Related Commercial Resources

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

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

Notes:

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

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

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

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

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

Agent	Comments
Physical forces	Handling, shock, and vibration can cause immediate or accumulative long-term damage to fragile objects.
	Risks often increase during construction work, when collections may have to be relocated or secured in situ.
	Mechanical systems may present a risk if vibration is transmitted through ductwork to works hung on adjacent walls or in particularly active air drafts.
	Vibration transmitted to objects may cause them to move, and to fall off of exhibit and/or storage shelves.
Thieves and vandals	Can be addressed by limiting access to mechanical systems to improve security.

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

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

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

Objects and Effects of Fluctuations	Low Sensitivity	Medium Sensitivity	High Sensitivity	Very High Sensitivity[b]
Flat sheets of paper, film, tape, leather, parchment, metal, with	**Support layer with finely dispersed image/data layers.**	**Layered structures with moderate strength, moderate differences in expansion.** Includes most photographs, negatives, and	**Layered structures with poor strength, moderate to high differences in expansion.** Includes thick images on parchment.	**Large reactive (to fluctuations) sheets restrained at periphery**. Includes large paper sheets

image or data layer. May delaminate, fracture, or distort permanently.	Includes most single sheets of paper with print, halftones, line drawings, inks, washes. **Laminates with low differences in expansion.** Includes most case-bound books (not leather or parchment book covers). Most CDs. Commercial signs painted on metal.	film. Most magnetic records. Thin, well adhered inks on parchment, such as deeds. Gouache on paper. Book bindings of vellum and/or wood. Gilded parchment, leather.	Globes. Thick oil-resin images on paper or cloth. Objects listed as medium vulnerability that have weakened substantially because of UV exposure, or aging already causing flaking.	adhered to stretchers, 19th-century photos on fabric and stretchers. Large prints adhered at all four corners (usually tear near the point of restraint).
Wood or wood assemblies. May crack, split, delaminate, or distort permanently.	**Single wood components, or assemblies designed to eliminate stresses.** Includes floating panels in furniture or room paneling; tongue-and-groove planking nailed or bolted on edge only (e.g., wainscoting), wood boxes on farm machinery (unless jammed because of painting, warping), hollowed-out totem poles, wooden tool handles. **Assemblies with prior damage that allows stress release.** Includes most old tables where all screws and joints are loose, any panels already split.	**Wood assemblies with uniformly distributed stresses during fluctuations.** Includes most plain wood furniture with tight joints, no prior splits, most veneers and marquetry that cover a continuous piece below, such as most 18th- and 19th-century chests of drawers. Furniture made with plywoods, such as Victorian catalog pieces. Fluctuation to higher relative humidity may not always cause visible damage, because many joints/panels are invisibly crushed, but this makes them more likely to split during lower relative humidity. **Large wooden objects.** Outer layers are constrained uniformly by the inner core because of gradient in response to relative humidity change.	**Wood assemblies with concentration of stresses during fluctuations.** Includes veneer over corner joints, such as many wardrobe doors, Art Deco furniture. Fretwork applied wooden ornaments. Assemblies with bolts, nails, screws that hold both sides of a single plank. Many musical instruments.	**Wood assemblies with attached or inlaid metal, horn, shell, etc., that spans more than 0.4 in. across the wood grain.** Attachment or inlays may delaminate or buckle. Includes masks with adhered shell, 18th- and 19th-century fine furniture, clocks with inlays.
Pigmented coatings on a support: paintings, gilding, lacquer. May crack, delaminate, flake.	**Acrylic paintings on canvas.** Includes many paintings since 1960 (may move to medium sensitivity if a heavy glue size was used, or if adhesion between layers is poor).	**Rigid paint layers on canvas, in moderate to good condition.** Includes most oil paintings on canvas (may move to high sensitivity if weakened by water damage or great age). Definitely move to high sensitivity if stretched too tight, or tightened during high relative humidity. Note: fluctuation from low relative humidity is a much higher risk to paintings on fabric than from high relative humidity; however, over 85% rh may cause canvas shrinkage and flaking of the ground plus paint layers Includes oil paint, gilding on narrow spans of wood, gilt furniture, picture frames.	**Oil paint, gilding, on wide spans of wood, or paint on other organic rigid supports with weak adhesion.** Includes most panel paintings, wide gilded panels. If seams are flawed, with rigid fills, etc., then may become very high sensitivity. Miniatures on ivory, because of poor adhesion and undulations of some ivories. Heavy modern paintings on smooth side of fiber-board may delaminate because of weak adhesion.	**Paint layers bridging seams or flaws that concentrate stress**. Includes polychromes, painted furniture, painted architectural wood elements. Note that hairline cracks over joints of doors or painting frames are usually considered normal, but not those in heavily lacquered furniture.
Other organic objects.	**Woven organic materials without edge restraints.** Includes most basketry. Textiles such as blankets, flags, simple costumes.	**High crimp woven organic materials with edge restraints.** May tear during fluctuation to high relative humidity. Includes needlepoint fixed to a stretcher.	N/A	N/A
Organic materials with zero			Includes teeth, boats made from stretched leather on rigid construction. Crack when relative humidity	

stress level at 100% rh.	drops below critical level (e.g., teeth below 50% rh).
Other objects where ratcheting mechanism may exist.	Objects where small parts continuously dislocate and block expansion of object. Elephant tusk positioned downwards: small parts fall down gravitationally during low relative humidity period and block material expansion during rises of relative humidity.

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

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

Table 4 ISO Storage Standards for Collections that Use Cold Storage

ISO Number	Collections Covered	Range of Relative Humidity	Range of *T*
18911:2010	Photographic films (except nitrate)	20 to 50%	50 to 45°F1
18920:2011	Photographic prints	30 to 50%	36 to 45°F
18923:2000	Magnetic tape	15 to 50%	36 to 45°F
18934:2011	Multiple media	30 to 50%	Room: 61 to 73°F
			Cool: 46 to 61°F
			Cold: 32 to 46°F
			Frozen –4 to 32°F

Table 5 Classes of Chemical Stability

High Stability	Medium Stability	Low Stability	Very Low Stability
Wood, glue, linen, cotton, leather, rag paper, parchment, oil paint, egg tempera, watercolor media, gesso. Serviceable examples up to 3 millennia old exist, from dry burial or dry enclosures at ~68°F. These examples were protected from any acid exposure (e.g., air pollution from Industrial Revolution), and have never been damp. Skin, bone, and ivory of the woolly mammoth have survived intact for over 40,000 years while frozen.	Current best estimate for stable photographic materials (e.g., 19th century black-and-white negatives on glass, 20th century black-and-white negatives on polyester film) to remain usable as images with little or no change.	Acidic paper (e.g., newsprint, low-quality books, papers post-1850) and some film become brittle and brown, difficult to access. Acetate film shrinks, image layer cracks. Celluloid and many early plastics become yellow, crack, distort. Natural materials acidified by pollution (textiles, leather) weaken, may disintegrate.	So-called unstable materials. Typical magnetic media (e.g., video/audio/data tapes, floppy disks) begins to be unplayable. Least-stable photographic materials decay (e.g. color prints fade in the dark; poorly processed items yellow, disintegrate; cellulose nitrate yellows, disintegrates, faster when packaged in large amounts). Many elastic polymers, from rubber to polyurethane foams, become brittle, or sticky, or disintegrate. Some acrylic paints on some canvas supports yellow rapidly.

Lifetimes at Various Temperatures*

	High Stability	Medium Stability	Low Stability	Very Low Stability
140°F, heat treat, sun	~4 years +	~1 year	~6 months	2 months
86°F, hot room	~250 years +	~75 years	~25 years	~7 years
77°F, warm room	~500 years +	~150 years	~50 years	~15 years
68°F, room	**Millennia ~1000 years**	**A few centuries ~300 years**	**One human lifetime ~100 years**	**One human generation ~30 years**
54°F, cool	~3200 years +	~1000 years	~320 years	~100 years
40°F, cold	11,000 years +	~3300 years	~1100 years	~330 years
–4°F, frozen	750,000 years +	~225,000 years	~75,000 years	~22,500 years

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

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

Table 6 Object Lifetime and Effects of Time Out of Storage

	68°F	50°F	40°F	30°F	20°F	−10°F
Relative lifetime compared to 68°F	1	4.4	10.5	25.9	67	178
Lifetime for very low stability objects, years	30	132	315	777	2000	5300
Time out of storage causing 50% loss		107 days/y	38 days/y	15 days/y	5.6 days/y	2.1 days/y
Lifetime remaining		66 y	158 y	389 y	1000 y	2700 y

Table 7 Examples of Corrections to Temperature Midpoint

Seasonal ±	Correction	Equal to Constant 50°F	Equal to Constant 68°F
±10°F gradual	−2°F	48 ± 10°F	66 ± 10°F
±15°F gradual	−4°F	46 ± 10°F	64 ± 10°F
±10°F sudden	−4°F	46 ± 10°F	64 ± 10°F
±15°F sudden	−8°F	42 ± 10°F	60 ± 10°F

Table 8 Hygric Half-Times (near 68°F)

Time Range	Objects or Enclosed Objects	Design Implications
A year or more >10^8 s	Wooden objects at least 0.5 in. thick if wrapped in heavy-gage polyethylene (0.008 in.**)**, with perfect seams. **Enclosures:** Paintings on canvas, paper, or photographs with several layers of matboard (or buffer) framed with glass front and impermeable backing board, perfect seals except for single pressure equalization pinhole, ~15 years. If acrylic sheet, 3/16 inch, ~11 months (Michalski 2005).	Risk only emerges if annual average space relative humidity is unacceptable to enclosed object.
~10^7 s Weeks to months	Large uncoated wood objects, 4 in. across the grain, 30 in. along end grain, 100 days. Books, exposed only on fore edge, tightly compressed ~25 days, if loosely compressed ~ 11 days (Derluyn et al. 2007). Bigourdan (2012) gives ~18 days, unspecified hardcover book, exposed all sides. **Enclosures:** Spools of 35 mm film inside metal can, 60 days (Adelstein et al. 1997). Paintings on canvas, paper or photographs with several layers of matboard (or buffer) framed with glass front and impermeable backing board, but gaps of 0.004 in. at top and bottom, 30 days. (Michalski 2005).	Hourly and daily relative humidity fluctuations create negligible risk. Seasonal space adjustments smoothed out. System loss lasting less than a week creates little risk.
~10^6 s Days to a week	Old panel painting, back "waterproofed," ~15 days (Stilwell and Knight 1934). Spools of 35 mm film, no can, 4 days (Adelstein et al. 1997). Uncoated wood slab, 0.5 in. across grain, 6 in. along end grain. Most wooden cabinetry when empty. Ivory, uncoated, handheld ~1 in. cylindrical (Lafontaine and Wood 1982). **Enclosures:** Paintings on canvas, paper, or photographs with several layers of matboard (or buffer) framed with glass front and impermeable backing board, but gaps of 0.02 in. at top and bottom (Michalski 2005). Hackney (1990) measured at most 6 days with glass frame and coated backing board; gaps must have determined performance. Archive box, paperboard or polypropylene, no holes, full, ~2 days (Batterham and Wignell [2008], estimated from measured damping of external daily fluctuation of ×4.)	Hourly and daily relative humidity fluctuations create little risk. System loss lasting several days can create high risk.
~10^5 s A day	Uncoated wood slab, 0.5 in. across the grain, 5 in. along end grain. Ivory, uncoated, handheld ~1 in. cylindrical (Lafontaine and Wood 1982).	Hourly relative humidity fluctuations create little risk. System loss lasting all day can create high risk.

	Partial enclosures: Paintings on canvas with continuous paint layer and impermeable backing board applied to frame (Di Pietro and Ligterink 1999).	
~10^4 s Hours	Bare acrylic paint, medium-thick layer. Bare oil paint, alkyd paint, thin layers. Uncoated wood, wood fiber boards, leather, skin, 1/8 in. thick.	Hourly relative humidity fluctuations or system loss can create risk.
<10^3 s Few minutes or less	Single sheet of paper, 4 min (Kupczak et al. 2018b). Includes book pages that are fanned open. Thin sheet of parchment, ivory. Thin layers of watercolor paint, gouache. Feathers, fur, hair. Lightweight textiles, costumes. Gelatin layer of photographic print or film. Sized canvas used for paintings.	Relative humidity fluctuation or system loss of only a few minutes can create risk. (Museums rarely display these objects unenclosed.)

Note. All plates considered exposed both sides unless noted otherwise. Adelstein et al. (1997) and Bigourdan (2012) reported 90% response times, converted here to halftimes by ×0.3 assuming exponential decay. Derluyn et al. (2007) measured a 2 in. square experimental book, closed on all sides but fore edge. Their times have been adjusted to a more realistic 4 in. depth, so ×4 (square law) is applied. Estimates from Michalski (2005) based on material data plus enclosure leakage equations. Wood objects and furniture based on Figures 11 and 12. Others are based on calculations using Equation (7) for a plate and diffusion coefficients from the literature.

Table 9 Airborne Pollutants: Sources and High-Vulnerability Materials

Airborne Pollutants	Indoor and Outdoor Sources	Effects on Materials
Aldehydes (RCHO)	Formaldehyde: formaldehyde-based resin in wood products, solid wood, paints and adhesives, natural history wet specimen collections, permanent press fabrics. Acetaldehyde: paints, adhesives, solid woods. Low-molecular-weight aldehydes can be transformed into their respective carboxylic acids in presence of strong oxidant such as peroxides released by oil-based paints or any paint films formed by oxidative polymerization.	Formaldehyde: Corrosion of lead at high relative humidity (>75%).
Amines (RNR)	Ammonia (NH3): alkaline-type silicone sealants, concrete, emulsion adhesives and paints, household cleaning products, visitors, animal excrement, fertilizer and inorganic process industries, underground bacterial activities. If combined with sulfate or nitrate compounds, it can form ammonium salts. Cyclohexylamine (CHA), diethylamino ethanol (DEAE), and octadecylamine (ODA): corrosion inhibitor in humidification systems, some vapor corrosion inhibitors.	Ammonia: blemishes on ebonite and efflorescence on cellulose nitrate. Other amines: thought to be responsible for blemishes on paintings and corrosion of bronze, copper, and silver.
Carboxylic acids (RCOOH)	Acetic acid (CH3COOH): acid-type silicone sealants (acetoxy cure), degradation of organic materials and objects such as cellulose acetate-based objects (vinegar syndrome) and wood products, most paints, flooring adhesives, human metabolism, linoleum, microbiological contamination of air-conditioning filters, oil-based paints, photographic developing products, some "green" cleaning solutions. Formic acid (HCOOH): degradation of organic materials, oil-based paints, wood products. Fatty acids (RCOOH): burning candles, cooking, flooring adhesives, human metabolism, linoleum, lubricant in HVAC systems, microbiological activities from air-conditioning or on objects, objects made of animal parts (including skins, furs, insect collections), oil-based paints, papers, paper and wood products, vehicle exhaust.	Acetic and formic acids: corrosion of copper alloys, cadmium, lead, magnesium, and zinc; efflorescence on calcareous materials (e.g., shells, corals, limestones, calcium-based fossils); fading of some colorants; efflorescence on soda-rich glass objects; lowering degree of polymerization of cellulose. Fatty acids: blemishes on paintings; corrosion of bronze, cadmium, and lead; ghost images on glass; yellowing of papers and photographic documents.
Nitrogen oxide compounds (NO_x)	Nitric oxide (NO): agricultural fertilizers, fuel combustion from vehicle exhaust and thermal power plants, gas heaters, and photochemical smog. Nitrogen dioxide (NO_2): degradation of cellulose nitrate and same sources as for NO, but mainly from oxidation of atmospheric NO. Nitric acid (HNO_3) and nitrous acid (HNO_2): oxidation of NO_2 in the atmosphere or on a material's surface, and the degradation of cellulose nitrate.	Deterioration of paper, fading of some artists' colorants, enhance the deterioration effect of SO_2 on leather and on metals.

Oxidized sulfur gases (SO_2 and H_2SO_4)	Sulfur dioxide (SO_2): degradation of sulfur-containing materials and objects such as proteinaceous fibers, pure pyrite or mineral specimens containing pyrite sulfur dyes, sulfur-vulcanized rubbers, petroleum refineries, pulp and paper industries, combustion of sulfur-containing fossil fuels. Sulfuric acid (H_2SO_4): oxidation of SO_2 in the atmosphere or on a material's surface.	Acidification of paper, corrosion of copper, fading of some artists' colorants, weakening of leather.
Ozone (O_3)	Electronic arcing, electronic air cleaners, electrostatic filtered systems, insect electrocuters, laser printers, photocopy machines, UV light sources, photochemical smog.	Fading of some artists' colorants, dyes, and pigments; oxidation of organic objects with conjugated double bonds such as rubber; oxidation of volatile compounds into aldehydes and carboxylic acids.
Particles (fine and coarse)	General: aerosol humidifier; burning candles; concrete; cooking; laser printers; renovations; spray cans; shedding from clothing, carpets, packing crates, etc. (due to abrasion, vibration, or wear); industrial activities; outdoor building construction; soil. Ammonium salts: reaction of ammonia with SO_2 or NO_2 in indoor or outdoor environments or on solid surfaces. Biological and organic compounds: microorganisms, degradation of materials and objects, visitor and animal danders, construction activities. Chlorides: sea salt aerosol, fossil combustion. Soot (organic carbon): burning candles, fires, coal combustion, vehicle exhaust.	General: abrasion of surfaces (critical for magnetic media), discoloration of objects (especially critical for those with surfaces with interstices [pores, cracks, or micro-irregularities] that entrap dust), may initiate or increase corrosion processes due to their hygroscopic nature. Ammonium salts: corrosion of copper, nickel, silver, and zinc; blemishes on varnished painting and furniture with natural resins and on ebonite; white deposit on object surface; lowering of the degree of polymerization of cellulose. Chlorine compounds: increase of rate of metal corrosion. Soot: discoloration of porous surfaces (painting, frescoes, statues, books, textiles, etc.), increased rate of metal corrosion. Carbon and metallic elements such as iron and magnesium can lower the degree of polymerization of cellulose.
Reduced sulfur gases (S^-)	Carbon disulfide (CS_2): polysulfide-based sealants; fungal growth; rotting organic matter in oceans, soils, and marshes. Carbonyl sulfide (OCS): degradation of wool, coal combustion, coastal ocean, soils, and wetlands, oxidation of carbonyl disulfide. Hydrogen sulfide (H_2S): arc-welding activities, mineral specimens containing pyrite, sulfate-reducing bacteria in impregnated objects excavated from waterlogged sites, polysulfide sealants, vulcanized rubbers, visitors, fuel and coal combustion, marshes, ocean, petroleum and pulp industries (kraft process), vehicle exhaust, volcanoes.	Corrosion of bronze, copper, and silver; discoloration of silver photographic images; darkening of lead pigments.

Source: Adapted from Tétreault (2003).

Table 10 Climate Zone Classifications for Select World Cities

Climate Zone	Type	Location	Climate Zone	Type	Location	Climate Zone	Type	Location
0A	Extremely hot, humid	Recife (Brazil)	3A	Warm, humid	Sydney (Australia)	5A	Cool, humid	Toronto (Canada)
		Bombay (India)			Shanghai (China)			Berlin (Germany)
		Manila (Philippines)			Atlanta (United States)			Chicago (United States)
0B	Extremely hot, dry	Ahmedabad (India)	3B	Warm, dry	Athens (Greece)	5B	Cool, dry	Rio Gallegos (Argentina)
		Niamey (Niger)			Tehran (Iran)			Taiyuan (China)
		Riyadh (Saudi Arabia)			Los Angeles (United States)			Denver (United States)
1A	Very hot, humid	Hanoi (Vietnam)	3C	Warm, marine	Nairobi (Kenya)	5C	Cool, marine	Esquel (Argentina)
		Mombasa (Kenya)			Cape Town (S. Africa)			Corum (Turkey)

		Miami (United States)			San Francisco (United States)			Bremerton (United States)
1B	Very hot, dry	Luxor (Egypt)	4A	Mixed, humid	Beijing (China)	6A	Cold, humid	Oslo (Norway)
		Lahore (Pakistan)			Paris (France)			St. Petersburg (Russia)
		Dakar (Senegal)			Philadelphia (United States)			Minneapolis (United States)
2A	Hot, humid	Sao Paulo (Brazil)	4B	Mixed, dry	Kabul (Afghanistan)	6B	Cold, dry	Chifeng (China)
		Haifa (Israel)			Adelaide (Australia)			Bozeman (United States)
		Dallas (United States)			Albuquerque (United States)	7	Very cold	Ulaanbaatar (Mongolia)
2B	Hot, dry	Cairo (Egypt)						Anchorage (United States)
		Lima (Peru)	4C	Mixed, marine	Brussels (Belgium)			
		Phoenix (United States)			Santiago (Chile)	8	Subarctic	Yellowknife (Canada)
					Portland (United States)			Fairbanks (United States)

Source: ASHRAE *Standard* 169-2013.

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

	Liquid Water Loads (Table 12)		Hygrothermal Loads (Table 12)	Necessary Envelope Performance (Table 12)				Design Considerations
Type of Control	**Rain Exposure (Moisture Zone)**	**Source Moisture**	**International Climate Zone(s)**	**Thermal Flows**	**Air Leakage and Stack Effect**	**Moisture Vapor**	**Hygrothermal Analysis**	**Comments**
AA								
Precision control	All	•	All	•	•	•	▪	Building envelope should be separated from interior enclosure of collections space.
A1, A2								
Precision control with seasonal changes	All	•	5A, 5B, 5C and colder	•	•	•	▪	Building envelope should be separated from interior enclosure of collections space.
	All	•	4A, 4B, 4C	◉	◉	◉	⋄	
	All	•	3A, 3B, 3C and warmer	•	•	•	▪	Building envelope should be separated from interior enclosure of collections space.
	All	•	6A, 6B, and colder	•	•	•	▪	
B								
Limited control with seasonal changes	All	•	5A, 5B, 4A, 4B, 3A, 3B	◉	◉	◉	□	
	All	•	5C, 4C, 3C	◉	○	○	□	
	All	•	2A, 2B and warmer	◉	•	◉	⋄	
	All	•	All B	◉	◉	○	□	Where diurnal temperature differences are large, insulation may be needed to prevent high relative humidity at night caused by cooling.

C								
Prevent relative humidity extremes	All	•	5C, 4C, 3C	◉	○	○	▢	
	All	•	All other zones	◉	◉	◉	▢	Moderated or controlled envelopes can eliminate or substantially reduce size of HVAC equipment.
D								
Prevent very high relative humidity	All	•	All B	◉	○	○	▢	Where diurnal temperature differences are large, insulation may be needed to prevent high relative humidity at night caused by cooling.
	All	•	5C, 4C, 3C	○	○	○	▢	
	All	•	All other zones	◉	◉	◉	▢	Moderated or controlled envelopes can eliminate or substantially reduce size of HVAC equipment.
Cool store	All	•	All	•	•	•	❖	Specialized collections enclosures separate from the exterior building envelope are typically used. Where cooling loads are low (e.g., climate zone 6 and colder) and in some subgrade locations, specially designed exterior envelopes can achieve this performance without a separate interior enclosure.
Cold or “frozen” store	All	•	All	•	•	•	❖	Specialized collections enclosures separate from the exterior building envelope are typically used.
Relative humidity controlled below critical value	All	•	All	•	•	•	❖	Vapor control is a priority in moisture zones A and C, and thermal control is typically needed to maintain relative humidity stability below critical values.

Legend:
Moisture and hygrothermal loads
• Controlled
◉ Moderated
○ Optional
Hygrothermal analysis
▢ Necessary
❖ Recommended
□ Optional

Table 12 Examples of Typical Envelope Assemblies or Features

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

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

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

Type of Collection and Building	Type of Control	Long-Term Outer Limits[a]	Annual Averages	Seasonal Adjustments from Annual Average[b]	Short-Term Fluctuations plus Space Gradients[c]	Collection Benefits and Risks[d]
Museums, Galleries, Archives and Libraries in modern purpose-built buildings or purpose-built rooms **Temperature at or near human comfort**	**AA** Precision control, no seasonal changes to relative humidity	≥35% rh ≤65% rh ≥50°F ≤77°F	For permanent collections: historic annual average of relative humidity and temperature. In public display areas, human comfort temperatures can apply.	No change to relative humidity Increase by 9°F; Decrease by 9°F	±5% rh, ±4°F	Mold germination and growth, and rapid corrosion avoided. No risk of mechanical damage to most artifacts and paintings. Some metals, glasses, and minerals may degrade if rh exceeds a critical value. Chemically unstable objects deteriorate significantly within decades at 68°F, twice as fast each 9°F higher.

Museums, galleries, archives, and libraries needing to reduce stress on their building (e.g., historic house museums), depending on climate zone[e]	**A1** Precision control, seasonal changes in temperature and relative humidity	≥35% rh ≤65% rh ≥50°F ≤77°F		Increase by 10% rh. Decrease by 10% rh. Increase by 9°F; Decrease by 18°F	±5% rh, ±4°F	Mold germination and growth, and rapid corrosion avoided. No mechanical risk to most artifacts, paintings, photographs, and books; small risk of mechanical damage to high-vulnerability artifact. (Current knowledge considers the specifications A1 and A2 as causing the same low risk of mechanical damage to vulnerable collections. Slow seasonal adjustment of 10% rh is estimated to cause the same mechanical risk as rapid fluctuations of 5% rh, because of significant stress relaxation occurring within three months of a slow transition.) Chemically unstable objects deteriorate significantly within decades at 68°F, twice as fast each 9°F higher.
	A2 Precision control, seasonal changes in temperature only	≥35% rh ≤65% rh ≥50°F ≤77°F		No change to relative humidity. Increase by 9°F; Decrease by 18°F	±10% rh, ±4°F	
	B Limited control, seasonal changes in relative humidity and large seasonal changes in temperature.[f]	≥30% rh ≤70% rh ≤86°F	For permanent collection: historic annual average of relative humidity and temperature.	Increase by 10% rh Decrease by 10% rh Increase by 18°F Decrease by up to 36°F	±10% rh, ±9°F	Mold germination and growth, and rapid corrosion avoided. Chemical deterioration halts during cool winter periods No risk of mechanical damage to many artifacts and most books. Tiny risk to most paintings, most photographs, some artifacts, some books. Moderate risk to high-vulnerability artifacts. Objects made with flexible paints and plastics that become brittle when cold, such as paintings on canvas, need special care when handling in cold temperatures. Chemically unstable objects deteriorate significantly within decades at 68°F, twice as fast each 9°F higher.
	C Prevent relative humidity extremes (damp or desiccation) and prevent high temperature extremes.	≥25% rh ≤75% rh ≤104°F[g]	Within 25% to 75% rh year-round. Temperature usually below 77°F		Not continually above 65% rh for longer than *X* days.[h] Temperature rarely over 86°F	Chemical deterioration halts during cool winter periods. Mold germination and growth, and rapid corrosion avoided. Tiny risk of mechanical damage to many artifacts and most books; moderate risk to most paintings, most photographs, some artifacts, some books; high risk to high-vulnerability artifacts Even greater care is needed than provided in B

						when handling objects made with flexible paints and plastics that become brittle when cold, such as paintings on canvas. Chemically unstable objects deteriorate significantly within decades at 68°F, twice as fast each 9°F higher.
						Chemically unstable objects deteriorate significantly within decades at 68°F, and twice as fast each 9°F higher. Conversely, cool winter season can extend their life.
Collections in open structured buildings, historic houses	**D** Prevent very high relative humidity (dampness)	≤75% rh	Relative humidity reliably below 75% rh		Not continually above 65% rh for longer than *X* days.[h]	Mold germination and growth, and rapid corrosion avoided. High risk of sudden or cumulative mechanical damage to most artifacts and paintings because of low-humidity fracture; but avoids high-humidity delamination and deformations, especially in veneers, paintings, paper, and photographs.

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

Type of Collection and Building	Type of Control	Specifications	Collection Benefits and Risks
Temporary exhibit space and unpacking space for loaned objects	Conditions will be stipulated in loan agreements[i]	Conditions will be agreed between lender and borrower. Based on the historic climate to which the object is accustomed, and a risk assessment of the borrower's environment and that of the transit process. Solutions to protect objects from climate shock should first be found in the creation of micro-climates (showcases, glazing, etc., potentially using buffering).[e,i]	Benefits and risks are assessed by the lender, and contractual specifications based on this assessment. Often, assessment is highly risk averse, precautionary. For the borrowing institution, the benefits are increased access to popular objects by visitors; risks are monetary and reputational damage if climate control does not meet conditions outlined in the loan contract.
Chemically unstable organic materials in modern purpose-built buildings or purpose-built rooms[j]	**Cool**	46 to 61°F, 30 to 50% rh As defined in ISO *Standard* 18934:2011. IPI (Adelstein 2009) uses an anchor of 54°F.	The benefit of low temperature storage is extended lifetime of objects that will be lost within a generation or two at room temperature. See the section Chemical Damage for details on quantifying the benefits. Biological damage is also much reduced. The risks are the many side-effects of such systems: high humidity or condensation during malfunctions, water exposure. Objects must be packaged appropriately to reduce risk of condensation during retrieval, and a transition space with intermediate climate may be required. Hourly, daily, and even longer humidity fluctuations do not affect most properly packaged objects at low temperatures.[e]
	Cold	32 to 61°F, 30 to 50% rh As defined in ISO-18934:2011. IPI (Adelstein 2009) uses an anchor of 40°F.	
	Frozen	–4 to 32°F, 30 to 50% rh As defined in ISO *Standard* 18934:2011 and Adelstein (2009)	
Unstable metal or glass in modern purpose-built buildings or purpose-built rooms	**Relative humidity controlled to avoid a critical relative humidity of a salt or hydrate**	Many different critical relative humidities for various materials. See the section on Critical Relative Humidity for details and sources of information.	

Notes for Tables 13A and 13B:

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

[b]Rate of seasonal adjustments in relative humidity set point should not exceed the short-term fluctuation limit each 30 days, and the rate for temperature adjustment should not exceed the short-term fluctuation limit each 7 days (e.g., for A1, a seasonal adjustment can be no faster than 5% rh change per 30 days and 4°F change per 7 days).

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

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

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

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

[g]An upper temperature limit is provided for a mixed collection that may contain objects with waxy materials that deform irreversibly beginning at ~104°F. This limit is set more cautiously for type B control, 86°F than type C control.

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

[i]In general, professional guidance currently refers to Bizot, which stipulates outer limits of 40 to 60% rh, and 61 to 77°F throughout the year. Ratified as of 2016 by ICOM-CC, IIC, AIC, AAMD, NMD, BM, and Bizo. See Michalski (2016) for details.

[j]See Table 5.

Table 14 Strategies for the Control of Airborne Pollutants

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

strategies for improvement.	outdoor pollutants in surrounding environment or indoor-generated pollutants are an issue.		damage to objects for at least 1 year.[c] Controlling these key pollutants makes it very likely that other pollutants will be controlled as well.
	- Quantitatively monitor[d] concentration of key pollutants and compare against suggested limits or with institutional targets.		
	- Do risk analysis of outdoor, room, and enclosure pollutant concentrations and determine most efficient solutions for minimizing impact of pollutants on specific objects or on collection in general. Adjust institutional target if necessary.		

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