CHAPTER 21

MUSEUMS, LIBRARIES, AND ARCHIVES

UNDERSTANDING and appreciating humanity's diverse cultures and history dictates preserving varied artifacts, ranging from books and documents to artwork, historical artifacts, technological accomplishments, specimens of national history, examples of popular culture, and once-common trade goods. Their importance ranges from national to regional or even local, but their symbolic and aesthetic values give them monetary worth frequently impossible to estimate. Thus, their preservation is worthwhile and may even be legally mandated. The loss of any one of these artifacts is a loss to all individuals.

Historical collections are vulnerable to many threats. Because they must be preserved indefinitely, the steps taken to protect them are sometimes extraordinary. Most threats can be addressed by properly maintained housing, with professional support. The level of acceptable risk is a compromise between the theoretically ideal environment and the practical. It is possible to slow deterioration drastically, but doing so undermines the ultimate function of museums, libraries, and archives: not only to preserve, but also to allow public and scholarly access. Additionally, extremely high control over all environmental parameters can ensure an object's survival, but at a price no cultural institution can justify or is willing to pay. Managing risk, not avoiding it altogether, is the objective.

This chapter addresses threats to collections that are minimized by a well-designed HVAC system that provides stability for low-access storage environments and also serves high-traffic visitors' areas.

Theoretically, many systems can successfully provide environmental control, if properly applied. Generally, cultural institutions have adequate funding for long-term maintenance of simple, efficient systems. In new construction, it is important not to let design ambitions escalate beyond an institution's operational resources: inadequate long-term maintenance can allow collections to deteriorate more quickly than expected, and control failures could cause serious damage. From the start, projects must consider both the design objective and the realistically available operation and maintenance resources.

General Factors Influencing Damage

In designing HVAC systems for collections, a good working relationship between the mechanical engineer, architect, interior designer, and owner/operator, especially client personnel responsible for preserving the collection, is critical. All limitations must be defined at the beginning of the design.

Artifacts and collections can be of one material (e.g., an archive of antique books), which simplifies target specifications, or combinations of materials with different levels of instability (e.g., a multimedia library that includes both books and film); in the latter case, target conditions are usually a compromise. For more details, see Michalski (1996a).

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The building's architecture and mechanical systems need to manage eight types of threats to collections; mechanical engineers need to appreciate and respect these concerns even if they do not appear to relate directly to a building's mechanical systems. Respecting all the risks gives the client an increased comfort zone for threats the HVAC system is designed to specifically control. The following threats, in decreasing order of seriousness, affect all types of collections.

Light damage is perhaps the most extensive threat to museum collections. Most materials undergo some form of undesirable, permanent photochemical or photophysical change from overexposure to light. It is, however, relatively easy to control at the architectural, design, and operational levels by eliminating ultraviolet light, limiting illumination intensity (measured in footcandles), and restricting total illumination duration (footcandle-hour).

Relative humidity also presents a risk. For each material, there is a level of environmental moisture content (EMC) consistent with maximum chemical, physical, or biological stability. When the EMC is significantly too low or too high, the associated relative humidity becomes a risk factor. Recent literature often calls humidity-related damage "incorrect relative humidity" to emphasize the concept of ranges of acceptable moisture content rather than absolute limits.

Temperature ranges for materials must also be controlled. Some polymers become brittle and are more easily fractured when the temperature is too low. At temperatures that are too high, damaging chemical processes accelerate. Thermal energy not only accelerates aging, but also can magnify the effects of incorrect relative humidity. Therefore, incorrect relative humidity and temperature are often taken together when deciding ideal parameters for important classes of materials such as for paper and photography.

Air pollution includes outdoor-generated gaseous and particulate pollutants that infiltrate the building, as well as indoor-generated ones. Mechanical air filters, which control coarse and fine particles, and gaseous filters are discussed in the section on Materials Damage Caused by Airborne Pollutants.

Pest infestation primarily includes insects consuming collections for food; mold, fungi, and bacteria also qualify as pests, but they can be limited by controlling relative humidity and ventilation.

Shock and **vibration** can cause long-term damage to sensitive objects. Handling and shipping tend to be the most common causes, but vibration can also be transmitted to objects by service vehicles during packing and shipping. Usually, HVAC design only needs to consider this risk if vibration is transmitted through ductwork to works hung on adjacent walls or in particularly active air drafts.

Natural emergencies are, fortunately, rare, and most institutions have (or should have) emergency response policies. However, avoidable emergencies could result from building and mechanical design malfunctions such as water pipe failure, especially over collections and storage facilities. The infrequency of these failures leads many to forget that just one failure, however rare, 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 irreplaceable objects.

Theft, **vandalism**, and **misplacing objects** can be addressed by limiting access to mechanical systems to improve security.

This chapter focuses on relative humidity, temperature, and air pollution design for HVAC systems. Many excellent books treat the subject of environmental management in museums and libraries extensively; consult the References for information not contained in this chapter.

ENVIRONMENTAL IMPACTS ON COLLECTIONS

DETERMINING PERFORMANCE TARGETS

Museums, archives, and libraries have two categories of indoor air requirements: general health and safety, comfort, and economy of operation as listed in ASHRAE *Standards* 55 and 62; and the collections' requirements. These are not simple, are not yet completely understood, and often conflict across collection types. The building envelope is often incapable of maintaining a strict set of chosen conditions. Thus, the risk of compromising on relative humidity and temperature specifications must be assessed. The following sections summarize the best information on these issues.

In terms of health and safety and the collection's requirements, building spaces can be categorized as shown in Table 1: (1) collection versus noncollection, (2) public versus nonpublic, and (3) "dirty" versus "clean." These subdivisions distinguish between areas that have very different thermal and indoor air quality requirements, outdoor ventilation rates, air supply strategies, etc. These areas often require separate HVAC systems. See Chapters 14, 29, and 30 for more information on dirty rooms. Noncollection rooms are not considered in this chapter because their HVAC requirements are similar to those in other public buildings, as discussed in Chapter 3.

The following sections provide a framework for developing appropriate climate and indoor air quality (IAQ) parameters for different museums, libraries, and archives. A single target is a compromise between large numbers of different, often contradictory requirements, but fortunately, many collections are sufficiently uniform to allow useful generalizations to be made about their needs. In this chapter, the term "effective" includes institutional value judgments as well as the science of deterioration (Michalski 1996b).

Temperature and Humidity

Biological Damage. Dampness accelerates mold growth on most surfaces, corrosion of base metals, and chemical deterioration in most organic materials. Of all HVAC-controllable environmental parameters, high humidity is the most important factor.

The most comprehensive mold data are from the feed and food literature. Fortunately, this provides a conservative outer limit to dangerous conditions. Mold on museum objects occurs first on surfaces contaminated with sugars, starch, oils, etc., but can also occur on objects made of grass, skin, bone, and other feed- or food-like materials. Water activity is identical to and always measured as the equilibrium relative humidity of air adjacent to the material. The equilibrium relative humidity provides a better measure than the EMC for mold germination and growth on a wide variety of materials (Beuchat 1987). Figure 1 shows the combined role of temperature and relative humidity. The study of the most vulnerable book materials by Groom and Panisset (1933) concurs with the general trend of culture studies from Ayerst (1968). Ohtsuki (1990) reported microscopic mold occurring on clean metal surfaces at 60% rh. The DNA helix is known to collapse near 55% rh (Beuchat 1987), so a conservative limit for no mold ever, on anything, at any temperature, is below 60% rh. Figure 1 in Chapter 24 suggests a similar lower boundary for mold: 62% rh.

Snow et al. (1944) looked for visible mold growth on materials inoculated with a mixture of mold species. These are plotted in Figure 2, and follow the same trend reported by Hens (1993) for the European building industry for wall mold and shown in Figure 1 in Chapter 23.

Thus, Figures 1 and 2 show practical dangers: growth in less than a summer season requires over 70% rh, and growth in less than a week requires over 85% rh

For both collection and occupant health, and given the need in museums to humidify air more than many applications in winter, care much be taken to avoid cold spots along ductwork.

Rapid corrosion above 75% rh occurs for two reasons: increased surface adsorption of water, and contamination by salts. The adsorption of water on clean metal surfaces climbs rapidly from 3 molecules or less below 75% rh to bulk liquid layers above 75% rh (Graedel 1994). This phenomenon is aggravated by most surface contaminants, as shown in studies of the role of dust on clean steel corrosion. The most common contaminant of museum metals, sodium chloride, dissolves and liquefies (deliquesces) above 76% rh.

Mechanical Damage. Very low or fluctuating relative humidity or temperature can lead to mechanical damage in artifacts. The fun-

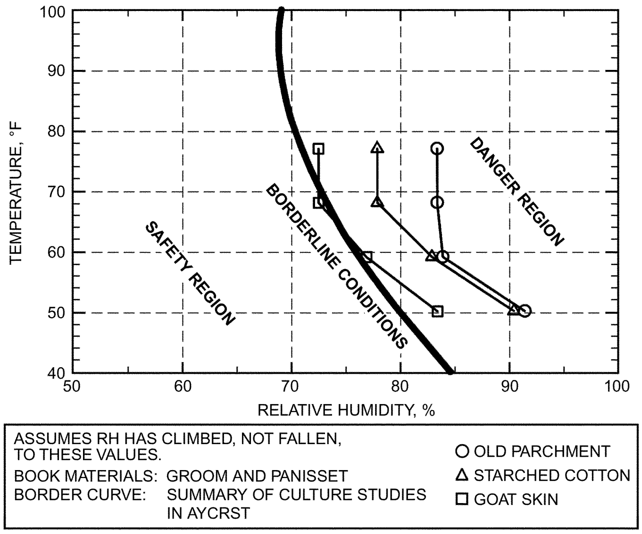

Fig. 1 Temperature and Humidity for Visible Mold in 100 to 200 days

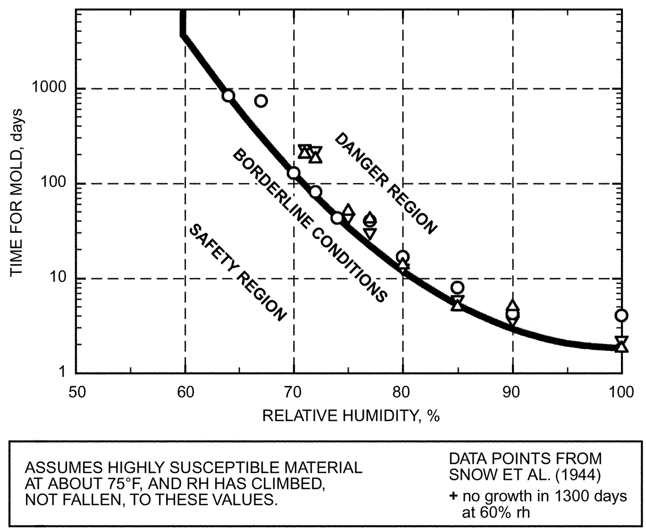

Fig. 2 Time Required for Visible Mold Growth

Table 1 Classification of Rooms for Museums and Libraries

		High Internal Source of Contaminants (Dirty)	Low Internal Source of Contaminants (Clean)
Collection	Non-public access	Conservation laboratories, museum workshops (VOCs, fumes, dusts) “Wet” collections (alcohol evaporation from poorly sealed jars in natural history collections) Photographic collections (“vinegar syndrome” produces acetic acid vapors)	Most storage areas, vaults, library stacks
	Public access	Displays of conservation work in progress (unusual and temporary)	Galleries, reading rooms
Noncollection	Non-public access	Smoking offices (unusual)	Offices (nonsmoking)
	Public access	Cafeterias, rest rooms, spaces where smoking permitted	Public spaces without food preparation or smoking

damental cause is expansion and contraction of materials, combined with some form of internal or external restraint. Very low humidity or temperature also increases the stiffness of organic materials, making them more vulnerable to fracture. Traditionally, these concerns have led to extremely narrow specifications, such as 50 ± 3% rh and 70 ± 2°F (LaFontaine 1979), which still form the basis of many museum and archive guidelines. These specifications were extrapolated from the observation that very large fluctuations fractured some objects, but with no experimental or theoretical basis for precise extrapolation to smaller fluctuations.

Research on objects (Erhardt and Mecklenburg 1994; Erhardt et al. 1996; Mecklenburg and Tumosa 1991; Mecklenburg et al. 1998; Michalski 1991, 1993), experience in historic-building museums, and comparison of historic buildings with and without air conditioning (Oreszczyn et al. 1994) led to reappraisal of these fluctuation specifications. Despite minor disagreement over interpretation, the practical conclusions are the same: the traditional very narrow tolerances exaggerated artifact needs. Between fluctuations of about ±10% rh with ±18°F and ±20% rh with ±36°F, risk of fracture or deformation climbs from insignificant to significant for a mixed historic collection, and climbs even more quickly for increasingly large fluctuations. The range of ±20 to 40% rh yielded common observations of cracked cabinetry and paintings.

Research models use a restrained sample of organic material (e.g., paint, glue, or wood) subjected to lowered relative humidity or temperature. The material both shrinks and stiffens. Daly and Michalski (1987) and Hedley (1988) collected consistent data on the increase in tension for traditional painting materials; and Michalski (1991, 1999) found consistent results with other viscoelastic data on paints and their polymers. For example, acrylic paintings do not increase in tension at low relative humidity nearly as much as traditional oil paintings. On the other hand, acrylic paints stiffen much more than oil paints between 70 and 41°F, greatly increasing acrylic paintings’ vulnerability to shock and handling damage. The increase in material tension can be calculated as the modulus of elasticity times the coefficient of expansion integrated over the decrement in relative humidity or temperature. Each factor is a function of relative humidity and temperature (Michalski 1991, 1998; Perera and Vanden Eynde 1987).

Modeling at the Smithsonian Institution used the material’s yield point (i.e., nonrecoverable deformation) as a threshold criterion for damage, and hence permissible fluctuations (Erhardt et al. 1994; Mecklenburg et al. 1998). From their data on expansion coefficients and tensile yield strain in wood, for example, they estimated a permissible relative humidity fluctuation of ±10% in pine and oak, greater for spruce. Modeling on paint and glue suggested ±15% rh as a safe range (Mecklenburg et al. 1994). More extensive data on compression yield stress across the grain are available for all useful species of wood in USDA (1987), which can be combined with elasticity data for that species and relative moisture content to obtain yield strain and yield relative humidity fluctuation. These vary widely but center near ±15% rh.

Alternative modeling at the Canadian Conservation Institute used fracture as the criterion for damage, and the general pattern of fatigue fracture in wood and polymers to extrapolate the effect of smaller multiple cycles (Michalski 1991). With a benchmark of high probability of single-cycle fracture at ±40%, known from observation of museum artifacts, fatigue threshold stress (10^7 cycles or more) can be extrapolated by an approximate factor of 0.5 in wood (±20% rh) and 0.25 in brittle polymers (±10% rh) such as old paint. This is consistent with the yield criterion: the yield stress in these materials corresponds to stresses that cause very small or negligible crack growth per cycle. Researchers also noted that the coefficient of expansion in wood and other materials is minimized at moderate relative humidity because of sigmoidal adsorption isotherms, so fluctuations at lower and higher relative humidity set points tend to be even riskier.

Both models assume uniformly restrained materials. As a first approximation, many laminar objects (e.g., paintings on stretchers, photographic records) fall in this class. Artifacts, however, tend to be complex assemblies of materials. Some are less vulnerable because of lack of restraint (e.g., floating wood panels, books or photographs with components that dilate in reasonable harmony); other assemblies contain sites of severe stress concentration that initiate early fracture. Michalski (1996b) classifies vulnerability for wooden objects as very high, high, medium (uniformly restrained components), and low. Each category differs from the next lower one by a factor of two (i.e., half the relative humidity fluctuation causes the same risk of damage).

Chemical Damage. Higher temperatures and moderate amounts of adsorbed moisture lead to rapid decay in chemically unstable artifacts, especially some archival records. The most important factor for modern records is acid hydrolysis, which affects papers, photographic negatives, and magnetic media (analog and digital). Sebor (1995) developed a graphical format for relating these two parameters to lifetime for book papers. An improved graphical representation is shown in Figure 3. Fortunately for HVAC design purposes, dependence on relative humidity and temperature in all records is very similar. Although the precise quantification and meaning of record lifetime is debatable, all authorities agree that the most rapidly decaying records (e.g., videotapes, acidic negatives) can become unstable within a few decades at normal room conditions, and much faster in hot, humid conditions. Figure 3 shows the relative increase in record lifetime under cold, dry conditions; the range in numbers on each line reflects the spread in available data. Extension of the plots below 5% rh is uncertain; the rates of chemical decay may or may not approach zero, depending on slow, nonmoisture-controlled mechanisms such as oxidation.

Lifetime improvement predictions for photographic data were devised by the Image Permanence Institute (Nishimura 1993; Reilly 1993) and implemented in a lifetime prediction wheel. These relative lifetime estimates are less optimistic about improvement with low relative humidity, but the general trend is the same as the Michalski plots. The Image Permanence Institute is developing a

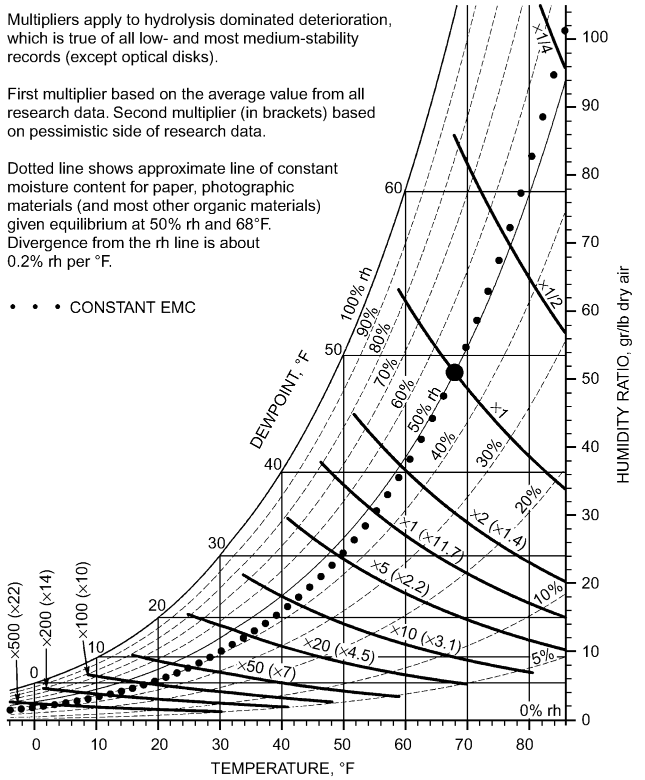

Fig. 3 Lifetime Multipliers Relative to 68°F and 50% rh

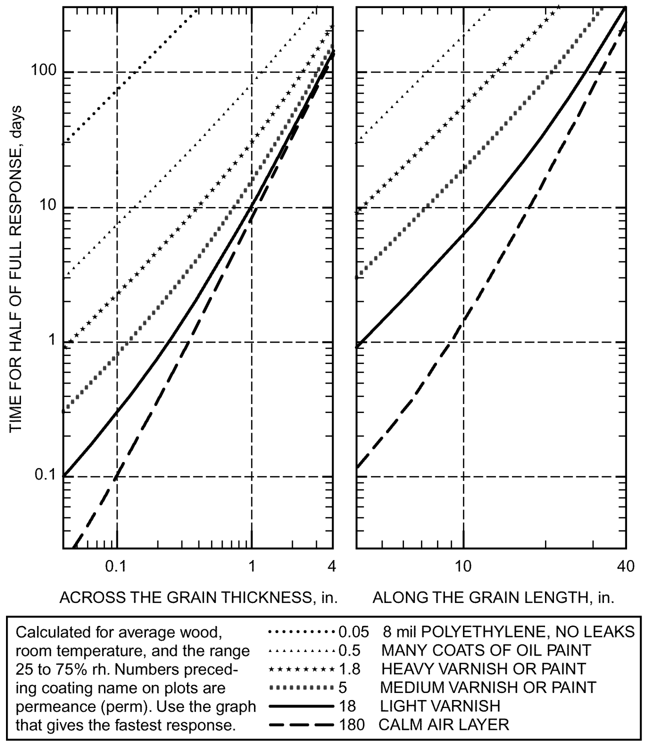

Fig. 4 Calculated Humidity Response Times of Wooden Artifacts

new data logger capable of displaying an integrated permanence index for organic materials with activation energies for aging similar to archival record paper.

Critical Relative Humidity

At some critical relative humidity, some minerals hydrate, dehydrate, or deliquesce. When part of a salt-containing porous stone, a corroded metal, or a natural history specimen, these minerals disintegrate the object. Distinct critical relative humidity values are known for dozens of minerals in natural history collections (Waller 1992). Pyrites, which contaminate most fossils, disintegrate if held above 60% rh (Howie 1992). Bronze, one of the most important archaeological metals, has a complex chemistry of corrosion, with several critical relative humidity values (Scott 1990). This variety means there is no universal safe relative humidity; particular conditions should be achieved for specific artifacts with local cabinets or small relative-humidity-controlled packages (Waller 1992). The only generalization is that anything over 75% rh is dangerous.

Response Times of Artifacts

Brief relative humidity fluctuations may not affect artifacts; very few museum objects respond significantly to fluctuations under an hour in duration. Hence, a 15 min cycle in HVAC output does not affect most artifacts, unless it is so large as to cause sudden damp conditions. Many objects take days to respond. Figure 4 shows calculated humidity response times of wooden artifacts. Figure 5 shows the interaction of air leakage, wood coatings, and textile buffering on the response of a chest of drawers; risk increases if the piece is displayed empty and open, rather than closed and full, because response time falls from months to days.

Very long fluctuations, such as seasonal changes, are slow enough to take advantage of stress relaxation in artifact components. Data on the effective modulus of elasticity of many oil and acrylic paints as a function of time, temperature, and relative humidity (Michalski 1991) and direct stress relaxation data for

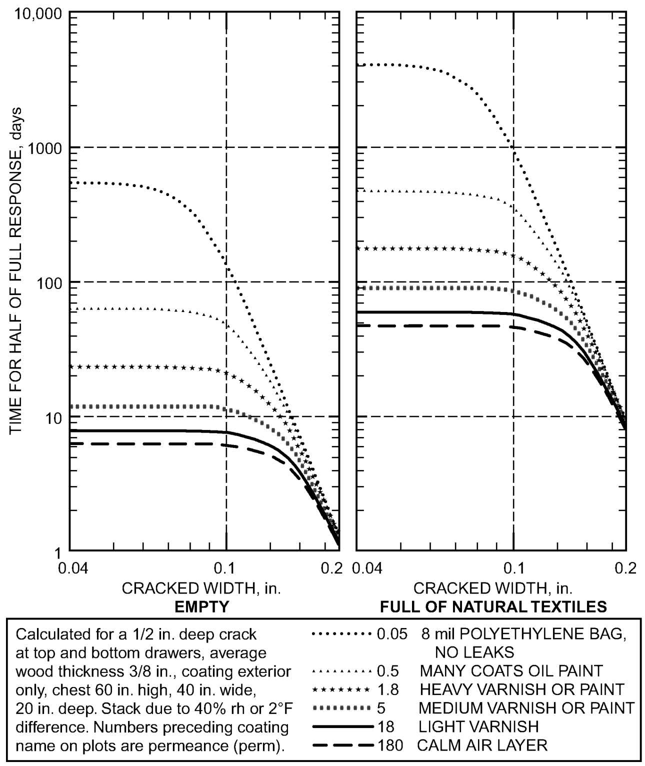

Fig. 5 Interaction of Air Leakage, Wood Coating, and Textile Buffering on Response of Wooden Chest of Drawers

Table 2 Sources of Airborne Pollutants

Airborne Pollutants	Indoor and Outdoor Sources
Amines (RNR)	*Ammonia (NH_3):* Alkaline silicone sealant, concrete, emulsion adhesives and paints, cleaning products, visitors, animal excrement, fertilizer and inorganic process industries, underground bacterial activities
	Diethylaminoethanol (DEAE), cyclohexylamine (CHA) and octadecylamine (ODA): corrosion inhibitor in humidification systems
	Aliphatic amines: epoxy adhesives
Aldehydes (RCOH) and carboxylic acids (RCOOH)	*Aldehydes:* Acetaldehyde (CH_3COH): some poly (vinyl acetate) adhesives (PVAc), wood construction products. *Formaldehyde (HCOH):* carpet-finishing components, fungicide in emulsion paints, fabrics-finishing components, gas ovens and burners, natural historical wet collection, ozone-generator air purifier, urea formaldehyde-based adhesive products, vehicle exhaust, tobacco smoke and other combustion
	Carboxylic acids: Acetic acid (CH_3COOH): acid silicone sealant, degradation of organic materials and objects [e.g., cellulose acetate based objects (vinegar syndrome) and wood products], human metabolism, 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, human metabolism, linoleum, microbiological activities in air conditioning or on objects, objects made of animal parts (including skins, furs, taxidermy specimens, insect collection), oil-based paints, skins, papers and wood products, vehicle exhaust
Nitrogen oxide compounds (NO_x)	*Nitric oxide (NO):* agricultural fertilizers, fuel combustion from vehicle exhaust and thermal power plants, gas heaters, lightning, photochemical smog
	Nitrogen dioxide (NO_2): degradation of cellulose nitrate and same sources as for NO, but mainly from oxidation of NO in atmosphere
	Nitric acid (HNO_3) and nitrous acid (HNO_2): oxidation of NO_2 in atmosphere or on a material’s surface, possibly degradation of cellulose nitrate
Oxidized sulfur gases (SO_x or S^+)	*Sulfur dioxide (SO_2):* degradation of sulfur-containing materials and objects (e.g., proteinaceous fibres, pure pyrite or mineral specimens containing pyrite sulfur dyes, sulfur vulcanized rubbers, petroleum refineries, pulp and paper industries), sulfur-containing fossil-fuel combustion
	Sulfuric acid (H_2SO_4): oxidation of SO_2 in the atmosphere or on a material’s surface
Ozone (O_3)	Electronic arcing, electronic air cleaners, electrostatic-filtered system, laser printer, photocopy machine, UV light, lightning, photochemical smog
Particles (fine and coarse)	*General:* atomizing humidifier; burning candles; cooking; laser printers; renovation; spray cans; shedding from clothing, carpets, packing crates, etc. (from abrasion, vibration, or wear); industrial activities; outdoor building construction; soil
	Ammonium salts (ammonium sulfate): reaction of ammonia with SO_2 or NO_2 in inside or outside or on solid surfaces
	Biological and organic compounds: microorganisms, degradation of materials and objects, visitors and animal danders, construction activities
	Chlorides: sea salt aerosol, fossil combustion
	Soot (organic carbon): burning candles, fires, coal combustion, vehicle exhaust
Peroxides (ROOR)	*Hydrogen peroxide (HOOH):* degradation of organic materials (e.g., rubber floor tile, wood products, microorganism activities, oil-based paints
	Peroxyacetyl nitrate (PAN): automobile exhaust (particularly from alcohol-based fuels), photochemical smog
Reduced sulfur gases (S–)	*Carbon disulfide (CS_2):* polysulfide-based sealant, 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 site, visitors, fuel and coal combustion, marshes, ocean, petroleum and pulp industry (kraft process), vehicle exhaust, volcanoes
Water vapor	Visitors, water-based paints and adhesives, wet cleaning activities, outdoor environment

Source: Tétreault (2003).

both paint (Michalski 1995) and wood imply that stress caused by a given strain applied over 1 day falls to 50% or less if that stress is applied over 4 months at moderate room temperatures. Thus, a 4 month seasonal ramp of ±20% rh should cause less stress in most artifacts than a 1 week fluctuation of ±10 rh.

AIRBORNE POLLUTANTS

Sources of Airborne Pollutants

Of the hundreds of air pollutants, only a few have been identified as dangerous for collections in museums and archives. Table 2 lists major airborne pollutants and their typical sources. Hydrocarbons and other VOCs, such as alcohols and ketones, may be important for other considerations such as human health and comfort, but generally are not threats to artifacts. Outdoor sources of airborne pollutants are primarily industrial and human activities. Inorganic outdoor pollutants that cause material damage were important in the past, but increasing use of alcohol-based fuels has directly increased the relative importance of organic species, especially formaldehyde and organic acids (Anderson et al. 1996; Schifter et al. 2000). Geological and biological activities release hydrogen sulfide and ammonia; the agricultural industry is also a major ammonia source (Allegrini et al. 1984; Walker et al. 2000). Inside buildings, construction materials emit organic carbonyls such as carboxylic acids and aldehydes (Grzywacz and Tennent 1994; Meininghaus et al. 2000).

Collections can themselves be sources of airborne pollutants (Grzywacz and Gailunas 1997). Collections with leather, fur, and wood elements can release reduced sulfides, aldehydes, carboxylic acids, or fatty acids. These contaminants may instigate or accelerate deterioration of other artifacts. Acetic acid emitted from degrading cellulose acetate films is another good example. In general, the major risks to collections from indoor-generated pollutants are from acetic and formic acids [one precursor of which is formaldehyde (Raychaudhuri and Brimblecombe 2000), which must also be controlled]. These gases are emitted from wood and wood-based materials as well as adhesives, finishing products, etc. Reduced sulfides (e.g., hydrogen sulfide and carbonyl sulfide) can be released from wools and silks (Brimblecombe et al. 1992; Watts 1999).

During construction or renovation at the building, room, or display case levels, high amounts of suspended particles (often including mold spores and vapors) are generated. Depending on the HVAC system, airborne pollutant concentrations may not reduce to acceptable levels for a few weeks up to several months after work is finished (Eremin and Tate 1999). Adhesives, coatings, and sealants initially release high levels of pollutants. In poorly ventilated enclosures or rooms, emission rates may be retarded because of equilibrium vapor pressures. Fortunately, levels of pollutants released by wet products in well-ventilated rooms usually decrease rapidly, though carboxylic acid emitted by alkyd or oil-based coatings decreases at a much slower rate (Chang et al. 1998; Fortmann et al. 1998). Even after emissions level off, the amount of acids released by these coatings can remain unsatisfactory for several years, even in ventilated rooms. Food preparation and service vehicles are also sources of contaminants, and require special consideration. The source of outside air for the HVAC system, especially intakes that deliver to collections is important, especially the intakes.

Research has shown that gaseous outdoor pollutants can easily penetrate all types of buildings, including modern HVAC-equipped construction, when no chemical filtration exists to remove them (Cass et al. 1989; Davies et al. 1984; Druzik et al. 1990). Particle intrusion from outside sources has also been well documented in art museums (Brimblecombe 1990; Nazaroff et al. 1993; Yoon and Brimblecombe 2001).

Materials Damage Caused by Airborne Pollutants

Pollutant-monitoring surveys of collections and laboratory studies have provided important data on the effect of airborne pollutants on materials (Table 3). Damage to materials is the sum of many parameters in the immediate environment. High levels of a single pollutant may cause serious damage even when all other conditions are ideal. However, when many pollutants act together and temperature, relative humidity, and light intensity are elevated, deterioration processes are almost always accelerated. The prior history of treatment, storage, or excavation may also aggravate chemical reactions. Tétreault's (1993) summary of materials damaged by pollutants can help determine which materials require special care. Airborne pollution control strategies, at the room and enclosure levels, have been summarized by Brokerhof (1998), Craft et al. (1996), Grzywacz (1999), Ryhl-Svendsen (1999), and Tétreault (1994, 1999b).

Damage to artifacts is cumulative and mostly irreversible. All efforts to reduce peaks or abnormal levels of pollutants in the building are beneficial. Damage to organic materials (e.g., papers, textiles) after short-term exposure to high pollutant levels may not be immediately observable, but may lead to premature failures (Bogaty et al. 1952; Dupont and Tétreault 2000; Graedel and McGill 1986; Oddy and Bradley 1989; Tétreault et al. 1998).

Autocatalytic degradation of film is a problem. Most cellulose nitrate film stock eventually becomes so unstable that fire and explosion are high risks. Frozen storage is the only option from a human health and safety perspective. Cellulose nitrate sculpture likewise degrades rapidly (Derrick et al. 1991). Degradation products may include nitric acid, when catalyzed by small amounts of sulfate esters remaining from manufacture, or nitrogen dioxide, in the case of uncatalyzed thermal or photochemical decomposition (Selwitz 1988).

Cellulose acetate film stock ("safety film") is also chemically unstable, but does not pose the fire or explosive hazard inherent in cellulose nitrate films. Over time, it deteriorates autocatalytically and liberates free acetic acid ("vinegar syndrome"). The amount of acetic acid liberated can be many orders of magnitude greater than any other single source in museums and archives. As such, it is a risk not only to the film itself, but also to all other acid-sensitive materials. Consequently, these films must be properly contained.

Table 3 Effects of Airborne Pollutants on Materials

Airborne Pollutants	Effects on Materials
Amines	*Ammonia:* blemishes on ebonite; corrosion of metal by ammonium salt; efflorescence on cellulose nitrate *Other amines:* expected to be responsible for blemishes on paintings; corrosion on bronze, copper and silver
Aldehydes and carboxylic acids	*Acetaldehyde and formaldehyde:* possible oxidation of the aldehyde to carboxylic acids in high relative humidity and in presence of strong oxidants *Acetic and formic acids:* corrosion on copper alloys, cadmium, lead, magnesium, and zinc; efflorescence on calcareous materials (e.g., land and sea shells, corals, limestones, rich calcium-based fossils); efflorescence on rich soda glass objects; lowering degree of polymerization of cellulose *Fatty acids:* blemishes on paintings; corrosion of bronze; cadmium, and lead; yellowing of papers and photographic documents
Nitrogen oxide compounds	Corrosion of copper rich silver; deterioration of leather and paper; fading of some artists' colorants
Oxidized sulfur gases	Acidification of paper; corrosion of copper; fading of some artists' colorants; weakening of leather
Oxygen	Degradation of proteins *Oxygen with ultraviolet radiations:* brittleness and cracking of organic objects; fading of colorants
Ozone	Fading of some artists' colorants, dyes, and pigments; oxidation of organic objects with conjugated double bonds (e.g., rubber); oxidation of volatile compounds into aldehydes and carboxylic acids
Particles	*General:* abrasion of surfaces (critical for magnetic media); disfiguration of objects [especially critical for surfaces with interstices that entrap dust (e.g., with pores, cracks, or microirregularities)]; may initiate or increase corrosion processes; may initiate catalysis forming reactive gases *Ammonium salts:* corrosion on copper, nickel, silver and zinc; blemishes on natural-resins-varnished furniture and on ebonite *Chlorine compounds:* increases rate of corrosion of metals *Soot:* disfiguration of porous surfaces (painting, frescoes, statues, books, textiles, etc.), increases rate of metals corrosion
Peroxides	Discoloration of photographic prints; fading of some artists' colorants; oxidation of organic objects and pollutant gases
Reduced sulfur gases	Corrosion of bronze, copper, and silver; darkens lead white pigment; discoloration of silver photographic images
Water vapor	Hydrolysis reaction on organic objects (e.g., cellulose acetate and nitrate-based objects), some dyes in color photographs, and polyurethane-based magnetic tape; increases deterioration rate of many cases (e.g., corrosion on metals); efflorescence on calcium-based materials; photo-oxidation of artists' colorants

Source: Tétreault (2003).

Organic carbonyl pollutants such as formaldehyde, acetic acid, and formic acid are the most damaging to collections (Brimblecombe et al. 1992; Grzywacz and Tennent 1997; Hatchfield and Carpenter 1986; Hopwood 1979). Organic carbonyl pollutants are a risk at a few parts per billion by volume in air, and can damage calcareous materials such as limestone, land and sea shells, metal alloys, low-fired ceramics, and less obviously to organic materials (Agnew 1981; Craft et al. 1996; Donovan and Moynehan 1965; Feenstra 1984; Fitz 1989; Gibson et al. 1997; Larsen 1997; Tennent et al. 1993; Thickett and Odlyha 2000; Zehnder and Arnold 1984).

Reduced-sulfide compounds such as hydrogen sulfide (H_2S) and carbonyl sulfide (COS) also significant threats at much lower concentrations, at a few parts per trillion (Brimblecombe et al. 1992; Watts 1999; Watts and Libedinsky 2000). Fortunately, sources of H_2S and COS are less prevalent than sources of organic carbonyl pollutants.

Another major source of damage is surface particle deposition. Large particles, PM10 (i.e., $\geq$10 μm), entering the building through air intakes are usually removed effectively by coarse particle filters. However, museum visitors are a significant source of large particles, which are tracked in on shoes, clothing, and the air surrounding them as they pass through the exterior doors (Yoon and Brimblecombe 2001). Visitor-borne particles are not usually removed by HVAC filters. Large particles settle predominantly on horizontal surfaces; they can also soil vertical surfaces near the floor and extending up to eye level. Yoon and Brimblecombe (2001) identified a relation between the proximity of visitors to objects and soiling. The main risks posed by large particles are aesthetic degradation, caused by a loss of gloss, and scratched surfaces, caused by hard soil dusts during cleaning.

Fine particles (PM2.5) are not removed well by many coarse particle filters. Soot is the most important particle type in this size range. It does not settle out of the air easily and is influenced by energetic air molecules, natural and forced convection, and turbulent air flows. Small particles collect on all surfaces (vertical, horizontal, downward-facing, or upward-facing). Black soot particles can be a major soiling risk on large, unprotected surfaces such as tapestries or on small, porous, soft natural history collections and book margins.

Ligocki et al. (1990) and Nazaroff et al. (1990, 1993) examined the origin, fate, and concentration of particles in several museums in southern California. The rates of particle deposition were established for a typical historical house and several museums with standard air-conditioning filtration. From the deposition rate, "time for perceptible soiling" was established, to characterize the building by when soiling could be expected to be barely visible to a normal observer. Bellan et al. (2000) showed that the amount of coverage by small black particles, similar to soot, on a white surface was just detectable at a surface coverage of 2.6%, if the observer could compare a sharp edge of soiled surface against a nonsoiled surface. This value is 12 times larger than published in earlier literature (Hancock et al. 1976). Druzik and Cass (2000) determined that, if the museums studied by Nazaroff et al. (1990) are typical of most medium-sized art museums with HVAC systems, the time to the onset of perceptible soiling of vertical surfaces is 24 to 86 years.

Some forms of chemical deterioration have been traced to particle deposition; the risk from new concrete has been covered extensively by Toishi and Kenjo (1975). However, little is known about direct chemical degradation of historic materials by these particles. It has been speculated that particle deposition may accelerate cellulose degradation and metal corrosion, based on known reaction pathways of suspended particles and other materials-science investigations, such as the corrosion of copper alloys by soluble nitrates (Hermance et al. 1971).

"Sustainable" Versus "Technically Feasible" Target Specifications. Responses to environmental factors vary, and often do not appear until the materials have significantly aged. Individual objects can also react differently than their nearest relatives in a class of objects. Providing the best available technology for a reasonably large collection to guard against all contingencies is not realistic. For most objects, it is feasible to create a safe and protective environment at a reasonable cost to the client such that they can be maintained indefinitely. Expanding protection beyond certain limits for smaller artifacts and smaller collections becomes less practical at the whole-building mechanical control level. For artifacts with specific problems or risks, it is usually better to provide microenvironments.

"Best available technology" often implies protection on a diminishing cost-benefit scale. Museums, libraries, and archives are frequently nonprofit organizations on tight budgets. Insisting on extraordinary humidity control or filtering out every air pollutant that is theoretically damaging endangers long-term sustainability. An insistence on best available technology may have the unintentional effect of highlighting the lack of useful engineering solutions rather than the more important role of HVAC systems as efficient, protective, and necessary.

DESIGN PARAMETERS

PERFORMANCE TARGET SPECIFICATIONS

Temperature and Relative Humidity

No two collections are identical. Ideally, temperature and humidity targets and tolerances for each facility are developed collaboratively by a conservator with expert knowledge of the damage factors and the realities of the collection, and a design engineer with extensive experience in designing systems that meet the needs of many different types of collections. That approach ensures specifications most likely to provide maximum life for the collection. Experienced experts are best equipped to identify areas of special risk and devise solutions, and to properly manage economic and other tradeoffs, although this level of expertise is not always available.

Table 4 summarizes the probable effects of various specification options, based on the best current knowledge (including all available data, research results, and judgment of conservators). Permissible fluctuations have been reduced to five classes: AA, A, B, C, and D. Gradients are conservatively considered to add to short-term fluctuations because artifacts can be moved from one part of a space to another, adding a space-gradient fluctuation to the dynamic fluctuations of the HVAC.

Class A is the optimum for most museums and galleries. Two possibilities with equivalent risks are given: a larger gradient and short-term fluctuations, or a larger seasonal swing. Stress relaxation is used to equate ±10% rh seasonal swing to a short ±5% rh. A major institution with the mandate and resources to prevent even tiny risks might move toward the narrower fluctuations of Class AA. However, design for very-long-term reliability must take precedence over narrow fluctuations.

Classes B and C are useful and feasible for many medium and small institutions, and are the best that can be done in most historic buildings. Class D recognizes that control of dampness is the only climatic issue.

Building Envelope Issues

Museums, libraries, and archives often ask mechanical engineers for "improved climate control" in buildings never designed for such purposes. Conrad (1995) grouped such buildings (and building parts) by their possibilities and limitations into seven categories. In an abridged version of his scheme, Table 5 lists the possible classes of fluctuation control possible each class of building. Local climate determines which possibility is most likely. For detailed guidance on thermal and moisture performance of building envelopes, refer to Chapters 22, 23, and 29 of the 2001 *ASHRAE Handbook—Fundamentals*.

Airborne Pollutant Targets

Fine particles (<2.5 μm diameter) and five gaseous pollutants are identified as the principal airborne pollutants for museums and archives (Table 6). Nitrogen dioxide, fine particles, ozone, and sulfur dioxide are generated mainly outside. Hydrogen sulfide can be generated inside the building [depending on materials (especially carpets and wall coverings), the number of visitors, and inside activities] or infiltrate the building envelope (depending on geographic location and factors such as biomass decay, volcanoes, sulfur springs, etc.). Acetic acid is mainly generated by wood, construc-

Table 4 Temperature and Relative Humidity Specifications for Museum, Library, and Archival Collections

<table>
<tr><th rowspan="2">Type</th><th rowspan="2">Set Point or Annual Average</th><th colspan="3">Maximum Fluctuations and Gradients in Controlled Spaces</th><th rowspan="2">Collection Risks and Benefits</th></tr>
<tr><th>Class of Control</th><th>Short Fluctuations plus Space Gradients</th><th>Seasonal Adjustments in System Set Point</th></tr>
<tr><td rowspan="6">General Museums, Art Galleries, Libraries, and Archives

All reading and retrieval rooms, rooms for storing chemically stable collections, especially if mechanically medium to high vulnerability.</td><td rowspan="6">50% rh
(or historic annual average for permanent collections)

Temperature set between 59 and 77°F

Note: Rooms intended for loan exhibitions must handle set point specified in loan agreement, typically 50% rh, 70°F, but sometimes 55% or 60% rh.</td><td>AA
Precision control, no seasonal changes</td><td>±5% rh, ±4°F</td><td>Relative humidity no change
Up 9°F; down 9°F</td><td>No risk of mechanical damage to most artifacts and paintings. Some metals and minerals may degrade if 50% rh exceeds a critical relative humidity.
Chemically unstable objects unusable within decades.</td></tr>
<tr><td rowspan="2">A
Precision control, some gradients or seasonal changes, not both</td><td>±5% rh, ±4°F</td><td>Up 10% rh, down 10% rh
Up 9°F; down 18°F</td><td rowspan="2">Small risk of mechanical damage to high-vulnerability artifacts; no mechanical risk to most artifacts, paintings, photographs, and books.
Chemically unstable objects unusable within decades.</td></tr>
<tr><td>±10% rh, ±4°F</td><td>RH no change
Up 9°F; down 18°F</td></tr>
<tr><td>B
Precision control, some gradients plus winter temperature setback</td><td>±10% rh, ±9°F</td><td>Up 10%, down 10% rh
Up 18°F, but not above 86°F
Down as low as necessary to maintain RH control</td><td>Moderate risk of mechanical damage to high-vulnerability artifacts; tiny risk to most paintings, most photographs, some artifacts, some books; no risk to many artifacts and most books.
Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.</td></tr>
<tr><td>C
Prevent all high-risk extremes</td><td colspan="2">Within 25 to 75% rh year-round
Temperature rarely over 86°F, usually below 77°F</td><td>High risk of mechanical damage to high-vulnerability artifacts; moderate risk to most paintings, most photographs, some artifacts, some books; tiny risk to many artifacts and most books.
Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.</td></tr>
<tr><td>D
Prevent dampness</td><td colspan="2">Reliably below 75% rh</td><td>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.
Mold growth and rapid corrosion avoided.
Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.</td></tr>
<tr><td rowspan="2">Archives, Libraries

Storing chemically unstable collections</td><td>Cold Store:
–4°F, 40% rh</td><td colspan="3">±10% rh ±4°F</td><td>Chemically unstable objects usable for millennia. Relative humidity fluctuations under one month do not affect most properly packaged records at these temperatures (time out of storage becomes lifetime determinant).</td></tr>
<tr><td>Cool Store: 50°F
30 to 50% rh</td><td colspan="3">(Even if achieved only during winter setback, this is a net advantage to such collections, as long as damp is not incurred)</td><td>Chemically unstable objects usable for a century or more. Such books and papers tend to have low mechanical vulnerability to fluctuations.</td></tr>
<tr><td>Special Metal Collections</td><td>Dry room:
0 to 30% rh</td><td colspan="3">Relative humidity not to exceed some critical value, typically 30% rh</td><td></td></tr>
</table>

Note: Short fluctuations means any fluctuation less than the seasonal adjustment. However, as noted in the section on Response Times of Artifacts, some fluctuations are too short to affect some artifacts or enclosed artifacts.

tion materials, or organic artifacts. It can be found at high levels in enclosures. Other pollutants in Table 5 do not require HVAC specifications because their sources, actions, and permissible indoor concentrations are equal to or less than those of the targeted pollutant of the same chemical group. For example, acetic acid is the most reactive carbonyl compound, so only this organic acid has been specified even though other carbonyls may be present. Strategies applied to control acetic acid concentrations also reduce levels of all organic carbonyl pollutants. The same logic applies to particles (PM2.5): strategies to reduce concentrations of fine particles also reduce coarse particles.

Table 6 combines pollutant information on object deterioration, troposphere benchmarks, ambient levels in urban areas, and reductions achieved by buildings with and without HVAC systems. The label “no observable adverse effect levels” (NOAEL) represents a new term suggested by Tétreault (1999a). NOAEL concentrations are designated for periods of 1, 10, and 100 years. Extensive sets of NOAEL are available (Canadian Conservation Institute 1999). Table 6 is based on the most sensitive material to the specified pollutant. Reductions cited for buildings with and without HVAC filtration systems are based on current experience (Grzywacz 1999; Grzywacz and Donohoe 2000).

It is often preferable to exclude pollutant sources by properly selecting products used inside [e.g., not using vinegar-based cleaning products or amine compounds as corrosion inhibitors in humidification systems (see Table 4)].

Table 5 Classification of Climate Control Potential in Buildings

Category of Control	Building Class	Typical Building Construction	Typical Type of Building	Typical Building Use	System Used	Practical Limit of Climate Control	Class of Control Possible
Uncontrolled	I	Open structure	Privy, stocks, bridge, sawmill, well	No occupancy, open to viewers all year.	No system.	None	D (if benign climate)
	II	Sheathed post and beam	Cabins, barns, sheds, silos, icehouse	No occupancy. Special event access.	Exhaust fans, open windows, supply fans, attic venting. No heat.	Ventilation	C (if benign climate) D (unless damp climate)
Partial control	III	Uninsulated masonry, framed and sided walls, single-glazed windows	Boat, train, lighthouse, rough frame house, forge	Summer tour use. Closed to public in winter. No occupancy.	Low level heat, summer exhaust ventilation, humidistatic heating for winter control.	Heating, ventilating	C (if benign climate) D (unless hot damp climate)
	IV	Heavy masonry or composite walls with plaster. Tight construction; storm windows	Finished house, church, meeting house, store, inn, some office buildings	Staff in isolated rooms, gift shop. Walk-through visitors only. Limited occupancy. No winter use.	Ducted low level heat. Summer cooling, on/off control, DX cooling, some humidification. Reheat capability.	Basic HVAC	B (if benign climate) C (if mild winter) D
Climate controlled	V	Insulated structures, double glazing, vapor retardant, double doors	Purpose-built museums, research libraries, galleries, exhibits, storage rooms	Education groups. Good open public facility. Unlimited occupancy.	Ducted heat, cooling, reheat, and humidification with control dead band.	Climate control, often with seasonal drift	AA (if mild winters) A B
	VI	Metal wall construction, interior rooms with sealed walls and controlled occupancy	Vaults, storage rooms, cases	No occupancy. Access by appointment.	Special heating, cooling, and humidity control with precision constant stability control.	Special constant environments	AA A Cool Cold Dry

Source: Adapted from Conrad (1995).

Table 6 Airborne Pollutant Performance Targets for Museum, Gallery, Library, and Archival Collections

Key Airborne Pollutants	Maximum Average Concentrations of Airborne Pollutants Allowed for Each Preservation Target, ppbv for Performance Target of: 100 y	10 y	1 y	Reference Concentration Range, ppbv: Clean Low Troposphere	Urban Area	Range of Indoor-Outdoor Ratio, %: HVAC without Filters[a] or NV[b]	HVAC with Filters
Acetic acid	100[c]	100	400	0.3 to 5	0.5 to 20[d]	>100	>100
Hydrogen sulfide	0.01	0.1	0.71	0.01 to 1	0.02 to 1	10 to 400	10 to 300
Nitrogen dioxide	0.1	1	5.2	0.2 to 20	3 to 200	1 to 90	1 to 30
Ozone	0.1	1	5.0	2 to 200	20 to 300	1 to 100	1 to 30
Sulfur dioxide	0.1	1	3.8	0.1 to 30	6 to 100	10 to 50	1 to 10
Fine particles ($PM_{2.5}$)	0.1	1	10	1 to 30	1 to 100	10 to 100	10 to 30

Source: Adapted from Tétreault (2003).
Note: This extrapolation of minimum risk for most collections over an extended period of exposition assumes temperature between 68 to 86°F, cleanliness of the collection, and below 60% rh; hypersensitive objects such as lead, vulcanized natural rubber, silver and most sensitive colorants are excluded and require special control measures.
[a]HVAC has no high-performance particle or gaseous filters.
[b]NV: natural ventilation.
[c]Because NOEAL of acetic acid on objects was found at high levels, concentration lower than 100 ppbv is not mandatory.
[d]Acetic acid levels can be as high as 10 000 ppbv inside enclosures made with inappropriate materials.

Deterioration of collections by airborne pollutants can be minimized by controlling relative humidity (below 60%, or below 50% for long-term preservation) and temperature (about 68°F). Cleanliness of the collection is also important because salts, fatty acids, or metallic dirt may initiate or accelerate some deterioration processes caused by gaseous pollutants.

For long-term preservation, levels of airborne pollutants should be below 0.03 $\mu g/ft^3$ or less than 1 ppb for inorganic gases and fine particles and in the double- or single-digit ppb range for organic carbonyl pollutants. Low levels of airborne pollutants can be achieved in many ways, including building design, filtration, maintenance, and operations. A building is a complex, dynamic environment that affects the indoor concentration and fate of airborne pollutants. Detailed discussion is beyond the scope of this chapter, but major factors influencing airborne pollutants include the following:

- Outdoor pollutant load
- Visitor traffic and indoor activities
- Location of outside air intake
- Location and type of air delivery vents in collection spaces
- Ratio of outside to recirculated air when the building is open to the public and staff, and when it is closed to the public
- Particle and gaseous filter efficiency and filter maintenance
- Location and fit of filters in HVAC system
- Janitorial, building, and grounds maintenance practices

Even the surface temperature of the walls and artifacts can influence particle deposition. For these reasons, the HVAC engineer has considerable flexibility in controlling filtration although some architectural, maintenance, and geographic factors are beyond control. Nevertheless, engineers should be aware of these issues and bring them into design discussion when appropriate.

Many institutions with a small or limited operating budget may prefer to use enclosures. Long-term preservation of collections in either rooms or enclosures must be discussed between the client, design engineers, and conservation professionals. In addition to decision factors already stated, ethical aspects of the exhibition, security, overall long-term preservation goals, object-pollutant interactions, and IAQ performances of the HVAC system and enclosures should taken in consideration

SYSTEM SELECTION AND DESIGN

A typical project consists of many different types of spaces, such as galleries, reading rooms, search rooms, laboratories, conference rooms, stacks, storage rooms, restaurants or cafeterias, auditoriums, rare book vaults, offices, lounges, and study rooms. Areas housing objects or collections are considered to need a special environment, defined by the criteria in the previous section, for preventive conservation or preservation.

The HVAC system for a preservation environment must maintain relative humidity, maintain temperature and air movement, and filter air, evenly throughout the space, with minimum risk of damage to the collections, at a cost the institution can support. Special HVAC system indications usually fall into two general categories: museums, including galleries and other spaces where environmentally sensitive objects are kept or displayed, and libraries, including archives and other spaces where primarily paper-based collections are stored and used, with some additional concern for film and other media.

One primary requirement is high performance with low or limited annual operating budgets. This shifts focus to capital investments in systems and features to minimize operating costs and problems.

Design Issues

Functional Organization. Maintaining an effective preservation environment depends heavily on HVAC systems, but other factors, such as basic architectural design (e.g., windows, vapor retardants) and building operation (e.g., hours of operation, availability of tempering sources), must complement HVAC design. Ideally, the HVAC engineer should be involved early in project planning to ensure that space layout does not present unnecessary problems. In the best case, collections are housed separately from visitors, users, staff, and all other functions. Where this is not possible, processes and activities that threaten collections should be physically and mechanically separated from the collections. Separate systems for collection and noncollection areas allow isolation of environments and can reduce project costs for noncollection areas.

A typical issue, particularly in fine art museums, is whether to treat executive offices as collection spaces. This should be considered carefully, not only for the added capital and operating cost, but also for the risks to the collection if offices are not so treated and are nonetheless used for collections display.

Frequently used entrances, such as the lobby and loading dock, are one of the most environmentally disruptive elements. The engineer should ensure that loads from these spaces are managed and isolated from the primary collection areas.

Substantial holdings of film ideally should be housed separately from other collections; for details, see the section on Materials Damage Caused by Airborne Pollutants.

Humidity-Tolerant Building Envelope. Winter humidification should be a high priority in a heated building in temperate or cold climates, but the humidity tolerance of the building must be considered. Often, the building envelope has problem condensation (on single-glazed windows, on window frames, or in the exterior wall or roof) in winter at interior humidities as low as 25%. This condensation can cause cosmetic or substantive damage to the building. In such cases there are three alternatives: (1) keeping winter humidity stable and below the point where problem condensation occurs; (2) retrofitting the building envelope to tolerate higher humidity; or (3) reducing the space temperature.

Depending on the humidity level that can be maintained without problems, a collection may require that the envelope be modified to support higher winter humidity. These changes benefit collections, but present considerable design challenges and expenses. If a collection needing a higher humidity does not dominate a building, but only a manageable minority of the spaces, then separate humidified storage containers, cases, cabinets, or rooms are an alternative. These must be carefully sealed and isolated to preserve their internal environment and to protect the building from the moisture.

Reliability. Most collections can tolerate several hours of lost conditions without major damage, but some are at risk even with brief losses of control. The engineer should evaluate equipment failure scenarios against collection sensitivities and likely maintenance efforts to see what reasonable precautions can be taken to minimize downtime and damage to the collection. Spare equipment may need to be kept at the project site to allow timely repairs.

Loads. Certain load characteristics of collection buildings should be considered in system design. Usually, the HVAC system should operate 24 h a day. Galleries and reading rooms tend to have high occupancy only at certain times. Some gallery occupancies are as high as 10 ft^2 per person, but stack or storage areas may have 1000 ft^2 per person or less. The system should be designed to handle this load as well as the more common part-loads. Many engineers design to 20 ft^2 per person because part of the room is never occupied. In other facilities, where the space is extensively used for receptions, openings, and other high-traffic activities, even higher density assumptions may be justified. Continual and close dialogue between the designer and client is therefore important.

Lighting loads vary widely from space to space and at different times of the day. The most common driver of sizing cooling in a museum is display lighting. The engineer should ensure that estimated lighting loads are realistic. Lighting typically varies from 2 to 8 W/ft^2 for display areas; figures as high as 15 W/ft^2 are sometimes requested by lighting designers, but are rarely needed. With growing awareness of damage caused by light, display areas for light-sensitive objects should have low illumination levels, and associated low lighting power densities.

Exhibit Cases. Exhibit cases should be designed to protect the collection from environmental extremes and excesses. Sealed or vented cases are typically used. Sealed cases rely on isolation from the ambient environment in the exhibition room and usually require passive or special conditioning systems independent of regular room air. Because sealed cases are subject to buildup of gaseous contaminants, they should be made of inert or low-emission materials, or those that emit gases benign to the objects with the sealed case. In a properly conditioned space, exhibit cases that are within, built into, or back up to this space can be vented.

Exhibit cases should not be conditioned by blowing supply air into the cases, or by drawing return air through the cases. Supply air temperature and humidity vary and can cause extremes if blown into a case. Even if temperature and humidity conditions are sensed inside the case as part of the control system, the typical high ratio of supply air to the case volume makes such treatments problematic. Acute temperature or humidity conditions in supply air are undiluted and immediately affect sensitive objects. Return air is more stable but tends to have higher levels of particulate contamination, leading to particle accumulation in the display case. Active conditioning of exhibit cases has been used successfully, but only by using purpose-designed equipment.

Two approaches for local mechanical control of display cases have been used: one machine per case, and one machine for many cases. The Royal Ontario Museum in Toronto uses one machine per case, circulating air in a closed loop between case and machine via small ducts (2 in. diameter). A prototype and design plans for a machine to supply many cases were developed by the Canadian Conservation Institute (Michalski 1982). The unit supplies filtered and humidity-controlled air via small tubes (typically 0.25 in. diameter) to each case without return air, relying instead on compensating leakage from the case. It uses multistage centrifugal blowers at about 10 in. of water and a silica gel column, which controls humidity.

Slow air-exchange units take full advantage of the case's buffering capacity, so relative humidity takes many days to rise or fall after mechanical failure, making repair response time less critical. Sease (1991) described several units retrofitted in the Chicago Field Museum. Beale (1996) compared cost and effectiveness of three approaches to relative humidity control in an existing museum building at the Boston Museum of Fine Arts: the CCI machine for many cases, HVAC retrofits for gallery zones, and silica gel in cases. Although case-controlling machines are cost-effective compared to whole-zone control, they have inadequate support (e.g., repair manuals, service parts, installation guidelines, troubleshooting guides).

Such systems are not configured like typical HVAC systems and have additional features, such as desiccant beds to stabilize supply air humidity. They are used primarily in cold climates, where conditioning large, historic galleries is problematic and case conditioning is often the only solution. Condition stability with such systems is less than ideal, and much less than sealed exhibit cases with passive conditioning agents. The primary value is where many cases need to be conditioned and rigorous sealing and reconditioning passive agents are impractical. Lights should always be housed in a separate ventilated compartment from the one housing the artifacts.

Cold Storage Vaults. Cold storage vaults extend the life of materials particularly sensitive to thermal deterioration, such as acetate films and color photographic materials. These vaults usually require special equipment; most successful systems are provided by experienced turnkey or design-build vendors (Wilhelm 1993).

Primary Elements and Features

The following primary HVAC elements and features provide a good preservation environment for a museum or library, as in Figure 6 (Lull 1990).

Constant Air Volume. Air should be constantly circulated at sufficient volume, regardless of tempering needs, to ensure good circulation throughout the collection space. In general, perimeter radiation and other sensible-only heating or cooling elements should be avoided, because they can create local humidity extremes near collections.

Cooling and Heating. The system should provide necessary cooling and heating, but must subordinate temperature control to stable relative humidity.

Humidification. Humidification should be provided by steam or water introduced in the air system. Evaluate the moisture source for contamination potential. Often, heating steam is treated with compounds (especially amines) that can pose a risk to the collection

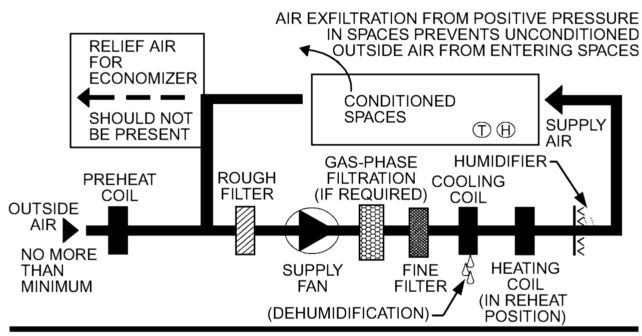

Fig. 6 Primary Elements of Preservation Environment HVAC System

(Volent and Baer 1985). Systems should be selected and designed to prevent standing pools of water, and should follow good humidification design as described in Chapters 1 and 20 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment*.

Unlike most other applications, HVAC design for this building type is often more concerned with humidity control than temperature control. The averaging effect of a common mixed return air and common humidifier on a central system is preferred, but sometimes adding zone humidifiers has been necessary to recover from unsatisfactory conditions, even when the same humidity level is desired in each zone on the same system. Attempt to identify and correct the cause of the condition before taking drastic measures.

Maintaining widely different conditions in zones using the same air handler can be difficult to achieve and waste energy. If possible, different zone conditions should have the same absolute moisture content, using zone reheat to modify space humidity for different relative humidity requirements.

Dehumidification. The most common problem in museums and libraries is inadequate or ineffective dehumidification. Modest dehumidification can be achieved with most cooling systems, limited by the apparatus dew point at the cooling coil, and requiring adequate reheat. Most problems derive from compromises in the cooling medium temperature or lack of reheat. Some chilled-water systems may not reliably deliver water that is cold enough, or may have chilled-water temperature reset or cooling coils that are too shallow for dehumidification to occur. Some reheat coils' heating sources may be unavailable in summer or too expensive to operate. Insufficiently cooled chilled water cannot be overcome by good design.

Sebor (1995) suggests the following typical approaches to more aggressive dehumidification:

- **Low-temperature chilled water**, usually based on a glycol solution, offers familiar operation and stable control but requires glycol management.
- **Direct expansion (DX) refrigeration** tends to be better for small systems and has lower capital costs, but generally is less reliable, requires more energy, and may require a defrost cycle.
- **Desiccant dehumidifiers** are less familiar, but can be quite effective if properly designed, installed, and maintained. Economy of operation is very sensitive to the cost of the regeneration heat source.

Dehumidification systems should be additions to a typical cooling system; they cannot maintain comfort conditions by themselves. For libraries or archives requiring cool, dry conditions, a desiccant system may be required. Chapter 22 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment* has further information on desiccants.

Outside Air. Because the goal is to maintain a close-tolerance environment, excessive amounts of outside air for economizer cooling are problematic. Outside air is almost always at nondesign temperature and humidity, and can introduce particles and gaseous pollution. Economizer cooling is often the primary cause of humidity fluctuations in museums and libraries and requires very large humidification systems; air-side economizers should not be used unless (1) bin analysis or other study shows outside air moisture content to be favorable for an economical number of hours, and (2) favorable outside air can be reliably selected by the control system. Outside air should be the minimum amount required to provide fresh air for occupants and to pressurize collection spaces. Relief air (see Figure 6) usually should not be used, unless required to support high outside-air requirements for high occupancy. Peak occupancies are rarely the norm, so outside air might be controlled by monitoring levels of carbon dioxide or other gases indicative of occupancy.

The added cost of preconditioning outside air, usually with a precooling coil, often benefits humidity control and economical operation. Cooling can reduce the amount of reheat needed for dehumidification, and may reduce static pressure on the primary fan by keeping the cooling coil dry.

Particle Filtration. To avoid buildup and cleaning problems, air cleaning should be effective down to the contamination particle size, typically <1 μm. This usually requires 90 to 95% atmospheric dust media filtration (per ASHRAE *Standard* 52.1) in a balanced particulate filtration system.

High-voltage electrostatic air cleaners may not be suitable because they can generate ozone, which can oxidize objects. An alternative is using permanently polarized electret-plastic filter media, which cannot generate ozone.

Gas-Phase Filtration. Where new construction materials, indoor pollutants, collection off-gassing, or infiltration of outside pollution threaten a sensitive collection, active control of gaseous contaminants may be required, especially for sensitive, valuable holdings such as metals and alloys, film, and rare books. See the discussion of Air Pollutants Targets in the Design Parameters section, and Chapter 45 for gas-phase filtration applications.

Air Distribution. High, monumental spaces are prone to thermal stratification; if this places collections at risk, then appropriate return and supply air may be required to ensure air motion across the entire space. Gallery and display area use and loads may change because of varied lighting and numbers of visitors. Although this can sometimes be addressed through temperature control zones, adjustable supply air may be more economical and more effective.

Supply air should not blow directly onto collections. Diffusing supply air along a wall can be a major problem in a gallery, where collections are displayed on walls. Floor supply should also be avoided because particles at foot level become entrained.

Controls. Sensors, thermostats, and humidistats must be located in the collection space, not in the return airstream. Temperature variation is usually preferable to prolonged humidity swings. This strongly affects controls design, because conventional control treats temperature as the primary goal and humidity as supplementary. Where comfort conditions are not required, humidity-controlled heating, which modulates heating within a very broad temperature dead band to seek stable or moderated humidity conditions, might be used (LaFontaine 1982; Marcon 1987; Staniforth 1984). By tracking system performance using the temperature control system, operators can adjust zones based on actual operating history. Operating at lower system volume at night when lights are off, but maintaining more than 6 air changes per hour, can save energy.

Types of Systems

The type of HVAC system used is critical to achieving project environmental goals. Proper airflow filters the air, controls humidity, and suppresses mold growth. Minimum airflow criteria vary from 6 to 8 air changes per hour (NBS 1983; Chapter 3 of this volume). These needs are usually best met with a constant-volume system.

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

Central air-handling stations keep filtration, dehumidification, humidification, maintenance, and monitoring away from the collection. The investment in added space and the expense of the more elaborate duct system provides major returns in reduced disruption to the collection spaces and a dramatically extended service life for the distribution system. Unlike most commercial projects, space turnover in museums is low and rezoning is rarely needed. In some museums, 60-year-old multizone duct systems have been reused. Renovating the old system is economical, with most renovations confined entirely to the mechanical rooms. This is in comparison to common duct distribution systems (e.g., terminal reheat, dual-duct, and variable air volume), where renovations often require a new duct system and terminal equipment, involving major expense from demolishing the old ducts, installing the new duct system, and reinstalling architectural finishes.

Constant-Volume Reheat. A constant-volume reheat system can present problems if improperly applied. In many institutions, terminal reheat with steam or hot-water coils located near or over collection spaces cause chronic problems from steam and water leaks. Efficient zone-level humidification often suggests placing the humidifier downstream from the reheat coil; if the reheat coil is located near or over collection spaces, preventive maintenance on humidifiers further complicates maintenance problems. Constant-volume reheat systems are very effective when reheat coils and humidifiers are installed entirely within the mechanical space, instead of at the terminal, feeding through what is effectively a multizone distribution system.

Multizone System. A multizone air handler with zone reheat and zone humidification can be a stable and relatively energy-efficient solution. However, multizone systems without individual zone reheat and individual zone humidification have proved problematic in many institutions, requiring retrofit of zone equipment for stable humidity control. With proper layout and equipment complement, a multizone system can reduce the amount of reheat and be very energy-efficient.

Bovill (1988, Figure 10) shows preferences for constant-volume and multizone systems in collection spaces. Without the need for many temperature control zones, but with the need for high air quality, the choices are constant-volume, multizone with bypass, dual-duct, and four-pipe induction. When air handlers are outside collection areas (as recommended), the best choices are constant-volume and multizone with bypass. When other systems are used, the client must be made fully aware of the possible compromises in performance, cost, and serviceability.

Dehumidification Coil. An important feature of multizone and dual-duct air handlers is a separate dehumidification coil upstream of both the hot and cold decks. This separate cooling coil, distinct from the one in the cold deck, is used during dehumidification demand. Air can be cooled to dew point even if it eventually flows through the hot deck. Without this feature, moist return air could be warmed in the hot deck and delivered back to the room without being dehumidified. An alternative is to locate a single cooling coil upstream of both decks, where the cold deck simply bypasses the hot deck, although this configuration can increase energy use.

Fan-Coil Units. Fan-coil units have been problematic when placed in and above collection areas. Fan-coil units expand and decentralize maintenance, requiring maintenance in collection areas and a net increase in overall facility maintenance. Because they cool locally, they need condensate drains, which can leak or back up over time. As all-water systems, they require four pressurized-water pipes to each unit, increasing the chance of piping leaks in collection areas. Also, fan-coil units rarely (if ever) can provide the filtration and humidity control required for collection spaces.

Variable Air Volume (VAV). VAV, though appropriate for other types of buildings, tends to be inappropriate for collection housing because of poor humidity control, inadequate airflow, maintenance disruption, leaks in the collection spaces, and inflexibility to meet environmental needs. A VAV system may be chosen because of space and budget constraints, but almost always the cost and space required for a properly designed VAV system (full filtration, local humidification, local dehumidification, minimum air volume settings, well-planned piping and maintenance access, well-documented operating instructions) give no advantages over constant-volume systems. VAV systems can save energy compared to constant-volume systems, but usually at the collection's expense.

If used, a VAV system should look much like a constant-volume reheat system, with the minimum airflow to prevent mold growth, contamination buildup, and uneven conditions in the conditioned space. Terminal equipment should include reheat for each zone and be located in mechanical rooms or other spaces where access and service do not endanger a collection. If VAV performance becomes a problem, it can be easily converted to a constant-volume reheat system with only an adjustment of controls.

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

Energy and Operating Costs

Operating a preservation environment is often costly, but it is necessary for long-term protection of a valuable collection. In most cases, the increase in usable life of a collection easily justifies the annual energy and operating costs to maintain the special environmental conditions. For institutions with small or limited operating budgets that cannot afford a major increase in annual energy cost, some compromises might be warranted or some initial capital investments made to reduce recurring annual costs. Careful commissioning using multiple instruments is helpful, and postconstruction tuning and off-hours volume reduction can reduce fan energy.

Scope of Special Environments. One of the best ways to reduce operating costs is to treat as little of the building as possible with the special environments. Spaces not needing preservation conditions should be on separate air systems that operate only when occupied.

Energy Efficiency. Using condenser heat to provide reheat for dehumidification can increase efficiency, and can substantially reduce dehumidification energy cost. Although an air-side economizer can cause problems, a water-side economizer can allow efficient winter cooling using condenser water. Because load varies between day and night operations, particularly in museums, night cooling loads are sometimes best met with a smaller off-hours chiller. Similarly, primary-secondary pumping with two-way control valves can be useful as loads vary over the day and across areas.

Daylighting. Using natural light is often proposed. Ayres et al. (1990) noted that this feature is always a net energy penalty. If used, the daylighting aperture should be minimized, and avoided as much as possible in and over collection areas. For lower risk of leaks and better-managed lighting, clerestories are preferred over skylights.

Humidistatically Controlled Heating. This specialized approach has limited application and must include safety controls, but is sometimes the only option that can handle envelope limitations in cold climates. In this approach, the heating system is controlled by a humidistat rather than a thermostat (LaFontaine and Michalski 1984); cold, damp air is heated until the relative humidity drops to 50%. Where interior temperatures drop consistently below 50°F, it solves the problem of humidity in a building that does not have an adequate envelope. Obviously, humidistatically controlled heating does not provide human comfort in winter, but many small museums, historic buildings, and reserve collection buildings are essentially unoccupied in winter. A high-limit thermostat is necessary to stop overheating during warm weather, and a low-limit thermostat is optional if water pipe freezing is a concern. This approach has been used in Canada (LaFontaine 1982; Marcon 1987), the United States (Kerschner 1992), and in many historic buildings in Britain (Staniforth 1984).

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

This approach is cost-effective in seasonal museums (especially for low-mass wood-frame buildings) in colder climates like the northern United States and Canada, and in maritime regions. Humidistat control does not work in warm, humid weather: without a high-limit thermostat it can heat hot, humid conditions to dangerous temperatures. In this case, humidistat control can be supplemented by domestic dehumidifiers.

Hybrid Systems. This approach involves enhancing preservation in museums and libraries by using an optimum combination of radiant and convective (forced-air) systems. Decoupling the heat transfer modes enables the designer to select more function-oriented HVAC components and to ensure higher accuracy and precision in control. Additionally, hybrid HVAC seems to satisfactorily balance between the needs of preservation and human comfort. For example, in a library, human comfort could be maintained primarily by thermal radiation, while lowered air temperature protected the half-life of the books. Moreover, because the forced-air system is freed from satisfying sensible heating and cooling loads, more accurate humidity control and faster response to humidity changes may be achieved (Kilkis et al. 1995). A typical hybrid system combines panel heating and cooling with a forced-air system. More information about panel heating and cooling can be found in Chapter 6 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment*. This approach may require piping fluids into exhibition areas, with the associated risks of damage from leaks and the greater maintenance challenges. These risks must be balanced against expected savings. Leakage risk might be minimized by using capillary tubing and operating the panel under negative pressure.

Maintenance and Ease of Operation. A common failing of designs is not accounting for ongoing operation and maintenance. Most designs work if properly adjusted and maintained, but many institutions do not have the staff, budget, or expertise to give the system the attention it needs. Maintenance needs for any system should be matched against the institution's staff capabilities. For large projects in larger cities, code-required staffing for the plant should be considered; sometimes, smaller reciprocating chillers can be used at night to preclude the licensed engineer needed to operate larger chillers. Small projects without HVAC maintenance staff may need package equipment that does not require daily attention.

Effects of maintenance activities on the collection must always be taken into account. For example, testing or accidental activation of a smoke removal system can radically change the collection environment. Transitions between winter and summer modes on economizers cause many operational problems. Tools and ladders in gallery and storage areas are a threat to the collection and special precautions need to be taken.

Contaminated air conveyance components (e.g., microbiological growth and other buildup) can contribute to pollution levels, lead to premature component failure, and affect heat transfer efficiency, resulting in higher utility costs. Regular inspection and cleaning is an important part of preventative maintenance.

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