factory recalibration (if available) or new equipment.

Location. Typical sensor placement is based on control points, with occasional reference data (e.g., discharge air conditions, space or return air conditions, outdoor air conditions). Generally, primary control sensors should be located in the collections spaces; each collections space should have at least one sensor associated with the control system. As environmental optimization in cultural heritage has increased in popularity, institutional staff may desire greater transparency in operation, with data available from multiple points to assess the performance of individual system components. Sensor locations may now consist of an expanded list of reference points, beyond typical control points, and may include

- Outdoor air
- Return air
- Mixed air
- Cooled air
- Heated/reheat air
- Humidified air
- Discharge/supply air after downstream equipment

Designers should work with institutional staff to understand future informational needs and determine appropriate sensor locations.

Stand-Alone Data Loggers. Many cultural heritage institutions use stand-alone digital data loggers to monitor a collection's environment for preservation purposes. These devices have the advantage of flexible deployment throughout a mechanical zone (close to the collection, or in areas of suspected microenvironments) compared to hard-wired control sensors, which, because of access, location, calibration, etc., may not always provide an accurate representation of what the collection experiences. Stand-alone data loggers are often equally as accurate as BAS/BMS sensors and may have the advantage of more regular calibration. Use of data loggers and data comparison should be discussed during predesign; ideally, data from both systems (data loggers and BAS/BMS) should be used to assess environmental performance and to identify potential issues with either set of equipment. Some institutions may still use hygrothermographs to record environmental data; however, without continuous maintenance and frequent calibration by trained personnel, these units are prone to large measurement errors and are generally no longer recommended for use in the cultural heritage field.

CO_2 Sensors. Consider using CO_2 sensors as a control mechanism in settings where there are opportunities to control outdoor air intake beyond a set volume. In storage environments and collections spaces that are only lightly occupied or that are occupied on a fixed schedule, there may be significant opportunities to reduce heat, moisture, and filtration loads by minimizing outdoor air quantities when fresh air requirements are flexible.

Variable-Frequency Drives

Now common for both fans and pumps, VFDs or VSDs should be included on most systems larger than residential/light commercial equipment; small drives are regularly found on rooftop and other package systems. As control equipment, their uses vary; drives may respond to differential pressure or to downstream damper control in a variable-air-volume system or, more critical in collections-centric zones, can be used for optimal part-load fan operation or soft stops/starts as part of programmed shutdowns.

8.2 SOFTWARE

BAS/BMS systems may be proprietary or open source, and selection typically depends on the institution's level of on-site expertise: some institutions do controls programming in house, whereas many use outside contractors. Engineers should work with institutional staff to determine the likely level of staff interaction with the system, and should select a product accordingly. Other considerations may include a preexisting contractor or product at a site, and the availability of qualified controls contractors in a given geographic area. All systems should ideally allow for

- **Data trending:** retention of historical data from multiple points, including sensor readings, damper positions, motor speeds and status, and other information. Trends should allow for a minimum of one year's worth of stored data.
- **Data export:** export of data to open file formats (e.g., plain text, CSV) that can be imported into other programs for storage or analysis.
- **Alarms and notifications:** contact to multiple individuals, including staff in both facilities and collections, by email, text, or other means.
- **Remote access:** ability to manage or adjust building/system operation from off site, through a virtual private network or other secure connection.
- **Read-only access:** for nonfacilities or controls staff who use the BAS/BMS interface to monitor environmental conditions or system operation.
- **End-user control** (as desired): most institutions with on-site facilities staff should be able to adjust space temperature and relative humidity set points, create operation schedules, have access to an emergency shutdown function, and be able to set new data trends.

9. SYSTEM DESIGN AND SELECTION

System and equipment selection varies greatly from institution to institution. In addition to the factors of control philosophy that influence control design discussed under the Controls Design section, system and equipment selection must consider additional input that may be determined during predesign, including

- Institutional staffing and in-house mechanical expertise
- Physical configurations and limitations for mechanical equipment
- Influence or requirements of historic structures and envelopes
- Maintenance (preventive and reactive) practices and budgets
- Availability of qualified technicians and contractors
- Availability of onsite utilities, including water, electric, natural gas, renewable power
- Preexisting equipment (e.g., chillers, boilers, perimeter systems, ductwork) that may influence equipment and design choices

In system upgrades or renovation projects, a combination of these factors may significantly predetermine the type of equipment selected, although not necessarily its capacity or control. In new construction, the designer may have far greater flexibility in selection.

Three key principles should be considered during system design and equipment selection:

- **Design for purpose:** cultural heritage design parameters may be significantly different from standard engineering designs for occupied spaces, ranging from frozen environments to narrow bands of relative humidity control for specific spaces. The first goal of any design must be to achieve the required preservation conditions for various building zones. These conditions are determined during predesign and may require further discussion/refinement, depending on design option. Integrated design should strive to find the most appropriate holistic design solution possible for a structure that (for new construction) may have more than five distinct environments managed by multiple air or water systems, plants with multiple chillers and boilers operating to different capacities, and the possibility of significant downstream equipment.
- **Design for operability:** design of mechanical systems for cultural institutions is often an exercise in the balance of cost, capability, and, in particular, technology. Ideally, system designs should be operated, maintained, and repaired by the organizational staff or local contractors; regardless of its efficiency or potential, technology whose repair requires two weeks of lead time from a contractor many hours away will be unsustainable. In many applications, simple designs with clear roles of components and clear control logic are more favorable than the latest complex technologies and subsystems. Possibly except for the largest institutions with significant facilities infrastructure, cultural heritage is rarely the best proving ground for new or untested technologies. Redundancy may be significant and affordable in certain applications (e.g., humidification), but limited by capital budgets in others; resiliency must be considered in every design, often as an understanding of the holistic building system (systems, envelope and structure, siting, etc.).
- **Design for longevity:** though all equipment has limitations on its useful lifespan, equipment selection for cultural heritage should focus on designs and equipment that provide the longest service life possible. Many cultural heritage facilities are part of nonprofit or educational institutions whose capital budget planning may be on a longer cycle than other organizations. Installing package units with a 15 year service life expectancy for an institution whose budget cycle will not allow additional capital investment for another 20 years creates a potential 5 year gap where operation and maintenance of appropriate preservation conditions may be a struggle. These discussions should be included during predesign and design, and engineers should clearly communicate the potential lifespan limitations of different equipment options to the institutional staff.

9.1 ENERGY AND OPERATING COSTS

Energy and operating costs of mechanical systems are primarily a function of the amount of energy work being done for a certain number of hours, commonly analyzed on a monthly or annual basis. With large portions of buildings requiring greater moisture control than many other applications, total energy consumption by cultural institutions can appear inflated compared to noncultural applications while still being comparable to similarly purposed buildings and, at least over the past 20 to 30 years, generally expected by the cultural heritage profession.

Energy work related to cultural heritage should first focus on achieving the desired environmental conditions with the least energy expenditure possible. Sometimes, predesign identifies limitations to the potential preservation environment driven by estimated energy costs; these instances require some compromise to achieve the best preservation condition achievable with the projected energy/utilities budget. Initial capital investments made to reduce recurring annual energy costs may be considered, and continuous commissioning and optimization can identify opportunities for energy reduction without altering preservation quality.

Energy Audits

During predesign, projects for existing buildings should consider an energy audit based, at minimum, on existing systems and their typical operation. Predesign teams may also consider comprehensive energy audits for the entire building, to identify the influence of additional energy factors (e.g., lighting) not addressed in a mechanical study. Data from the audit should be analyzed for evidence of excessive operation, with these findings informing future system design. After construction, institutions may perform periodic energy audits to inform continuous commissioning or optimization processes.

Life-Cycle Cost Analysis (LCCA)

Applied to mechanical systems, LCCA is the assessment of the whole cost of the potential installed system over its estimated lifespan. This exercise, which can be applied on a whole-building scale, greatly assists in selecting the most appropriate design solution when several options appear viable. Typically, LCCA for systems should include estimates of

- Capital costs: purchase and installation
- Energy costs, whether using fossil fuels or renewables
- Operation, maintenance, and repair costs
- Component replacement costs, where system components (coils, motors, humidifiers, downstream equipment, etc.) may be replaced without changing the primary cabinet or system

LCCA studies should carefully identify the variables being compared, especially regarding differences in systems versus differences in environmental conditions. For example, comparative analysis of potential system designs that achieve the same environmental conditions (e.g., water-based subcool/reheat versus direct expansion cooling and electric reheat) is different from comparing LCCA for a water-based subcool/reheat system designed for either 20°C/50% rh or a 18°C/40% rh.

Energy Efficiency

Energy efficiency may be achieved either through direct equipment efficiency (e.g., more efficient coils or compressors) or through operational efficiencies, such as airflow control, outdoor air control, and strategies for nonpeak operation. In general, system designs should include the most efficient equipment selections possible given budget and institutional infrastructure. Potential operational efficiencies, which are highly dependent on performance and use of the final populated space, should be accounted for through flexible operational design (e.g., VFDs, modulating dampers and valves, programmable thermostats in smaller applications) and tested during continuous commissioning or optimization work before adoption.

Lighting and Daylighting

Lighting and daylighting, as they pertain to system design and operation, have several components to consider. Light-emitting diodes (LEDs) are increasingly common choices for collections environments in both new construction and renovation, and unlike other lights (fluorescent, incandescent, halogen) have comparatively little impact on overall system operation and design. Although LED fixtures do produce heat, the quantities are considerably smaller. Engineers should consult with lighting designers regarding lighting choices, their potential heat output, and what load must be accounted for in design calculations. Renovations of systems serving existing environments using a variety of heat sources should consider a lighting audit to determine existing thermal loads from space or exhibit lighting.

Daylighting is often proposed, especially for noncollections areas. Generally, daylighting should be avoided for all storage environments and avoided, or severely limited, for most exhibition spaces. Preservation assessment for possible light impact on collections should be conducted in conjunction with any lighting design. Ayres et al. (1990) noted that daylighting is always a net energy penalty. If used, the daylighting aperture should be minimized, and avoided as much as possible in and over collection areas. For lower risk of leaks and better-managed lighting, clerestories are preferred over skylights. In applications where daylighting is unavoidable (e.g., historic structures), light-reducing and blackout shades and UV filters can reduce exposure of collections to both visible light and ultraviolet wavelengths, as well as reduce potential heat gain.

Hybrid (Load-Sharing) HVAC Systems

As detailed in Chapter 6 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*, hybrid HVAC systems use multiple means of heat transfer to control a specific environment. Most commonly, this involves collocating radiant and forced-convection systems. Most of the sensible loads are assigned to radiant panel systems, whereas latent loads and the remaining sensible loads are assigned to forced-convection systems. Decoupling the HVAC functions primarily into sensible and latent heat transfer components allows the designer to select better function-oriented HVAC components and ensure higher accuracy and precision in control, potentially at lower energy expenditure. Application has been limited in collections environments; where the approach is used, infloor radiant may be the most appropriate application because of the potential for microclimates against radiant wall panels in exhibition and storage environments. One key detractor for application in cultural heritage is the possible higher cost of installation and maintenance of dual systems.

Historic structures, house museums, and recent buildings can present a similar scenario from a legacy perspective when institutions seek to combine modern forced-air cooling and dehumidification with original hydronic systems using radiators or a perimeter heat loop for either a portion or the whole of the sensible heating load. The heat transfer mode remains the same (both systems operate by convection), but the operational challenge is similar to that with other hybrid heating system designs: management and control of a hydronic system in conjunction with forced-air control. Balance and efficient operation can be excessively difficult to achieve; new construction, with opportunities for insulated glazing and perimeter forced air zones, can generally avoid using dual hydronic and forced-air systems.

Dual Fuel and Multiple Energy Sources

Dual-fuel and multiple-energy-source systems are typically seen in residential or light-commercial applications, often as a package unit that incorporates both fuel and electric heat depending on demand. Application of these units in cultural heritage is relatively limited, but as new technologies develop, other multiple-energy-source systems have begun to emerge, particularly for smaller applications and heating/dehumidification side. Water heating may use recovered waste heat from various applications or use solar thermal collectors, with a traditional boiler for back-up; the hot water can then be used for heating, reheat for dehumidification, or regeneration for a desiccant system. Variants on hybrid designs, especially with renewable energy sources, may be particularly applicable in design situations where regular utilities are limited (e.g., well-water or tank fuel-storage systems) or the cost of certain forms of energy is prohibitively high.

Maintenance and Ease of Operation

As discussed previously, maintenance, accessibility, and ease of operation and repair are critical components of any proposed mechanical design. System design should enable both preventive and reactive (i.e., breakdown) maintenance by either existing institutional staff or an identified contractor in the local area. Specialized equipment with no local maintenance or repair support should be carefully considered for potential benefit versus risk because of lack of maintenance, and alternative options should be explored. For large projects in larger cities, code-required staffing for the plant should be considered; sometimes, smaller reciprocating chillers can be used at night to preclude the licensed engineer needed to operate larger chillers. Specific aspects to consider as part of design review may include

- **Accessibility of the primary unit and individual components.** Package units should have adequate clearance on all sides for maintenance, repair, and cleaning. For larger air handlers, access doors should provide access to all sections, and before and after all downstream equipment; installation should be careful not to block these with piping or ductwork. Valves and dampers must be accessible for preventive maintenance and repair. Above-ceiling units should be limited if possible because of access issues, and ideally should not be located in collections areas because of leak and access risks.
- **Exterior equipment (rooftop, ground-level pad, etc.) versus interior mechanical rooms.** Exterior equipment installations typically suffer in longevity, especially in salt-air environments. Where possible, equipment installations should be indoors, with adequate air exchange and access.
- **Clear component labeling.** Piping and ductwork should be clearly labeled with its purpose and direction of flow, as should primary airflow on the unit and all sections. Basic flow schematics should be available for all air handlers and hydronic systems. This practice should also be applied in construction with clear labeling of piping, ductwork, and airflow.
- **Identification and labeling of manual shutoffs.** Primary shutoff points (electrical disconnects, manual valves) should be easy to locate and clearly labeled.
- **Availability of drains and fire suppression.** Floor drains should be local to equipment, and fire suppression (whether a central system or handheld) should be available.

Effects of maintenance activities on the collection must always be considered. For example, testing or accidental activation of a smoke removal system can radically change the collection environment. Tools and ladders in gallery and storage areas are a threat to the collection, and special precautions must be taken. Contaminated air conveyance components (e.g., mold growth and other build-up) can contribute to pollution levels, lead to premature component failure, and affect heat transfer efficiency, resulting in higher utility costs. Regular inspection and cleaning are an important part of preventive maintenance.

9.2 DESIGN ISSUES

Zoning/Functional Organization

As discussed in the section on Zoning (under Controls Design), three general environmental zones must be considered not only for control but also for system layout and design: noncollections spaces, occupied collections spaces, and unoccupied collection storage environments. Efficient operation is typically best achieved when each of these zones is served by mechanical systems dedicated to that particular environment; this approach avoids unnecessary energy usage (e.g., significant dehumidification for a noncollections zone) and improves the likelihood of maintaining environmental control.

The design engineer should be involved from the start of project planning to ensure that space layout does not present unnecessary problems. For both functional organization and design efficiency, spaces in similar environmental zones should be kept physically contiguous, with the occupied collections zone and the unoccupied storage environments adjacent to one another. This allows not only for efficient ducting, but also for efficient interior wall (thermal and vapor barrier) construction. Appropriate zoning should minimize the necessity for downstream subzone equipment (VAV/reheat, subzone humidification) in most occupied and unoccupied collections zones.

Activities that pose a potential threat to collections environments (food areas, loading docks, fabrication and rough shops, maintenance and housekeeping, etc.) should be kept away from collections zones, with exhaust from these areas located away and downwind from any fresh air intakes for collections systems and the rest of the building. One key exception to this practice may be relative-humidity-controlled crate storage, which may share a zone with occupied collections areas. Loading docks should ideally be positively pressurized, and shared walls with collections zones should be carefully designed to mitigate any potential energy transfer, whether from a load perspective or to reduce risk of condensation or other issues. Where possible, a separate loading dock may be specified for cleaner transfer of collections materials and crates, with direct access to crate storage and collections intake work areas.

System Design and Envelope Performance

System designs that call for interior moisture control, whether humidification or dehumidification, must carefully consider the likely performance of the existing or designed envelope for both thermal insulation and vapor transfer. These issues are commonly discussed for exterior envelopes, but the same issues can exist with excessive thermal or vapor differentials across interior walls.

Thermal insulation/barriers should be adequate to moderate heat transfer through the structure, with particular attention paid to thermal bridges (e.g., wall studs, floor/wall junctions, roof/wall junctions) that may be sources of heat gain/loss or potential condensation points.

Vapor incursion or loss occurs by two primary paths: air leakage/gaps and diffusion. Air leakage or gaps speed heat transfer, but may be defeated for thermal loads with positive pressurization. Vapor carried by air cannot be fully mitigated pressurization: it slows the process by slowing air transfer, but vapor flow and equilibration between interior and exterior spaces continue independently based on vapor, rather than air, pressure. The differential between interior and exterior vapor pressures also drives diffusion (movement of water vapor through permeable materials) from areas of higher vapor pressure to lower. Diffusion manifests differently depending on exterior climates and interior environments. When exterior moisture conditions are higher than interior conditions, whether typically or seasonally, vapor may move inward, especially during dehumidification, adding to system load and causing efflorescence or other damage on interior surfaces. During humidification, vapor is typically forced outward through the envelope, and may limit the possible control of the interior environment and damage the structure's exterior. Diffusion in either direction, combined with interior wall temperatures, can cause significant structural damage ranging from mold growth in warm environments to structural failure in situations of repetitive freeze/thaw cycles.

Windows, doors, and skylights can pose risks as potential condensation points, as well as points of heat transfer. Repetitive condensation on doors and windows places that element at risk, and the potential transfer of that moisture to the wall or floor can lead to issues ranging from mold and wood rot to cracking and masonry damage because of freeze/thaw.

Older structures, especially those with historic significance, can be particularly problematic, especially in projects that propose indoor moisture control. Where envelope performance is in question, the first step is to reassess environmental goals: considering either higher or lower relative humidity ranges to minimize differences in vapor pressure or, in cold climates, lowering temperature to raise relative humidity rather than using mechanical humidification. If specific conditions are necessary for long-term preservation, alternatives for containment of preservation environments should be considered, such as

- Microenvironments (cabinetry, certain housing solutions, small-scale freezing)
- Offsite, purpose-built storage, which may provide better environmental control with better energy efficiency
- Limited envelope upgrades in part of the structure, often called **box-in-box** solutions, where interior surfaces are built in to provide room for installation of thermal and vapor barriers

Reliability and Resiliency

Designs should include some way to manage the interior environment during periods of interrupted operation, such as maintenance, equipment failure, power outages, and disasters.

Redundancy and back-up equipment may be applicable in the largest of cultural heritage applications, but capital cost, load cycling for long-term operability, and limited availability of physical space are all factors against redundancy as a typical practice. Rather, discussion commonly turns to reliability and resiliency as risk mitigation strategies for interrupted operation. Better understanding of collection equilibration times to environmental changes and improved building and envelope construction often mean that collections, particularly storage areas, may be able to hold appropriate environmental conditions for longer periods than previously understood. The design team should discuss scenarios, with designs reflecting potential response to events to minimize downtime. Spare equipment may be kept on site to allow for timely repairs, modulating outdoor air dampers may be set to fail closed to minimize infiltration, and in certain environments architectural and systems allowances may be made to provide natural ventilation in long-term disaster or recovery scenarios.

Stand-alone generators may be part of this strategy, but their design and siting should be reviewed carefully for load capacity, accessibility, weight restrictions (for rooftop applications), fuel availability, and locations of fuel storage tanks, which pose their own significant disaster risk.

Loads

Accounting for design capacities for both sensible and latent energy is critical in cultural heritage applications and collections environments. Though common when specifying some systems types such as four-pipe subcool/reheat and desiccant designs, adequate latent capacity is often disregarded with two-pipe and standard package unit designs, resulting in environments that may be able to maintain temperature control, but commonly see relative humidity conditions rise beyond safe limits as exterior temperatures climb and cooling capacity is dedicated to the sensible load.

Certain specific load characteristics of cultural heritage buildings should be considered in system design. Occupancy patterns can vary widely among zones. Noncollections zones and occupied collections zones tend to have high occupancy only at certain times, which may include events outside of normal operating hours. Some gallery occupancies are as high as 1 m^2 per person, but unoccupied storage zones may have 100 m^2 per person or less. Systems should be designed to handle maximum loads as well as the more common part loads. Many engineers design to 2 m^2 per person because part of the room is never occupied. In zones where spaces are extensively used for receptions, openings, and other high-traffic activities, even higher density assumptions may be justified. Continual and close dialogue between the designer and the institution is critical. Where possible, especially in renovation projects, designers should request actual gate counts and event attendance to solidify load estimates.

Lighting loads vary widely by space and by time of day. For some applications, the most common driver of cooling load in a museum is display lighting, particularly where incandescent, halogen, fluorescent, or metal-halide bulbs are still used. The engineer should ensure that estimated lighting loads are realistic. Lighting typically varies from 20 to 85 W/m^2 for display areas; figures as high as 160 W/m^2 are sometimes requested by lighting designers, but are rarely needed. With growing awareness of damage caused by light, display areas for light-sensitive objects should have low illumination levels and associated low lighting power densities. The proliferation of LEDs has minimized many of the heat load concerns.

Shelving, Storage Cabinetry, and Compact Storage

Designers should be actively involved in discussions about collections storage designs, which can have significant impact on space airflow and the potential for microclimates. As a general rule, storage solutions fall into four categories for their interaction with the overall room environment:

- **Stationary library or museum shelving:** aisle widths and varying shelf heights generally allow for adequate airflow throughout the footprint. High-density storage environments with standard shelf heights spaced for storage efficiency may greatly restrict airflow between stacks while still allowing airflow through the aisle.

  - Airflow should be parallel to or above the stack orientation; perpendicular airflow will be blocked by the first stack, risking microenvironments and poor circulation throughout the stack.
  - Proximity of diffusers: diffusers less than 1 m from shelving may expose collections to dangerously high relative humidity microenvironments that can induce mold germination, particularly during dehumidification operations.

- **Compact library and museum storage (including sliding art racks):** minimized footprints, minimal gaps when closed, and narrow spaces between racks can greatly reduce airflow through the assembly. Compact shelving often contains a mix of storage assemblies, including shelving, open bins, flat-files, and cabinets.

  - Diffusers must be above the compact assembly and configured for side supply to throw air across the top of the assembly to ensure adequate dispersal.
  - Carriages should be designed with spacers to allow a 40 to 60 mm gap between carriages when closed, to allow air movement within the assembly.
  - Density of materials and tightly closed carriages can behave as a sealed package that tends toward developing microenvironments.
  - For large art rack installations, airflow should be parallel to rack orientation. Perpendicular airflow will be blocked by the first rack, risking microenvironments and poor circulation throughout the installation.
  - Proximity of diffusers: diffusers less than 1 m from shelving may expose collections to dangerously high relative humidity microenvironments that can induce mold germination, particularly during dehumidification.

- **Storage cabinetry (standard):** comes in various configurations, including flat file storage. These generally restrict airflow, but may include vent ports to allow for minimal air exchange, vapor equilibration, and off-gassing;
- **Storage cabinetry (gasketed):** comes in various configurations but is specifically gasketed to minimize air exchange and provide microenvironments or buffering for relative humidity conditions; may be maintained with silica desiccant.

In all applications, designers must advocate for sufficient spacing for airflow between storage furniture and exterior walls. Poor airflow can lead to high temperature or high relative humidity microenvironments, particularly near exterior walls with inadequate thermal resistance.

Integrating HVAC with Design of Exhibit Cases, Closed Cabinets, and Packaging

As discussed in the section on Response Times of Artifacts, the hygric response time of an enclosure containing hygroscopic materials will almost always exceed 24 h and can reach many months. This is analogous to the thermal mass (flywheel) effect of a building, but with hygric response times typically an order of magnitude longer. Design of sustainable and reliable building humidity control should take advantage of the hygric flywheels filling the building, not fight them. Feeding HVAC supply air into cases, though often proposed, usually results in very erratic conditions inside the cases since the moisture and thermal loads of the cases are a tiny fraction of the room loads. Barrette (1985) describes the failure of a system using AHUs attached to very large display cases at the Metropolitan Museum, and their (successful) decision to adopt "passive" relative humidity control instead.

When the annual average relative humidity of the space is suitable for the object or collection, a completely passive approach is best. Many objects can adapt to a stable relative humidity somewhere between 35 and 60%, and the annual average relative humidity inside many buildings (with HVAC) in many climates is also in this range. The role of the enclosure is to smooth out relative humidity fluctuations. If the only fluctuations are hourly or daily, and the enclosures are more than half full of hygroscopic materials, then ordinary enclosures (e.g., metal storage cabinet full of paper files, photographic materials in impermeable packaging) can perform well enough. If the fluctuations are seasonal, or the enclosure has only a small fraction of its volume filled, then achieving an adequate response time requires special attention to seal details and probably additional humidity buffers (Tétreault and Bégin 2018). The key to achieving long response times is reducing enclosure leakage (Michalski 1994; Thickett et al. 2007). Measuring and specifying acceptable case leakage is well established in museums (Thickett et al. 2007).

When the annual average relative humidity is not acceptable for the object or collection, routine intervention becomes necessary. The most reliable intervention is using a removable humidity buffer, typically silica gel. When the enclosure drifts to an unacceptable relative humidity, the (reusable) buffer is removed and replaced with one that has been equilibrated (reconditioned) to the desired relative humidity. This technique has been used to maintain middle, very low, or very specific relative humidity conditions in display cases (Thomson 1986), shipping crates (Richard et al. 1991), boxes with mineral specimens (Waller 1992), and film packages in cold storage (McCormick-Goodhart 2003). This method provides resilience: if the reconditioning process is abandoned (not unusual), all high risks from incorrect relative humidity are still mitigated as long as the annual average does not exceed 65% rh. Tétreault and Begin (2018) provide a recent manual on the application of silica gel buffers for museums.

Active mechanical control systems for relative humidity alone have been made for museum enclosures, especially display cases. These can be very small commercial units hidden in a single case, or designs for a larger package that feeds many cases via small-diameter tubes (Shiner 2007). Often these are used as short-term solutions to a loan requirement. For permanent collections, experience shows that the key factor for long-term success is that the units have a known parts and maintenance provider, and that they are adopted and maintained by facilities staff, not by the conservation or exhibits staff alone.

9.3 SPECIALIZED SPACES

Cold/Frozen Storage Vaults

Cold or frozen storage vaults extend the life of materials particularly sensitive to chemical deterioration (e.g., cellulose acetate, color photographic materials), or those that require cold/frozen conditions for their own stability as well as the potential threat they pose to other collections materials (e.g., cellulose nitrate). Design environmental conditions (see Table 13B) for cold/frozen environments typically require dehumidification beyond what can be achieved by chilled-water or glycol-mix systems. Direct expansion (DX) systems, though common as the primary equipment for cold/frozen environments in other industries, are typically only used for sensible cooling in these environments for cultural heritage. Dehumidification is handled as a separate process, typically via desiccant equipment, which achieves the preservation requirement for cold temperatures at controlled relative humidity conditions.

Design and construction of frozen vaults, in particular, should be carefully considered from a space need perspective: many cultural heritage institutions have only limited quantities of media that require frozen storage. For smaller collections, storage needs may be met with stand-alone solutions such as frost-free freezers. Depending on intended usage patterns, frozen storage may not be the best solution (see Table 6).

Cellulose nitrate is classified as a hazardous material; beyond preservation requirements, consult NFPA *Standard* 40-2019 and local fire codes for safe storage and disposal requirements. Smaller quantities can potentially be safely managed with approved cabinetry; vaults that hold larger quantities have specific construction requirements, including fire-rated walls and explosion venting.

Antechambers may be necessary in certain applications, especially where vault temperatures are colder than the typical ambient dew point (whether seasonal or year-round). The antechamber microenvironment should allow the object to fully equilibrate to a temperature higher than the final environment's dew point, with relative humidity in the safe range for the media. Some collection packaging practices may eliminate the necessity of the antechamber; application varies by institution and should be discussed during predesign.

Conservation Laboratories

Detailed discussion of HVAC design for laboratories can be found in Chapter 17. Further details on containment, collection, and removal of airborne contaminants such as particulates, vapors, and hazardous gases can be found in Chapter 33.

9.4 PRIMARY ELEMENTS AND FEATURES

Figure 16 shows the basic components of a cultural heritage HVAC system, and their typical order along the airstream. A few aspects of this order are different from many other applications: the cooling coil precedes the heating coil, to allow dehumidification followed by reheat; and the fine filter is last in line, to capture particulates created by any of the preceding components. A desiccant dehumidifier is common in cool and cold storage systems that need relative humidity control. The following sections outline details, as well as the many variations on this system.

Air Volumes

Air volume design in most cultural heritage applications should account for varying needs; individual functional zones may have volume requirements that change based on occupancy, space usage, loads, and other factors. In all cases, the design goal should be to provide the appropriate volume required to meet the need, without expending energy on work applied to volumes that are unnecessary. Collections zones should have supply and return air ductwork designed to equal volumes to allow for recirculation without risk of negative pressurization during low-occupancy, minimal outdoor air operation. Diffusers with adjustable outlets should be selected to allow appropriate zone balancing. The specific application of constant-volume and variable-air-volume designs is discussed in the section on System Types.

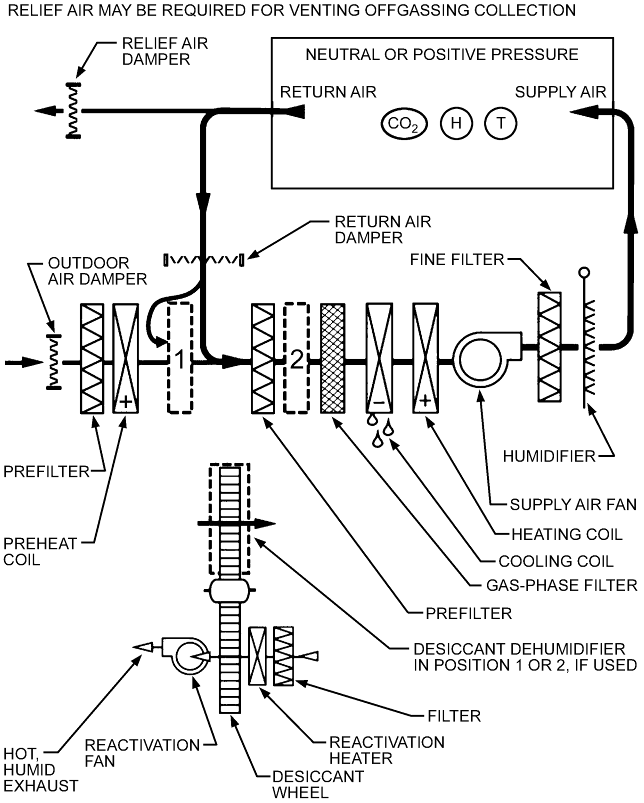


Fig. 16 Basic Components of HVAC System for Museums, Galleries, Archives, and Libraries

Fans

Every forced-air convection system, ranging from air-handling units to computer room air-conditioning (CRAC) systems and fan-coil units (FCUs), has at least a supply fan; depending on total air volumes, physical extent of the zone, outdoor air and exhaust design, etc., return fans may also be required. For institutions with the appropriate infrastructure, fan-wall/fan-array designs have distinct advantages over single-fan designs, including ease of motor maintenance/replacement and improved redundancy/resiliency. In either single-fan or fan-wall solutions, each motor should typically be equipped with a VFD; for systems with both supply and return fans, designers should ensure that VFDs are installed on both motors.

Fans may also be required for processes separate from the primary mechanical design. Ceiling and other circulation fans can be very effective for mitigating stratification and microenvironments, and some designs, especially in historic structures, should include fans for natural ventilation or other purposes.

Heating Equipment

Equipment for sensible heating in cultural heritage applications varies widely; direct-fire solutions are occasionally applied to storage warehouses and as components in desiccant regeneration, and indirect-fire systems, ranging from residential-type systems used in many historic structures to roof-top package systems, are common in smaller applications. Heat pumps may appear in smaller structures in hot environments, and electric heat can be applied in various settings, as the primary heat source or as a downstream component. Coil-based designs are most common in larger cultural heritage applications, and may be served with hot water or steam from boilers or a central plant. Heat generation systems can vary, including steam and oil with converter, modular boilers, and scotch marine boilers. Downstream reheat coils (common in VAV systems, but may exist without) most commonly use hot water or electricity.

Locations of heat application can vary; preheat may be required to protect downstream coils from freezing. For cultural heritage institutions, heat should typically be applied downstream of a cooling coil to allow for dehumidification. Reheat coils as part of downstream VAV configurations are typically best used for increased sensible temperature control. If used as the sole source of reheat, the capacity of downstream in-duct coils should be carefully considered and sized appropriately.

Cooling Equipment

The most common equipment for sensible cooling is coil based, including DX (refrigerant) systems, chilled water, and glycol. Evaporative cooling, common in arid regions, can be difficult to apply in cultural heritage settings because of reduced sensible temperature and moisture control. Designs using evaporative systems should carefully consider performance during any wet/rainy seasons; alternative design or additional equipment may be required for dehumidification. Ice storage systems with glycol may be an option in larger applications with appropriate infrastructure.

Cooling coils are commonly used for both sensible cooling and dehumidification in a subcool/reheat configuration. Location of cooling should typically allow for both sensible temperature control and dehumidification, with the cooling coil located upstream of the heating coil.

Screw compressors are recommended to generate chilled water at 2°C for use in chilled-water coils, which generally have copper fins and tubes.

Humidification

Humidification should be provided by clean steam or deionized water introduced in the air system. Evaluate the moisture source for risks of pollutants; building/plant steam should typically be avoided as a source for humidification, unless used to generate clean steam via a steam-to-steam heat exchanger. Often, steam used in closed loops to heat is treated with compounds (especially amines) that can pose a risk to the collection (Volent and Baer 1985). Systems should be selected and designed to prevent standing pools of water, and should follow good humidification design (see Chapters 1 and 22 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*).

Humidification equipment varies based on the application. In all applications, deionized or reverse osmosis water (based on institutional needs and availability) are preferred, whether for isothermal or adiabatic systems. Isothermal is generally more common, especially in year-round or seasonally cold environments, and steam is commonly generated via steam-to-steam heat exchangers or electronic steam humidifiers. Adiabatic systems (i.e., evaporative pan humidifiers, spray-coil wetted-element systems, pressurized-water atomizers, ultrasonic humidification) are more common in warmer climates. All materials in humidification equipment should be selected to minimize mold growth and degradation of system components.

Humidification should typically be located downstream of cooling and heating coils, and preferably in the primary air-handling unit. Mechanical design for cultural heritage is often more concerned with controlling humidity than temperature. The averaging effect of a common mixed-return air and common humidifier on a central system is preferred, but downstream zone humidifiers may be necessary to boost relative humidity because of specific environmental requirements or loads. If local low humidity conditions exist, try to identify and correct the cause of the condition before applying further mechanical solutions. Duct installations, whether on a common supply or in downstream subzone applications, should follow design requirements for absorption and be provided with drainage from the ductwork. Downstream humidifiers should not be located above collections areas; if it cannot be avoided, the ductwork approaching and downstream of the humidifier should be fitted with an additional catch pan with a drain and water alarm beneath the duct to provide protection for the collection. Widely different conditions in zones using the same air handler can be difficult to maintain and inefficient. If possible, different zone conditions should have the same absolute moisture content, using zone reheat to modify space humidity for different relative humidity requirements.

Designers should review maintenance requirements for humidifiers with institutional staff or contractors; electronic steam humidifiers and systems using building water can require particularly intensive maintenance to maintain design conditions and remain operable. Humidification in structures with limited envelope capacity should be carefully considered, and typically avoided.

Dehumidification

Dehumidification is the single most critical mechanical process for many cultural heritage institutions, and should be a central focus of most system designs. The required environmental conditions often determine the means of dehumidification. Sebor (1995) suggests the following typical approaches to more aggressive dehumidification:

- **Low-temperature chilled water**, usually based on a glycol solution, offers familiar operation and stable control but requires glycol management.
- **DX refrigeration** tends to be better for small systems and has lower capital costs, but generally is less reliable, requires more energy, and may require a defrost cycle.
- **Desiccant dehumidifiers** can be effective if properly designed, installed, and maintained. Economy of operation is very sensitive to the cost of the regeneration heat source. Active desiccants are typically preferred in collections settings and have become common features in cool/cold environment designs. Liquid desiccant systems eliminate (1) the need to cool the air below the dew point, and (2) reheat, both of which are very important cost factors for sustainability. Note that the possible application of liquid desiccant systems to collection environments should be carefully discussed with collections/preservation staff because of the potential risk of any aerosolized desiccant media coming in contact with collection materials.

Subcool/reheat designs, typically using cooling and heating coils, can generally achieve dew-point conditions as low as 2 to 3°C, depending on the chilled water/glycol temperature. Lack of dehumidification capacity may originate with design assumptions or equipment selection, or may be caused by issues including compromises in the cooling medium temperature, inadequate reheat, dirty or blocked coils, and poor flow or valve control.

Desiccant dehumidification, most commonly used for low dew points necessary in cold/frozen environments, is now being applied for dew-point control in some applications at 4°C and higher. Desiccant technology (typically a silica-gel rotary wheel design) can be installed as part of the primary system or as a separate component that feeds into the main air handler. For zones with minimal latent loads, or in designs using a high volume/percentage of outdoor air, designers may choose to focus on dehumidification of the outdoor airstream, rather than on the mixed air. For smaller applications and systems, package desiccant systems may be put in line with outdoor or return air. Dehumidification systems should be additions to a typical cooling system; they cannot maintain comfort conditions by themselves. For collections requiring cool, dry conditions, a desiccant system may be required. Chapter 24 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* has further information on desiccants.

Note: stand-alone dehumidifiers, common in residential and smaller applications, are not recommended for use in cultural heritage settings except in emergency scenarios. Risks to collections (e.g., electrical fires, flooding from basin overflow) generally outweigh benefits. If stand-alone dehumidifiers are used in collections environments, it should only be during occupied hours, with units emptied and unplugged before staff leave.

Outdoor Air

Outdoor air should typically be limited to the minimum necessary in cultural heritage applications. Intakes should have modulating dampers balanced with return air dampers on the system. Siting of the physical intake is critical; potential locations should be evaluated for various factors, including pollutants (e.g., vehicles, equipment, kitchen exhaust), prevailing wind directions, and sources of moisture/particulates (e.g., sprinklers, landscaping). In most applications, outdoor air intakes should fail closed on a shutdown or power outage, with the ability to manually adjust the damper if natural ventilation is required.

Preheat, precooling, or dehumidification may be best applied to the incoming outdoor airstream, increasing operational efficiency.

Ductwork

Ductwork selection varies by application; sheet metal, flexible fiberglass (flex duct), cloth, and others can be appropriate duct choices. Fiberboard is typically not recommended for cultural heritage institutions because of the potential for media breakdown over time.

All supply air ductwork should be insulated on the exterior, but return air ductwork should be insulated on the exterior if the difference between the duct condition and the ambient space is enough to make condensation possible. All duct joints, both in the duct itself and in the insulation, should be sealed against air leaks. Interior ductwork insulation/lining is not recommended in cultural heritage applications because of the potential for trapping moisture and the eventual breakdown into particulates that can deposit in collections areas. Where external insulation is not possible, or there are significant sound attenuation needs, interior duct lining may be considered if it meets hospital and health care facility standards: fiber free, closed cell, antimicrobial coated, low-VOC certified, and moisture and mold resistant. These sections must be clearly labeled on design drawings and should be discussed with institutional staff regarding ongoing maintenance and eventual replacement.

9.5 FILTRATION

Design

Particulate filtration is essential for removal of contaminants that could foul the HVAC system, as well as particles that might degrade or deface collections being preserved. For this reason, particulate filtration is addressed here in two steps: prefiltration and fine-particulate filtration.

Physical location of the filtration stages affects HVAC system performance, energy use, and ultimately protection of collections. In **upstream filtration**, all filtration is placed upstream of the cooling/heating and fans in system. All filters are essentially prefilters, even though fine-particle filtration may be present in the HVAC system. When all filters are upstream, it is common practice to stack filters, with a MERV 7 or 8 prefilter on a MERV 14 or 15 fine particle filter in the same section. This is done to preserve the life of the fine-particle filter. However, evaluate whether the cost of energy outweighs the savings of the fine-filter life: most collection areas are fairly clean environments. Eliminating the prefilter can be a very effective improvement to airflow and energy savings.

In **upstream/downstream filtration**, prefiltration is installed upstream of the cooling/heating and fan components and final filters downstream of all mechanical equipment. This more effective approach prevents a failure of HVAC components from fouling the ductwork and preservation areas downstream. In this case, it is important to filter at a minimum of MERV 11 for any chilled-water systems to prevent microbial fouling of the coils. MERV 7 or 8 is at best only 50% effective in this particle size category, and does not provide the protection needed against biofilm growth.

Performance

Prefiltration is required to prevent fouling in cooling coils and dust build-up in the fan, ductwork, or other HVAC components. It also protects and prolongs the functional service life of gas-phase filters and fine-particle filters. These fouling-size particles and microbes tend to be between 2 and 6 μm and accumulate into biofilms on coils and other wet areas in HVAC systems. MERV 7 or 8 filters by definition will not protect HVAC systems from this particle challenge and should be replaced by a minimum of MERV 11.

In some cases, prefiltration for HVAC system protection is the only filtration in a collection area. If this is the case, MERV 13 is recommended.

Fine-particulate filtration protects artifacts and collections in the facility. These **accumulation-size** particles fall in the MERV E-1 range of particles (0.3 to 1 μm). Removal efficiencies of a minimum of 85% of the E-1 range are sufficient for preservation of most collections. MERV 15 filters by definition are minimum 85% in the E-1 range, and minimum 90% in both the E-2 (1 to 3 μm) and E-3 (3 to 10 μm) ranges.

Some collections may require efficiencies higher than MERV 15 for long-term preservation. Options include microenclosures with minimal airflow and separate filtration, or HEPA (99.97% at 0.3 μm) filtration for the entire common area. Whenever HEPA filtration is used as the final filtration, seriously consider upgrading the prefiltration to protect the life of the HEPA filters.

Framing systems should be able to seal the air filters without bypass air leakage in housings and unit access doors. System designs with positive locking mechanisms for filters are beneficial, as is using gaskets rather than framing components on filters.

High-voltage electrostatic air cleaners should be used with caution because of their potential to generate ozone, which can damage collections (see Table 9).

Outdoor air infiltration of gaseous pollutants, materials off-gassing in new construction, and similar off-gassing of furnishings may put some collections at risk. Sensitive collections, such as those containing some metals and alloys, film, various papers and low-fired ceramics, should be carefully enclosed or controlled by an active **gas-phase filtration** system, depending on which method is most appropriate for reaching the desired preservation target (see the section on Control Strategies for Objects with High Vulnerability to Pollutants).

The primary compounds of concern include hydrogen sulfide, nitrogen dioxide, ozone, sulfur dioxide, and undesired volatile organic compounds, all of which are removable with molecular filtration. The specific sorbent must be chosen for the various gaseous contaminants indigenous to the facility, because removal and retention properties are not all the same. Some gases are easily removed with activated carbon, whereas others may require treated sorbents or beds. Using potassium-permanganate-treated media is not recommended because of the risk from the highly oxidative dust to collections and space surfaces.

Service life of molecular filtration media should be carefully evaluated. Much service life testing has focused on the potential mass removal capacity of the sorbent when immersed in a challenge chemical; although this information may be useful, its ability to remove pollutants from an airstream may not be achievable even though the sorbent is not spent.

If a molecular filtration system is used, some gas-filter designs require dusting filters downstream, because the aging gas filters can release dust that can affect the HVAC system and collection.

Gas-phase filtration system design should also consider institutional staffing and preventive maintenance practices; infrastructure must be able to support timely media replacement, in both labor and material cost. Consider gaseous contaminant monitoring and analysis before fully adopting gas-phase filtration; designers may choose to include the gaseous filter section in the design, but wait to install media until need has been determined.

9.6 SYSTEM TYPES

The type of HVAC system used is critical to achieving environmental goals; appropriate types may vary by zone based on use. In any cultural heritage application, proper airflow filters the air, controls moisture and relative humidity, adjusts temperature for either collection needs or human comfort, and inhibits mold growth and oxidation.

For any design, maintenance access and minimizing risk to the collection from disruptions and leaks from overhead or decentralized equipment are primary considerations. Water or steam pipes over and in collection areas present the possibility of leaks, as do air-handling units. Some systems can provide full control without running any pipes to the zones, but others require two to six pipes to each zone, which often must be run over or in collection areas and are, unfortunately, the pipes most likely to leak. Leaks and maintenance can prevent effective use of spaces and result in lost space efficiency.

Central air-handling stations keep filtration, dehumidification, humidification, maintenance, and monitoring away from the collection. The investment in added space and expense of the more elaborate duct system provide major returns in reduced disruption to the collection spaces and a dramatically extended service life for the distribution system. Where existing duct systems can be reused, renovating the existing system is economical, with most renovations confined entirely to the mechanical rooms. Duct distribution systems that are heavy on downstream equipment (e.g., terminal reheat, dual-duct, variable-air-volume) may require a new duct system and terminal equipment as part of a renovation, incurring major expense from demolishing the old ducts, installing the new duct system, and reinstalling architectural finishes.

Variable-Air-Volume and Constant-Volume

Air volume design can depend on several factors, including

- Sensible and latent loads in a space
- Collection degradation
- Practical airflow based on system design

In most cultural heritage applications, variable-air-volume (VAV) systems, in single-zone or multizone configurations, are appropriate.

Note: multizone VAV systems should not be used to serve multiple functional zones. Rather, the approach should be to account for varying loads within the same functional zone. (See the sections on Zoning and on Zoning/Functional Organization)

Multizone VAV has the distinct advantage of providing better temperature and relative humidity control to individual subzones with different sensible loads; both multi- and single-zone VAV design can achieve significant energy-savings in climates with diurnally or seasonally variable sensible and latent loads. Single-zone VAV designs in cultural heritage typically vary air volumes and occasionally sensible reheat temperatures; cooling coils, if used for dehumidification, most often have a single leaving air set point.

Constant-volume system designs may be necessary in certain scenarios. Some geological collections can emit radon, and may require constant volume and increased air change rates. Interior zones (e.g., storage rooms surrounded by a perimeter zone and with limited outdoor air) and some climates may experience essentially the same latent and sensible loads constantly, limiting the effectiveness of VAV designs. Even in these cases, initial designs should consider the inclusion of at least a VFD: actual air volume requirements may be different than design modeling, and the VFD allows adjustment of the optimal volume, even if the system operates at a constant volume moving forward.

For small volumes and applications, such as some cold/frozen storage vaults, constant volume (CV) may be the most practical design, whether based on equipment airflow requirements or simply because a VAV design offers no noticeable preservation or energy advantage.

Institutional capabilities and infrastructure must inform air volume and airflow designs. VAV control and equipment can quickly add to control/operational complexity and maintenance requirements; consider staff capabilities and/or the availability of qualified contractors before finalizing the design.

VAV or CV Reheat

A reheat system can present problems if improperly applied. In many institutions, terminal reheat with steam or hot-water coils located near or over collection spaces causes chronic problems from steam and water leaks. Subzone humidification control guidance often suggests placing the humidifier downstream from the terminal reheat coil; if the reheat coil is located near or over collection spaces, preventive maintenance on humidifiers further complicates the maintenance requirements. Reheat systems for collections zones are most effective when reheat coils and humidifiers are installed entirely within the mechanical space, instead of at the terminal end, feeding through what is effectively a multizone distribution system.

Multizone Systems

A multizone air handler with sufficient dehumidification capacity at the primary unit, zone reheat, and zone humidification can be a stable and relatively energy-efficient solution. However, multizone systems without individual zone reheat and zone humidification have proved problematic for many institutions, requiring retrofit of zone equipment for stable humidity control. With proper layout and complementary equipment, a multizone system can reduce the amount of reheat and be very energy efficient. Multizone systems should consider dehumidification in the outdoor airstream or upstream of the heating coil to ensure that sufficient dehumidification is available to the entire airstream. Note that multizone designs are still best applied to spaces with similar dehumidification requirements; mixing collections and noncollections spaces in the same multizone design typically leads to inefficiency and difficulty maintaining space conditions. Future renovation or changes in space usage can significantly impact design viability, again leading to issues with efficiency and management of the preservation environment.

Dual-Duct Systems

As with multizone systems, dual-duct designs can work well in cultural heritage if zoning is carefully considered. Downstream mixing boxes must be controlled and maintained to guard against overcooling and the resultant high-relative-humidity conditions. A critical consideration for dual-duct designs is a separate dehumidification coil upstream of both the hot and cold decks. This separate cooling coil, distinct from the one in the cold deck, is used during dehumidification demand. Air can be cooled to dew point even if it eventually flows through the hot deck. Without this feature, moist return air or outdoor air could be warmed in the hot deck and delivered back to the room without being dehumidified. An alternative is to locate a single cooling coil upstream of both decks, or in the outdoor air.

Fan-Coil Units

Fan-coil units have been problematic when placed in and above collection areas. Fan-coil units expand and decentralize maintenance, requiring maintenance in collection areas and a net increase in overall facility maintenance. Because they cool locally, they need condensate drains, which can leak or back up over time. As all-water systems, they require four pressurized-water pipes to each unit, increasing the chance of piping leaks in collection areas.

Fan-Powered Mixing Boxes

Fan-powered mixing boxes are usually inappropriate for cultural heritage facilities. Although fan-powered mixing boxes can help ensure air circulation to suppress mold growth, they do not allow effective air filtration for particles and gases. These fans also increase local maintenance requirements and present an added fire risk. If they include reheat, there is an added risk from leaks (with water or steam reheat) or fire (with electric reheat).

10. CONSTRUCTION

(This section is based, with permission, on Maekawa et al. [2015].)

The system design is physically realized through the procurement, construction and installation of equipment. Conformance with the design intent and the owner's project requirements (OPR) is confirmed through various methods, including review and acceptance of the contractor's technical submittals for materials and equipment to be supplied; in-factory acceptance of complex equipment before shipment; qualification and certification of tradespersons for certain critical installation activities such as welding; and field observation and inspection of equipment and systems during installation.

Construction quality, including cleanliness of systems during construction, is critical; all incomplete piping and ductwork should be kept closed or sealed during installation to prevent introducing dust and debris.

11. COMMISSIONING

(This section is based, with permission, on Maekawa et al. [2015].)

Start-up, testing, and balancing are performed once an environmental management system is installed. Preparation includes the following:

- **Design conformance:** The installed system must be checked for conformance with the design intent and the owner's project requirements. Specifically, the leaktightness of air and hydraulic systems must be verified by pressure testing; pump and fans checked for proper rotation; valves and control devices checked for correct actuation/response; and the electrical continuity and proper polarity of electrical wiring and connections must be confirmed. Sensors, instrumentation, and control devices must be checked for correct calibration and signal/response.
- **Cleaning:** Hydraulic systems must be flushed clean using start-up strainers, and air systems operated with construction filters; both operations must continue until cleanliness requirements are met, as indicated by the amount of construction-related debris and particulates captured in the strainers and filters.
- **Start-up:** Operation of each piece of equipment must be initiated in accordance with a start-up procedure provided by the equipment manufacturer. It is essential to adhere to the manufacturer's start-up procedures, because the manufacturer's warranty period begins with the initial power-up of equipment; failure to follow start-up instructions can void the warranty.

On completion of preliminary testing, cleaning, and start-up of individual components, equipment, and assemblies, the start-up sequence and shut-down sequences for the entire system must be verified before the system can be operated. After successful system start-up and shut-down, the system can be balanced for operation and construction commissioning can occur, as follows:

- **Balancing:** The balancing phase consists of measuring system air and fluid flows, making adjustments, and balancing the flows to match design flow rates. This may require adjusting airflow using dampers in ducts and/or pulleys or belts at the fans. Similarly, water flow rates in hot- or chilled-water systems must be measured, adjusted, and balanced. Both cooling and reheating capacities may also need to be adjusted by refrigerant compression or by regulation of cooling or heating fluid flow rates, to produce design heating, cooling, or dehumidification. Electrical loads from equipment must also be verified.
- **Construction commissioning:** After testing and balancing, construction commissioning occurs, during which system performance is checked against the owner's performance requirements and verified. In climates with wide ranges of thermal and moisture loads over four seasons, performance verification may take up to 12 months; in climates with more consistent thermal and moisture loads throughout the year, performance verification might be accomplished in 6 months.

12. TRAINING AND DOCUMENTATION

(This section is based, with permission, on Maekawa et al. [2015].)

The facilities staff at the building where the environmental management system is installed should be familiar with the owner's performance requirements and knowledgeable about design intent, operation, maintenance, and basic troubleshooting of the system. In-house knowledge of the OPR helps protect the collections, minimize unnecessary service calls, maintain system operation within performance specifications, and avoid premature failures. After system start-up, testing, and full commissioning, the facilities staff and building maintenance personnel must be trained in the operation and maintenance of the environmental management system. Training should start with the fundamentals of the system's design intent, followed by explanation of the contents of the operations and maintenance manual prepared for the system. Training should also include

- Hands-on practice by facilities staff with each of the necessary service/maintenance operations and control systems adjustments
- Basic trouble-shooting procedures for the system
- Operation of the monitoring features of the environmental management system and early identification of performance issues

Complete documentation of the environmental management from inception through start-up is a product of the commissioning process and is provided to the facility owner. The system documentation should include the OPR, design intent of the environmental control system, design documents, performance specifications, technical submittals, inspection reports, calibration records, testing and balancing reports, a detailed sequence of operation, start-up and shut-down procedures, a maintenance schedule for each of the system's components, and simple diagnostic and/or troubleshooting procedures.

13. OPTIMIZATION

(This section is based, with permission, on Maekawa et al. [2015].)

Operation of any environmental management system requires a program of preventive maintenance, ongoing performance monitoring, and periodic performance assessment and evaluation for overall effectiveness in collections conservation and in energy use.

If changes in operational parameters, collections conditions, or energy efficiency are noted, the current system's performance should be revisited as per the steps described in the Context and Predesign section, including

- Define realistic and achievable objectives and criteria; resolve competing objectives
- Identify possible environmental management strategies
- Evaluate and select the preferred strategy or strategies

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ASHRAE members can access *ASHRAE Journal* articles and ASHRAE research project final reports at technologyportal.ashrae.org. Articles and reports are also available for purchase by nonmembers in the online ASHRAE Bookstore at www.ashrae.org/bookstore.

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