Climate guidelines

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Canada is committed to reducing its greenhouse gas emissions (consult Canada's climate plans). One of the central strategies for achieving this goal, *Clean Canada*, specifically notes that "to build a cleaner, healthier, more affordable future that we can be proud to have our children inherit" we must improve "building codes and standards so our homes and buildings use less energy" (Environment and Climate Change Canada 2019). Museums and archives worldwide have come under increasing criticism for their adherence to energy-intensive climate guidelines that were created long before climate change and its causes were recognized. By 2020, many in the museum and archive community were re-examining their old climate control assumptions and asking for better advice from the experts. The Climate guidelines resource is the Canadian Conservation Institute's (CCI's) answer. This resource replaces the previous CCI resource Environmental guidelines for museums. It considers the most recent specifications used by mechanical engineers for climate control in museums, galleries and archives. It balances two responsibilities faced by heritage institutions: reducing risks to the collection heritage at the same time as acting sustainably.

The resource contains two tools and four sections.

ClimaSpec

ClimaSpec is a quick and easy search tool for finding CCI advice on climate guidelines. You select the type of object or collection, and the tool provides brief summaries of CCI advice. The tool includes two calculators: a lifetime calculator for acidic materials in archives that decay rapidly at room temperature and a mould calculator that estimates the time required for mould development at various RH levels.

Climate Control Decision Tool

CCI's Climate Control Decision Tool is a quick and easy tool for obtaining climate advice about your situation. Answer the short list of questions about your institution and collections to obtain basic advice on climate control.

Climate guidelines overview

The "Climate guidelines overview" section provides a detailed description of the issues that arise when making decisions about climate control.

ASHRAE types of control

The "ASHRAE types of control" section provides detailed description and explanation of the practical implications of each type of control as defined in the chapter "Museums, Galleries, Archives, and Libraries" in the *ASHRAE Handbook*, which is used by mechanical engineers throughout Canada, the US and elsewhere. CCI has adopted these definitions and terminology for its climate control advice.

Explanation of the mould and lifetime calculators

The "Explanation of the mould and lifetime calculator" section provides detailed information, including equations and the relevant literature sources, for the two calculators in ClimaSpec.

Climate guidelines glossary

The "Climate guidelines glossary" section provides a list of the key terms used in this resource with their definitions. Some of the terms are also explained in greater detail on one of the pages in this resource.

Climate guidelines overview

Stefan Michalski

On this page:

List of abbreviations

ACH	air changes per hour
ACD	air changes per day
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CCI	Canadian Conservation Institute
RH	relative humidity
SI	International System of Units

Introduction to guidelines and specifications

In this resource, the term "guidelines" will mean both qualitative and quantitative advice on climate control methods for large and small museums, whether by mechanical systems, microclimate enclosures or simply by leaving well enough alone. In contrast, a climate specification is a numerical set of performance targets needed by designers (usually of mechanical control systems, but sometimes of exhibit cases, shipping crates, etc.).

Climate specifications for museums have been, and remain, complex and contentious. They can significantly affect a museum's traditional financial budget as well as its carbon footprint budget, which has become increasingly important. Climate specifications have usually been aimed solely at the designers of mechanical systems, but meeting those targets in the long term will only be feasible and sustainable if the museum integrates the design of the mechanical system with the design of the building and its microclimate enclosures. In many scenarios, it will either be the building alone or the enclosures alone that reliably achieve the specifications. When making decisions about climate control, all three elements must be considered: the building envelope, mechanical systems and microclimate enclosures.

Purpose and limitations of climate guidelines

The climate near an object [that is, the temperature and relative humidity (RH)] sometimes has a big effect on the preservation of that object. Other times, it does not. For some objects, it is the temperature that matters most; for others, it is the RH. Sometimes, the average conditions are most important. At other times, it is the fluctuations. A single object can contain many components, each with conflicting requirements in terms of climate. A collection can contain many different types of objects. Eventually, you must ask how significant these effects are and what loss of value they cause. Determining what climate the collection actually requires is complicated.

A second list of climate requirements comes from the staff and visitors, who want human comfort. And a third list of climate requirements comes from the building, which is very often a part, or even the largest part, of the heritage asset.

A fourth and, until recently, invisible, list of requirements comes from our planet. Any attempt by an institution to maintain a particular climate will consume time, money and, most importantly, energy, all of which are in conflict with the sustainability of our planet and our need to limit climate change.

Climate guidelines for heritage institutions are an attempt to satisfy the requirements associated with all four of these elements: the collection, the people, the building and the planet. Trying to meet all possible requirements is usually hopeless, since few overlap. This then becomes a human argument because different stakeholders champion their own sets of requirements. The only feasible approach is to try to define and then meet the essential climate requirements of all four elements (Michalski 1998).

In a risk management approach, you make such decisions by asking each group what is the worst, rather than the best, that can happen for them. In other words, you find a climate specification that minimizes the total risk. The challenge with this approach is that it cannot be generalized accurately. The risks to the collection, those to the building, those to the occupants and those to the planet all depend on value judgments. It is very much a case of think and value globally, but act and value locally.

There are no standards but many guidelines

Numerous organizations, both standards bodies and professional associations, have published climate guidelines. Consult Michalski (2016) for a recent review of their differences and the history of their origins.

Climate specifications and climate guidelines for museums, galleries and archives are sometimes mistakenly called "climate standards." Unlike building codes driven by life safety concerns, there are no legally binding standards for climate control in heritage institutions. There are, however, legal contracts between lending and borrowing institutions that usually include climate specifications that must be met. For certain government programs, such as the Designation of Institutions and Public Authorities Program or the Canada Travelling Exhibitions Indemnification Program, designation depends on meeting a particular climate specification.

How to find your climate guidelines

To begin the selection process for a climate guideline, start with ClimaSpec. This search tool provides specific information about the role of temperature and RH for each type of object. It provides guidelines for climate control as well as possible climate specifications (in terms of the nomenclature used in the *ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Applications*). ClimaSpec also has a mould calculator and a lifetime calculator (consult the Explanation of the mould and lifetime calculators page for background details). As a supplement to its climate advice, ClimaSpec provides information on the role of pollutants and their control, since filtration is always part of a climate control system.

After using ClimaSpec, you may find that your collection contains several different categories of objects in terms of sensitivity to fluctuations. You may also wonder how a designation under the Designation of Institutions and Public Authorities Program or your participation in Canada's Indemnification Program will influence your climate control decisions. The Climate Control Decision Tool asks a sequence of questions that directs you to specific pieces of advice related to a climate guideline.

The role of the "Museums, Galleries, Archives, and Libraries" chapter

Since the first edition of the *ASHRAE Handbook* in 1999, the Canadian Conservation Institute (CCI) has adopted the "Museums, Galleries, Archives, and Libraries" chapter as its primary source for climate control specifications. The *ASHRAE Handbook* is the primary reference manual for mechanical engineers in Canada, the US and many other countries. Committees of technical experts write its chapters via discussion and consensus, and then the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) membership reviews their work. CCI staff members were part of the technical committee that created the original 1999 chapter. It has been the aim of both CCI and the chapter committee to write guidelines that could be trusted by engineers as well as the heritage community. One of the committee's most significant innovations are the levels of control (now called "types of control") labelled AA, A, B, C and D, which have since been widely adopted in the heritage community.

In the 20 years between the 1999 and 2019 editions, chapter content on temperature and RH had remained unchanged, but sustainability — environmental, economic and financial — has forced climate control thinking to evolve further, not only in our field but also throughout the heritage sector. This evolution is evident throughout the 2019 edition. A risk management perspective has become essential. What are our preservation goals, and what are the costs and benefits of each type of control?

For the 2019 edition, the chapter committee revised the chapter completely, starting with a risk management introduction, followed by an emphasis on selecting an annual average that is as energy efficient (sustainable) as possible. This replaced a universal and often wasteful guideline of 50% RH and 20°C. The categories AA, A, B, C and D are still in place, albeit slightly modified. Sub-types of low-temperature storage (cool, cold and frozen) were revised to be consistent with recent guidelines from the International Organization for Standardization and the Image Permanence Institute (IPI). Specifications for temporary exhibit space and unpacking space for loaned objects were given a separate category. (The sections on pollution and on system design were also completely revised.) As in 1999, CCI staff members were part of the committee in 2019, and CCI fully supports the 2023 edition that was available at the time of writing.

While CCI recommends that anyone engaged in a project involving climate control decisions should obtain a copy of the most recent version of the ASHRAE chapter, this resource provides explanations of all key issues. The ASHRAE types of control page summarizes the ASHRAE climate specifications, and ClimaSpec provides specific recommendations for individual groups of objects.

Integration with building design, microclimate design and sustainability

As emphasized in the *ASHRAE Handbook*, you cannot begin to select a design target for the mechanical systems without first considering the local climate, the building envelope and the use of microclimate enclosures. It is outside the scope of this resource to examine these issues in detail, but they can be summarized as follows.

For any collection, whether planning the design of a new building or working within an old building, consider the following:

- Use ClimaSpec to find out what climate your collection actually requires and what damage is possible if you do not meet these requirements.
- From a risk management perspective, establish what this possible damage means to your collection in terms of loss of value. Determine what is acceptable and what is not. This varies with your institution's mandate and any legal obligations. What balance do you wish to make between preservation, accessibility and your budget? Consult "Step 1: Establish the context" in *The ABC Method: A risk management approach to the preservation of cultural heritage*.

If you are planning the design of a new building, consider the following:

- Share an understanding of the *ASHRAE Handbook* chapter "Museums, Galleries, Archives, and Libraries" and this online resource with staff and consultants.
- Recognize sustainability as a fundamental design issue and a win-win perspective rather than an addendum to be lost during inevitable budget trimming.
- Recognize the role of microclimate enclosures, specifically in reducing response times to fluctuations and exposure to pollutants (consult Appendix C: The response times of objects and the multiple benefits of enclosures). Integrate these benefits into the design of the building and its mechanical systems.

If you are working with an existing building, consider the following:

- Apply the latest energy management tools to the building and its systems to obtain not only energy savings but also improved performance and reliability. For basic energy tracking and benchmarking, consider using Portfolio Manager from Energy Star. RETScreen is a more advanced tool offered by Natural Resources Canada, with additional features for feasibility assessments and performance analysis of facilities. RETScreen training courses are offered by the Canadian Institute for Energy Training (CIET), and free resources are available on the YouTube RETScreen eLearning channel.

- Recognize that microclimate enclosures play an even more important practical role in climate control when the whole space cannot be brought to desired conditions, specifically in reducing response times to fluctuations and exposure to pollutants (consult Appendix C: The response times of objects and the multiple benefits of enclosures). Integrate these benefits into the design of the building and its mechanical systems.
- Recognize that the "proofed fluctuation" concept is especially powerful when making decisions about sustainable climate control for permanent collections. If the collections have been in the same location for many years, and the same pattern of climate fluctuations occurs each year, then the worst cracks and deformations that can be caused by that pattern of fluctuations have already occurred. This concept is described further in Appendix B: Sensitivity to fluctuations and the application of proofed fluctuations, as well as in *Agent of deterioration: incorrect relative humidity*.

Incorrect climate is one risk among many

CCI made comprehensive risk assessments of five heritage institutions in order to uncover any patterns of common risks. In the two historic house museums and the art gallery, the top three risks to the collections (and to the building if it is part of the heritage asset) did not include incorrect climate. Consistently, the top risks were fire, water damage and physical forces (Karsten et al. 2012). In the provincial archives and the science and technology museum, however, incorrect temperature was a significant risk due to the rapid deterioration of some photographic materials and acidic paper housed at room temperature.

Smaller museums in historic buildings that have operated for many years without special climate control sometimes decide that they need to acquire museum-grade climate control. For a permanent collection that has been in place for decades and has not received conservation treatment, the worst cracks and deformations that can be caused by temperature and RH fluctuations have already happened. If, however, it is known that the climate in the museum building has worsened recently, then analyze what has changed, why and how you might return to the previously proofed and non-threatening pattern.

Some forms of incorrect climate do continue to damage collections. For example, damp will cause mould over a certain period of time, which you can estimate by using the Mould Calculator in ClimaSpec. Causes and solutions for damp are outlined in Figure 5 of *Agent of deterioration: incorrect relative humidity*.

Pollutants can be considered a form of incorrect climate, and filtration is usually part of a climate control system. As with damp, pollutants cause damage that accumulates. Causes and solutions for pollutants are described in *Agent of deterioration: pollutants*.

Time-lapse videos of deterioration

Most of the deterioration processes due to incorrect temperature or incorrect RH are slow. It takes days, if not weeks, for them to emerge. To demonstrate some of these processes, CCI has created time-lapse videos that illustrate some of the deterioration phenomena.

Appendix A: The four parameters of a climate specification

Parameter 1: Long-term outer limits or danger boundaries

Long-term outer limits are danger boundaries in RH and temperature beyond which mixed collections may be at increasing risk of damage. When the annual average (baseline) selected is far from the traditional middle values of 50% RH and 20°C and this baseline is then combined with suggested seasonal adjustments, the resulting range of temperatures and RH could exceed these danger boundaries for a mixed collection. This is illustrated in Figure 15 in the “Museums, Galleries, Archives, and Libraries” chapter of the *ASHRAE Handbook*. ASHRAE control types C and D are defined solely in terms of their long-term outer limits.

The particular deterioration phenomena that determine the setting of danger boundaries are discussed in the following sections.

Mould

While it is not possible to avoid common species of bacteria and mould, you can prevent the damp conditions that allow their growth. Bacteria require RH bordering on wet conditions (over 99% RH), but mould can grow at an RH as low as 65%. Detailed data about the relationship between RH and mould growth is shown graphically on the Explanation of the mould and lifetime calculators page. ClimaSpec uses equations derived from these graphs to calculate the days to mould growth at different relative humidities.

Lifetime of chemically decaying organic materials

As discussed further in the section Parameter 2: Annual averages or baseline, some objects decay rapidly at human comfort temperatures, some decay moderately quickly and others decay very slowly. These rates of decay all double (approximately) for every rise of 5°C. The *ASHRAE Handbook* suggests upper limits for each type of control as a warning that everything organic in mixed collections will last less than half, or less than one quarter, of its lifetime when temperatures exceed those limits. Where available for specific materials, ClimaSpec provides more specific advice about outer limits than what is suggested in the ASHRAE chapter.

Chemical decay of metals and minerals

Moisture causes and accelerates the corrosion of metals and the disintegration of many minerals. The dependence on humidity usually jumps suddenly at a critical RH due to hydration or to deliquescence of a salt, so the critical RH values become danger boundaries. Where available, ClimaSpec provides these critical RH values to establish specific danger boundaries for metals and minerals.

Physical transformations

Some materials will soften, or even melt, at sufficiently high temperatures. Others will become brittle and fragile at sufficiently low temperatures. Consult *Agent of deterioration: incorrect temperature* for an overview and ClimaSpec for specific objects. For some heritage objects, these damaging temperatures are within the range of potential natural exposures outdoors, certainly, and often indoors.

Parameter 2: Annual averages or baseline

Temperature and RH values that satisfy human comfort are not necessarily satisfactory for collection preservation. Cooler and dryer conditions preserve all materials longer but are uncomfortable for occupants. Maintaining cool or dry conditions in summer is also energy intensive. A climate control decision considers the wide range of lifetimes in a typical collection and balances them with human comfort and sustainability.

Lifetime of chemically decaying organic materials

The annual baseline recommendation presumes that an institution wants its collections to remain in a good state of preservation for at least a century, if not longer. Natural materials such as wood, cotton and linen last thousands of years at normal room conditions, but only if they have not been acidified during manufacture or during exposure to pollution. On the other hand, acidic papers become brown and brittle within decades (consult *Caring for Paper Objects*); acidified leather book bindings disintegrate; films, audiotapes and videotapes become sticky, shrivelled and unplayable (consult *Caring for Audio, Video and Data Recording Media*); and celluloid plastics and polyurethane foam become yellow and disintegrate (consult *Caring for Plastics and Rubbers*).

Acid hydrolysis is the major mechanism behind the decay of all these particularly unstable materials, and this process needs moisture. The rate of decay of these materials decreases by a factor of about two for each 5°C drop in temperature and by another factor of about two for each halving of RH. You can make detailed estimates of the remaining lifetime for various scenarios of temperature and RH using the Lifetime Calculator in ClimaSpec. All the technical background for such calculations is contained on the Explanation of the mould and lifetime calculators page.

Human comfort

This resource focuses on the preservation of collections and the sustainability of the design solution in a museum environment, not on human comfort. Of course, a final specification for a project will balance human comfort with the risks and benefits to the collection (and with sustainability). Very different compromises can be made in display areas and storage areas in terms of temperature and RH. Enclosure solutions allow RH for particular objects to be controlled distinctly from the room.

Local climate and building envelope capability

Local climate and the characteristics of the building envelope determine the feasibility and sustainability of any climate control target. These issues were more strongly emphasized in the 2019 and 2023 editions of the ASHRAE chapter than in previous editions. The annual baseline selected for temperature and RH, in combination with seasonal adjustments, will determine the size of climate control systems and their energy consumption.

Parameter 3: Seasonal adjustments from the annual average or baseline

Seasonal adjustments are intentional changes in the temperature and RH settings designed to reduce energy consumption in winter and summer. Seasonal adjustments have been common in smaller museums and galleries but were considered less than ideal and inappropriate for larger institutions. This attitude has shifted in favour of sustainability. The 2019 and 2023 editions of the ASHRAE chapter emphasize that sustainability considerations should play a much larger role in decisions about seasonal adjustments, regardless of the scale of the institution.

Parameter 4: Short-term fluctuations plus space gradients

Short-term fluctuations, or simply short fluctuations, may be caused by the mechanical system cycling on and off many times per day, by the day-night cycle or by the effects of the weather outside. Short fluctuations can be unintentional, as in the typical sawtooth pattern of a simple system switching on and off, or it can be intentional, as in a complex system that is designed with a deadband between opposing processes, such as heating versus cooling and humidification versus dehumidification. The word “short” was not defined in the 1999 to 2015 editions of the ASHRAE chapter, and users often asked for clarification. In the 2019 and 2023 editions, the following note was added: “Short-term fluctuation means any fluctuation shorter than the times specified […] for rate of seasonal adjustment (i.e., 30 days for relative humidity fluctuations, 7 days for temperature fluctuations).” (ASHRAE 2023)

Space gradients refer to the change in RH and temperature that occurs between a hot or cold wall or floor and the room average. It also refers to the change between the air supply vents and the return air conditions. Of course, in real systems such gradients are unavoidable and often large. This specification is not aimed at every location in the room; it is only aimed at the locations where collections are held. It is not intended to lead to designs with unusually high air exchange rates and high energy consumption. Rather, it is intended to encourage the adoption of as many passive design features that reduce gradients as possible (for example, high insulation of the envelope, good distribution of air movement, as well as adequate separation of collection fittings and collection objects from obvious sources of such gradients). Such advice applies as much to simple systems in historic buildings as it does to purpose-built facilities with sophisticated systems. Consult Figures 5 and 6 in *Agent of deterioration: incorrect relative humidity*.

System failure is a bigger risk than routine fluctuations

From a risk management perspective, the most important fluctuations are the occasional extreme fluctuations caused by system failure, such as a very low RH due to humidification failure during a cold winter or high humidity in summer due to faulty air conditioning. A once-in-30-years extreme event in RH is much more damaging to an unpackaged collection than a modest increase in the size of short fluctuations throughout those 30 years. Long-term reliability remains a secondary concern in many mechanical system designs, and an example where enclosures, such as moistureproof packaging of objects and sealed cabinets, play an essential role in collection risk management. Consult Appendix C: The response times of objects and the multiple benefits of enclosures.

Sensitivity to fluctuations and the proofed fluctuation

The sensitivity of objects to fluctuations in RH and temperature has been the single most contentious issue in setting climate control specifications, and it often becomes an obstacle to more sustainable climate control decisions. The issue of object sensitivity and the role of history in establishing a proofed fluctuation are discussed in more detail in Appendix B: Sensitivity to fluctuations and the application of proofed fluctuations.

Appendix B: Sensitivity to fluctuations and the application of proofed fluctuations

Four levels of initial sensitivity to fluctuations

In previous publications, we have used the terms “vulnerability” and “sensitivity” interchangeably. Here, sensitivity will refer to the physical response of an object to an agent of deterioration, such as fracture due to RH fluctuations, whereas vulnerability will refer to the consequent loss of value, which depends on many additional factors.

By “initial sensitivity,” CCI means the sensitivity level of an object to temperature and RH fluctuations on the day it was made (assuming it has reached equilibrium with its local RH), before any fluctuations have taken place. After the object experiences some fluctuations, it is said to be “proofed” to that size of fluctuation, and it is no longer sensitive to less extreme fluctuations (Michalski 1993, 2007). If fractures in an object are adhered, however, then the object returns to a new initial, unproofed state.

Different objects have different sensitivity levels to fluctuations in temperature and RH. The level of initial sensitivity (before any exposure to fluctuations) is determined by the following four factors:

- The amount that the reactive components expand and contract for a given size of fluctuation (the expansion coefficient).
- The elasticity of affected components, which depends on the age of the material as well as the temperature and RH prior to the fluctuation.

- The geometry of the assembled components. Are reactive components restrained, or, worse, are weak, brittle components attached to strong, reactive components?
- Unevenness in the thickness of stressed components or their attachment to restraining components, which causes localized stress concentration.

For practical purposes, objects with materials that respond to RH can be divided into four categories, each twice as sensitive to fluctuations as the previous, as shown in Table 1.

Table 1: the four levels of initial sensitivity to RH fluctuations (objects with no prior exposure to fluctuations since manufacture or since reattachment)

	Low sensitivity (half or less of medium sensitivity)	**Medium sensitivity**	**High sensitivity (double the sensitivity of medium)**	**Very high sensitivity (double the sensitivity of high)**
Type of assembly and component flaws	Components are free to move relative to each other	Uniform restraint of components (distributed attachment) and no notches	Uneven restraint of a component or uniform restraint plus notches	Uneven restraint plus localized movement, such as a paint layer or veneer across a moving wood joint
Approximate stress concentration	×1/2 or less	×1	×2	×4
Damage at ±40% RH	Between no damage and small damage	Small to severe damage (benchmark 1)	Severe damage (benchmark 2)	Very severe damage
Damage at ±20% RH	Between no damage and tiny damage	Between no damage and small damage	Small to severe damage	Severe damage
Damage at ±10% RH	No damage	Between no damage and tiny damage	Between no damage and small damage	Small to severe damage

Damage at ±5% RH	No damage	No damage	Between no damage and tiny damage	Between no damage and small damage

The lower four rows in Table 1 map the degree of damage expected for various combinations of RH fluctuation (rows) and object sensitivity (columns). The degree of damage is determined by extrapolating from the cell that contains benchmark 1. Benchmark 1 is based on the common observation as well as available experimental evidence that evenly restrained responsive materials will probably not fracture in one cycle until the humidity goes from a middle value near 50% RH (common in summer in Canada) down to a very low value of about 10% RH (common in heated buildings in winter). Examples of responsive materials that are evenly constrained include wood panels held evenly at their edges, oil paintings on canvas with uniform layers of paint held evenly by a strainer or skins stretched uniformly in a kayak or umiak.

Furthermore, we can observe that when cracks or tears do occur (severe damage), they are located at flaws or notches, which corresponds to the cell that contains benchmark 2. The remainder of the table is extrapolated from these benchmarks.

Note that each diagonal row of cells (from top left to bottom right) predicts the same degree of damage. This is because these diagonals link cells of equal stress: as you move one step down in the table, the fluctuation size is halved; as you move one step to the right, stress concentration doubles. For the same reasons, each diagonal has double the stress of its neighbour to the left.

Table 1 does ignore four known corrections to the stresses created by fluctuations, but these corrections would not change the four broad categories of sensitivity. Besides, all four corrections tend toward making Table 1 conservative in its advice. The four corrections are the following:

- Stress in wood, leather, paper, plastics, coatings, etc., relaxes over time, so very slow fluctuations cause less stress. Consult Michalski (2007) for further discussion.
- Objects take time to respond to fluctuations. If the fluctuation is shorter than the object's response time, stress is less than predicted. This is discussed further in Appendix C: The response times of objects and the multiple benefits of enclosures.
- The phenomenon of hysteresis during RH fluctuations means that a fluctuation of ±20% RH causes less than half the dimensional change of ±40% RH, a fluctuation of ±10% RH causes less than half the dimensional change of ±20% RH and a fluctuation of ±5% RH causes less than half that of ±10% RH. Since the table is built from the historic evidence of fracture at ±40% RH, then hysteresis makes the extrapolations of stress to smaller fluctuations progressively less than estimated in Table 1.

- The humidity expansion coefficient varies with RH. When plotted as a function of RH, it follows an S-shaped curve. Below 25% RH and above 75% RH, the coefficient progressively increases. The result is that a fluctuation of ±40% RH (top row of Table 1) will cause more than just double that of ±20% RH. (This correction to the relationship between ±40% RH and ±20% RH is in addition to the hysteresis correction which applies to all steps between ±40% RH and ±5% RH.) In summary, the simplified extrapolation to rows with smaller fluctuations than ±40% RH yields cautious estimates.

Expressions of damage in the cells of Table 1 for high and very high sensitivity appear at first glance to suggest that a great deal of damage across collections will occur during relatively small fluctuations. These categories, however, never apply to a whole object or even most of the object in the sense of the whole object disintegrating. Common sense and experience tell us that the world did not fall apart before modern climate control. High and very high sensitivity applies to specific locations within objects and usually to badly designed objects from the perspective of durability. For example, it applies to the paint that crosses a weakened joint in a lacquered wooden chair or a panel painting, the paper near pins holding a large sheet to a rigid frame and the skin of an umiak where it is attached to the frame with too few cords that are also too narrow. Since in historic items, those locations fractured long ago, it can only refer now to the repairs and infills bridging those same locations.

The ASHRAE chapter contains an extensive table that expands on the generic content of Table 1. ClimaSpec uses that table, and other sources, to provide quick access to specific sensitivity assessments of each collection or object that you wish to understand.

Initial sensitivity to fluctuations is not a precise science

Specific numbers used to specify fluctuations in this resource, such as ±10%, ±20%, ±5°C and ±10°C, should not be taken to mean that the science is precise to within 1% RH or 1°C and that risk suddenly changes at precisely these values. These are round numbers based on the best available estimates of risk. Numbers such as ±8% RH or 6°C have not been employed because they might imply a precision that does not exist at present. [Unfortunately, conversion of these round numbers, that originated in SI (metric) units, into US customary units, as needed for the ASHRAE inch-pound (I-P) edition, creates numbers that are not round, but they must be left as is for consistency.] Even if one day the science does become very precise, it will only provide a precise probability of damage at each fluctuation and not a guarantee that fracture occurs precisely at that fluctuation.

A loan contract is a precise obligation

Refining recommendations for the long-term preservation of your own collections does not remove contractual obligations entered into for loans or for programs such as the Designation of Institutions and Public Authorities Program or the Canada Travelling Exhibitions Indemnification Program. A precise specification in a design contract or a loan contract is a precise statement of obligations, even if it borrows round numbers from an imprecise science. Unfortunately, it is not easy to measure actual RH conditions with sufficient precision to know if the contract has been met. Measuring RH to better than ±5% RH requires costly instrumentation. As noted elsewhere, there is only one way to guarantee climate safety with regards to precious objects: a reliable microclimate enclosure.

Collection history and proofed fluctuations

Cracks in objects, that is delaminations as well as visible cracks, cannot form again in the same location, unless the old fracture has been reattached or adhered. When exposed to the same fluctuation that caused the crack, the crack simply opens and closes (Michalski 1993, 2007). Studies of cracks in wood furniture located in buildings with wide but consistent fluctuations, and for which historic photographs are available, have shown that the cracks were indeed all old and had not visibly progressed (Ekelund et al. 2018). Recent analysis of the mechanics of paint layers suggests that craquelure reaches saturation, beyond which new cracks will not develop (Wu et al. 2014; Bratasz and Vaziri Sereshk 2018). Such limits on accumulation of damage despite reoccurrence of the hazard is very different from other deterioration processes that continue to accumulate until the material disintegrates, such as repetitive events of mould, continual chemical deterioration, light fading and pollution damage. If the largest fluctuation experienced by an object in the past was a 30% RH drop from an annual average of 50% RH (a drop to 20% RH), then all the mechanical damage likely to occur from a single fluctuation of that size has already occurred. Therefore, a future drop in RH that is slightly smaller than this previous drop of RH cannot cause a new crack.

Proofed fluctuation, as established by previous climate history, is extremely important in establishing realistic and sustainable targets that cause low risk to collections. The Climate Control Decision Tool asks about climate history in some situations in order to establish collection sensitivity. Similarly, ClimaSpec identifies different sensitivities and recommendations depending on the climate history of the object or collection.

Fatigue fracture

Many thousands of additional fluctuations similar to the one that is considered the object's proofed fluctuation can lead to further crack growth through a process called "fatigue." This is a subtle correction to the application of proofed fluctuation, and it has been incorporated into advice provided by ClimaSpec.

Figure 1 and Tables 2 and 3 come from a review (Michalski 2014) of the best available fatigue studies for materials essential to heritage collections: wood, paints and gesso. Plots such as those in Figure 1 are called S-N curves (stress versus number of cycles) or Wöhler curves. The S-shaped curve usually drawn through S-N curves has been simplified to three straight lines:

- the initial plateau that falls from 1 to about 0.9 at 30 cycles,
- the transition region from 30 to over 300,000 cycles and

- the final plateau, known as the “endurance limit,” that begins at about 1,000,000 cycles.

At the endurance limit, fatigue damage ceases. Although of interest to vibration studies, exposure to 1,000,000 cycles (that is, 1,000,000 fluctuations) is far beyond what is relevant for daily fluctuations (2,700 years), let alone seasonal fluctuations.

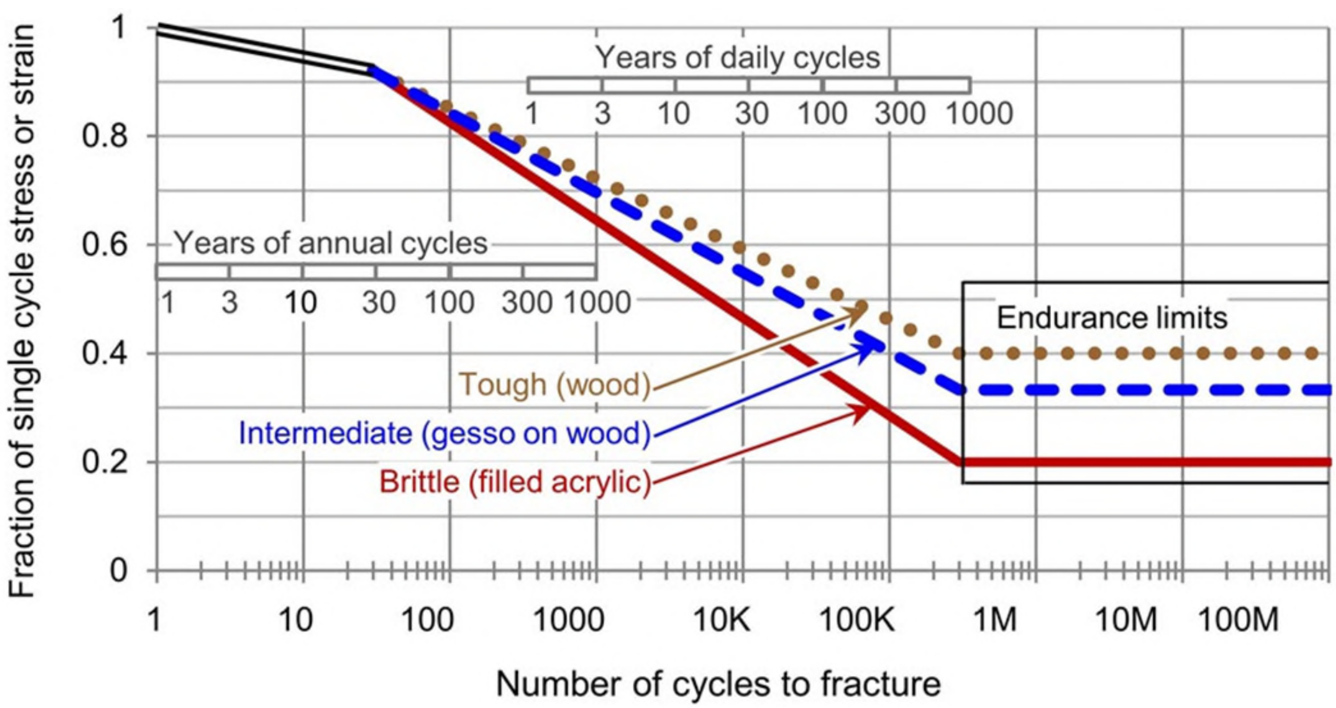

Figure 1. Fatigue graph (S-N curves) for materials that range from tough to brittle (Michalski 2014).

Description for Figure 1

Figure 1 contains a single graph with three plots. The horizontal axis is a logarithmic scale of the number of cycles to cause fracture, and the vertical axis is the stress or strain that causes that fracture, expressed as a portion of the stress or strain that causes fracture in one cycle. The three plots all begin on the left at *x* = 1 and *y* = 1. They drop towards the lower right at *x* = 1 million cycles and *y* values between 0.2 and 0.4.

Table 2: fatigue factors for materials that range from tough to brittle (selected from Figure 1) for the practical range of annual cycles

Type of materials	1 year	3 years	10 years	30 years	100 years	300 years	1000 years
Tough materials, such as wood	1	0.98	0.95	0.92	0.84	0.78	0.71
Intermediate materials, such as gesso on wood	1	0.98	0.95	0.92	0.83	0.75	0.70
Brittle materials, such as filled acrylic	1	0.98	0.95	0.92	0.82	0.72	0.46

Table 3: fatigue factors for materials that range from tough to brittle (selected from Figure 1) for the practical range of daily cycles

Type of materials	1 year	3 years	10 years	30 years	100 years	300 years	1000 years
Tough materials, such as wood	0.78	0.71	0.65	0.59	0.51	0.45	0.40

Intermediate materials, such as gesso on wood	0.76	0.69	0.62	0.54	0.48	0.39	0.32
Brittle materials, such as filled acrylic	0.72	0.63	0.45	0.35	0.29	0.28	0.20

The lines in Figure 1, or the rows in Tables 2 and 3, can be thought of as equivalent combinations of fluctuation size and fluctuation number. For example, following the last row of Table 3 for brittle materials such as filled acrylic, a single annual fluctuation of size ±*X*% RH is equivalent to 30 years of annual fluctuations of size 0.92 × ±*X*% RH or to 100 years of annual fluctuations at 0.82 × *X*% RH, and so on.

In practice, even daily or weekly fluctuations are unlikely to be precisely the same size, so fatigue, even from daily or weekly fluctuations, is determined simply by the biggest fluctuation of the year (the winter and summer peaks). It is the scale of annual fluctuation shown in the lower left corner of Figure 1, and provided in Table 2, that concerns us.

To obtain an estimate of future risk, based on a history of many fluctuations, rather than just one historic fluctuation, you use the ratio of the future and historic factors. As an example, if you know that for the last 30 years there has been a consistent annual fluctuation of size ±*X*% RH, and you want to know what is a safe fluctuation for the next 100 years for a brittle material, then find in Table 2 the factor for 30 fluctuations (0.92) and the factor for 100 fluctuations (0.82). Now calculate the ratio of those two factors (the factor for 100 years ÷ the factor for 30 years), which is 0.82 ÷ 0.92 = 0.89. If you know that in the last 30 years, RH had an annual average near 50% but fluctuated by ±30% (so down to 20% RH each winter), then keeping future fluctuations at or below 0.89 of ±30% RH (that is, ±27% RH) will provide safety for the next 100 years. In other words, do not let winter RH drop by more than 27% from the average of 50% RH (do not go below 23% RH).

Note that this is not a huge difference from the 20% RH of the last 30 years. Very slight reductions in fluctuation from the worst historic fluctuations have huge benefits.

You can read these fractions directly from Figure 1 or Tables 2 and 3, or you can use the following equation for the middle portion of the plot for brittle material, which is good for the range of 30 cycles to 300,000 cycles.

Equation 1: $\pm X_f\%\ RH = \pm X_h\%\ RH * \{[0.18*\log10(n_h) + 1.19] / [0.18*\log10(n_f) + 1.19]\}$

Where

$\pm X_f\%\ RH$ = maximum future fluctuation that must not be exceeded

$\pm X_h\%\ RH$ = size of known historic fluctuations

n_h = number of known historic cycles (30 and above)

n_f = number of future cycles to consider (maximum 300,000)

In summary, fatigue refines the proofed fluctuation concept as follows: for every *n* years of known historic pattern of fluctuations, you can project that staying within this proofed pattern for the next *n* years will cause very low risk of new fractures. Furthermore, if you make very modest reductions in future fluctuations compared to the proofed pattern, then you can project many times further than *n* years.

Do not hide how bad your climate control might have been in the past. This history of proofed fluctuations is the best estimate of the sensitivity of any collection and the best guide when choosing sustainable options for climate control.

Damp can reduce a proofed fluctuation

At a very high RH (well over 75%), wood can be crushed if it is prevented from expanding (for example, tenons held tightly within a mortise). On return to moderate RH, the wood remains crushed. At a very high RH, the animal glue holding these joints and veneers in place changes from strong and inflexible to weak and pliable and to almost a jelly near 100% RH. As a result, the components of joints and veneers in furniture that were exposed to damp will re-adhere in slightly changed positions when they return to moderate RH. In extreme cases, veneers detach and buckle when damp and remain buckled when RH returns to moderate values. A proofed fluctuation that was established in the range of 0% to 75% RH might be reduced after a period of damp. CCI has observed this effect in veneered wood joints using acoustic emission (Hagan 2021). We can expect that other objects based on animal glue or size, such as paintings on canvas, may suffer from the same effect.

In practical terms, periods of damp not only cause severe mechanical damage in and of themselves, but they can reduce a proofed fluctuation that was established for fluctuations that occurred below 75% RH. The extent of such reduction remains uncertain.

Appendix C: The response times of objects and the multiple benefits of enclosures

This Appendix provides technical background to the response time estimates of ClimaSpec. It also explains why integrating microclimate enclosures into building design and mechanical systems is essential for a sustainable, risk-based approach to collection use and collection care.

The meaning of response time

When an object at equilibrium with its surrounding temperature and RH is exposed to a change in temperature or RH, it takes time to fully respond (to reach a new equilibrium with its new environment). The general form of the response is a curve, as shown by the lower graph in Figure 2.

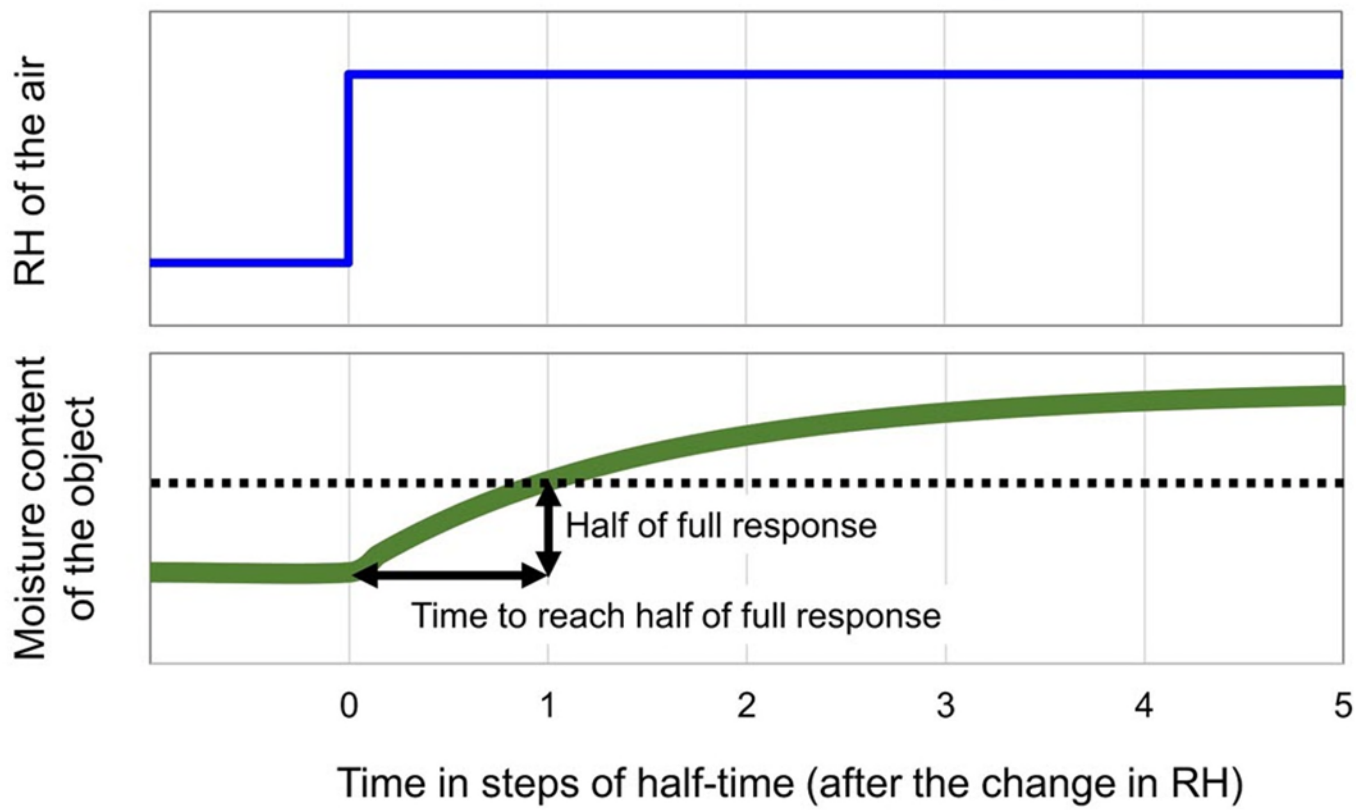

Figure 2. Moisture content change in an object over time, in response to a sudden change in RH of the surrounding air.

Description for Figure 2

Figure 2 contains two graphs. The horizontal axis is time, shown in steps of half-time. The top graph is for RH, showing a single sharp step from an initial RH to a steady final RH. The bottom graph is for the moisture content of the object, and it shows a smooth gradual climb to a final plateau of full response to the RH change. A horizontal dashed line marks the midway level of this moisture content curve.

The response time (also called the half-time) is specified as the time it takes to reach one half of the eventual maximum response. There are several advantages to specifying half-time rather than a full response. Half-time is unambiguous; whereas the phrase “full response” depends on what fraction of the response is a full response. Is it 90%, or 99% or 99.9% of the eventual change? Half-time also has the advantage of providing a conservative estimate of the time period within which you should act to reduce risks due to a fluctuation.

The meaning of enclosures

For climate control purposes, an enclosure is any bag, box, case, cabinet, crate, etc., that reduces contact between an object’s surface and the humidity and pollutants in the room. In practice, this means not only that the enclosure material has low permeability to moisture or pollutants, but also that the enclosure is relatively airtight, since in most situations, the primary path for moisture and pollutants are small openings in the enclosure. (Details are given in the following sections.) Although you can also think of a new or historical coating on an object as a form of enclosure, for preventive conservation advice, CCI means only enclosures that are easily removed when necessary.

Integration of enclosures with the building and its systems

From a risk management perspective, the risks to collections from various kinds of RH fluctuations can be divided into two very different types (Michalski 2016):

- **Frequent events**: The routine fluctuations of hours, days and seasons that, over time, determine the proofed fluctuations of the collection. These may be caused by natural cycles of the outdoor climate or by routine fluctuations of the mechanical system.
- **Rare events**: These are extreme changes in temperature or RH that occur decades or even centuries apart. Very few rare events that have been recorded are natural, such as the exceptionally cold winter of 1928 in London that caused an extreme drop in RH in the National Gallery. Afterwards, staff observed unusual and significant damage to panel paintings, and this observation led to an official research inquiry (Michalski 2016). More commonly, however, these rare events are failures of mechanical systems at the end of their life (typically 30 years), which can create very high or very low RH. (Cold-storage crashes that cause RH to reach 100% become tragedies only when the stored objects are not packaged.) Occasionally, these system events occur at the beginning of a new mechanical system’s life, hence the need for debugging new systems before exposing unpackaged collections. Sometimes these events are the result of a collection’s move into improved RH conditions, after decades of stable storage at a very different annual average of RH.

From a risk management perspective of many decades of preservation, a rare event, or even just a 10% chance of a rare event, is the dominant risk due to climate fluctuations. The only fail-safe against such risks is enclosures. Enclosures are increasingly part of basic preservation strategies and not only for institutions such as historic house museums without climate control (consult *Agent of deterioration: incorrect relative humidity – Vignette 2. Simple display boxes that reduce incorrect RH*), but also for major museums with precious objects that want to reduce long-term risks (consult Figures 10a and 10b in Basic requirements of preventive conservation).

You might then ask: what purpose do climate control systems serve beyond those needed for human comfort if all objects are in enclosures? Aside from the fact that museums large and small will use the risk-reduction ability of enclosures for targeted objects (objects of exceptional value, exceptional sensitivity and exceptional risk of vandalism), the practical reality is that simple enclosures cannot mitigate temperature changes for more than a few hours and most cannot mitigate seasonal shifts in RH. What even simple enclosures can do is mitigate rare crashes that might last several days or even weeks before repairs are made and rare weather events that overwhelm the system. They also greatly reduce access by external pollutants. (Consult Technical Bulletin 32 *Products Used in Preventive Conservation* for materials that are not themselves a source of pollutants.) Whereas you might have reasons to avoid enclosures in a display, simple packaging for objects in storage is the only means to rationally obtain long-term risk management (consult Technical Bulletin 32).

In summary, long-term preservation that is also sustainable is dependent on the integration of the strengths of mechanical systems (making the average temperature and RH different from outdoors) and enclosures (smoothing out RH fluctuations, blocking pollutant exposure) with the strengths and limitations of the building. This recognizes that the local climate is not just a design condition but probably a determinant of the proofed fluctuations of local collections.

Relative humidity response times of objects with and without enclosures

Some of the content of the following two sections appeared first in the 1999 edition or the 2019 and 2023 editions of the *ASHRAE Handbook* chapter "Museums, Galleries, Archives, and Libraries," prepared by the author while a member of CCI staff but also as a member of the committee responsible for that chapter. The content has been abridged and updated here.

Table 4 provides RH response times for objects and enclosed objects. Where available, direct measurements have been cited. Other estimates are based on calculations, which are explained in the section Equations behind the calculations of response times.

The range of response times may seem extraordinary, but it is the result of two phenomena:

- Response varies as the square of a material's thickness. A piece of wood that is 50 times thicker will take 2500 times longer to respond. (For example, a 5 cm thick plank in a dugout canoe versus a 1 mm thick piece of wood in a guitar body or violin will take 50 × 50 times longer to respond.)

- The enclosure effect. Compared with open air, a reasonably airtight enclosure can reduce the rate of access of both moisture and pollutants by a factor of 10 to 100 or more. Objects that respond to RH in a few hours in open air, such as watercolours, or tarnish in a few weeks, such as uncoated silver, will take months, if not years, to respond or tarnish in a well-sealed enclosure of impermeable materials. Two examples include a sealed frame with glass and a backing board for watercolours and an airtight display case for silver.

Table 4: RH response times (near 20°C)

Time range	Objects	Enclosed objects	Design implications
Greater than 10^8 seconds (a year or more)	• Wooden objects at least 12 mm thick, if wrapped in heavy-gauge polyethylene 200 µm thick, with perfect seams: at least 350 days	• Paintings on canvas, paper or photographs with several layers of matboard (or buffer) framed with a glass front and impermeable backing board, perfect seals except for a single pressure-equalization pinhole: approximately 15 years • Enclosure made of 4 mm acrylic sheet: approximately 11 months (Michalski 2005)	• Risk only emerges if the annual average RH in the space is unacceptable for the enclosed object
Approximately 10^7 seconds (weeks to months)	• Large uncoated wood objects, 100 mm across the grain, 700 mm along end grain: 100 days • Books, exposed only on fore-edge, tightly	• Spools of 35-mm film inside a metal can: 60 days (Adelstein et al. 1997) • Paintings on canvas, paper or photographs with several layers of matboard (or buffer) framed with a glass front and	• Hourly and daily RH fluctuations create negligible risk • Seasonal space adjustments are smoothed out • System loss lasting less than

	compressed: approximately 25 days • Books if loosely compressed: approximately 11 days (Derluyn et al. 2007) • Unspecified hardcover book, exposed all sides: approximately 18 days (Bigourdan 2012)	impermeable backing board, but gaps of 0.1 mm at the top and bottom: 30 days (Michalski 2005)	a week creates little risk
Approximately 10^6 seconds (days to a week)	• Thick layers of oil paint, alkyd paint from days to weeks for thin to thick layers • Old panel painting with back waterproofed: approximately 15 days (Stillwell and Knight 1934) • Spools of 35-mm film, no can: 4 days (Adelstein et al. 1997) • Uncoated wood slab, medium-density wood: 20 mm across the grain, 5 days; 130 mm along end grain, 5 days • Wooden cabinet, when empty with	• Paintings on canvas, paper or photographs with several layers of matboard (or buffer) framed with a glass front and impermeable backing board, but gaps of 0.5 mm at the top and bottom (Michalski 2005) • Hackney (1990) measured at most 6 days with glass frame and coated backing board (such a short response time must have been due to leakage through gaps) • Archive box, paperboard or polypropylene, no holes, full: approximately 2 days	• Hourly and daily RH fluctuations create little risk • System loss lasting several days can create high risk

	a light varnish and gaps under 1 mm, approximately 7 days • Ivory, uncoated, about 25 mm diameter cylindrical shape (Lafontaine and Wood 1982)	(Batterham and Wignell 2008, estimated from their measured damping of external daily fluctuation of ×4)	
Approximately 10^5 seconds (a day)	• Uncoated wood slab, 8 mm across the grain, 50 mm along end grain • Ivory, uncoated, about 25 mm cube shape (Lafontaine and Wood 1982)	• Paintings on canvas with continuous paint layer and impermeable backing board applied to frame (Di Pietro and Ligterink 1999)[1]	• Hourly RH fluctuations create little risk • System loss lasting all day can create high risk
Approximately 10^4 seconds (hours)	• Bare acrylic paint, medium thick layer • Bare oil paint, alkyd paint, thin layers • Uncoated wood, wood fibreboards, leather, skin, 3 mm thick	• Response times of enclosures containing hygroscopic objects will not be this fast unless gaps are many millimeters wide. The objects then respond as if the enclosure was not present	• Hourly RH fluctuations or system loss can create risk
Less than 10^3 seconds (a few minutes or less)	• Single sheet of paper: 4 minutes (Kupczak et al. 2018) (includes	• Response times of enclosures containing hygroscopic objects will not be this fast unless gaps are many	• RH fluctuation or system loss of only a few

	book pages that are fanned open) • Thin sheet of parchment or ivory • Thin layers of watercolour paint or gouache • Feathers, fur and hair • Lightweight textiles and costumes • Gelatin layer of photographic print or film • Sized canvas used for paintings	millimeters wide. The objects then respond as if the enclosure was not present	minutes can create risk[2]

[1] These objects are only partially enclosed.
[2] Some of these objects have a tradition of enclosures, such as works on paper. Others, such as textiles and costumes, do not.

Technical notes for Table 4: Calculations for objects shaped as flat plates assume exposure on both sides unless noted otherwise (consult the section Equations behind the calculations of response time). Adelstein et al. (1997) and Bigourdan (2012) reported 90% response times. These are converted for Table 4 to half-times by the factor of 0.4, assuming an approximately exponential decay curve such as in Figure 2, where 90% response occurs at 2.4 half-times, so half-time is 1 ÷ 2.4 = 0.42 of the time for 90% of response. Derluyn et al. (2007) measured a 50 mm square experimental book, closed on all sides except the fore-edge. Their times have been adjusted to a more realistic 100 mm depth, so increased by four times (times vary as the square of thickness). Estimates from Michalski (2005) are based on material data plus enclosure leakage equations. Estimates for wooden objects and furniture are based on Figures 3 and 4.

Charts for the response time of wooden objects

Wooden objects form a large part of many heritage collections. Since their thicknesses range from about a millimetre to almost a metre, and given the square law noted earlier, the response times of wooden objects vary from minutes to years. The wide variety of coatings on wood further complicates predictions. Some common objects have been listed previously in Table 4, but Figures 3 and 4 provide a more complete map of the phenomenon and also show the enormous benefits of wrapping wooden objects in airtight polyethylene film when not on display.

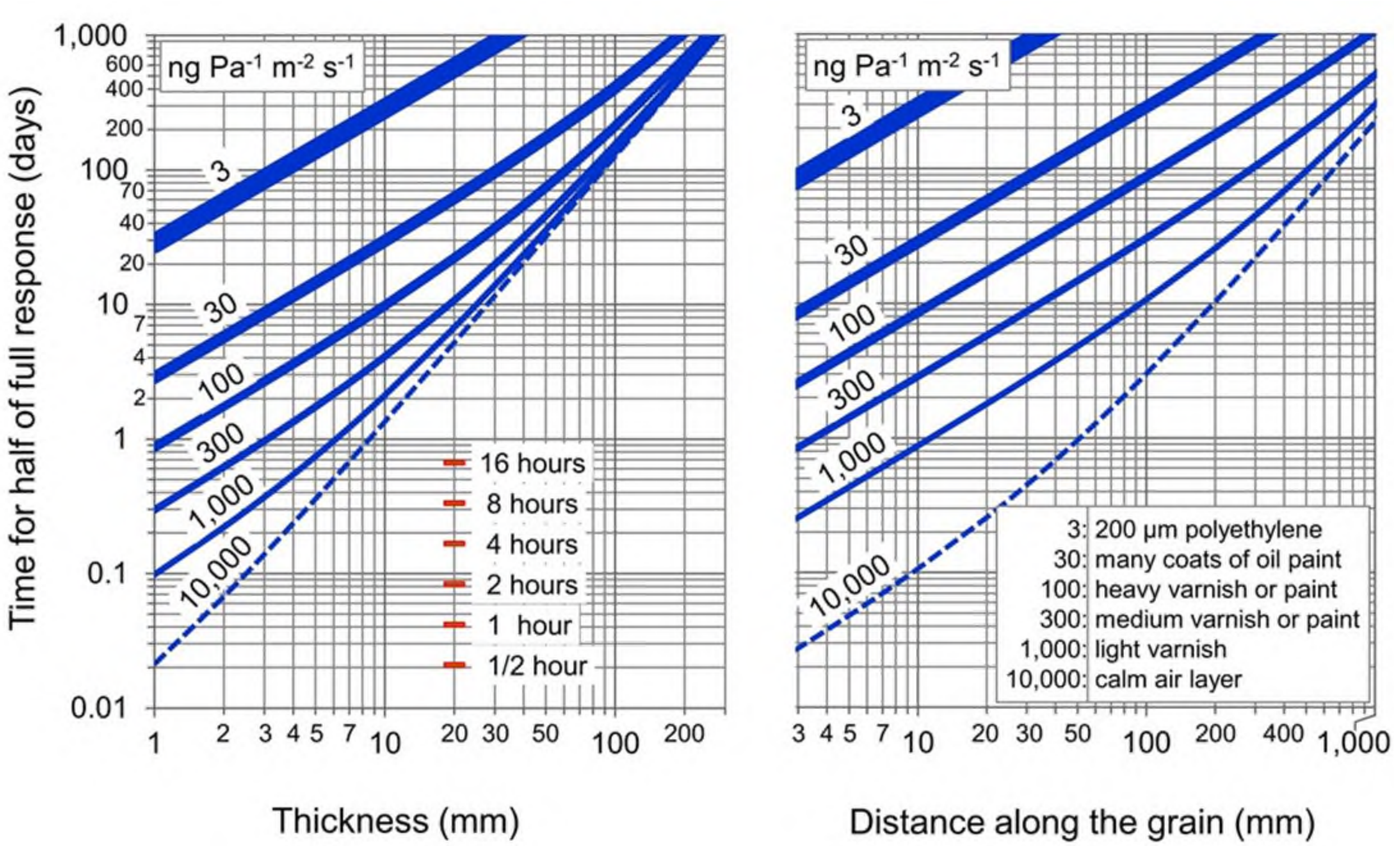

Figure 3. Response time in days (near 20°C) of medium-density wood to RH changes. Left graph for across the grain, right graph for along the grain. This assumes both sides (or both ends) are exposed.

Description for Figure 3

Figure 3 contains two graphs, side by side. Both share a vertical axis labelled “Time for half of full response (days).” The horizontal axis of the left graph provides the thickness in millimetres. On the right graph, the axis provides the distance along the grain in millimetres. Each graph has six plots. All plots slope smoothly from bottom left to top right and appear to converge at top right. Key points along the six plots of the left-hand graph and right-hand graph are provided in Table 5 and Table 6, respectively.

Table 5: response time in days (near 20°C) of a medium-density as a function of its thickness, as shown in Figure 3 (left)*

Permeance ng/Pa/m²/s	Example of a coating with this permeance	1 mm thick	2 mm thick	5 mm thick	10 mm thick	20 mm thick	50 mm thick
3	200 µm polyethylene	30	60	140	300	600	1,500
30	Many coats of oil paint	3	6	15	30	60	170
100	Heavy varnish or paint	0.9	2	5	10	22	80
300	Medium varnish or paint	0.3	0.6	2	4	10	50
1,000	Light varnish	0.1	0.2	1	2	7	36
10,000	Calm air layer	0.02	0.07	0.4	1	5	32

*Some values are off the range of the graph.

Technical note for Tables 5 to 8: permeance is a measure of the rate of moisture transfer across a layer of material as a function of the vapour pressure of water acting across that layer.

Table 6: response time in days (near 20°C) of medium-density wood when the exposed face is end grain, as shown in Figure 3 (right)*

Permeance ng/Pa/m²/s	Example of a coating with this permeance	5 mm thick	10 mm thick	20 mm thick	50 mm thick	100 mm thick	200 mm thick
3	200 µm polyethylene	140	300	600	1,500	3,000	6,000
30	Many coats of oil paint	14	30	60	140	300	600
100	Heavy varnish or paint	4	9	20	40	90	200
300	Medium varnish or paint	1.4	3	6	15	30	70
1,000	Light varnish	0.4	1	2	5	11	25
10,000	Calm air layer	0.05	0.1	0.3	1	3	10

*Some values are off the range of the graph.

The graph on the left side of Figure 3 and its selected values in Table 5 consider a plank of wood exposed on both faces. The graph on the right side of Figure 3 and its selected values in Table 6 consider a wooden object exposed only on its end grain. For objects that have both kinds of directions exposed, first find both sets of predictions, and then select the shortest time, which will still overestimate the response time somewhat.

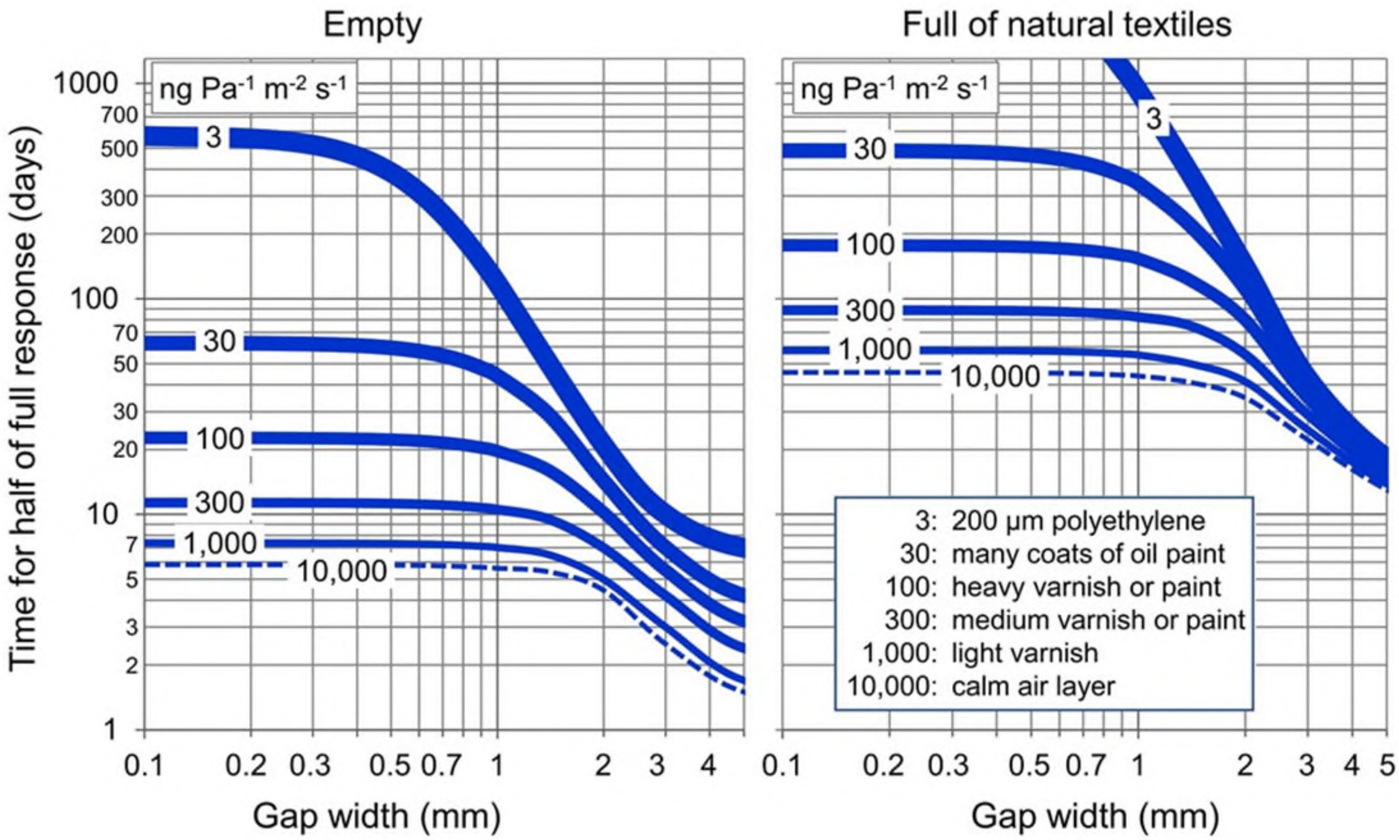

Figure 4. Dependence of response time in days (near 20°C) of a wooden cabinet or chest of drawers as the width of the gaps at the top and bottom increases. (Object is 1.5 m high, 1 m wide, 0.5 m deep; wood thickness is 1 cm; gaps are 15 mm deep and extend from side to side.)

Description for Figure 4

Figure 4 contains two graphs, side by side. Both share a vertical axis labelled “Time for half of full response (days).” The horizontal axis of both graphs provides the gap width in millimetres. There are six plots in each graph, all similarly S-shaped. Key points along the six plots of the left-hand graph and the right-hand graph are provided in Table 7 and Table 8, respectively.

Table 7: dependence of response times in days (near 20°C) of a wooden cabinet or chest of drawers that is empty, on the width of gaps at the top and bottom, as shown in Figure 4

Permeance ng/Pa/m²/s	Example of a coating with this permeance	0.1 mm gap	0.5 mm gap	0.7 mm gap	1 mm gap	2 mm gap	3 mm gap	5 mm gap
3	200 µm polyethylene	600	400	250	120	20	10	7
30	Many coats of oil paint	60	60	50	40	14	7	4
100	Heavy varnish or paint	20	20	20	20	10	6	3
300	Medium varnish or paint	11	11	11	10	7	4	2
1,000	Light varnish	7	7	7	7	5	3	2
10,000	Calm air layer	6	6	6	6	4	3	2

Table 8: dependence of response times in days (near 20°C) of a wooden cabinet or chest of drawers that is full of textile, on the width of gaps at the top and bottom, as shown in Figure 4

Permeance ng/Pa/m²/s	Example of a coating with this permeance	0.1 mm gap	0.5 mm gap	0.7 mm gap	1 mm gap	2 mm gap	3 mm gap	5 mm gap
3	200 µm polyethylene	4,000	3,000	2,000	1,000	140	40	9
30	Many coats of oil paint	500	500	400	350	100	40	9
100	Heavy varnish or paint	200	200	170	150	80	35	9
300	Medium varnish or paint	90	90	90	80	55	30	8
1,000	Light varnish	60	60	60	50	40	25	8
10,000	Calm air layer	45	45	45	45	35	20	8

Figure 4 and Tables 7 and 8 consider wooden furniture that is coated on the outside but not the inside. Such furniture may have drawers or doors with gaps at the top and bottom, which allow exterior air to flow in and come in contact with the bare wood interior. Although such furniture in a museum is usually empty and often open for display of the interior, historically, such furniture was closed as well as filled with clothing or bedding, which would have been an excellent humidity buffer.

In Figure 4, the horizontal plateaus on the left are regions where air leakage through gaps is insignificant and the wood coating dominates half-time. The plots drop drastically on the right as the air leakage through cracks dominates. On the far right, the plots begin to bend upwards as the air leakage into the furniture interior is so large that the pieces of wood, which are uncoated on the inside, behave simply as fully exposed slabs of wood that are coated on only one side. (This final stage of behaviour, which affects only the left-hand graph, was not considered in versions of the figure that appear in the 1999, 2019 and 2023 editions of the *ASHRAE Handbook*.)

The lessons from Figure 4 and Tables 7 and 8 are that this type of furniture, that was usually closed, well fitted and full of textiles, could have survived large fluctuations in RH for many weeks or even months, historically. However, when the furniture was empty in a museum, it was much more responsive to short fluctuations. If left permanently open, the furniture reverts to the times of exposed wood pieces, given in Figure 3 and Tables 5 and 6. Finally, for single pieces of wood, well-sealed heavy-gauge polyethylene film offers stability well beyond one year if you avoid gaps in the packaging.

Concerns about temperature fluctuations on microclimate enclosures

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 RH despite drops from room temperature to freezing and back. Stolow (1966) provided complete data and equations for the counterintuitive result that with natural hygroscopic materials, the humidity in the enclosure even drops slightly when the temperature drops (the opposite of empty enclosures) due to the slight shift downwards of moisture isotherms at lower temperatures.

Thomson (1964) showed that the transition point between RH-controlled enclosures (RH is stable or drops slightly) and mostly uncontrolled empty enclosures for hygroscopic materials such as wood occurred when there was about 1 kg of material per cubic metre of enclosure. Humidity control was fully in place when 10 kg of material was present in each cubic metre of enclosure (about 2% by volume). Later authors have 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 consensus is that such occasional side effects do not outweigh the benefits (Richard 2007; Shashoua 2014).

The effect of temperature on response times

Lower temperatures greatly increase response times and, conversely, higher temperatures shorten them. This has been demonstrated in measurements of archival materials (Adelstein et al. 1997). You can estimate that response times, such as those in Tables 5, 6, 7 and 8 and in Figure 3, which are for 20°C, will double for each drop of 10°C (for example, ×2 for storage at 10°C, ×4 for storage at 0°C, ×8 or more for storage at -10°C). The cause is the drop in the diffusion coefficient of moisture in solids as the temperature drops. The estimates for the chest of drawers, Figure 4 and Tables 7 and 8, will also see the times double with each decrease of 10°C, but for slightly different reasons. When the gaps are too small to affect half-times (the left-hand plateaus in the graph), the reasons are the same as above. When gap leakage dominates half-times, the reason is that the moisture capacity of infiltrating air drops by half for each 10°C drop.

Equations behind the calculations of response time

The response time of a plate (a shape that applies to many cultural objects and that provides an upper bound to cylinders, cubes, spheres, etc.) is given by Crank (1979) as the following:

Equation 2: $t_{½} = 0.049 * d^2 / D$

Where

$t_{1/2}$ = half-time of the microclimate enclosure, seconds

d = thickness of plate (or sheet), m

D = diffusion coefficient m^2/s

Values of the diffusion coefficient can be found in various handbooks, such as Siau (2012) for wood, and Park and Crank (1968) for polymers.

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, eqn. 39):

Equation 3: $t_{½} = 0.69 * (V_h * \alpha * \rho) / (N * V_e * C_{ws})$

Where

$t_{1/2}$ = half-time of the microclimate enclosure, seconds, hours or days (depends on leakage units)

V_h = volume of the hygroscopic material, m^3

V_e = volume of the enclosure, m^3

α = hygric capacity (slope of the moisture isotherm) kg/kg

ρ = bulk density of the hygroscopic material, kg/m^3

N = leakage, expressed as air changes per second, per hour or per day

C_{ws} = concentration of water in the air at saturation, kg/m^3

The critical role of leakage (*N*) for enclosed objects can be seen by following the example in Table 4 of paintings or works of art 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 several orders of magnitude. This is due to the key role of infiltration in determining *N* and the fact that infiltration through narrow cracks varies with the cube of crack width; that is, reducing crack width by a factor of 2 will reduce air infiltration by a factor of 8 (Michalski 1994).

Equation 1 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 kg/m^3. Using a conservative density where ρ is about 600 kg/m^3 and a conservative hygric capacity where α is about 0.05, then

Equation 4: $t_{½} = 1200 * V_h / (N * V_e)$

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-gauge, 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 ACD will rarely have 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 (Thickett et al. 2007).

Some estimates in Table 4 are based on this equation 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 3 was generated using this approach with wood data from Siau (2012) for medium-density wood near 50% RH. When barriers provide useful resistance (consult the upper lines in each plot in Figure 3), the plots have a slope of 1 (linear). When coatings provide negligible resistance, such as the boundary layer of air in a calm room, the slope of the plots changes to the square law of equation 1. There is only a slight curve as thickness drops to 1 mm across the grain. Kupczak (2018) has measured the contribution of the boundary layer of air, which is measurable but far from being rate determining, even for a single sheet of paper. In practical terms, thinner objects respond more quickly (for example, a violin, ivory miniature and paper sheet), but they also benefit much more than thicker objects from even simple coatings or enclosures (such as cases, cabinets and packaging).

Figure 4 was generated by using the same series resistance model but by using leakage equations for an enclosure found in Michalski (1994). Besides the assumption of the dimensions noted in the caption for Figure 4, the graph also assumes that the typical stack pressure driving air infiltration is due to either a 1°C temperature difference or a 40% RH difference. Consult Michalski (1994) for further explanation of these numbers.

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ASHRAE types of control

Stefan Michalski

On this page:

List of abbreviations

ANSI American National Standards Institute
ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers
CCI Canadian Conservation Institute
HDD heating degree days
HVAC heating, ventilating and air conditioning
IPI Image Permanence Institute
ISO International Organization for Standardization
NECB National Energy Code of Canada for Buildings
RH relative humidity

Introduction

Since the first edition of the “Museums, Galleries, Archives, and Libraries” chapter in the *ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Applications* was developed in 1999 (hereafter referred to as the “ASHRAE chapter”), the Canadian Conservation Institute (CCI) has contributed extensively to its content and has adopted its framework and nomenclature in providing advice to professionals in Canada on control of the museum climate.

In this resource, each American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) type of control is illustrated within the specified limits in a hygrothermograph chart. For more information on which types of control are recommended for particular objects and collections, consult ClimaSpec in the left-hand menu.

The 1999 to 2015 editions of the ASHRAE chapter included the guidelines for temperature and relative humidity (RH) under Table 3: Temperature and RH Specifications for Collections. In the 2019 edition, this became Table 13: Temperature and Relative Humidity Specifications for Collections in Buildings or Special Rooms. While the overall structure and categories used in the two tables remain very similar, the 2019 revision reflects a general shift seen in the entire chapter towards a greater emphasis on local and sustainable targets rather than on universal fixed specifications.

The 1999 to 2015 editions used the phrase “levels of control.” In the 2019 edition, this was changed to “types of control” to minimize the false assumption that types AA, A, B, C and D or the subtypes cool, cold and frozen represent hierarchies of quality. Although system complexity and energy costs range between types, each has its use for particular collections in particular circumstances.

Climate specifications

Climate specifications for the preservation of collections have four parameters:

- long-term outer limits or danger boundaries,
- annual averages or baselines,
- seasonal adjustments from the annual average and
- short-term fluctuations plus space gradients.

The 1999 to 2015 editions of the ASHRAE chapter specified only the last three parameters. The first was added in 2019. For an explanation of why these four parameters were created, consult Climate guidelines overview – Appendix A: The four parameters of a climate specification. This resource focuses on the numeric specifications of these four parameters for each type of control.

The meaning of annual average

The term “annual average” in the ASHRAE chapter (1999 to 2023 editions) has caused some confusion. (A previous term, “set point,” had also proved problematic.) Take, for example, a user who selects 20°C as the annual average and an increase of 5°C in summer and a decrease of 10°C in winter as the maximum permissible seasonal adjustments. Implementing both these seasonal adjustments will result in a temperature of 25°C in summer and 10°C in winter, and it will make the annual average 17.5°C. This prompts the user to question whether they have applied a summer increase of 7.5°C to an average of 17.5°C. For clarity in the detailed examples of hygrothermographs in this resource, CCI uses the term “annual baseline” where the 2019 and 2023 ASHRAE chapters have used “annual average.”

Limits to the rate of seasonal adjustments due to the limits on short-term fluctuations

In the 2019 and 2023 editions of the *ASHRAE Handbook*, “short-term fluctuations” (not defined in previous editions) were defined as “…any fluctuation shorter than the times specified…for rate of seasonal adjustment (i.e., 30 days for relative humidity fluctuations, 7 days for temperature fluctuations).” With the new emphasis placed on sustainability, and the recognition that energy savings increase when seasonal adjustments are increased, the interpretation of “short-term fluctuations” becomes important when implementing large seasonal shifts over short periods of time.

The committee that wrote the 2019 edition had extensive discussions on whether the short-term fluctuation limits for temperature in types of control AA, A1, A2 and B had been set too narrowly. These discussions centred on the need to encourage sustainability and the lack of any evidence in the literature that mechanical risk from temperature fluctuations would occur until fluctuations were much larger than those that had been specified.

The justification for these narrow temperature tolerances is not based on the temperature effects per se but, rather, on the RH fluctuations that they cause near the objects. If temperature changes occur quicker than the thermal response time of an object, or quicker than the response time of the heating, ventilating and air-conditioning (HVAC) system in adjusting the moisture content (dew point) of the air, then the RH at the surface of the object can fluctuate by up to 3% for each 1°C fluctuation. An example would be a 6% RH fluctuation for a 2°C change in temperature. This means that you must limit temperature changes capable of creating these RH effects to ±2°C so as to be consistent with the ±5% RH short-term limit.

To establish a safe rate of temperature adjustment, begin with the following premise: the thermal response time of most objects ranges from hours to a few days, and the thermal response time of most buildings is similar. Over the course of a week, therefore, the objects and the building fabric can reach equilibrium with any sudden adjustment in temperature of the HVAC system. If you keep weekly adjustments of temperature within ±2°C, then the RH discrepancy at the surface of the objects (and the surfaces of the building fabric) will not exceed ±5%RH.

Sustainability issues

The climate control issue of most concern to conservators is RH, unless they are working with archival collections (in which case, temperature is the primary concern.). However, for engineers looking for energy savings, the reverse is true: temperature and ventilation requirements are their primary concerns. To balance the needs of both groups, there are two new ASHRAE 2019 guidelines: selecting an annual baseline that is in keeping with the local climate and making seasonal adjustments in temperature. The traditional belief that mixed collections require year-round stable temperatures for preservation has been proven false. To implement temperature baselines that are very different from human comfort conditions, together with large seasonal adjustments, will require separation of storage rooms from occupied rooms. (You can reduce the risk due to the transition between storage areas and display areas, whereby objects, in effect, traverse a large space gradient. This is done by wrapping and insulating objects during transit, which is the procedure for external transit and for retrieval from cool or cold storage.)

A major cause of energy inefficiency in traditional HVAC systems in museums was the cycling of the heating and cooling systems (and their humidifying and dehumidifying processes), especially during the shoulder seasons of spring and fall. Energy-efficient designs use a deadband, which is a narrow range of temperature and humidity separating the settings of the two systems. Each system can overshoot its setting slightly without triggering the opposing system. This approach is even more successful if the building is well insulated and airtight and contains a large mass of collections that are hygroscopic; that is, they can act as a large reservoir for heat and humidity. For these kinds of efficient design, where each system operating alone causes very little fluctuation, the ASHRAE guideline for short-term fluctuations can be used to set the permissible deadband. For more information on savings with suitable deadbands, consult the ASHRAE Standard 90.1-2019, *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

A final sustainability issue is the building itself, not simply in terms of heritage but in terms of global building stock. In the past, a stringent approach to temperature and RH controls for collections caused many heritage institutions (much more often than other institutions) to damage their buildings inadvertently due to condensation in the walls. In cold climates, winter humidification caused condensation in the walls; in hot and humid climates, summer air conditioning also caused condensation in the walls. Seasonal adjustments in temperature make it possible to save not only energy but also the buildings themselves. It’s important to take full advantage of the seasonal adjustments permitted and the relative humidities suggested in the ASHRAE chapter.

CCI has made an initial survey of energy consumption by museums in Canada. The survey suggests that institutions with the highest level of climate control use about two to three times more energy than those with basic control for human comfort. Several factors probably contribute to the increased energy consumption and variability, so it's impossible to say, definitively, that climate control targets alone are the driving factor.

The energy intensity of Canadian heritage facilities will become clearer as relevant data is collected through the Survey of Commercial and Institutional Energy Use and incorporated into Energy Star's Portfolio Manager software for energy tracking and benchmarking. But here is what is already certain. Museums that are still using a traditional specification for the highest level of climate control (rather than a specification adapted to the local climate) are not making use of seasonal adjustments and are not re-examining their systems for improvements in efficiency. These museums are energy wasteful and unsustainable. Large museums can benefit from adopting the same performance analysis tools, such as RETScreen (developed by the Government of Canada), that other institutions are using to achieve energy-efficiency targets. Contact CCI for more information.

Integrating HVAC design with microclimate enclosures

Trying to control both temperature and RH through a building's HVAC system is always complicated and will inevitably fail from time to time. The most reliable means of reducing RH fluctuations, especially the very large spikes resulting from a system failure, is the incorporation of microclimate enclosures (display cases, cabinets, sealed picture frames, plastic bags, etc.). An abundance of literature in the conservation field explains the techniques and pitfalls of using microclimate enclosures. Technical Bulletin 33 *Silica Gel: Passive Control of Relative Humidity* explains the use of extra buffering material.

Microclimate enclosures are not only recommended for institutions unable to control RH in their building. They are also recommended for institutions with precious objects that could be damaged when the state-of-the-art system eventually fails; for institutions that maintain 50% RH for their mixed collection and also store corroded metals or weeping glass objects that could be damaged at this level; and for large institutions who want to lend objects to smaller institutions that lack the required level of RH control in their building.

Misuse of the ASHRAE terminology

It has become conventional to use the ASHRAE type of control specifications as a shorthand for describing the performance of a system. But a statement such as "My system is AA most of the time" can be misleading. Any mechanical damage a collection suffers is a result of the worst hours and days it faces each year and not the better conditions it is under for the other 99% of the year. Each ASHRAE type of control applies 24/7, 365 days of the year, year after year. Any building, even an uncontrolled historic house, can have days or even weeks when the climate conforms to a specific type of control. This does not mean that the building (and its systems) meets that specific type of control. This is very different from the usual assumption in HVAC design for human comfort, where conditions outside specifications for 1% (or 3%) of the year (conventional design tolerances) are acceptable.

It is, however, permissible and logical to state either that “My institution always remains within AA conditions during the summer months, the time period for which we have requested the loan” or that “The interior of this airtight display case maintains A1 conditions throughout the year by the combination of the temperature control provided by the room systems and of the RH control provided by the enclosure.”

Precisely what is meant by “most of the time,” be it 99% or 97% of the time, during each year or each decade has not yet been formalized in the ASHRAE chapter, and it remains a complex question. What is certain, again, from a risk management perspective is that microclimate enclosures are essential for any valuable objects that are highly sensitive to RH fluctuations.

ASHRAE climate zones

In the 2019 and 2023 ASHRAE chapters, climate zones are used to provide advice on the type of control that is feasible in different locations and the building envelope performance necessary to achieve such control. For significant capital projects and whenever an engineer or architect is involved, the current ASHRAE chapter as well as local and national building codes must be consulted. The following is a brief summary for non-experts.

There are many different climate zone maps. Probably the most widely known are those for gardeners, where higher numbers are warmer climates. For HVAC design purposes, ASHRAE created its own system (Figure 1) with higher numbers for colder climates. It is based on four climate factors, one of which is the amount of heating required over the cold season (heating degree days [HDD] below 18°C). ASHRAE has published zone maps and tables for locations worldwide, including hundreds of locations in Canada (ASHRAE 2021). Canada’s building code as well as many provincial codes refer to the data of the National Energy Code of Canada for Buildings (NECB), which defines zones solely on HDD. For the ASHRAE zones of interest to Canada (Figure 1), the NECB zones are very similar but without the separation into A, B, C due to precipitation differences. HDD data for Canada that also accounts for the effects of climate change is readily available online, for example in the climate data portal called ClimateData.ca.

Table 1 summarizes the strategies to adopt, by climate zone, to meet the requirements of each ASHRAE type of control. It contains abridged information from ASHRAE (2023) as well as strategies other than building envelope design. The table can be simplified even further: ASHRAE AA and A types of control need a special building envelope. ASHRAE C and D are the realistic (and very sustainable) options for historic buildings everywhere. ASHRAE B is feasible in older buildings in warmer zones (4 and 5), but out of reach for most of Canada (zones 6 to 8).

Table 1: building strategies for all Canadian climate zones

Type of control	Climate zones	Strategies
AA	All of Canada: 4C, 5A, 5C, 6A, 6B, 7 and 8	Build a purpose-built building with a special envelope design, for example, unusual airtightness and unusual insulation. The need for a purpose-built building increases as the zone number increases. For retrofitting historic structures, use a box-in-a-box approach that is, separately controlled interior rooms (van Schijndel 2010) or a dynamic buffer zone solution (Pasqualini 1999). Use microenvironments for reliable RH control over the long term (for example, decades) or for materials with special RH requirements such as corroded metals.
A1 and A2	5A, 5C, 6A, 6B, 7 and 8	As AA.
A1 and A2	4C (only near Victoria, BC)	As AA, but it may be possible to relax the envelope design a little.
B	4C, 5A and 5C	If the temperature is controlled to human comfort in winter, historic buildings may survive without a retrofit, but careful envelope analysis and some retrofitting may be required. If heating is controlled by a humidistat, average envelope performance may suffice. Use microenvironments to reduce RH fluctuations or for materials with special RH requirements such as corroded metals.
B	6A, 6B, 7 and 8	If temperature is controlled to human comfort in winter, follow AA advice. If heating is controlled by a humidistat, average envelope performance may suffice. Use microenvironments to reduce RH fluctuations or for materials with special RH requirements such as corroded metals.
C	All of Canada: 4C, 5A, 5C, 6A, 6B, 7 and 8	An envelope design equivalent to successful residential buildings in that climate zone is sufficient, as humans and objects both require an RH above 25% and below 75%. Some retrofitting of historic buildings may be necessary at higher zone numbers. Use microenvironments to reduce RH fluctuations or for materials with special RH requirements such as corroded metals.
D	All of Canada: 4C, 5A, 5C, 6A, 6B, 7 and	If the temperature is allowed to follow the external daily average of temperature (for example, uninsulated buildings), then only good airtightness is required to allow dehumidification systems to function. In

	8	zones with a B suffix (dry), smart ventilation alone may be sufficient. Use microenvironments to reduce RH fluctuations or for materials with special RH requirements such as corroded metals.
Cool Cold Frozen RH control	All of Canada: 4C, 5A, 5C, 6A, 6B, 7 and 8	A special envelope design is essential, for example, unusual airtightness and unusual insulation. Using a box-in-a-box approach (that is, separately controlled and insulated interior rooms) is a common solution. If heated human comfort zones are not needed, cool or cold storage may be achieved at low cost simply by following average outdoor temperatures in zones 7 and 8. Use microenvironments to reduce RH fluctuations and to prevent extreme RH when systems fail.

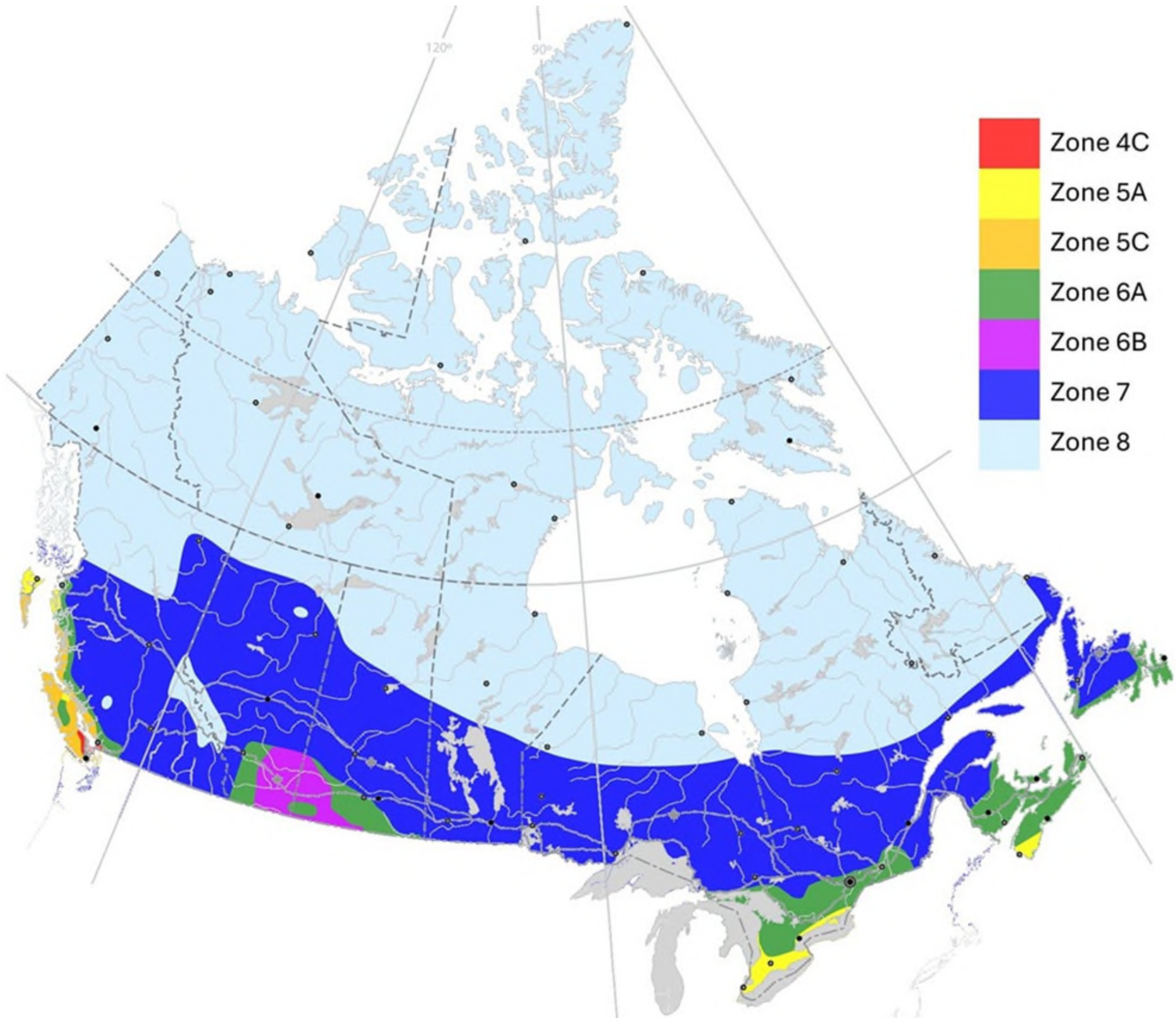

Figure 1. Climate zones of Canada based on ASHRAE (2021).

Description for Figure 1

Figure 1 contains a map of Canada with the various ASHRAE climate zones shown in different colours.

ASHRAE AA

Definition of ASHRAE AA

All parameters and statements of benefits and risks are as given in ASHRAE (2023).

Type of collection and building: museums, galleries, archives and libraries in modern purpose-built buildings or purpose-built rooms. Temperature is at or near human comfort level.

Type of control: precision control with no seasonal changes to RH.

Table 2: the four patameters of ASHRAE AA

Long-term outer limits	Annual averages (baseline)	Seasonal adjustments from annual average (baseline)	Short-term fluctuations plus space gradients
10°C to 25°C	• For permanent collections: historic annual average of temperature • In public display areas: human comfort temperatures can apply	• Increase by 5°C • Decrease by 5°C	±2°C
35% to 65% RH	• For permanent collections: historic annual average of RH	No change to RH	±5% RH

Collection benefits and risks of ASHRAE AA

Benefits to the collection include the prevention of mould germination and growth as well as the prevention of rapid corrosion. There is no risk of mechanical damage to most objects and paintings. However, some metals, glasses and minerals may degrade if RH exceeds a critical value. At 20°C, chemically unstable objects deteriorate significantly within decades. For each increase of 5°C in temperature, the rate of deterioration doubles. For more specific benefits and risks of various temperature and RH conditions for particular objects, consult ClimaSpec.

Comments on ASHRAE AA

In the 1999 to 2015 editions of the ASHRAE chapter, the definitions of "seasonal adjustments" and "short-term fluctuations" remained the same. Changes to the 2019 edition included the introduction of long-term outer limits and a greater emphasis on the historic annual averages as an appropriate setting, rather than a default to 50% RH and 15°C to 25°C.

The AA type of control is the traditional, very narrow guideline of decades past, with a modest amount of seasonal temperature adjustment added. It should not be interpreted as the perfect guideline. It ignores the considerable problem of chemically unstable materials in 20th-century collections (which benefit from cooler and dryer conditions), and there is no evidence that it decreases mechanical risks for actual collections, as compared to type A1 or A2. In addition, there are no records of any institution worldwide that has demonstrated meeting AA conditions throughout a room over the course of many years. Even systems that keep fluctuations within the AA range 97% of the time will fall outside its boundaries several days per year and several weeks per decade. This is an aspirational target for institutions with a purpose-made building located in a moderate climate zone.

From a risk management perspective, this target should not be pursued if

- resources allocated to the system and its operation could be used more effectively in addressing much greater risks to the collection;
- its implementation could result in damage to a historic building that may have a value similar to or greater than that of the collections; or
- its implementation could call for large energy expenditures due to an inadequate building envelope.

For recommendations on making statements on the use of AA (or any ASHRAE guideline), such as "My system is AA most of the time," consult the section Misuse of the ASHRAE terminology.

Hygrothermograph examples of ASHRAE AA

Example 1

In Figure 2, the annual baseline of temperature is 20°C (red dotted line), and the seasonal adjustments were set to the maximum increase and decrease of 5°C. These temperature settings could be used for collection storage: a winter setting of 15°C for January and February and a summer setting of 25°C for July and August. Spring and fall months are set at 21°C. Because the seasonal adjustments are not symmetric, the actual annual average is 20.5°C. The system in this example has fully programmable settings so that the temperature setting (smooth white line within the red oscillations) can be adjusted in small steps, perhaps two or three times a week during the months of

March, June, September and December. Note that the long-term outer limit of 25°C applies to the temperature setting (white line) and not to the peaks of the short-term fluctuations that cross the limit.

(Please note that the charts in this resource are all idealized in order to illustrate the specification more clearly, and they apply to a typically Canadian climate.

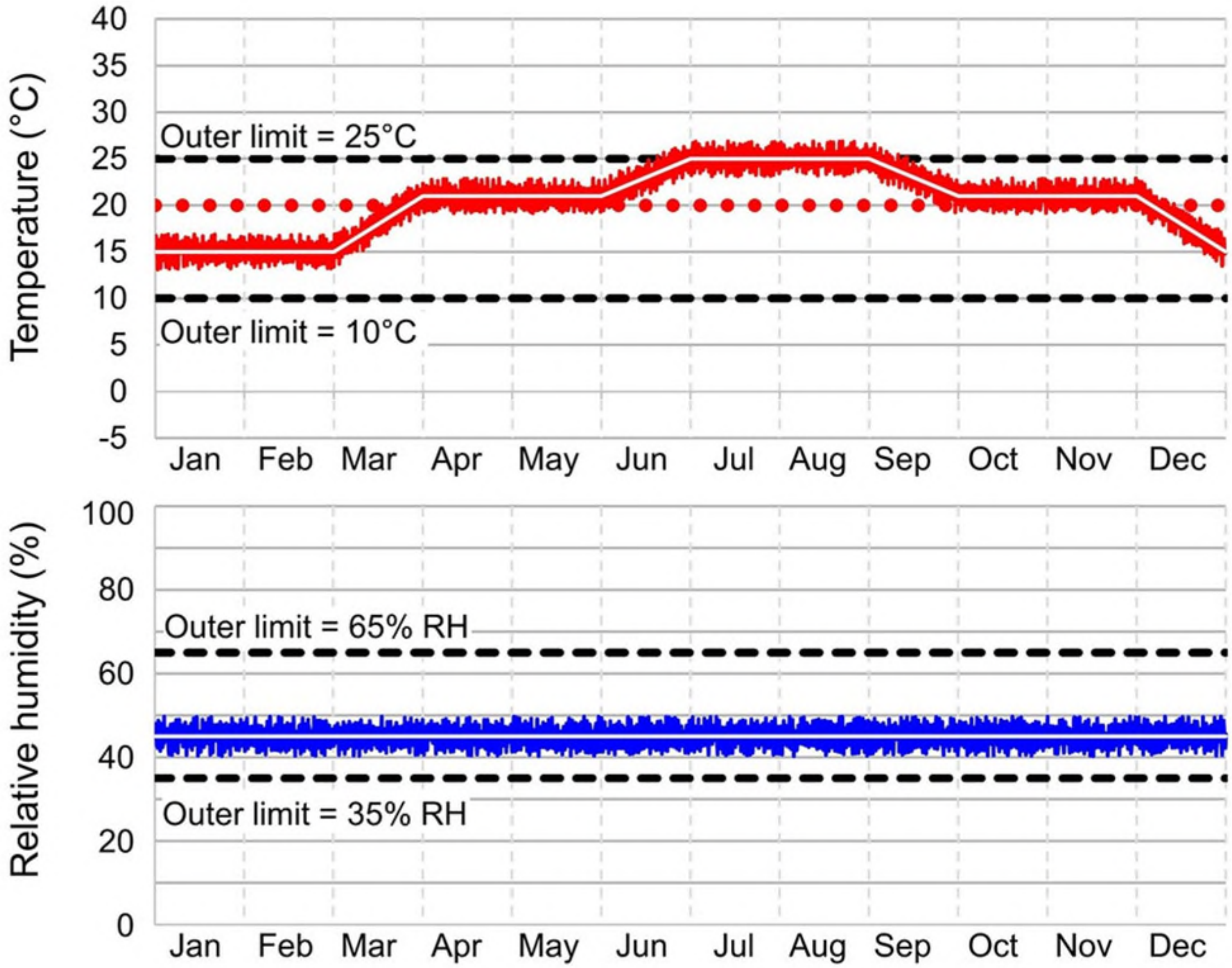

Figure 2. An example of a chart showing temperature and RH over one year in a building where staff selected the maximum permissible seasonal adjustments and short-term fluctuations that conform to ASHRAE AA type of control, using a few large but slow adjustments in temperature.

Description for Figure 2

Figure 2 contains two graphs, one above the other. The top one shows temperature; the bottom one shows RH. The horizontal axis is time, showing all 12 months of the year. The temperature graph shows a main plot that changes gradually from month to month but has many short-term fluctuations superimposed. There are two flat dashed lines for upper and lower outer limits. The RH graph shows a similar group of plots, but the main plot is completely flat.

The adjustments in seasonal temperature settings of Figure 2 (a gradual 6°C increase over the course of March, and a 6°C decrease over the course of December) may appear to violate the short-term fluctuation limit of ±2°C for AA. This 6°C adjustment would certainly not be permitted if it was made in a single step on March 1 and December 1. As discussed in the section Limits to the rate of seasonal adjustments due to the limits on short-term fluctuations, CCI considers a gradual implementation that does not exceed the short-term fluctuation limit of ±2°C each week to be consistent with the intent of the ASHRAE guidelines.

In Figure 2, the annual baseline of RH and the actual annual average are the same: 45% RH. There are no seasonal adjustments (flat white line within the blue oscillations).

Example 2

In Figure 3, the annual baseline of temperature is 20°C (red dotted line). The winter and summer plateaus are the same as in Figure 2 and could be used for collection storage, but here the seasonal adjustments are made once each month, in steps of 2°C. This is within the permissible short-term fluctuation of ±2°C. Because the monthly adjustments are symmetric, the actual annual average is also 20°C. Note that the long-term outer limit of 25°C applies to the temperature setting (white line) and not to the peaks of the short-term fluctuations that cross the limit.

Such a slow pattern of temperature adjustments will not be very energy efficient if the local climate changes more abruptly between winter and summer. The advantage of a larger temperature adjustment made gradually over the course of one month, as seen in Figure 2, is that it follows more closely a climate with rapid changes in seasonal temperatures (or with abrupt seasonal changes in occupancy and access).

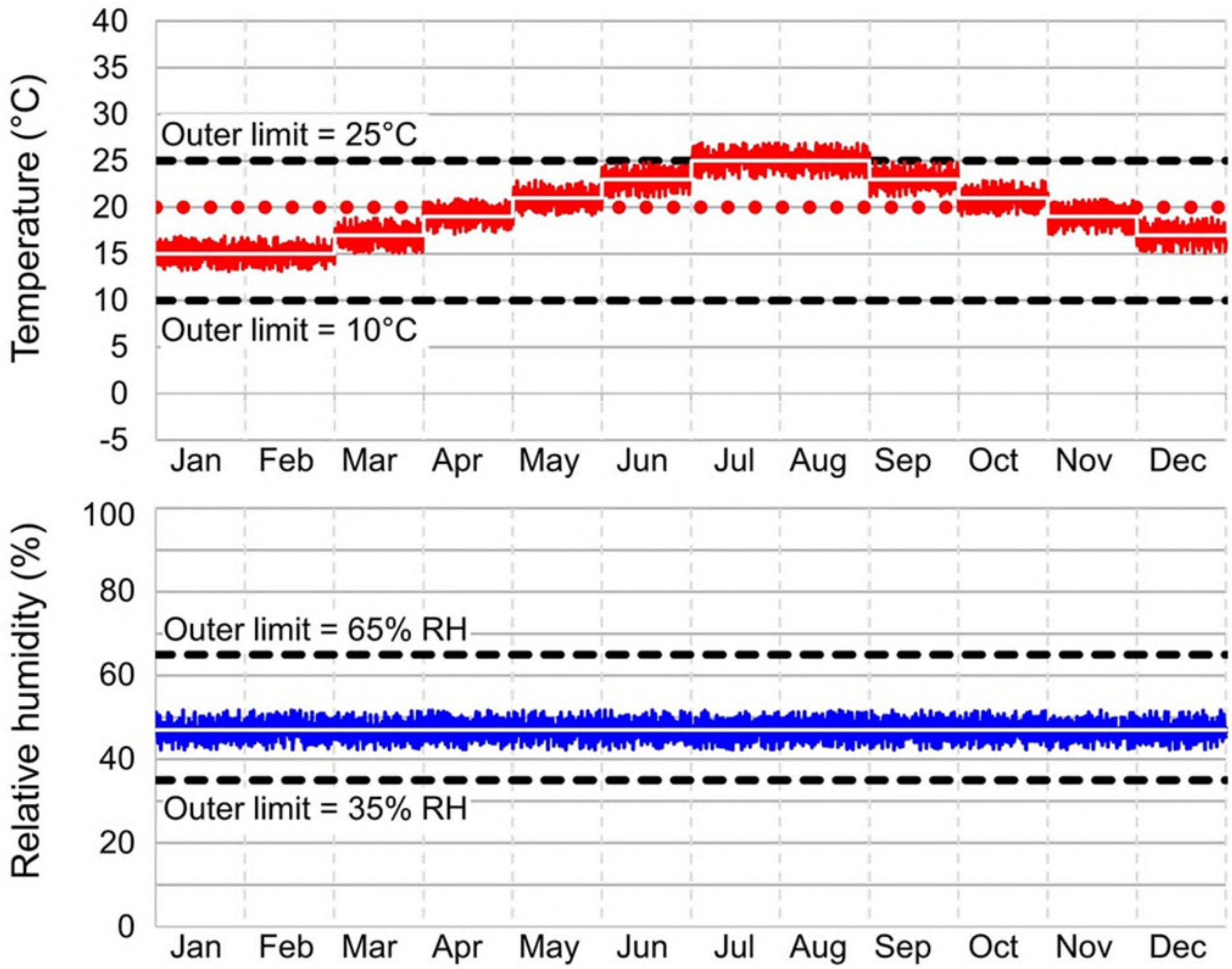

Figure 3. An example of a chart showing temperature and RH over one year in a building where staff selected the maximum permissible seasonal adjustments and short-term fluctuations that conform to ASHRAE AA type of control, using many abrupt but small adjustments in temperature.

Description for Figure 3

Figure 3 contains two graphs, one above the other. The top one shows temperature; the bottom one shows RH. The horizontal axis is time, showing all 12 months of the year. The temperature graph shows a main plot that changes in steps from month to month, with short-term fluctuations superimposed. There are two flat dashed lines for upper and lower outer limits. The RH graph shows a similar group of plots, but the main plot is completely flat.

In Figure 3, the annual baseline of RH was set at 47% all year (white line). The actual annual average is the same. The RH setting of 47% will not cause condensation problems during the winter in this building only because the temperature is allowed to drop to 15°C. In summer, 47% RH is within the capacity of the dehumidification system only because the temperature is allowed to rise to 25°C.

ASHRAE A1 and A2

A1 and A2 come with the same collection benefits and risks but differ slightly in their combination of seasonal and short-term RH fluctuations. Prior to the 2019 edition of the ASHRAE chapter, these alternative combinations were both labelled A, which could have led to confusion.

Definition of ASHRAE A1

Type of collection and building: museums, galleries, archives and libraries in modern purpose-built buildings or purpose-built rooms. Temperature is at or near human comfort level.

Type of control: precision control with seasonal changes in temperature and RH.

Table 3: the four parameters of ASHRAE A1

Long-term outer limits	Annual averages (baseline)	Seasonal adjustments from annual average (baseline)	Short-term fluctuations plus space gradients
10°C to 25°C	• For permanent collections: historic annual average of temperature • In public display areas: human comfort temperatures can apply	• Increase by 5°C • Decrease by 10°C	±2°C
35% to 65% RH	• For permanent collections: historic annual average of RH	• Increase by 10% • Decrease by 10%	±5% RH

Definition of ASHRAE A2

Type of collection and building: museums, galleries, archives and libraries in modern purpose-built buildings or purpose-built rooms. Temperature is at or near human comfort level.

Type of control: precision control with seasonal changes in temperature only.

Table 4: the four parameters of ASHRAE A2

Long-term outer limits	Annual averages (baseline)	Seasonal adjustments from annual average	Short-term fluctuations plus space gradients
10°C to 25°C	• For permanent collections: historic annual average of temperature • In public display areas: human comfort temperatures can apply	• Increase by 5°C • Decrease by 10°C	±2°C
35% to 65% RH	• For permanent collections: historic annual average of RH	No change to RH	±10% RH

Collection benefits and risks of ASHRAE A1 and A2

Benefits to the collection include the prevention of mould germination and growth as well as the prevention of rapid corrosion. There is no risk of mechanical damage to most objects, paintings, photographs and books. However, a small risk of mechanical damage exists for high-sensitivity objects. (In the current understanding, the guidelines A1 and A2 cause the same low risk of mechanical damage to vulnerable collections. Namely, a slow seasonal adjustment of 10% RH is estimated to cause the same mechanical risk as a rapid fluctuation of 5% RH. This is due to significant stress relaxation that occurs within three months of a slow transition.) At 20°C, chemically unstable objects deteriorate significantly within decades. For each increase of 5°C in temperature, the rate of deterioration doubles. For more specific benefits and risks of various temperature and RH conditions for particular objects, consult ClimaSpec.

Comments on ASHRAE A1 and A2

In the 2019 edition of the ASHRAE chapter, the two subcategories were given distinct names: type A1 and type A2. The seasonal adjustments and short-term fluctuations under type A remained unchanged from the 1999 to 2015 editions. However, the 2019 edition included the introduction of long-term outer limits and a greater emphasis on the historic annual averages as an appropriate annual baseline, rather than a default to 50% RH and 15°C to 25°C.

The letter “A” was chosen as the designation in the 1999 edition because this level was felt to be sufficient for major institutions that maintain mixed collections in a purpose-built building and that have a mandate to maximize preservation. This remains the opinion of the ASHRAE chapter committee and of CCI.

The mechanical risk outlined in Collection benefits and risks of ASHRAE A1 and A2 applies only to objects which have never been exposed to fluctuations since manufacture or since they were repaired. An object that has been exposed to a significant fluctuation will have fractured as much as is possible due to a single cycle of that size of fluctuation. For more information, consult Climate guidelines overview – Appendix B: Sensitivity to fluctuations and the application of proofed fluctuations.

The larger seasonal adjustments of A1 and A2 (as compared to AA specifications) are a recognition that even major museums must face energy and sustainability constraints and that these temperature adjustments are not a significant risk to most collections. That said, maintaining a collection within A1 or A2 specifications is still a resource-intensive task in most Canadian climates. Given the phenomena of proofed fluctuations, control type B is sufficient for many permanent collections.

Hygrothermograph examples of ASHRAE A1

Example 1

In Figure 4, the annual temperature baseline is set at 20°C (red dotted line). The seasonal adjustments follow a typical pattern used in a collection storage context: a winter setting of 12°C for January and February and a summer setting of 25°C for July and August. Temperatures in the spring and fall months change gradually up to the summer high of 25°C before falling again. The system is fully programmable, so the temperature can be adjusted in small steps, perhaps twice a week (white line). The largest transitions, an increase of 8°C in March and a decrease of 8°C in December, are just within the CCI suggestion that seasonal adjustments should not exceed a rate of 2°C per week. The actual annual average that results from these settings,19.8°C, is close to the annual baseline. Note that the long-term outer limit of 25°C applies to the temperature setting (white line) and not to the peaks of the short-term fluctuations that cross the limit.

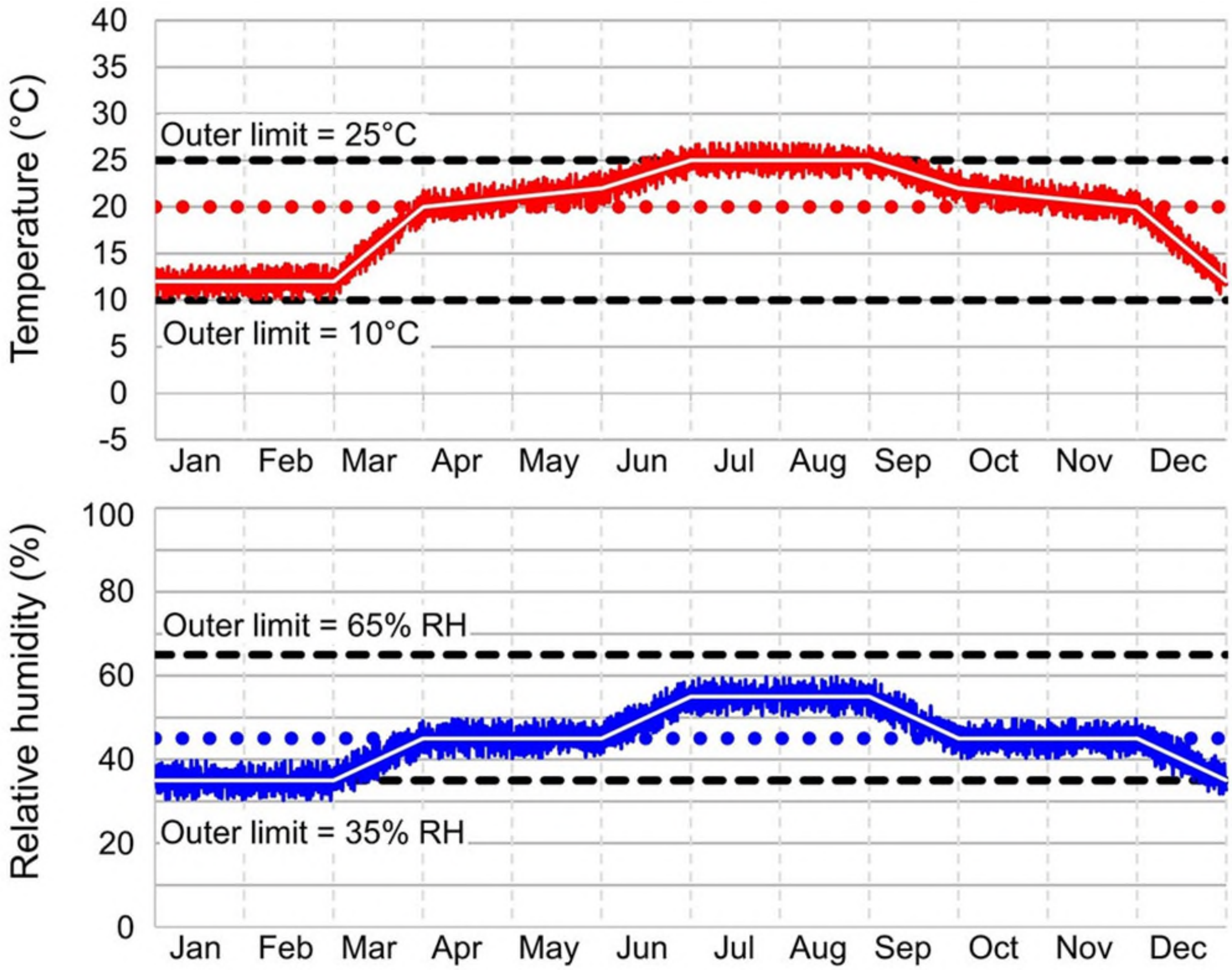

Figure 4. An example of a chart showing temperature and RH over a whole year in a building where staff selected the maximum permissible seasonal adjustments and short-term fluctuations that conform to ASHRAE A1 type of control, using a few large but slow adjustments in temperature and RH.

Description for Figure 4

Figure 4 contains two graphs, one above the other. The top one shows temperature; the bottom shows RH. The horizontal axis is time, showing all 12 months of the year. The temperature graph shows a main plot that changes gradually from month to month, with short-term fluctuations superimposed. There are two flat dashed lines that indicate the upper and lower outer limits. The RH graph shows a similar group of plots and a similar gradual change from month to month.

In Figure 4, the annual baseline for RH is set at 45% RH (blue dotted line). The settings (white line) change smoothly during the months of temperature adjustment (March, June, September and December). The summer plateau is set at 55% RH, and the winter plateau is set at 35% RH. With symmetrical seasonal adjustments, the actual annual average RH is the same as the annual baseline: 45% RH. Note that the long-term outer limit of winter, 35% RH, applies to the RH setting (white line) and not to the lowest trough of the short-term fluctuations (blue spikes).

Example 2

In Figure 5, the annual baseline of temperature is 19°C (red dotted line). The temperature settings of the HVAC system can only be changed monthly (white line), so this is done at the beginning of each month. The total range available, with six monthly changes limited to two degrees each, is only 12°C, so the range goes from 25°C in July to 13°C in January. Since the changes are symmetric, the actual annual average is also 19°C. Note that the long-term outer limit of 25°C applies to the temperature setting (white line) and not to the peaks of the short-term fluctuations that cross the limit. Such a pattern of temperature adjustments will not be energy efficient if the local climate is very different. The advantage of a larger temperature adjustment made over the course of a month, as in Figure 4, is that it is easier to follow more closely a climate with rapid changes between winter and summer conditions (or with abrupt seasonal changes in occupancy and access).

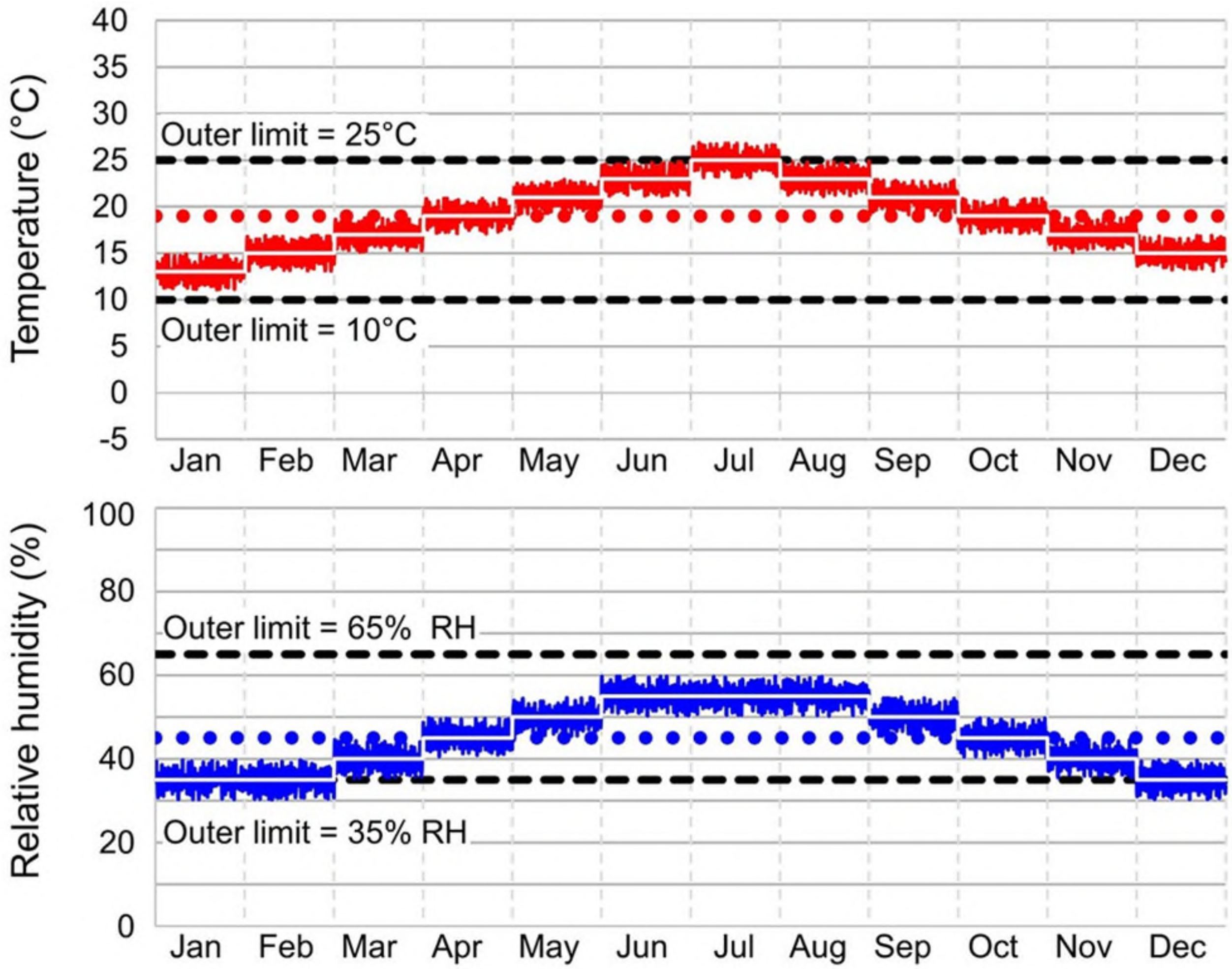

Figure 5. An example of a chart showing temperature and RH over a whole year in a building where staff selected the maximum permissible seasonal adjustments and short-term fluctuations that conform to ASHRAE A1 type of control, using many abrupt but small adjustments in temperature and RH.

Description for Figure 5

Figure 5 contains two graphs, one above the other. The top one shows temperature; the bottom one shows RH. The horizontal axis is time, showing all 12 months of the year. The temperature graph shows a main plot that changes in steps from month to month, with many short-term fluctuations superimposed. There are two flat dashed lines for upper and lower outer limits. The RH graph shows a similar group of plots, and the main plot changes in steps from month to month.

In Figure 5, the annual baseline for RH is set at 45% RH (blue dotted line). The setting (white line) is changed monthly by 5% RH, which is within the permissible short-term fluctuations of ±5% RH. The seasonal adjustments are the maximum permissible (an increase or decrease by 10% RH): summer RH is set at 55%, and winter RH is set at 35%.

Hygrothermograph examples of ASHRAE A2

Example 1

In Figure 6, the pattern of seasonal adjustments in temperature is the same as in Figure 5, except that the annual baseline is two degrees lower, at 18°C (red dotted line). The seasonal adjustments follow a typical pattern used in a collection storage context: a winter setting of 10°C for January and February and a summer setting of 23°C for July and August. Spring and fall months are set at 20°C. Spring and fall months change gradually up to the summer high of 23°C before falling again. The system is fully programmable, so the temperature can be adjusted in small steps, perhaps twice a week (white line). The largest transitions, an increase of 8°C in March and a decrease of 8°C in December, are just within the CCI suggestion that seasonal adjustments should not exceed a rate of 2°C per week. The actual annual average that results from these settings is 17.8°C. Note that the long-term outer limit of 10°C applies to the temperature setting (white line) and not to the lowest troughs of the short-term fluctuations that cross the 10°C limit.

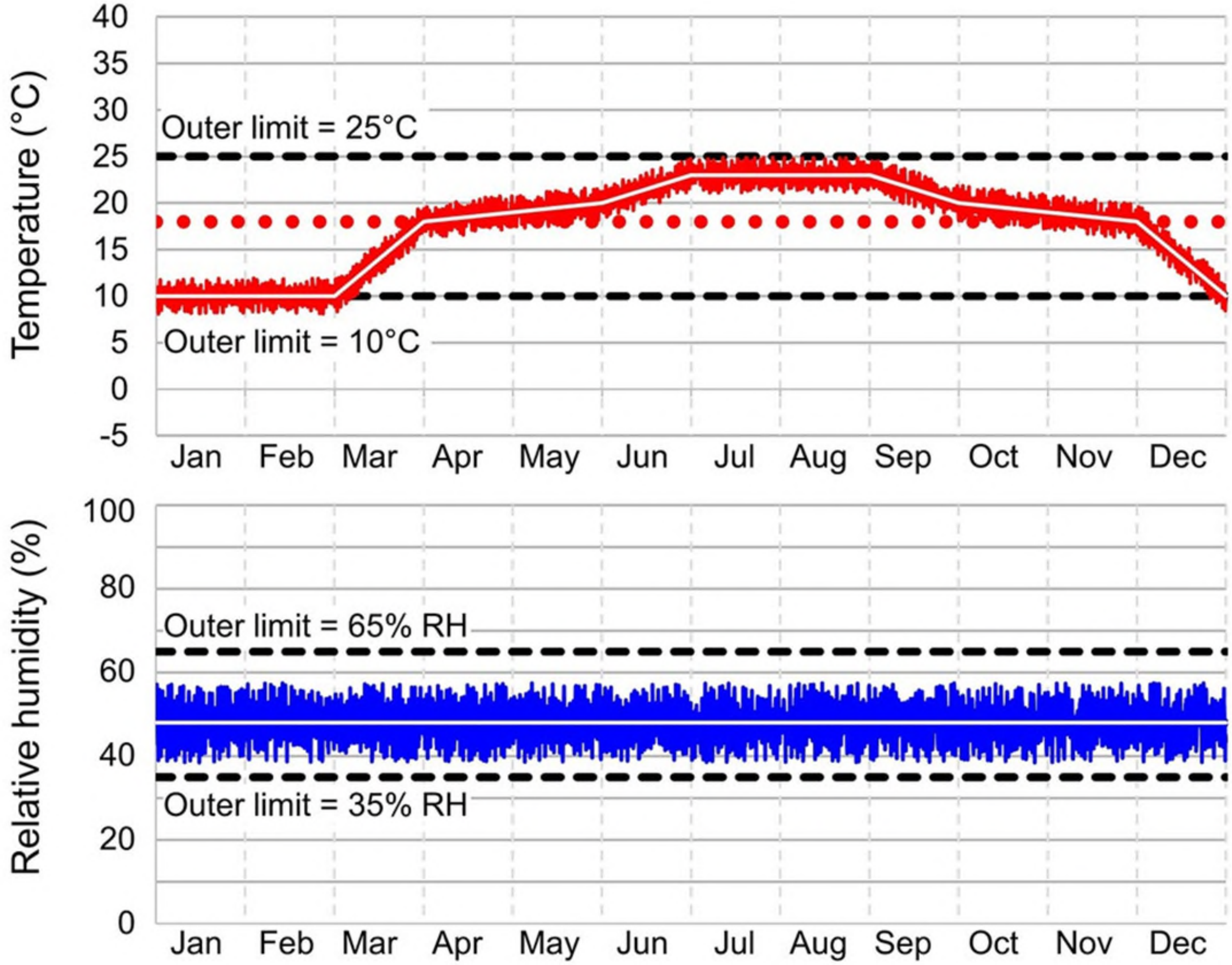

Figure 6. An example of a chart showing temperature and RH over a whole year in a building where staff selected the maximum permissible seasonal adjustments and short-term fluctuations that conform to ASHRAE A2 type of control.

Description for Figure 6

Figure 6 contains two graphs, one above the other. The top one shows temperature; the bottom one shows RH. The horizontal axis is time, showing all 12 months of the year. The temperature graph shows a main plot that changes gradually from month to month, with many short-term fluctuations superimposed. There are two flat dashed lines for upper and lower outer limits. The RH graph shows a similar group of plots, but the main plot is flat with larger rapid fluctuations superimposed than in previous figures.

In Figure 6, the annual baseline of RH is set at 48% RH (flat white line).

Example 2

In Figure 7, the pattern of seasonal adjustments in temperature is a typical one, as used in a display area: an annual baseline of 21°C (red dotted line). The summer high is set at 24°C in July and August, and winter drops to 18°C in January and February. Seasonal adjustments are made in monthly steps that remain within the permissible short-term fluctuation of ±2°C. The short-term fluctuations in temperature are only half of the maximum permissible. The actual annual average that results from these symmetric adjustments is the same as the nominal average, 21°C.

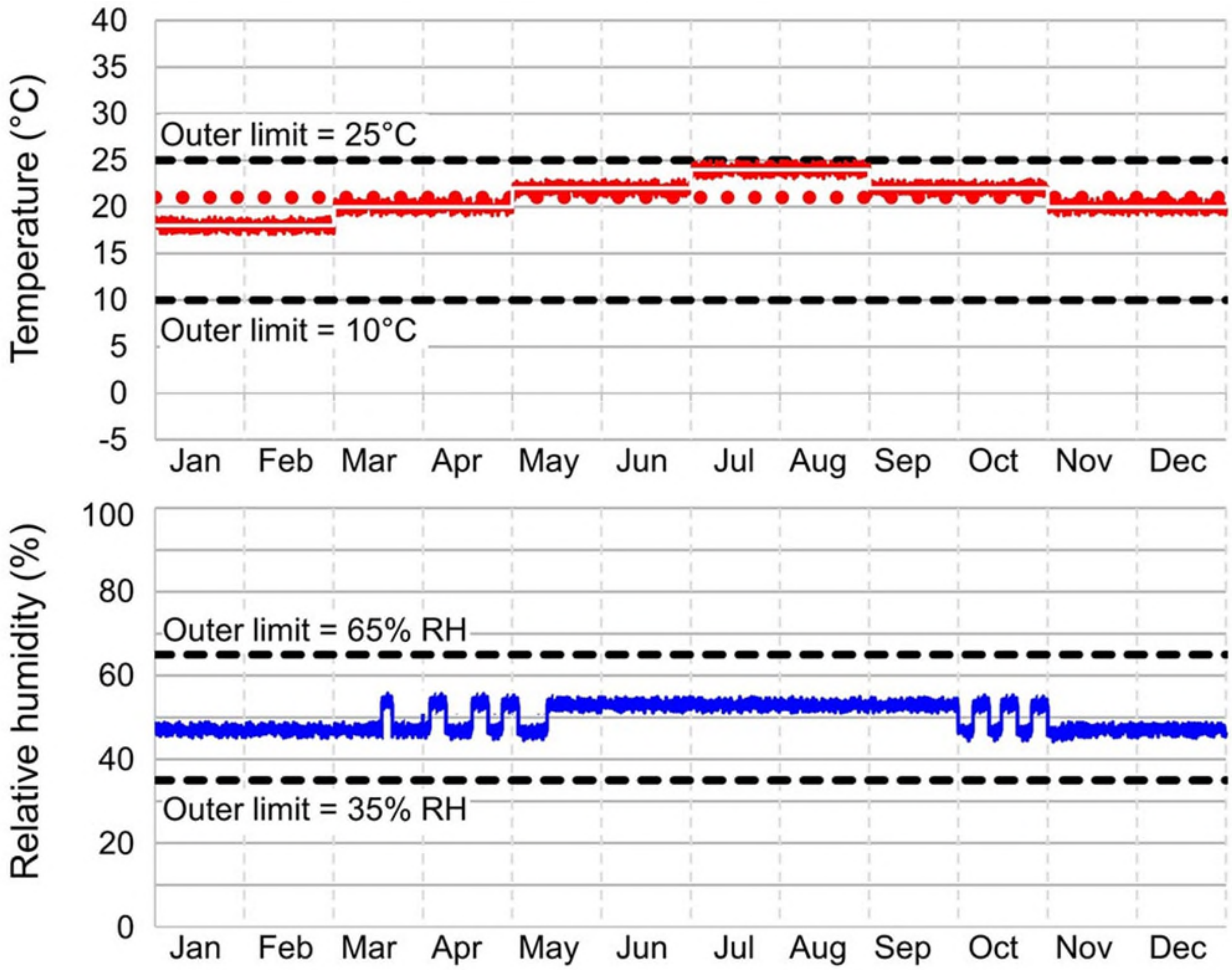

Figure 7. An example of a chart showing temperature and RH over a whole year in a building where the HVAC system operates with a deadband but still remains within the short-term fluctuation specifications of ASHRAE A2 type of control.

Description for Figure 7

Figure 7 contains two graphs, one above the other. The top one shows temperature; the bottom one shows RH. The horizontal axis is time, showing all 12 months of the year. The temperature graph shows a main plot that changes in steps from month to month, with many short-term fluctuations superimposed. There are two flat dashed lines for upper and lower outer limits. The RH graph shows a similar group of plots, but the main plot changes more erratically during spring and fall months.

In Figure 7, the RH is set at an annual baseline of 50% RH (for clarity, the blue dotted line is not shown). The humidification and dehumidification systems are each capable of control within ±2% RH, so the permissible range of short-term fluctuations, ±10% RH, is used to accommodate a deadband of 6% RH between the operation of the humidification system (47% ± 2% RH) and the dehumidification system (53% ± 2% RH). The RH has to change by 8 percentage points (for example, 47% RH to 55% RH) before it triggers the opposing system. The frequent switching between the opposing systems only occurs in the spring and fall seasons. The RH plot of these swing seasons in Figure 7 is simplified for clarity. Sometimes, you can expect the alternation between humidification and dehumidification to occur more often than the weekly events shown, but it would still be much less frequently than when no deadband exists.

ASHRAE B

Definition of ASHRAE B

Type of collection and building: museums, galleries, archives and libraries needing to reduce stress on their building (for example, historic house museums), depending on the climate zone.

Type of control: limited control with seasonal changes in RH and large seasonal changes in temperature.

Table 5: the four parameters of ASHRAE B

Long-term outer limits	Annual averages (baseline)	Seasonal adjustments from annual average (baseline)	Short-term fluctuations plus space gradients
Less than or equal to 30°C	• For permanent collections: historic annual average of temperature	• Increase by 10°C • Decrease by up to 20°C	±5°C
30% to 70% RH	• For permanent collections: historic annual average of RH	• Increase by 10% • Decrease by 10%	±10% RH

Collection benefits and risks of ASHRAE B

Benefits to the collection include the prevention of mould germination and growth as well as the prevention of rapid corrosion. In addition, chemical deterioration slows during cool winter periods (as long as the RH is kept at moderate levels). There is no risk of mechanical damage for many objects and most books. However, there is a tiny risk to most paintings and photographs and to some objects and books. A moderate risk exists for high-sensitivity objects. Objects made with flexible paints and plastics that become brittle when cold, such as paintings on canvas, need special care when being handled in cold temperatures. At 20°C, chemically unstable objects deteriorate significantly within decades. For each increase in temperature of 5°C, deterioration happens twice as fast. For more specific benefits and risks of various temperature and RH conditions for particular objects, consult ClimaSpec.

Comments on ASHRAE B

The short-term fluctuations in the 2019 edition remain unchanged from previous editions, and the seasonal adjustment for summer also remains the same. However, the 2019 edition included the introduction of long-term outer limits (although an upper limit on temperature of 30°C was already stated in the 1999 to 2015 editions) and a greater emphasis on the historic annual averages as an appropriate annual baseline, rather than a default to 50% RH and 15°C to 25°C.

The mechanical risk outlined in Collection benefits and risks of ASHRAE B applies only to objects which have never been exposed to fluctuations since manufacture or since they were repaired. An object that has been exposed to a significant fluctuation will have fractured as much as is possible due to a single cycle of that size of fluctuation. For more information, consult Climate guidelines overview – Appendix B: Sensitivity to fluctuations and the application of proofed fluctuations.

The B type of control differs from A1 primarily in its extended range of permissible lower temperatures. Seasonal adjustments in RH are no greater than A1, but short-term fluctuations are double (±10% compared to ±5%). In warmer parts of Canada, that is zones 4 and 5 (Figure 1), ASHRAE B is a reasonable target for collections in historic buildings that can tolerate the intervention of climate control systems. However, care must be taken to ensure that these systems do not cause damage to the building either because of condensation due to excessive humidity during cold winters or excessive air conditioning in humid summers. In colder parts of Canada, ASHRAE B is feasible in historic buildings if one abandons human comfort temperatures and takes full advantage of winter setback, or if heating is controlled by a humidistat. If parts of the collection are still at risk from the range of RH permitted by ASHRAE B, then you can mitigate these risks by providing microclimate enclosures such as airtight display cases, cabinets and packaging in storage.

Hygrothermograph example of ASHRAE B

In Figure 8, the facility has no air-conditioning system, only a heating system. Given the known temperature history of summers that approaches 30°C during the afternoon, the annual baseline of temperature is set as 21°C (red dotted line). The thermostat (white line with black lines on each side for clarity) is set manually to an energy saving 10°C when the museum is closed to the public, from November 1 to March 1, and then set to 19°C when the museum is open. Sometime in April, the temperature begins to climb, and the museum can only use natural ventilation, window shutters and tree shading to limit the rise in temperature. Given the steep drop in temperature during winter, the actual annual average in Figure 8 is about 19°C.

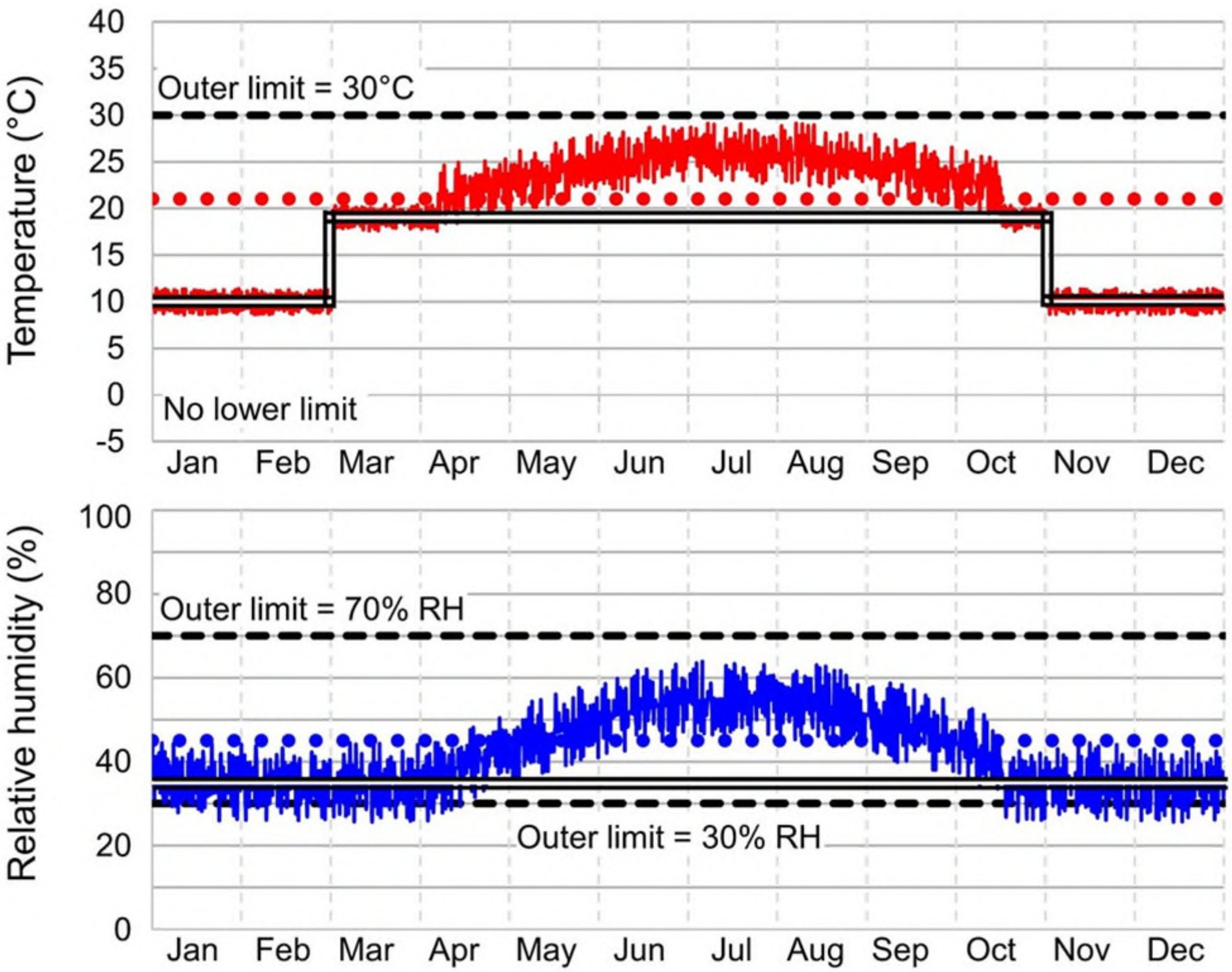

Figure 8. An example of a chart showing temperature and RH over a whole year in a building where staff selected the maximum permissible seasonal adjustments and short-term fluctuations that conform to ASHRAE B type of control.

Description for Figure 8

Figure 8 contains two graphs, one above the other. The top one shows temperature; the bottom one shows RH. The horizontal axis is time, showing all 12 months of the year. The temperature graph shows a main plot that is a constant cool value during the winter months, that jumps abruptly in spring by several degrees and that climbs to a summer peak and then drops until fall, when it suddenly drops to the steady cool winter temperature. There are many short-term fluctuations superimposed throughout. There is one flat dashed line for the upper outer limit but no lower limit. The RH graph shows a similar group of plots and a similar gradual shift upwards in summer. There are larger rapid fluctuations superimposed than in previous figures. There are two flat dashed lines for upper and lower outer limits.

In Figure 8, the facility has a humidification system but no dehumidification system. The RH is set at an annual baseline of 45% (blue dotted line), since this will allow the permitted seasonal adjustment for summer (increase by 10% RH) to cover the known monthly averages of July and August, which are 55%. The setting of the winter humidification system must therefore be of at least 35% RH (white line with black lines on each side for clarity). Since the winter temperature is set to 10°C, the risk of wall condensation due to 35% RH ± 10% is low. The actual annual average in Figure 8 is about 19°C.

ASHRAE C

Definition of ASHRAE C

Type of collection and building: museums, galleries, archives and libraries needing to reduce stress on their building (for example, historic house museums), depending on the climate zone.

Type of control: prevent RH extremes (damp or desiccation) and high temperature extremes.

Table 6: the four parameters of ASHRAE C

Long-term outer limits	Annual averages (baseline)	Seasonal adjustments from annual average (baseline)	Short-term fluctuations plus space gradients
Less than or equal to 40°C	Temperature usually below 25°C	Temperature not specified	Temperature rarely over 30°C
25% to 75% RH	Within 25% to 75% RH year-round	RH not specified	Not continually above 65% RH for longer than *X* days[1]

[1] The ASHRAE chapter points the reader to a mould growth graph (ASHRAE 2023, Figure 3) to determine the number of days required for visible mould at an RH between 65% and 75%. This graph is the same as the red line of the graph provided on the Explanation of the mould and lifelime calculators page. The results of thie graph, the time for visible mycelium, are provided by the Mould Calculator in ClimaSpec.

Collection benefits and risks of ASHRAE C

Benefits to the collection include the prevention of mould germination and growth as well as the prevention of rapid corrosion. In addition, chemical deterioration slows during cool winter periods (as long as the RH is kept at moderate levels). There is a tiny risk of mechanical damage to many objects and most books and a moderate risk to most paintings, most photographs, some objects and some books. There is a high risk to high-vulnerability objects. Even greater care than what is provided in ASHRAE B is needed when handling objects made with flexible paints and plastics that become brittle when cold, such as paintings on canvas. At 20°C, chemically unstable objects deteriorate significantly within decades. For each increase of 5°C in temperature, the rate of deterioration doubles.

The mechanical risk outlined in Collection benefits and risks of ASHRAE C applies only to objects which have never been exposed to fluctuations since manufacture or since they were repaired. An object that has been exposed to a significant fluctuation will have fractured as much as is possible due to that size of fluctuation. Subsequent fluctuations must match or exceed this prior fluctuation, the proofed fluctuation, in order to cause new fractures.

For more information, consult Climate guidelines overview – Appendix B: Sensitivity to fluctuations and the application of proofed fluctuations. For more specific benefits and risks of various temperature and RH conditions for particular objects, consult ClimaSpec.

Comments on ASHRAE C

The core of the ASHRAE C definition in the 1999 to 2015 editions was that RH remains within 25% to 75% year-round. In the 2019 and 2023 editions, this range is still the core definition, but it is also used to specify the outer limits of RH. Temperature guidelines remain almost the same in 2019 and 2023 compared to 1999, that is, rarely over 30°C and usually below 25°C. However, an outer limit of 40°C was added. This was in recognition of the fact that although chemical deterioration greatly accelerated as the temperature climbed from 25°C to 30°C and then to 40°C, the deterioration that was feasible with brief exposure to high temperature (which defines the outer limits) was physical. In this case, it was the softening of many waxes and adhesives above 40°C (consult Table 2 in the *Agent of deterioration: incorrect temperature*).

Short-term fluctuations of temperature and RH were not specified in the 1999 to 2015 editions, but in the 2019 and 2023 editions, the short-term fluctuations for RH were defined as not continually above 65% for longer than *X* days. The reader was directed to a graph to estimate *X*, the time for mould growth in the RH range of 65% to 75%. This was in recognition of the fact that although mould growth accelerates greatly above 75% RH, there was still the smaller risk of slow mould growth in the range of 65% to 75%. The Explanation of the mould and lifetime calculators page contains a graph of the time for mould growth, and the Mould Calculator in ClimaSpec provides estimates of the times for growth at various relative humidities.

As with all previous types of control, the 2019 and 2023 editions also place a greater emphasis on the historic annual averages as an appropriate setting, rather than a default to 50% RH and 15°C to 25°C. Below 25% RH and above 75% RH, the rate of hygroscopic response to each change in RH is as much as double or triple that seen within this range. Hygroscopic materials under stress are more brittle below 25% RH. Many types of furniture and cabinetry were designed to tolerate moderately low RH but not the desiccation occurring below 25% RH. At the other extreme, mould and rapid corrosion increase rapidly above 75% RH.

Thus, ASHRAE C must be recognized as providing the great majority of the benefits of climate control at a fraction of the costs of more narrowly defined controls. ASHRAE C is a reasonable target for collections in historic buildings that use basic HVAC systems because these collections are already proofed to this pattern of RH fluctuations and the building would be damaged by condensation due to excessive humidity during cold winters. If parts of the collection are still at risk from these conditions, such as some new objects that have been acquired from locations with better conditions, then provide climate control for these objects through the use of microclimate enclosures such as airtight cases in display areas or cabinets and packaging in storage.

Hygrothermograph example of ASHRAE C

In Figure 9, the graph represents the behaviour of a building with winter heating where the heating is controlled by a humidistat (Lafontaine and Michalski 1984) to prevent RH from dropping below 25% RH. This keeps the building within the RH guideline for ASHRAE C. In this particular climate, the result is a winter temperature hovering around 4°C, with sizable spikes in temperature as the system attempts to stabilize RH during variable weather patterns. During the summer, the local climate together with the building behaviour and some natural ventilation result in conditions within the upper limits of temperature for ASHRAE C. (There is no annual baseline in this situation, nor any seasonal adjustments; there is simply the actual range and actual annual average, which is about 15°C.) This would be typical of a historic building with some heating due to sun exposure and some thermal inertia that smooths out very large weekly changes in weather.

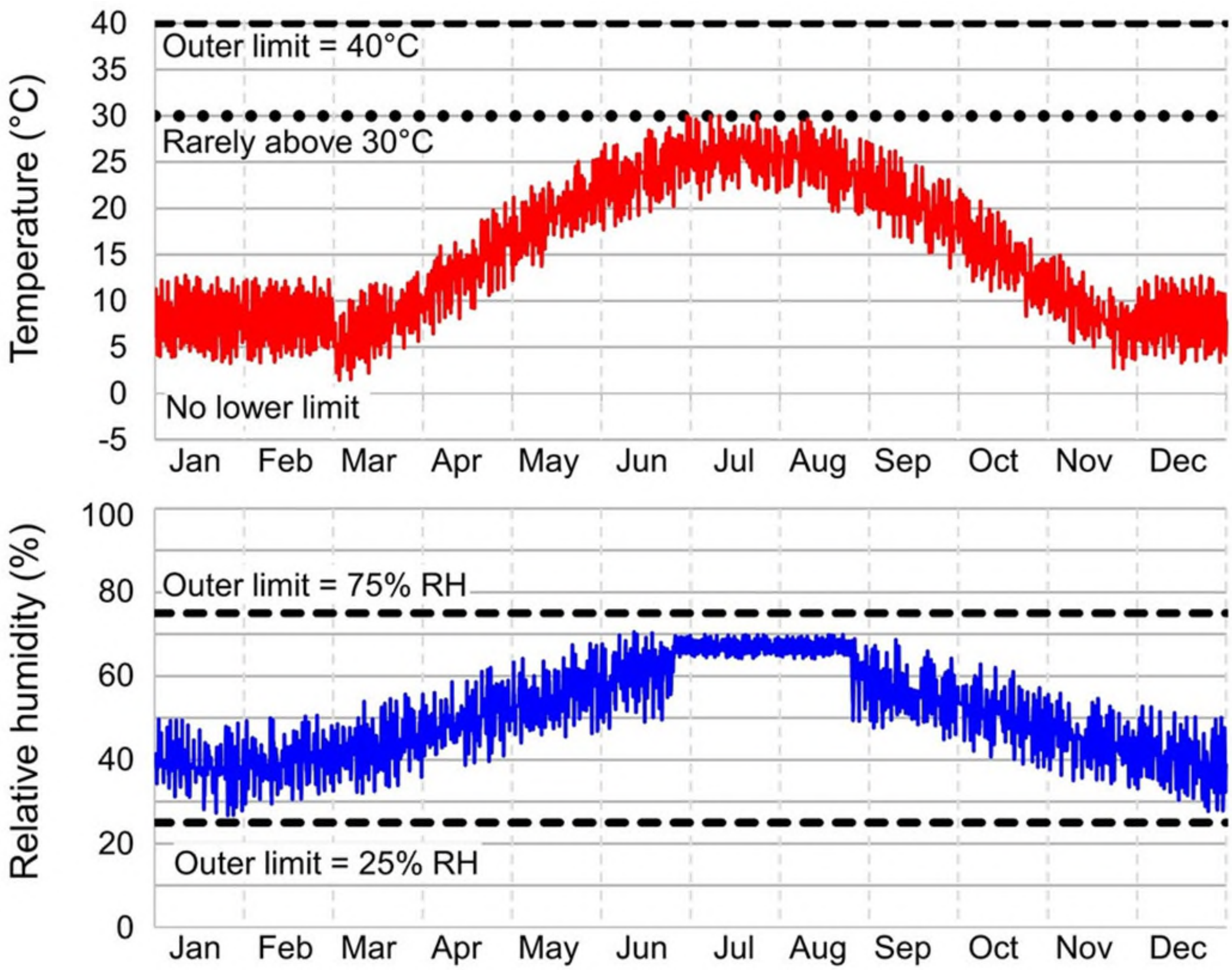

Figure 9. An example of a chart showing temperature and RH over a whole year in a building that conforms to ASHRAE C type of control.

Description for Figure 9

Figure 9 contains two graphs, one above the other. The top one shows temperature; the bottom one shows RH. The horizontal axis is time, showing all 12 months of the year. The temperature graph shows a main plot that changes gradually from a winter low to a summer high with many short-term fluctuations superimposed. There are two flat dashed lines for upper and lower outer limits. The RH graph shows a similar group of plots and a similarly shaped main plot that oscillates around 40% in winter and 70% in summer. The oscillations during July and August are much smaller than those in the remainder of the year.

In Figure 9, the RH plot shows that the RH did not exceed 70% in the summer, which was due to the installation of a dehumidifier. The setting of 70% RH is based on an estimate of the lowest RH that could cause mould growth to start if it was continuous for three months.

There were times when the institution considered heating this space in winter, which would have resulted in RH well below the 25% limit (as will be seen in ASHRAE D type of control). The thoughtful decision not to heat this space was an active intervention that achieved a C type of control rather than a D type of control. (There is no baseline in this situation, nor any seasonal adjustments; there is simply the actual range and actual annual average, which is 51% RH.)

ASHRAE D

Definition of ASHRAE D

Type of collection and building: collections in open structured buildings and historic houses.

Type of control: prevent very high RH (dampness).

Table 7: the four parameters of ASHRAE D

Long-term outer limits	Annual averages (baseline)	Seasonal adjustments from annual average (baseline)	Short-term fluctuations plus space gradients
Temperature not specified	Temperature not specified	Temperature not specified	Temperature not specified
Less than or equal to 75% RH	RH reliably below 75%	RH not specified	Not continually above 65% RH for longer than *X* days[1]

[1] The ASHRAE chapter points the reader to a mould growth graph (ASHRAE 2023, Figure 3) to determine the number of days required for visible mould at an RH between 65% and 75%. This graph is the same as the double red line in Figure 1 on the Explanation of the mould and lifetime calculators page. The results of this graph, the time for visible mycelium, are provided by the Mould Calculator in ClimaSpec.

Collection benefits and risks of ASHRAE D

At 20°C, chemically unstable objects deteriorate significantly within decades. For each increase of 5°C in temperature, the rate of deterioration doubles. Conversely, a cool winter season can extend the lifetime of such objects. Benefits of ASHRAE D include the prevention of mould germination and growth as well as the prevention of rapid corrosion. There is a high risk of sudden or cumulative mechanical damage to most objects and paintings because of low-humidity fractures, but this type of control prevents high-humidity delamination and deformations, especially in veneers, paintings, paper and photographs. For more specific benefits and risks of various temperature and RH conditions for particular objects, consult ClimaSpec.

Comments on ASHRAE D

The core of the ASHRAE D definition is simply that RH remains below 75%. This core definition also becomes the specification of the outer limits (that is, the outer limits do not extend beyond the core definition). Short-term fluctuations were not previously specified for ASHRAE D, and they are not specified in the 2019 and 2023 editions. No temperature guidelines were provided in previous editions, and that also remains the same.

Damp (over 75% RH) causes the following deterioration processes: rapid mould, rapid corrosion, delamination and tenting of paintings on canvas, detachment of veneers held by glues and adhesion of the image layer of photographic materials to anything that comes in contact with them. Reliably avoiding damp is probably the single most beneficial goal of any climate control system. Although such a basic target is not normally considered an engineering design condition, it does become a legitimate goal for any buildings, historic or otherwise, with poor-quality envelopes. It is also a legitimate target for intelligent, if unorthodox, mechanical systems in a simple building located in a humid or marine climate zone. Of course, sources of damp are often the result of water leaks from above or ground water from below, and these should be addressed at the source before using an HVAC solution.

Hygrothermograph example of ASHRAE D

In Figure 10, the building only has winter heating and no summer cooling. The heating is set for 18°C, and the system maintains it within ±2°C. Heating is switched off at the end of May and switched back on mid-October (not earlier, even if occupants complain). Since ASHRAE D has no temperature specifications, these variations are all within the guideline. (There is no annual baseline in this situation, nor any seasonal adjustments; there is simply the actual range and actual annual average, which is about 20°C.)

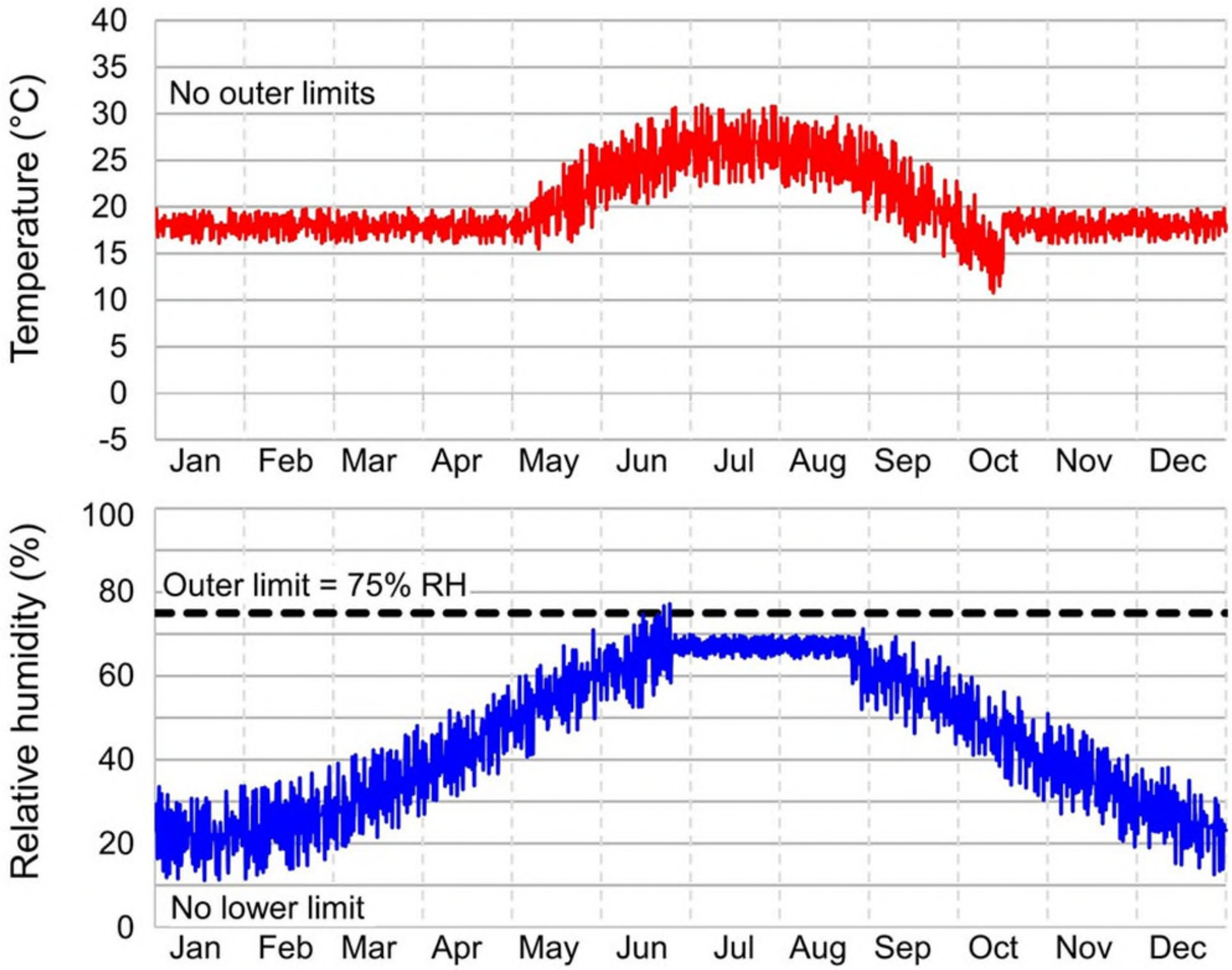

Figure 10. An example of a chart showing temperature and RH over a whole year in a building that conforms to ASHRAE D type of control.

Description for Figure 10

Figure 10 contains two graphs, one above the other. The top one shows temperature; the bottom one shows RH. The horizontal axis is time, showing all 12 months of the year. The temperature graph shows a main plot that changes gradually from a winter low to a summer high, with many short-term fluctuations superimposed. The RH graph shows a similar group of plots and a similarly shaped main plot that oscillates around 20% in winter and around 70% in summer. The oscillations in July and August are much smaller than during the remainder of the year.

In Figure 10, the RH plot shows that the RH did not exceed 70% in the summer. This was due to the installation of a dehumidifier during two to three months in the year (the only active intervention taken in this otherwise uncontrolled facility to meet the ASHRAE D type of control). (There is no annual baseline in this situation, nor any seasonal adjustments; there is simply the actual range and actual annual average, which is 43% RH.) The limit of 70% RH is based on an estimate of the lowest RH required, if exceeded for three months, to cause mould growth to start.

Temporary exhibit space and unpacking space for loaned objects

Definition of a temporary exhibit space and of an unpacking space for loaned objects

Type of collection and building: temporary exhibit space and unpacking space for loaned objects.

Type of control: conditions will be stipulated in loan agreements.

In current practice, the most probable guideline used for loans will be the one adopted by many museums and conservation organizations, commonly called the Bizot guideline. Consult Michalski (2016) for a historical summary of the Bizot guideline and the organizations that have ratified it: the International Council of Museums Committee for Conservation (ICOM-CC), the International Institute for Conservation of Historic and Artistic Works (IIC), the Association of Art Museum Directors (AAMD) and the British Museum. The Bizot guideline is defined primarily in terms of outer limits for the duration of the loan. These are shown in Table 8.

The Bizot guidelines also stipulate that

- a conservator for the lending institution will make judgments about which objects are safe to travel in these conditions, and
- microclimate enclosures (they refer to them as “microenvironments”) will be used to provide more stable RH whenever necessary.

Table 8: the components of the Bizot loan guideline

Long-term outer limits	Annual averages (baseline)	Seasonal adjustments from annual average (baseline)	Short-term fluctuations plus space gradients
16°C to 25°C	Temperature not specified	Temperature not specified	Temperature not specified
40% to 60% RH	RH not specified	RH not specified	Maximum ±10% RH in 24 hours

Collection benefits and risks of the use of a temporary exhibit space and an unpacking space for loaned objects

The lender will assess the benefits and risks to its objects and base its contractual specifications on this assessment. Often, the assessment will be highly risk averse and precautionary.

The organizations that have adopted the Bizot guideline do not state the expected benefits and risks. However, since a loan of a few months following the Bizot guidelines is the same as an ASHRAE A2 type of control with average RH set to 50%, you can assume, conservatively, that you will achieve the benefits and risks described for ASHRAE A2 (with the benefits being slightly better). For more specific benefits and risks of various temperature and RH conditions for particular objects, consult ClimaSpec.

Comments on the use of a temporary exhibit space and an unpacking space for loaned objects

Not all loan agreements will use the Bizot guidelines. Some organizations do add further stipulations to the short-term fluctuations, and these are often the same as those in ASHRAE AA. Some lenders will simply ask for ASHRAE AA with a fixed average of 50% RH and 21°C (very traditional narrow guidelines).

Cool, cold and frozen storage

Definition of cool, cold and frozen storage

Type of collection and building: chemically unstable organic materials in modern purpose-built buildings or purpose-built rooms.

Type of control: cool, cold and frozen.

There are three types of low-temperature control specified in the ASHRAE chapter. These were adapted from the two primary sources of climate control advice for archival materials requiring a low temperature to survive longer than a couple of decades: ISO 18934:2011, *Imaging Materials – Multiple Media Archives – Storage Environment* and the *IPI Media Storage Quick Reference* from the Image Permanence Institute, authored by Adelstein.

Table 9: the four parameters of the ASHRAE cool category

Long-term outer limits	Annual averages (baseline)	Seasonal adjustments from annual average (baseline)	Short-term fluctuations plus space gradients
Temperature not specified	In the range of 8°C to 16°C	Temperature not specified	Temperature not specified
RH not specified	In the range of 30% to 50% RH	RH not specified	RH not specified

Table 10: the four parameters of the ASHRAE cold category

Long-term outer limits	Annual averages (baseline)	Seasonal adjustments from annual average (baseline)	Short-term fluctuations plus space gradients
Temperature not specified	In the range of 0°C to 8°C	Temperature not specified	Temperature not specified
RH not specified	In the range of 30% to 50% RH	RH not specified	RH not specified

Table 11: the four parameters of the ASHRAE frozen category

Long-term outer limits	Annual averages (baseline)	Seasonal adjustments from annual average (baseline)	Short-term fluctuations plus space gradients
Temperature not specified	In the range of -20°C to 0°C	Temperature not specified	Temperature not specified
RH not specified	In the range of 30% to 50% RH	RH not specified	RH not specified

Collection benefits and risks of cool, cold and frozen storage

The benefits of low-temperature storage include the extended lifetime of objects that would be lost within a generation or two if kept at room temperature. (Consult Explanation of the mould and lifetime calculators – Explanation of the Lifetime Calculator for details on quantifying the benefits.) In addition, biological damage is much reduced. The risks include the many side effects of such systems, such as high humidity or condensation in cases of malfunctions and water exposure. Objects must be packaged appropriately to reduce the risk of condensation during retrieval, and the institution may require a transition space with an intermediate climate. Hourly and daily (or even longer) humidity fluctuations will not affect most properly packaged objects at low temperatures. For more specific estimates of chemical lifetimes of all types of materials at a selected temperature and RH, consult the Lifetime Calculator in ClimaSpec.

Comments on cool, cold and frozen storage

Within the ASHRAE chapter, detailed guidelines about short-term fluctuations are not provided for cool, cold and frozen. Readers expecting to design low-temperature storage should consult the various ISO standards for specific forms of media. Low-temperature storage is also a possibility for modern art collections that contain not only media objects typical of archives (videotape and colour photographs), but also artworks and decorative arts made with unstable plastics from the 20th century.

Although the short-term fluctuations are not specified in ASHRAE cool, cold and frozen, almost all practical applications can assume that the objects (such as film, photographs, videotapes, furs and items made of rubber or plastics) will be packaged in moistureproof and airtight containers or bags. Packaging will block all RH fluctuations that occur externally for less than a few days or sometimes months. Inside, the object will remain at the average RH. Consult ClimaSpec for estimates of the passive RH control of a packaged object (its humidity half-time) or Table 4 in Climate guidelines overview – Appendix C: The response times of objects and the multiple benefits of enclosures.

Moderate temperature fluctuations, such as ±5°C, that are not exceeded during the normal operation of even basic low-temperature systems, whether special vaults or domestic freezers, are not a risk to properly packaged objects. Very large temperature fluctuations that occur during retrieval are not so easily ignored.

The discussion in the ASHRAE chapter covers the issue well. It begins by noting that retrieval from cold storage raises the question of what procedures to use for acclimatization, including whether to build a transition space. A transition space mitigates two risks: condensation during retrieval, which is the major risk; and direct mechanical effects of the temperature change, which is a minor one. However, a transition space adds complexity to the construction of cold storage and its operation. It also represents a large fraction of lost storage space in smaller institutions.

The greatest risk of condensation happens during the re-entry process to warm conditions or in case of a cooling system failure. Therefore, it is essential that objects in cold storage remain inside moistureproof packaging or bags and that these packages remain closed 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.” (ASHRAE 2023)

When moving objects 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 materials with low chemical stability (Shashoua 2014).

Special climates for unstable metal or glass

Definition of special climates for unstable metal or glass

Type of collection and building: unstable metal or glass in modern purpose-built buildings or purpose-built rooms.

Type of control: RH-controlled to avoid a critical RH of a salt or hydrate.

No detailed guidelines are provided in the ASHRAE chapter; institutions would need to specify the critical RH based on their collections and the literature. Some guidelines are provided in ClimaSpec.

Collection benefits and risks of the use of special climates for unstable metal or glass

There are no specified benefits and risks in the ASHRAE chapter for this type of control. The assumed benefits are the prevention of any deterioration mechanisms driven by hydration or dehydration of compounds in objects, such as contaminated metals. The risks are the effects of this special RH on other materials in a complex object (for example, the possible fracture of the wooden or bone handle of a metal tool kept at a very low RH to reduce corrosion). For some benefits and risks of specific temperatures and RH conditions for particular objects, consult ClimaSpec.

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Explanation of the mould and lifetime calculators

On this page:

List of abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CCI	Canadian Conservation Institute
ICOM-CC	International Council of Museums, Committee for Conservation
IPI	Image Permanence Institute
ISO	International Organization for Standardization
RH	relative humidity

Explanation of the Mould Calculator

Stefan Michalski and Tom Strang

Sources of data and derivation of the equations

Figure 1 collects several authors' data on the time required for mould growth. The solid blue line is a curve fitted by Michalski (1993) to data by Snow et al. (1944) on the time required for visible mycelia to appear on dried grass, linseed cake and bone meal (black points). Of the foodstuffs Snow et al. studied, these were the most representative of a broad class of museum objects, cellulosic and proteinaceous. These data and the fitted curve (solid blue) appear in previous Canadian Conservation Institute (CCI) publications, such as Figure 4 in *Agent of deterioration: incorrect relative humidity* and Technical Bulletin 23 *Guidelines for Humidity and Temperature for Canadian Archives*. Figure 1 is also a figure in the 1999 to 2023 editions of the chapter "Museums, Galleries, Archives, and Libraries" in the *ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Applications*. The relative humidity (RH) equation for this curve (shown in the legend at the top right) is used to calculate the "probable time for noticeable mould" in the Mould Calculator of ClimaSpec found in the left-hand menu.

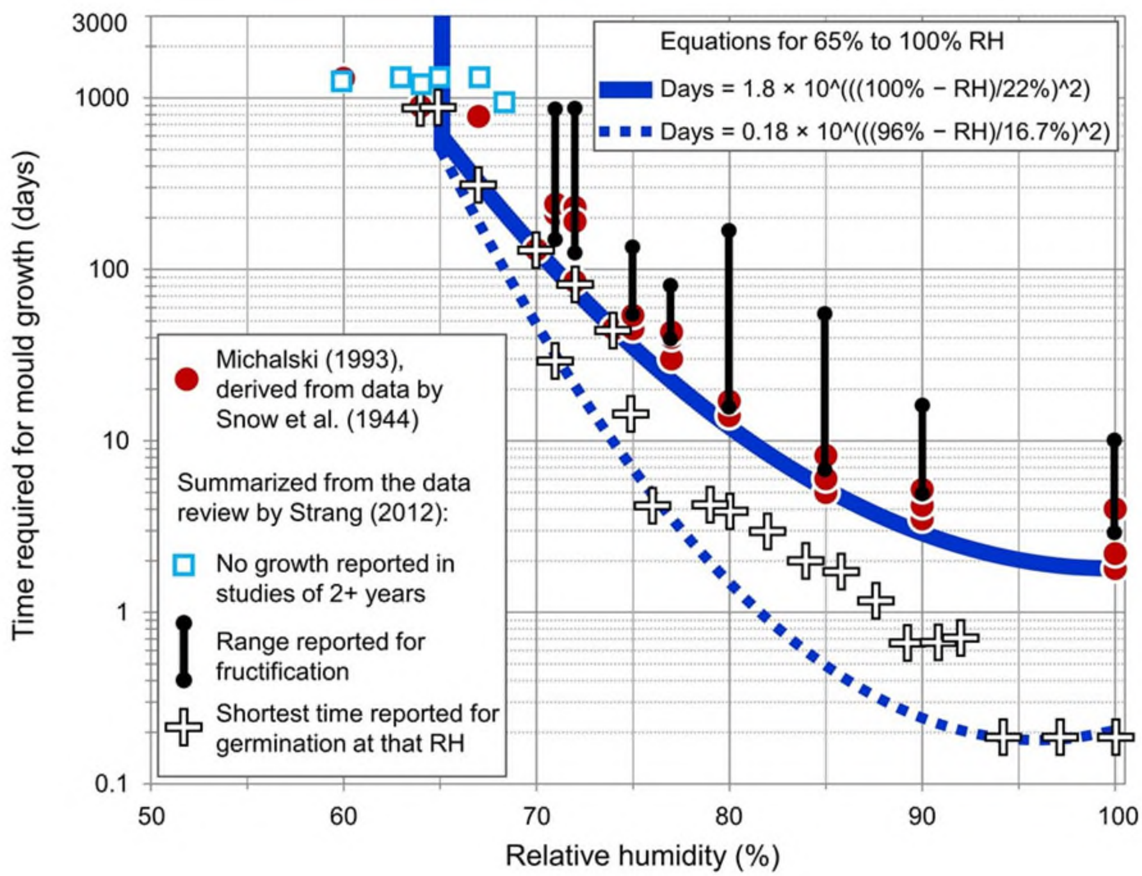

Figure 1. The dependency on RH of the time (in days) required for mould growth.

Description for Figure 1

Figure 1 contains a single graph with two plots. The vertical axis is a logarithmic scale from 0.1 to 3000 in the number of days required for mould growth. The horizontal axis is a linear scale from 50% to 100% RH. The plots are both smooth curves, starting from 65% RH at the upper left and descending to plateaus at 100% at the lower right. Clusters of data points justify each plot, described in the main text. Table 1 provides selected key points on the two curves.

More recently, Strang (2012) compiled more data from research that used media designed to maximize mould growth, especially gelatin. Gelatin is the mould-sensitive layer in photographic materials, the sized canvas of paintings and their linings and glue-sized papers. Figure 1 summarizes the key parts of his compilation. The black vertical lines span the range of times reported at each RH for fructification. These are consistent with the double red line for visible mycelia, inasmuch as fructification would occur after growth of mycelia, that is, would take slightly longer (be higher than the double red line). The germination data (a large cloud in Strang's original graphs) is represented here by just the outer edge of that cloud, indicating the shortest times reported for germination at each RH (the white crosses). The dashed blue line is fitted so as to just skirt outside these white crosses. The calculator uses the equation for this dashed blue line (shown in the legend in the top right corner) to provide the shortest probable time for germination of spores.

Table 1: the dependency on RH of the time (in days) required for mould growth

Outer limits	64% RH	65% RH	70% RH	75% RH	80% RH	85% RH	90% RH	100% RH
Outer limit for fructification	None in 1000+ days	500	130	35	12	5	3	2
Outer limit for germination	None in 1000+ days	600	50	12	1.5	0.5	0.2	0.2

Note: Numbers in Table 1 have been rounded to one or two significant digits.

Static versus dynamic relative humidity

Sedlbauer (2001) developed a dynamic model for mould growth during fluctuating conditions that has been incorporated into the building performance software known as WUFI (Wärme Und Feuchte

Instationär / transient heat and moisture transport). Such dynamic models are beyond the scope of the Mould Calculator in ClimaSpec. Instead, we consider static conditions, using data from numerous studies that maintained constant RH, as plotted in Figure 1, and temperature.

Conservatively, you can apply the calculator to two fluctuating conditions. If RH is fluctuating but always above 65% RH, then enter the RH of the most humid periods into the calculator. (This provides a precautionary value: the shortest possible time for growth.) If and when RH drops below 65% and does so long enough for the materials to reach equilibrium with this lower RH, then any mould that was growing can be considered dead. (The cycle of growth must begin again from spores when RH goes above 65%.)

Multiple tactics for practical prevention of mould

Preventive conservation against mould is multifaceted. It is unusual (though not impossible) for high RH (damp) to occur uniformly and in a stable manner throughout a room. Mould is usually a localized event, triggered by external sources of water, condensation, poor ventilation, inappropriate packaging, temperature gradients, etc. (consult figures 5 and 6 in *Agent of deterioration: incorrect relative humidity*). Cleanliness of the objects also plays a role, not just in terms of spores but also in terms of nutrients that sustain mould growth. Methods for controlling these factors and many more are described in detail in Technical Bulletin 26 *Mould Prevention and Collection Recovery: Guidelines for Heritage Collections*.

Health issues

Mould is a great risk to occupants of the space, not just to the collections. When confronting mould events, please refer as soon as possible to Technical Bulletin 26 *Mould Prevention and Collection Recovery: Guidelines for Heritage Collections*. For a more detailed text on health issues with mould, as well as the numerous situations that support mould in buildings, consult Adan and Samson (2011).

Explanation of the Lifetime Calculator

Stefan Michalski

This section provides technical background to the Lifetime Calculator that is part of ClimaSpec. This calculator provides estimates of the lifetime of organic objects that decay rapidly by chemical processes at moderate temperatures and RH as well as the improvements possible by various patterns of colder or drier conditions. (Some of the content of the following sections appeared first in the 2019 edition of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers [ASHRAE] chapter, prepared by the author as a member of the committee responsible for that chapter. It has been revised here.)

Estimates of object lifetimes at room temperature, as listed in Table 2 and provided in ClimaSpec, can vary. The lifetimes may be up to three times shorter or longer than those stated for each object. Likewise, when choosing a lower temperature and lower RH, using the best available models and data, the subsequent lifetime improvement may vary from the prediction. This is due primarily to uncertainty in the activation energy, as illustrated by the shaded areas in Figure 2. Despite these uncertainties, calculators of the lifetime benefits of cold and dry storage are considered useful by the authors cited as well as the research institutions that they represent.

To begin, two simple rules of thumb
Before engaging with charts, calculators and equations, a simple rule of thumb quantifies what is at stake: a drop in temperature of 5°C (for example, from 21°C to 16°C) doubles the object's lifetime. This is true for materials that decay rapidly by chemical processes at normal storage conditions (for example, poor-quality paper, many photographic films and magnetic tapes and discs). Another drop of 5°C doubles the object's lifetime again. Thus, a drop from 21°C to 11°C quadruples lifetime. And so on. Conversely, each rise of 5°C cuts lifetime in half.

A second rule of thumb is that a reduction in RH by one half (for example, 50% to 25%) doubles (or more) the object's lifetime (Michalski 2002).

These rules of thumb can set the stage for the consideration of temperature-controlled storage. However, calculating complex seasonal scenarios for energy savings is necessary when fine-tuning the balance between preservation costs and sustainability or when considering the impact of intermittent exposure to warm conditions or thermal pest control events. The Lifetime Calculator in ClimaSpec serves this need.

The idea of object lifetime
There are three outputs from the Lifetime Calculator:

- a benchmark lifetime for the selected object at moderate temperature (about 20°C) and moderate RH (about 50%);
- the lifetime multiplier at a selected temperature and RH scenario; and
- the product of the first and second, that is, the predicted lifetime at the selected scenario.

"Lifetime" has a clear and unambiguous meaning (more or less) when applied to humans. For deteriorating objects, however, "lifetime" becomes ambiguous. To specify it, we must make three difficult judgments:

- What is the cultural value or utility of the object, such as art objects with aesthetic value or documents kept as records of information?

- Are there measurable characteristics that affect value, such as yellowing, loss of strength or loss of readability?
- What is the criterion for unacceptable loss of a particular characteristic, for example, unacceptable yellowing for use on display or insufficient document strength for direct access by researchers?

These definitions are unambiguous for only a few types of heritage objects. For example, when digital media or magnetic media become unreadable, it is clear that their archival utility as information carriers has "died." The Lifetime Calculator in ClimaSpec always provides a description of the characteristic that is being assigned to the lifetime estimate and, if possible, of the impact on the object's utility. However, you should always interpret the loss of utility and value within your own context. An unreadable videotape may be dead to an archive and partially dead for a video installation in an art gallery but still useful in a room that displays the technology of a 1980s home.

In order to justify and design cold storage, you might avoid all the uncertainty of these cultural judgments and simply consider the relative improvement in collection lifetime provided by colder and drier conditions, such as "10 times longer" (which the Lifetime Calculator provides). However, given the costs of colder and drier storage, you still need to establish that, without such storage, the lifetimes of the objects in question are somehow too short when considering the institution's preservation mandate. In another instance, you might need to establish whether the lifetime of some materials will be significantly shortened by undergoing a high-temperature pest control treatment.

In archives, it has become common practice to use cold storage for entire collections (photographic films is one example). This is not the practice in museums and art galleries, which can lead to the decay of many 20th-century objects within a curator's lifetime. These objects include rubber, celluloid, acetates, polyurethane foams, colour photographs, etc. (consult Table 2, right-hand column).

Historical evidence for benchmark lifetimes

Benchmark information in Table 2 was first compiled in Technical Bulletin 23 *Guidelines for Humidity and Temperature for Canadian Archives*. Extensive notes and references for most of the materials in the table are contained in that publication. When the table was next prepared for the CCI resource *Agent of deterioration: incorrect temperature*, non-archival materials were added. However, optical disc entries were deleted because more specific lifetime estimates had become available in CCI Note 19/1 *Longevity of Recordable CDs, DVDs and Blu-rays*. Lifetimes range from 5 years to over 100 years, depending on the manufacturing process.

The final version of the table is used elsewhere on the CCI website and was also included in the 2019 and 2023 editions of the ASHRAE chapter "Museums, Galleries, Archives, and Libraries."

In ClimaSpec, these and other sources are used to provide benchmark lifetimes.

Table 2: benchmark lifetimes of materials at moderate temperatures (about 20°C) and moderate RH (about 50%)

Benchmark lifetimes	Materials
1000 years	• Wood, glue, linen, cotton, leather, rag paper, parchment, oil paint, egg tempera, watercolour media and gesso: there are serviceable examples of all these that are from 1 to 3 millennia old, from dry burial or dry enclosures at about 20°C. The materials in these examples were protected from any acid exposure, such as air pollution in the Industrial Revolution, and have never been damp. • Skin, bone and ivory of the woolly mammoth have survived intact for over 40 millennia while frozen.
300 years	• This is the current best estimate for stable photographic materials to remain usable as images with little or no change (for example, 19th-century black and white negatives on glass and 20th-century black and white negatives on polyester film).
100 years	• Acidic paper and some film become brittle and brown, making it difficult to access (for example, newsprint and low-quality books or papers made post-1850). • Acetate film shrinks, and the image layer cracks. • Celluloid and many early plastics become yellow, crack and distort. • Natural materials acidified by pollution (textiles, leather) weaken and may disintegrate.
30 years	• unplayable (for example, floppy discs and tapes of video, audio or data). • The least stable photographic materials decay (for example, colour prints fade in the dark, poorly processed items yellow and disintegrate, and cellulose nitrate yellows and disintegrates faster when packaged in large amounts). • Many elastic polymers, from rubber to polyurethane foams, become brittle or sticky or they disintegrate. • Some acrylic paints on some canvas supports yellow rapidly.

Logarithmic categories for material lifetimes

Timelines for our own lives or for historical events usually consist of uniform, linear steps of years or decades. This does not work well for the categories of chemical lifetimes of materials, which are best spaced as multiples. For example, each category can be several times more durable than its neighbour. The question becomes: how precisely can we segregate such categories? CCI has found that the categories used in Table 2 (30 years, 100 years, 300 years and 1000 years) are sufficient to capture practical generalizations. In technical terms, these categories follow a logarithmic scale (base 10), with two steps for each log unit. The midway point between 1 and 10 is $10^{½}$ = 3.16, which is rounded to 3 for simplicity.

For a few well-studied materials, such as paper and photographic film, assuming you know the acidity and have a precise definition of end of life, you might be able to make more precise predictions than implied by these logarithmic categories. In general, to say that a material such as acidic paper is in the 100-year group of Table 2 means that its lifetime is probably around 100 years; however, it might be anywhere from a factor of three smaller to a factor of three larger. Thus, each category has an uncertainty extending to its adjacent categories.

Plotting the effect of temperature on lifetime

The key chemical parameter for predicting the effect of temperature change on the lifetime multiplier is the activation energy (E_a). A compilation of activation energies for organic materials in heritage collections (Reilly et al. 1995; Nishimura 1996; Michalski 2002), such as paper, film, photographic dyes, magnetic media and resin varnishes, shows that the activation energy of more than three quarters of the materials studied falls within the range of 80 to 120 kJ/mol. A recent study of the thermal decay of the strength of wood yields E_a = 85 kJ/mol, so also within this range (Froidevaux and Navi 2013). Most recently, values ranging from 93 kJ/mol to 130 kJ/mol were measured in different modern printing papers. In Figure 2, this total range of 80 kJ/mol to 130 kJ/mol is shown by the grey shaded area.

This range of activation energy can also be derived theoretically with no consideration of specific materials other than stipulating that the chemical process takes at least several decades to approach completion at room temperatures (Michalski 2002). Thus, both the empirical data and the theory suggest that this range of activation energy can be used as a universal value for heritage materials, such as those listed in Table 3. The middle value of this range, 100 kJ/mol, a convenient round number, was selected for the graphs of lifetime multipliers in Technical Bulletin 23 *Guidelines for Humidity and Temperature for Canadian Archives*.

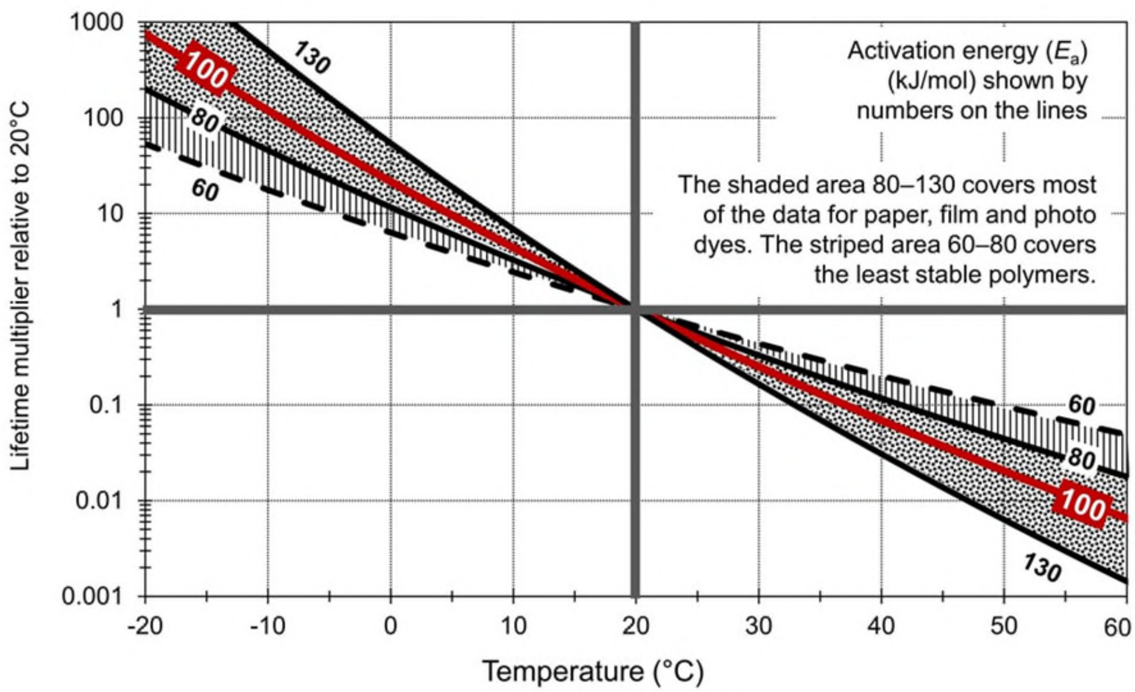

Figure 2. Dependence of lifetime on temperature for various activation energies (E_a).

Description for Figure 2

Figure 2 contains a single graph with four plots. The vertical axis is a logarithmic scale of the lifetime multiplier relative to 20°C. The horizontal axis is the temperature in degrees Celsius. The four plots are all regular curves that stretch from the upper left corner to the lower right and cross over each other at 20°C and a lifetime of 1.

Table 3: dependence of lifetime multiplier on temperature for various activation energies (E_a)

Activation energy (E_a) kJ/mol	−20°C	−10°C	0°C	5°C	10°C	15°C	20°C	25°C	30°C	60°C
130	5500	500	54	20	7	2.6	1	0.4	0.2	0.002
100	750	120	20	10	4	2.1	1	0.5	0.3	0.007
80	200	45	12	6	3	1.8	1	0.6	0.3	0.02
60	60	20	6	4	2	1.6	1	0.7	0.4	0.05

Note: Numbers in Table 3 have been rounded to one or two significant digits.

For materials that decay significantly within a few decades or less, such as polyester polyurethane that can turn to powder (the weak link in magnetic media and a material popular with artists in the late 20th century) or natural resin varnishes that yellow unacceptably, activation energies fall into a lower range of 60 to 80 kJ/mol (Michalski 2000), indicated by the striped zone in Figure 2.

Plotting the effect of relative humidity on lifetime

Although all authors agree on the role of temperature and activation energy in calculating the lifetime multiplier, a variety of models exist for calculating the effect of RH. All agree that lower RH decreases the rate of decay, but by exactly how much remains uncertain, simply because there is not enough experimental data to confirm one model over another.

The five most widely known models, in chronological order, are as follows (the technical basis of each model is discussed in a later section, Equations for lifetimes):

1. Sebera (1994) popularized his earlier pioneering work in a report for the Commission on Preservation and Access. He coined the term “isoperms” for lines of equal lifetime in charts, such as in Figure 4.
2. The Image Permanence Institute’s preservation index, originally provided as a preservation wheel, is now available in a web app, eClimateNotebook. The tool is based on the table of multipliers published by Reilly et al. (1995).
3. Equations and charts were published in Technical Bulletin 23 *Guidelines for Humidity and Temperature for Canadian Archives*.
4. Equations and charts were published in journal articles by researchers from University College London and the National Archives, London (Strlič et al. 2015).

5. Equations and charts were published for specific types of printing paper by researchers from CCI and the Centre de recherche sur la conservation (Paris) (Tétreault et al. 2023). These are also available as a calculator (Paper Permanence Calculator) on the Preventive conservation tools page.

The predictions of the five models for the effect of RH on lifetime relative to lifetime at 50% RH are plotted in Figure 3. In the region from 30% RH to 60% RH, the models overlap with no practical differences in their predictions. Dropping from 50% RH to 25% RH increases lifetime by two or slightly more for all models, as suggested earlier in the rule of thumb. Conditions above 60% RH should be avoided anyway to reduce the risk of gelatin layers in photographs sticking to adjacent surfaces and the risk of mould, which begins at 65% RH (consult the Mould Calculator in ClimaSpec). Generally, conditions below 25% RH should be avoided to reduce the risk of deformation or fracture.

In summary, the five models give similar predictions in the region that is considered practical for most collections. That said, the possible mass desiccation of collections, such as newspaper stacks, that can tolerate RH below 25% (which would be much less energy intensive than equivalent cold storage) depends very much on which model is best at predicting lifetime multipliers below 25% RH.

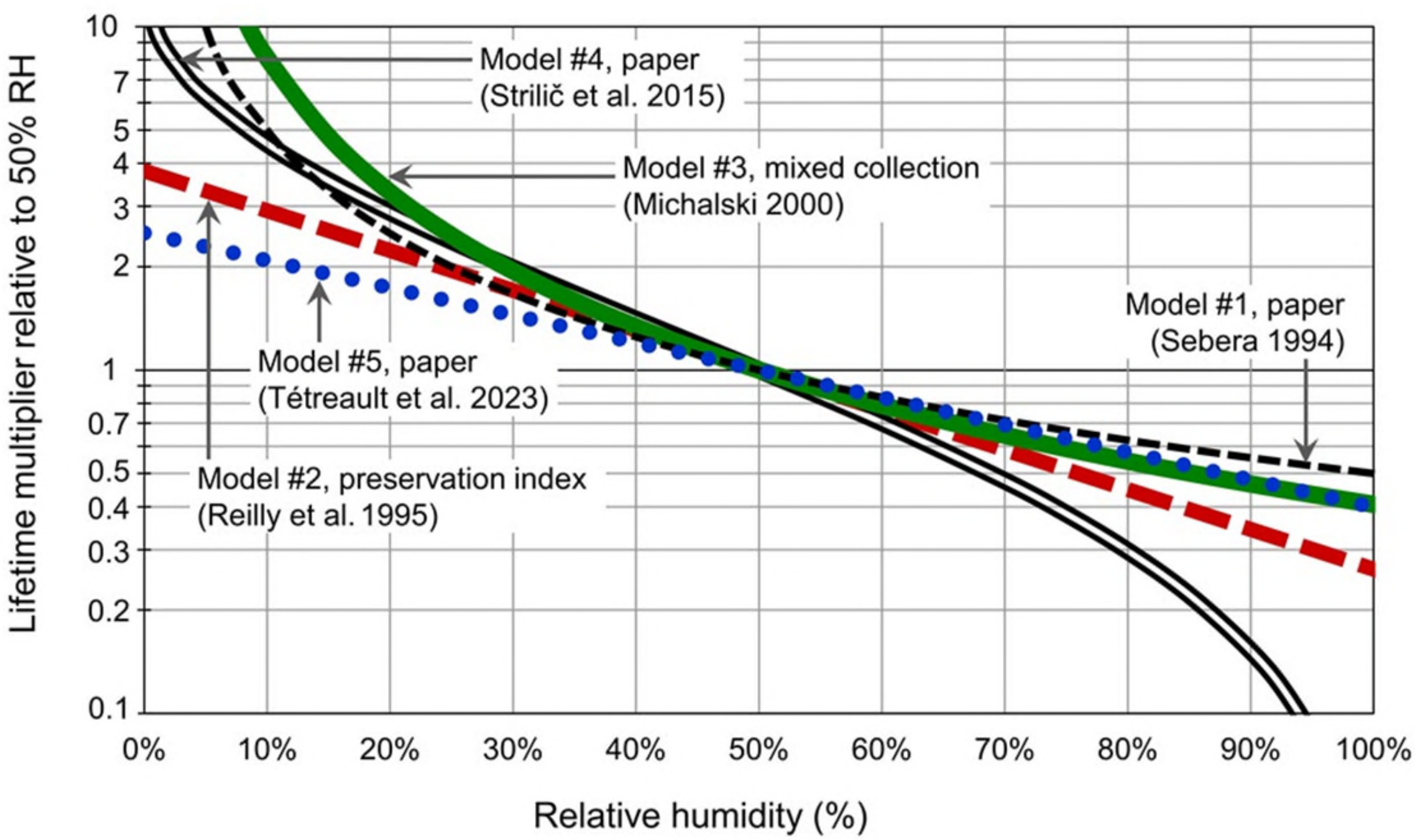

Figure 3. The effect of RH on the lifetime multiplier, relative to 50% RH and at a temperature of around 20°C, according to five models.

Description for Figure 3

Figure 3 contains a single graph with five plots. The vertical axis is a logarithmic scale of the lifetime relative to 50% RH. The horizontal axis is RH. The five plots are all regular curves that stretch from the upper left corner to the lower right and cross over each other at 50% RH and a lifetime multiplier of 1. The plots are model #1, #2, #3, #4 and #5.

Table 4: dependence of lifetime multiplier on RH at around 20°C

Model	10% RH	20% RH	30% RH	40% RH	50% RH	60% RH	70% RH	80% RH
#1 Sebera	5.0	2.5	1.7	1.3	1	0.83	0.71	0.62
#2 Reilly et al.	2.9	2.2	1.7	1.3	1	0.77	0.59	0.45
#3 Michalski	8.1	3.3	1.9	1.3	1	0.79	0.65	0.54
#4 Strlič et al.	4.6	2.9	2.0	1.4	1	0.70	0.48	0.30
#5 Tétreault et al.	2.1	1.7	1.4	1.2	1	0.82	0.68	0.57

Plotting the effect of temperature and relative humidity on lifetime

Sebera (1994), the first author to propose a graphical representation of the relationship between lifetime, temperature and RH, used a rectangular graph as shown in Figure 4 and called the lines of constant lifetime “isoperms.” Strlič et al. (2015) proposed the term “isochrones.” Figure 4 plots current models #2, #3, #4 and #5. Although the authors of model #5 propose different E_a for different types of printing papers, their model is plotted for E_a = 101 kJ/mol. According to the authors, this is consistent with the E_a for acidic newsprint.

These four models give almost identical results in the practical range of RH (60% down to 30%) and in the majority of the practical range of temperatures. The IPI model does predict that one needs temperatures that are up to 3 degrees less then the other two models suggest for the same lifetime, but this is not a significant difference when deciding to adopt cool or cold storage.

Rather than one CCI model, all four current models (#2, #3, #4 and #5) are presented in Figures 4 and 5 and associated tables and in the section Equations for lifetimes. This is done for two reasons: to provide the reader with an impartial comparison of current models; and to demonstrate that, while the differences are interesting to the researchers, the practical advice is identical: use cool or cold storage for rapidly decaying objects whenever possible.

Figure 5, a psychrometric chart, is an alternative graphical representation of lifetime multipliers (isoperms, isochrones). This chart shows the conventional way that engineers map temperature and RH when designing systems. The horizontal axis is temperature, and the vertical axis is the weight of water vapour in the air (absolute humidity). RH becomes a set of curved lines (from 10% up to the maximum of 100% RH). If, for example, you want to find combinations of temperature and RH to give materials lifetimes that are 10 times longer than shown in Table 2, look for the plots labelled “×10” in Figures 4 or 5 (or in Table 5, the column labelled “×10”), and you will find that for 50% RH, the three models range between 3°C and 5°C, so about 4°C. If you choose 30% RH, then the ×10 multiplier is at 7°C to 9°C, so about 8°C.

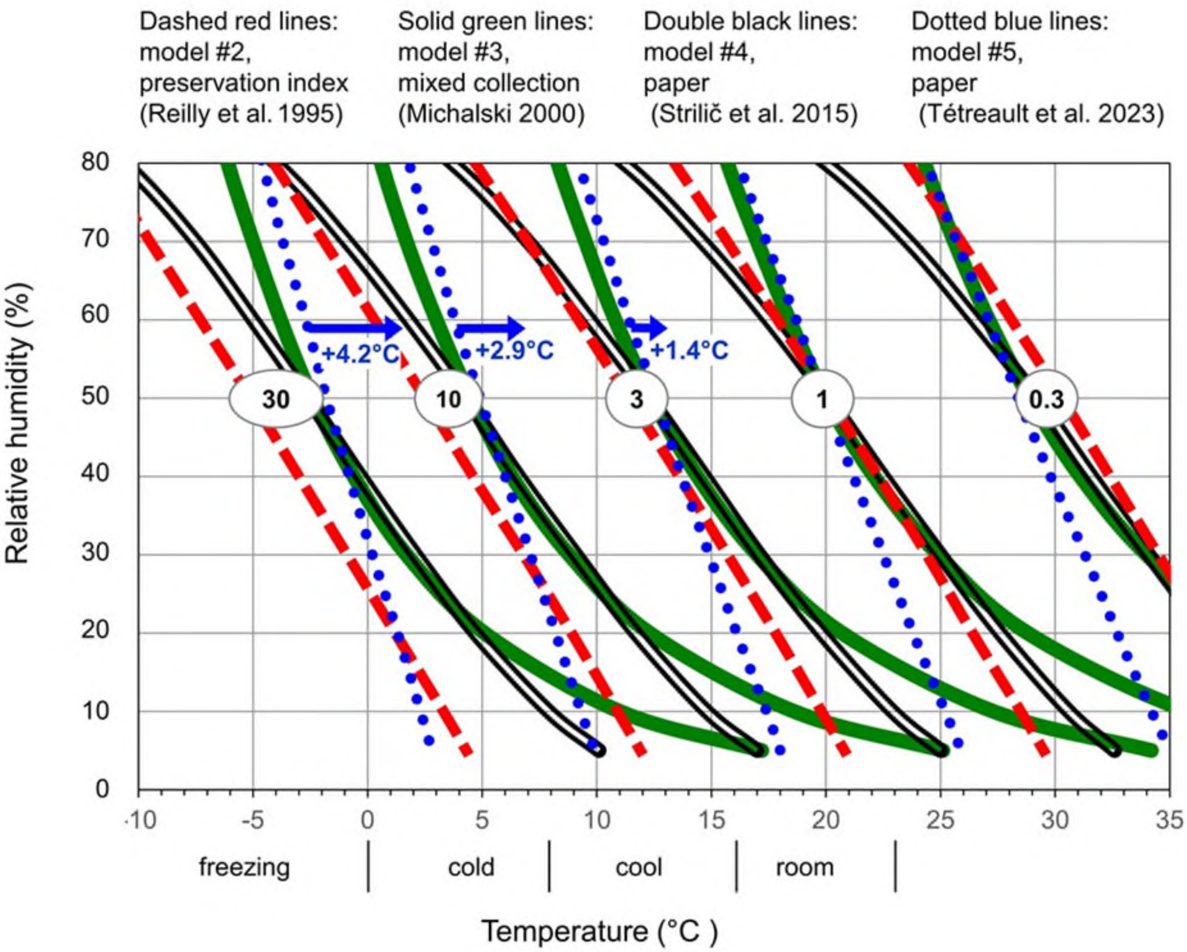

Figure 4. Lifetime multipliers (isoperms, isochrones) for models #2, #3, #4 and #5, plotted on rectangular coordinates of temperature and RH. (Model #5 is based on the newsprint that the authors analyzed and whose E_a = 101 kJ/mol. The blue arrows show the shift in relation to the other types of papers that were analyzed and whose E_a = 127 kJ/mol.) The temperature ranges labelled “freezing,” “cold,” “cool” and “room” are as defined in the ISO standard for the storage of multiple media types (ISO 2011).

Description for Figure 4

Figure 4 contains a single graph with five groups of four plots each. The vertical axis is RH. The horizontal axis is temperature in degrees Celsius. All five groups are approximately parallel. The curves are regular and steeply sloped downwards. Each of the five groups is labelled with a relative lifetime multiplier, from a low of ×0.3 up to a high of ×30. The four plots labelled "×1" all pass through the point 20°C and 50% RH.

Table 5: temperatures (°C) at various relative humidities for which the lifetime multiplier is a given value

Lifetime multiplier	×0.3 for models #2, #3, #4 and #5	×1 for models #2, #3, #4 and #5	×3 for models #2, #3, #4 and #5	×10 for models #2, #3, #4 and #5	×30 for models #2, #3, #4 and #5
10% RH	39, 46, 40, 34	29, 36, 31, 25	20, 27, 23, 17	11, 19, 15, 9	3, 11, 8, 2
20% RH	37, 38, 32, 33	26, 29, 28, 24	18, 21, 20,16	9, 12, 12, 8	1, 5, 5, 1
30% RH	35, 34, 34, 31	24, 25, 25, 23	16, 17, 17, 15	7, 9, 9, 7	-1, 2, 2, 0
40% RH	32, 31, 32, 30	22, 22, 23, 21	14, 14, 15, 14	5, 6, 7, 6	-3, -1, 0, -1
50% RH	30, 29, 29, 28	20, 20, 20, 20	11, 12, 12, 13	3, 5, 4, 5	-5, -2, -3, -2
60% RH	28, 27, 27, 27	18, 18, 18, 19	9, 11, 10, 11	0, 3, 2, 4	-7, -4, -5, -3
70% RH	26, 26, 24, 26	16, 17, 15, 17	7, 10, 7, 10	-2, 2, -1, 3	-9, -5, -7, -4

Notes:

1. Some values shown in Table 5 go beyond the scale in Figures 4 and 5.

2. Model #5 is calculated based on the newsprint that the authors analyzed and whose E_a = 101 kJ/mol.

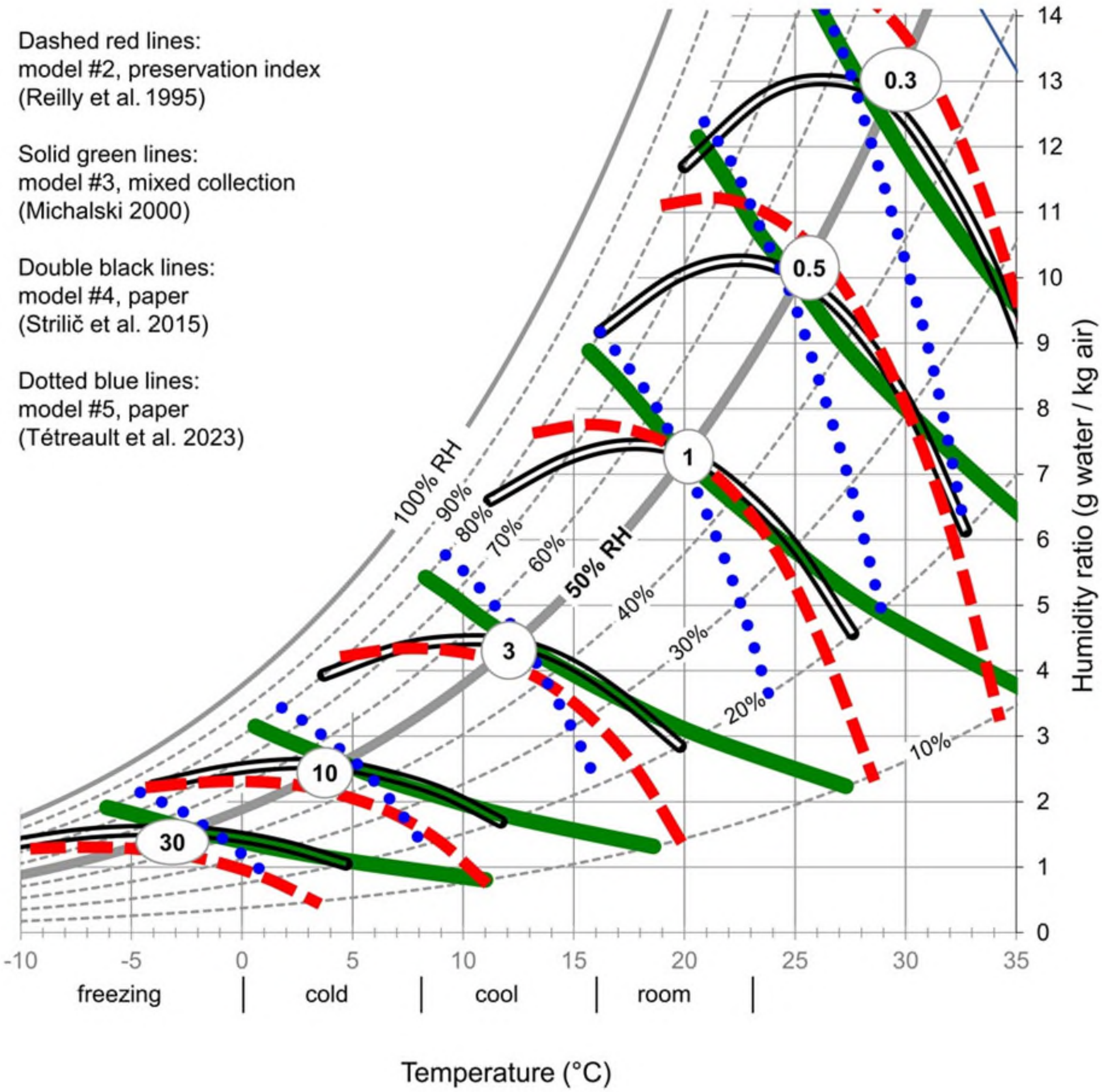

Figure 5. Lifetime multipliers of models #2, #3, #4 and #5 plotted on the psychrometric chart. The temperature ranges labelled “freezing,” “cold,” “cool” and “room” are as defined in the ISO standards for media storage. (In the 2019 and 2023 editions of the ASHRAE chapter, a printing error caused lines for model #3 in the figure to disappear.)

Description for Figure 5

Figure 5 contains a single graph with six groups of four plots. The horizontal axis is temperature in degrees Celsius. The vertical axis is the humidity ratio, in grams of water per kilogram of air. Lines of RH, from 10% to 100%, curve smoothly upwards on these axes and form a background set of coordinates for the main plots. The six groups of four plots are regularly curved. Each group is labelled with a relative lifetime multiplier, from a low of ×0.3 up to a high of ×30. The four plots labelled “×1” all pass through the point 20°C and 50% RH.

ClimaSpec allows complex scenarios

The Lifetime Calculator in ClimaSpec has several advantages over charts and tables:

- It allows you to enter complex scenarios with seasonal setbacks month by month for energy savings.
- It allows the calculation of the effect of occasional removal from storage to warmer or more humid conditions.
- Where available, it uses specific values of activation energy for the material.

The Lifetime Calculator defaults to model #3, consistent with other CCI publications.

Equations for lifetimes

All lifetime calculators proposed in the conservation science literature recognize that for organic materials that decay rapidly due to chemical instability (such as materials listed in the right-hand column of Table 2), the mechanism is acid hydrolysis. It increases with the acidity of the material, RH and temperature. The lifetime can be expressed as the product of three functions (*f*): one function dependent on the acidity of the material, one dependent on temperature and one dependent on RH or, for some authors, the related parameter, moisture content.

Equation 1: $t_L = C * f(\mathrm{pH}) * f(T) * f(\mathrm{RH, MC})$

Where

C = a constant for each material, units of time

pH = acidity of the material

t_L = lifetime, units of time

T = temperature, K

RH = relative humidity, dimensionless

MC = moisture content (of the material), dimensionless

The equation for the dependence of lifetime on temperature (the second term in Equation 1), named after its discoverer, Svante Arrhenius, has been used for practical chemical engineering for over a century. In terms of lifetime (rather than the reciprocal, rate of reaction), the Arrhenius equation becomes:

Equation 2: $f(T) = \exp(E_a/(R^*T))$

Where

R = Gas (Boltzmann) constant, 8.314 J/(mol·K)

E_a = activation energy, J/mol

For ease of comparison, the five authors' proposals for the dependence of lifetime on RH and temperature have been rearranged into the same general form of Equation 1. The purpose of presenting these five proposals is not to imply any preference, nor to offer any critique of their respective validity. Each has been published in peer-reviewed publications over the last 30 years. Rather, the purpose is to show that, despite the differences in their derivation and their sample materials, their predictions of the benefit of cool and cold storage converge in ranges practical for collections managers.

In each of the following equations, the constant (C) has been set so that the equation gives the lifetime multiplier (t_{LM}) in comparison to the lifetime at 20°C and 50% RH. For clarity, the activation energy term has been placed in curly brackets { }.

Model #1

Although not plotted in Figures 4 or 5, Sebera's (1994) model for isoperms is noted here for its historical significance in the field of archive preservation. Sebera used a modified form of the Arrhenius equation; it includes a second dependence on temperature placed outside the exponential. Subsequent authors omitted this since it has a relatively minor effect. For activation energy, Sebera reviewed available data on paper and proposed a range between two values: 125 and 146 kJ/mol (25 and 35 in his original units of kCal/mol). His estimates of E_a are above the currently accepted values (from later studies), so his isoperms exaggerate the benefit of cold storage. In the absence of any data to the contrary, he assumed that lifetime was simply proportional to RH. Sebera's equation becomes:

Equation 3: $t_{LM} = C * 1/T * \exp[\{125 \text{ or } 146\}/(R^*T)] * (1/\text{RH})$

Where

t_{LM} = lifetime multiplier, relative to a value of 1 at 20°C and 50% RH

Model #2

The authors (Reilly et al. 1995) derived parameters from extensive data on acetate film. The equations were not published verbatim, but the authors' published table of lifetime multipliers can be fitted to the following equation. The RH term has a small temperature correction. The equation of Reilly et al. becomes:

Equation 4: $t_{LM} = 4.69E{-}17 * \exp[\{94.9\}/(R{*}T)] * \exp[RH * (0.02087 {*}T - 8.79)]$

Model #3

The author (Michalski 2000) derived activation energy from a large review of data on paper, film and dyes. The dependence on RH was derived from a re-analysis (Michalski 1993) of extensive paper-aging data at several relative humidities produced by Graminski et al. (1978). Michalski's equation becomes:

Equation 5: $t_{LM} = 6.17E{-}19 * \exp[\{100\}/(R{*}T)] * (1/RH)^{1.3}$

Model #4

The authors (Strlič et al. 2015) derived equations from their extensive data on new as well as old papers. The RH term has a small temperature correction. The equation of Strlič et al. becomes:

Equation 6: $t_{LM} = 9.468E{-}21 * \exp[\{119\}/(R{*}T)]$

$* \exp[-36.72 * \{\ln(1 - RH)/(1.67{*}T - 741.82)\}^{(1/(5.7622 - 0.012{*}T))}]$

Although the full Equation 6 is used for Figures 4 and 5, it is informative to see what model #4 looks like if fitted to an equation of the same form as the one for models #1, #2 and #3. Throughout the practical range of relative humidities (20% to 60%) and the practical range of temperatures (20°C down to −10°C), the following equation gives results within 10% of that of Equation 6 when using an activation energy (E_a) of 100 kJ/mol:

Equation 7: $t_{LM} = 1.00E{-}17 * \exp[\{100\}/(R{*}T)] * \exp[-3.7{*}RH]$

Model #5

The authors (Tétreault et al. 2023) derived an equation from a study of modern printing papers. Although acidity (pH) played a key role in the lifetime of the types of paper they analyzed, they found that an equation for lifetime multipliers could be independent of acidity. Their primary conclusion was that different groups of modern printing papers had sufficiently different E_a (97 kJ/mol to 130 kJ/mol) such that it was useful to consider those differences, as can be done with the Paper Permanence Calculator that is based on their model and that can be found on the Preventive conservation tools page. Their equation for isoperms, that is, relative lifetime, is as follows (Tétreault et al. 2023; equation 14):

Equation 8: $t_{LM} = 2.46 * \exp[(0.572-0.00822*T)RH] * \exp[(\{E_a\}]/R)*(1/T – 1/293.15)$

For the figures and tables in this document, and for the sake of generalized comparison among models, their model is calculated for E_a = 101 kJ/mol, their value for acidic newsprint.

In summary, when using an equation of the same form as Equation 1, models #2, #3, #4 and #5 all suggest very similar activation energy (E_a), around 95 kJ/mol to 101 kJ/mol. Model #5 does suggest higher values for some types of printing paper.

For the effect of RH, however, there are significant differences between models below 20% RH and above 60% RH. There is not enough data at these extremes of RH to establish which is correct. Among the different models, the RH term differs in two ways. First, authors Reilly et al. (1995), Strlič et al. (2015) and Tétreault et al. (2023) assume that the fundamental variable is moisture content, which does depend in turn on RH, but only when adjusted for different temperatures. Then, authors Sebera (1994) and Michalski (2000) assume that RH is the fundamental parameter. A more important difference, however, is the choice of function: some authors use an exponential function (Reilly et al. 1995; Strlič et al. 2015, Tétreault et al. 2023); others (Michalski 1993, 2000, 2002; Sebera 1994; Erhardt and Mecklenburg 1995; Zou et al. 1996) use a power law, (which includes Sebera's use of index 1, linear dependence). Models using an exponential function have the odd aspect of implying that hydrolysis continues at 0% RH (that is, without moisture), whereas a power law implies that hydrolysis stops when moisture is absent. Hence, the rapid divergence of the models at RH below 20% (as well as above 60%) in Figures 4 and 5. As noted earlier, this divergence is not of practical impact since no one is currently recommending storage at such low relative humidities (or at high humidities), but it does become relevant when explaining how much the low RH of unhumidified buildings in winter has benefited acidic collections in the past and can again in the future.

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Climate guidelines glossary

absolute humidity
A measure of humidity in terms of the weight of water vapour per unit volume of air. At 20°C, the absolute humidity of 100% RH is 17.3 g/m^3.

Note: This measure of humidity is useful for engineers designing mechanical systems, but it is not useful for predicting the moisture content of objects in a collection.

See also: relative humidity

climate
The temperature and relative humidity (RH) of the air. When applied in a museum or archive context, it can refer to the long-term and short-term behaviours of temperature and RH.

Note: The broader term usually refers to long-term trends in the weather outdoors.

See also: environment

climate control
The maintenance of a particular temperature and RH inside a building, room or enclosure by the use of machinery (active climate control) or humidity buffers and insulation (passive climate control).

deliquescence
The formation of a solution by certain salts that absorb moisture from the air above a critical RH value.

Note: For example, table salt (NaCl) deliquesces at 75% RH and above.

enclosure
A physical barrier that surrounds an object (or objects). It can be a bag, a box, a display case, a storage cabinet, a shipping crate, etc.

Note: For the purposes of this resource, an enclosure blocks some or all of the agents of deterioration (for example, physical forces, water, pollutants and incorrect RH).

environment
All the conditions that surround and influence an object.

Note: For the purposes of this resource, this includes the agents of deterioration (for example, physical forces, water, pollutants, light, ultraviolet, incorrect temperature and incorrect RH).

See also: climate

lifetime
The time (usually in years) for an object to deteriorate to a state at which it no longer has value or utility to the institution.

Note: For example, the time required for digital media to become unreadable or the time it takes an archive document to become too brittle to be handled easily. For further details, consult Explanation of the mould and lifetime calculators – The idea of object lifetime.

microclimate
The local climate in a small region of space. A microclimate can be created on purpose by the use of an enclosure, which usually controls RH but may occasionally control temperature.

Note: A microclimate can also arise naturally, without sharp boundaries. For example, the air within a few centimetres of a cold floor has a much higher RH than the majority of the room and is often the cause of local mould growth.

microclimate enclosure
An enclosure designed to maintain a particular microclimate. It is usually designed to stabilize the RH, but it may also be designed to reduce temperature fluctuations, as in the case of shipping crates.

microenvironment
The local environment in a small region of space surrounding an object. A microenvironment can be created on purpose by the use of an enclosure in order to control several agents of deterioration.

Note: A microenvironment can also arise naturally, without sharp boundaries. For example, the air within a few millimetres of any material that is emitting volatile organic compounds will pollute an adjacent object.

microenvironment enclosure
An enclosure designed to maintain a particular microenvironment. It may be designed to limit one or more of the agents of deterioration.

proofed fluctuation
The largest fluctuation in RH that an object or collection has experienced in the past. It is a key

parameter in sustainable climate control decisions because future fluctuations that are less than the proofed fluctuation have a very low probability of causing significant new fractures.

Note: In the most common Canadian situation, where the annual average of RH is moderate and the biggest risk to collections from fluctuations occurs during the low RH of winter, it refers to the lowest RH of winters past.

Note: For further discussion of the refinements in its application to the risk management of collections and decisions about climate control, consult Climate guidelines overview – Appendix B: Sensitivity to fluctuations and the application of proofed fluctuations.

relative humidity (RH)

RH is the ratio of the partial water vapour pressure to the saturation water vapour pressure at the same temperature. It can also be expressed as the ratio of the concentration of water vapour to the saturation concentration of water vapour at the same temperature.

Note: Unlike absolute humidity, RH is the measure of humidity that correlates well with the moisture content of objects, as well as with the rate of mould growth and with our own perception of damp and dryness.

Note: RH is expressed as a percentage.

See also: absolute humidity

risk management

The process within an organization that has as its goal the minimization of the largest risks to its collections.

Note: Risk management does not attempt to address all risks.

Note: For more detail, consult *The ABC Method: a risk management approach to the preservation of cultural heritage*.

sensitivity

The response of a material or object to a dose of an external agent, measured as a ratio between the response and the dose.

Note: For example, the number and size of fractures caused in an object by a certain size and number of RH fluctuations or the amount of fading of a colour after exposure to a certain amount of light.

See also: vulnerability

vulnerability
Adopted in various fields of risk (and disaster) management to refer to the susceptibility of an institution or a community to a hazard. It is a complex assessment that considers not only the direct effects on objects and people but also the eventual loss of value caused by those effects, given the mitigating factors of the resilience of the institution and community. *HTML*

See also: sensitivity

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