CHAPTER 21

MUSEUMS, GALLERIES, ARCHIVES, AND LIBRARIES

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UNDERSTANDING and appreciating humanity's diverse cultures and history dictates preserving 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. From project inception, both the design objective and realistically available operation and maintenance resources must be considered.

Communication with the client is especially critical when designing systems for museums, galleries, archives, and libraries because of the uniqueness of the criteria: the inherent risk associated with environmental conditions. The design team must include not only museum administrators but also collections' managers, curators, conservators, and security. Administrators are responsible for fiscal decisions, whereas the collection managers are responsible for care of the collection. Curators build the collection and design exhibitions. Conservators are charged with preservation of the collection. Security staff is critical to safekeeping of the collection. Many HVAC system design decisions are based on the needs of the collection and the use of the various spaces. To design the best system, all relevant parties must be part of the process. This chapter can only explain why temperature, humidity, light, and indoor air quality (IAQ) requirements are critical; the team must decide the exact specifications.

This chapter focuses on relative humidity, temperature, and air pollution design for HVAC systems, and describes various systems that are applicable for these spaces. The goal is to illustrate special needs of collection spaces in museums, galleries, archives, and libraries. See the References and Bibliography for additional resources.

Note that this chapter does not apply to libraries designed for public access, with collections that are not intended for archival preservation. These facilities may include collections designed for general public use or school-aged children, and may have significant quantities of electronic documents in disk format or tape. The types of controls (humidity, thermal, or particulate and molecular phase filtration) required for collections of archival preservation are not practical for these facilities (see Chapter 3 for additional information).

In nonarchival libraries, there may be no HVAC system, or the HVAC systems may be designed specifically for human comfort during occupied hours. In this application, the HVAC systems may shut off during unoccupied or low-occupancy times for energy savings.

This chapter may not apply and should be bypassed if one or more of the following conditions exist with the scope of design for a library (see Chapter 3 for additional information):

- HVAC system is cycled off during unoccupied periods
- HVAC system is turned off seasonally
- HVAC system is designed to cycle on/off with thermal satisfaction alone
- Natural ventilation is the only method of air circulation

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).

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, and restricting total illumination duration.

The preparation of this chapter is assigned to TC 9.8, Large Building Air-Conditioning Applications.

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 or formaldehyde 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 Some public and school library stacks and reading rooms

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. Any temperature change also changes the relative humidity. Therefore, careful and close control of relative humidity requires temperature control in the same magnitude of importance.

Air pollution includes outdoor-generated gaseous and particulate pollutants that infiltrate the building, as well as indoor-generated ones. Even very low levels of contaminants can adversely affect the condition of collections. Particulate filtration to control both coarse and fine particles and gaseous filtration are discussed in the System Selection and Design section.

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, temperature, indoor air quality, and ventilation.

Shock and **vibration** can cause long-term damage to sensitive objects. Vibration can 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. Additionally, excess vibration could potentially lead to objects vibrating off of exhibit and/or storage shelves.

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. Building systems also rely on the infrastructure to provide utilities and communications. Where the infrastructure is not reliable or of adequate capacity, provisions should be made for temporary or alternative supply.

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 and Bibliography for information not contained in this chapter.

ENVIRONMENTAL EFFECTS 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 62.1; and the collections’ requirements, which are not yet completely understood, and often conflict across collection types. 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. However, many collections are uniform enough to allow useful generalizations to be made about their HVAC requirements. In this chapter, the term “effective” includes institutional value judgments as well as the science of deterioration (Michalski 1996b).

Temperature and Humidity

Current Standards. The classic reference for conservation professionals is Thomson’s (1994) *The Museum Environment.* Set points of 50% rh and 68°F were listed as an example for temperate climates and unfortunately taken as ideal (in the United States, 68°F was frequently rounded up to 70°F). Misuse is a danger associated with listing standards or settings: numbers in a table can be extracted or used without understanding the associated text. This is why the parameters in this chapter are presented for different classifications of collections or building types. Environmental settings should be determined for collection types and must consider the climate zone where building is located. Photographic collections in the Pacific Northwest have different needs than porcelain in equatorial regions. The design engineer cannot be expected to know the needs of the collection, but can consult the other members of the team, especially the conservators, collection managers, and curators. Ideal set points are a compromise between comfort for museum visitors and staff and the minimum temperature and relative humidity for the collection.

Davis (2006) reports that decreasing temperature from 70 to 65°F and relative humidity from 50 to 45% significantly increases expected lifetime. A useful tool to measure aging rates or deterioration rates is the Preservation Calculator created by the Image Permanence Institute (IPI 2006), which can be downloaded for free from the IPI Web site at http://www.imagepermanenceinstitute.org/shtml_sub/dl_prescalc.shtml. This software calculates the **preservation index (PI)**, which expresses the preservation quality of a storage environment for organic materials. It is a useful tool to understand the effects of temperature and relative humidity on natural aging of organic collections. Comparing the former "ideal" set points (70°F and 50% rh) with current recommended parameters (65°F and 45% rh), the PI increases from 39 to 64 years, or 64%. IPI also developed software that includes a more sophisticated preservation calculator and takes into account collection types, light, and more.

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. This 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. Chapter 23 suggests a similar lower boundary for mold in food crops.

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.

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 must be taken to avoid cold surfaces where condensation might occur, such as on windows and ductwork.

Rapid corrosion above 75% rh occurs for two reasons: increased surface adsorption of water, and contamination by salts. Water adsorption on clean metal surfaces climbs rapidly from 3 molecules or less below 75% rh to bulk liquid layers above 75% rh (Graedel 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 of artifacts. The fundamental 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.

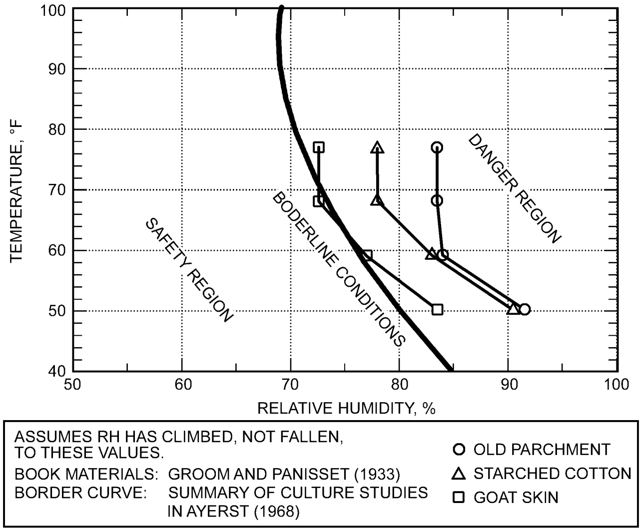


Fig. 1 Temperature and Humidity for Visible Mold in 100 to 200 days

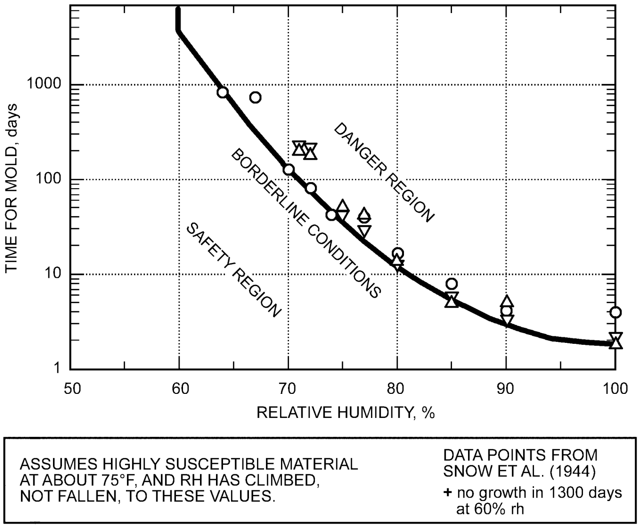


Fig. 2 Time Required for Visible Mold Growth

Research on objects (Erhardt and Mecklenburg 1994; Erhardt et al. 1996; Erlebacher et al. 1992; Mecklenburg and Tumosa 1991; Mecklenburg et al. 1998, 2005; 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.

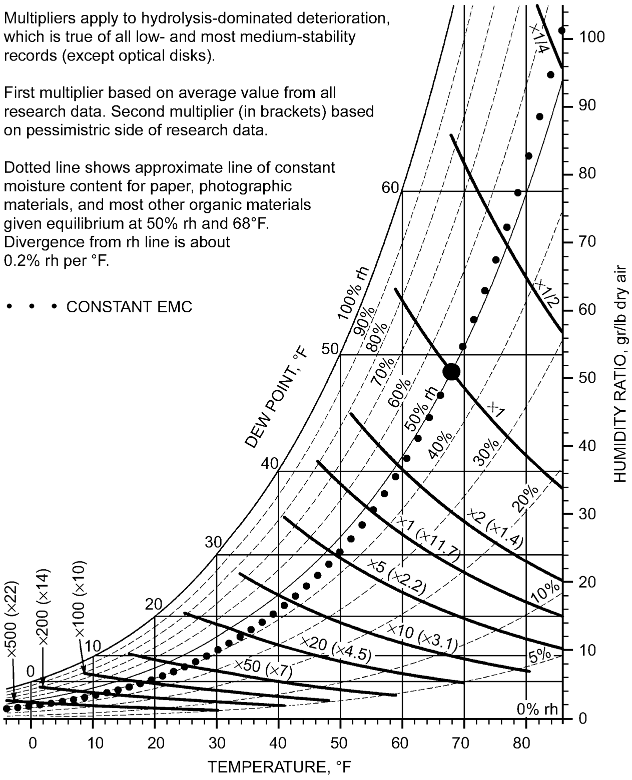
Research models use a restrained sample of organic material (e.g., paint, glue, or wood) subjected to lowered relative humidity or temperature. The material both shrinks and stiffens. Daly and Michalski (1987) and Hedley (1988) collected consistent data on the increase in tension for traditional painting 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). Mecklenburg et al. (2005) demonstrated that oil paints and acrylic paints are not adversely affected by low relative humidity but by low temperatures. Their research also shows that most oil paints shrink very little from 60 to 10% rh.

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 and Mecklenburg 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 (1999), 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: 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; rates of chemical decay may or may not approach zero, depending on slow, nonmoisture-controlled mechanisms such as oxidation.



Multipliers apply to hydrolysis-dominated deterioration, which is true of all low- and most medium-stability records (except optical disks).

First multiplier based on average value from all research data. Second multiplier (in brackets) based on pessimistic side of research data.

Dotted line shows approximate line of constant moisture content for paper, photographic materials, and most other organic materials given equilibrium at 50% rh and 68°F. Divergence from rh line is about 0.2% rh per °F.

• • • CONSTANT EMC

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

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 has developed a 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.

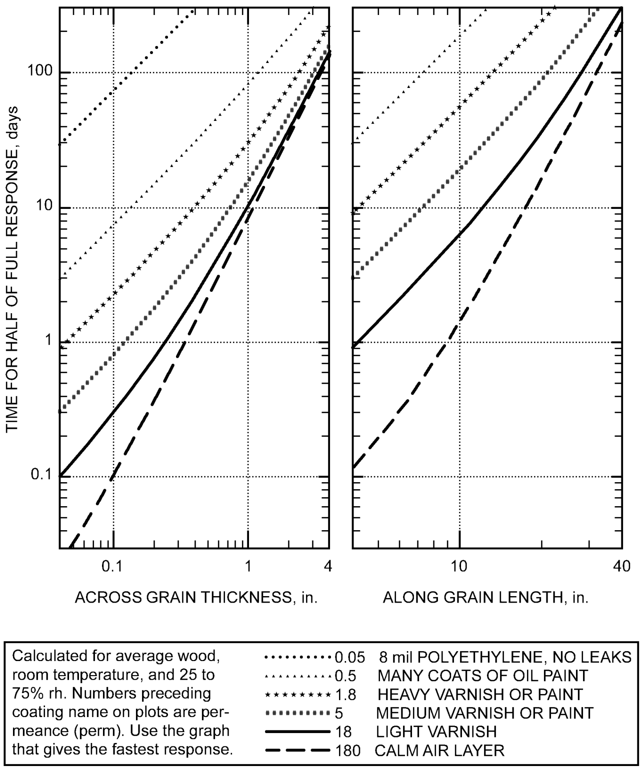


Fig. 4 Calculated Humidity Response Times of Wooden Artifacts

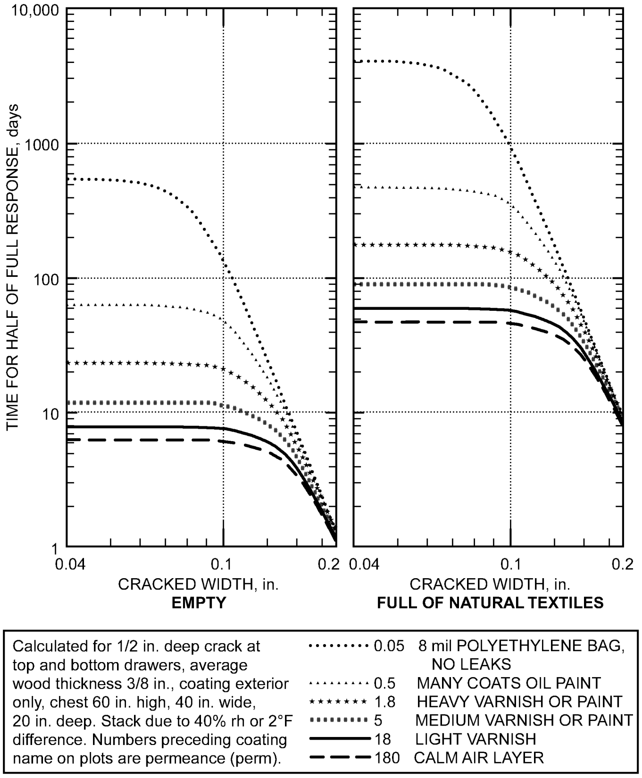


Fig. 5 Interaction of Air Leakage, Wood Coating, and Textile Buffering on Response of Wooden Chest of Drawers

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 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

Research shows 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).

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; Grzywacz 2006). 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.

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, their typical sources, and materials at

Table 2 Major Gaseous Pollutants of Concern to Museums, Galleries, Archives, and Libraries: Sources and At-Risk Materials

Gaseous Pollutants[a]	Major Sources and Some Important Minor Sources	At-Risk Materials
	Important Inorganic Pollutants	
Sulfur dioxide (SO_2) Sulfur dioxide can react with water vapor in the air and form both **sulfurous acid (H_2SO_3)** and **sulfuric acid (H_2SO_4)**. Outdoors in high humidity, acidic gases coalesce into superfine, suspended droplets, or aerosols, known as acid rain. A similar reaction occurs indoors, where acidic gases are deposited on surfaces and can cause damage.	***OUTDOOR SOURCES*** **Natural sources** • Marine biological activity and active volcanoes • Atmospheric reactions of hydrogen sulfide: H_2S reacts rapidly with oxygen and forms both SO_2 and H_2SO_4 **Industrial processes** • The primary source of SO_2 is the combustion of sulfur-containing fossil fuels, including coal, gasoline, and diesel fuel • Industrial processes associated with pulp and paper production, cement industry, and petroleum refineries, especially when less-expensive, higher-sulfur-content fuels are used • Fireworks (can be localized, short-term risk) ***INDOOR SOURCES*** • Sulfur-containing fuels, such as kerosene and coal, used to cook and heat (relevant for historic houses as well as museums in areas that predominantly use these fuels) • Firewood used to cook and heat • Vulcanized rubber • Propane- or gasoline-powered machines, equipment, and generators	• Can be absorbed onto cellulosic materials, such as **paper**, including historic wallpaper, and **textiles**, where it catalytically hydrolyzes to H_2SO_4. H_2SO_3 and H_2SO_4 can also be absorbed directly onto these materials (the acid depolymerizes the cellulosic structure, and though damage is invisible, affected materials are embrittled and weakened) • SO_2 and related acids react with animal skins, such as **leather** and **parchment** [this breaks down the molecular structure and weakens the material; as a result, surface becomes powdery and is easily abraded (red rot)] • With its pollutant progeny, reacts with acid-sensitive **pigments**, resulting in typically nonreversible color change (e.g., lead white is converted to black lead sulfate, resulting in darkened color); lead-tin yellow, chrome yellow, verdigris, chrome orange, emerald green, and chrome red, among others, also are darkened by sulfates • Fades **dyestuffs**, affecting color of watercolors, textiles, costumes, etc. • Most **metals**, including copper, silver, bronze alloys, and aluminum, are susceptible to corrosion by any acidic species, causing irreversible damage • Silver salts in **photographs** are attacked, darkening the image • Attacks stone such as **limestone**, **marble**, **dolomite**, and other carbonate minerals or calcareous materials such as **shells**, **clays**, and **tiles**; at-risk objects include sculpture, natural history collections, and low-fire ceramics • When adsorbed on soot or carbon particles on dirty objects, can be oxidized to sulfuric acid or sulfurous acid, a risk for all **acid-sensitive** materials
Nitrogen oxides (NO_x) NO_x is a collective term for **nitrogen monoxide (NO)** and **nitrogen dioxide (NO_2)**. Colorless NO is a primary vehicular pollutant. It reacts with other chemical species in the air to produce many other reactive nitrogen compounds, especially NO_2, a pungent red gas partly responsible for the color of photochemical smog. Oxidation (by ozone, UV irradiation, etc.) of nitrogen oxides generates **nitrous acid**, **HNO_2**, and **nitric acid**, **HNO_3**. This occurs indoors and outdoors. These acidic analogues are highly reactive.	***OUTDOOR SOURCES*** **Natural sources** • Natural sources include lightning and biological processes such as soil microbes, vegetation, biomass fires, etc. • Agricultural fertilizers **Industrial processes** • Combustion of fossil fuels for industry and vehicles (high concentrations associated with urban traffic and thermal power plants) • Fireworks (temporary but relevant source) ***INDOOR SOURCES*** **Gas-phase reactions** • Formation of acids: reaction of NO and NO_2 on interior surfaces, including glass, and with carbon and carbonaceous aerosols generates HNO_2 and HNO_3, respectively **Indoor activities** • Stoves, heaters, fireplaces, and other sources of combustion • Tobacco smoke • Dry-process photocopiers • Degradation of cellulose nitrate objects **Construction materials/activities** • Generators and heavy equipment that use fuel-combustion engines	• Nitrous and nitric acids can damage the same **acid-sensitive materials** attacked by sulfuric or sulfurous acids • NO_2 enhances deterioration effects of SO_2 on **leather**, **metals**, **stone**, etc. • Corrosion of **copper-rich silver**. • Nitrogen pollutants fade **dyed fibers** in textiles, costumes, drapery, tapestries, etc. Reactions with **dyestuffs** alter color of textiles • Nitrogen pollutants fade certain **inks** as well as **organic pigments** in illuminated manuscripts, etc. • Nitrogen pollutants degrade **fibers** made from rayon, silk, wool, and nylon 6, causing yellowing and embrittlement • Nitrogen pollutants corrode **zinc**; synergistic effect with H_2S • Affects tarnishing of **copper** and **silver** by hydrogen sulfide
Reduced sulfur compounds **Hydrogen sulfide (H_2S)** **Carbonyl sulfide (COS)** **Carbon disulfide (CS_2)** **Hydrogen sulfide (H_2S)** smells like rotten eggs. It is responsible for the odor	***OUTDOOR SOURCES*** **Natural sources** • Volcanoes, geothermal steam, geysers, sulfur wells, hot springs • Oceans, seas, marine areas • Marshes, soils, and wetlands • Biological activity, decomposition of organic material, release from vegetation, biomass burning, forest fires, tropical forests, etc.	• H_2S destroys immature **plant tissue** (relevant for natural history or botanical collections) • **Lead pigments: carbonates** (hydrocerussite or lead white) and **oxides** (e.g., red lead pigment) are susceptible to darkening by H_2S • **Metals: copper** metal exposed to H_2S develops a black copper sulfide layer, eventually replaced by a green patina of basic copper sulfate; extremely damaging to **silver** and its salts; tarnishes silver objects; reacts with silver salts in photographs; reacts with

Table 2 Major Gaseous Pollutants of Concern to Museums, Galleries, Archives, and Libraries: Sources and At-Risk Materials (*Continued*)

Gaseous Pollutants[a]	Major Sources and Some Important Minor Sources	At-Risk Materials
common to hot springs, as well as that noticed at wastewater treatment plants. Hydrogen sulfide is extremely toxic to people, but is detectable at very low concentrations (1 ppb). Collections are susceptible to reduced sulfur compounds at even lower levels (ppt).	**Industrial processes** • Fuel and coal combustion • Production of viscose rayon, vulcanization of rubber, etc. • Petroleum production, paper processing, and wood pulping **Atmospheric chemistry** • H_2S and COS can be formed by oxidation of carbonyl disulfide ***INDOOR SOURCES*** **Collections and objects** • Mineral specimens that contain pyrite (iron sulfide, FeS_2); sulfate-reducing bacteria in waterlogged objects **Display case materials** • Offgassing from sulfur-containing proteins in materials used in exhibition and display case design, especially silks, wools, and felts • Adhesives, especially those made from animal hide, such as rabbit skin glue **Construction materials/activities** • Arc welding (can be significant during renovation) **Flooring materials** • Wool carpets	silver inlays, silver gilt, etc.; reacts with **bronze**, **lead**; has synergistic effect with NO_2 to corrode **zinc** (see NO_2) • Low-fire **ceramics** • **Stone**, especially interior building stone • **Leather** (see sulfur dioxide)
Strong Oxidizing Pollutants		
Ozone (O_3) is a major constituent of smog that directly affects people, plants, and property. **Peroxyacetyl Nitrate (PAN) (CH_3-COO-O-NO_2)** is a principal secondary pollutant in photochemical smog **Peroxides (—O:O—)**, the simplest of which is hydrogen peroxide (HO:OH), are extremely reactive because of the oxygen-oxygen bond. Strong oxidizing pollutants present a great risk to collections. Oxidants break down the structure of organic materials by attacking carbon-carbon double bonds. Oxidants can also react with other gaseous pollutants, such as NO_x, to create acidic analogs; radicals such as the hydroxyl radical, •OH; and other destructive reaction by-products [e.g., oxidation of aldehydes into acetic acid (see organic carbonyl pollutants entry)].	**Ozone-Specific Sources** ***OUTDOOR SOURCES*** • Smog: tropospheric (ground-level) ozone is a major secondary pollutant of vehicular and industrial emissions ***INDOOR SOURCES*** • Office/building equipment, including dry-process photocopiers and other office equipment • Electrical arcing, including electrostatic air cleaners or filter systems and electronic insect killers **PAN-Specific Sources** ***OUTDOOR SOURCES*** • Secondary pollutants from urban traffic emissions produced by gas-phase reactions between hydrocarbons and nitrogen oxide compounds, and reactions between organic carbonyl pollutants and hydroxy radicals (•OH) • Pollutants from ethanol-fueled vehicles • Forest fires **Peroxide-Specific Sources** ***OUTDOOR SOURCES*** • Secondary pollutant generated by nitrogen oxide chemical reactions with hydrocarbons, VOCs, and organic carbonyl pollutants. • By-product of atmospheric reactions of pollutants from gasohol fuels ***INDOOR SOURCES*** • Emission from deterioration of organic materials (e.g., rubber floor tiles) • Oil-based paints • Microorganism activities	• Artists' colorants: fading of **dyes** and **pigments** • Oxidation of organic compounds with double bonds (e.g., embrittles and cracks **rubber**) • **Electrical wire coatings** (of concern to industrial collections) • **Plants** (of concern to botanical and natural history collections) • Embrittles **fabrics**, **textiles**, and **cellulosic materials** • Enhances tarnishing of **silver** by reduced sulfur compounds • Causes discoloration of **photographic prints** • Attacks **paint binders** • Affects **leather**, **parchment**, and **animal skins** (of concern to natural history collections) • Adsorbed onto **building products** (plasterboards, painted walls, carpet, linoleum, pinewood, and melamine-covered particleboard), where it can react with and damage surfaces or be re-released into environment

Table 2 Major Gaseous Pollutants of Concern to Museums, Galleries, Archives, and Libraries: Sources and At-Risk Materials (*Continued*)

Gaseous Pollutants[a]	Major Sources and Some Important Minor Sources	At-Risk Materials
Organic Carbonyl Pollutants: Aldehydes and Organic Acids		
Organic carbonyl pollutants **Aldehydes** • **Formaldehyde (HCHO)** • **Acetaldehyde (CH_3CHO)** **Organic acids** • **Formic acid (HCOOH)** • **Acetic acid (CH_3COOH)** Most materials damage by organic carbonyl pollutants is attributed to acetic acid or to formaldehyde. It is suspected that damage credited to formaldehyde is really due to its oxidized form, formic acid. Correspondingly, oxidation of acetaldehyde generates acetic acid. However, the risk from direct emissions of acetic acid is greater. (See also specific entries for organic acids, aldehydes, and formaldehyde.)	***OUTDOOR SOURCES*** **Atmospheric chemistry** • Secondary pollutants resulting from atmospheric reactions with industrial and vehicle pollutants • Precipitation: gases concentrate in fog, rain, and snow **Natural sources** • Biogenic emissions from vegetation • Biomass burning, forest fires, rainforest slash and burn, etc. • Biodeterioration of organic materials ***INDOOR SOURCES*** **Gas-phase reactions** • Indoor reactions of outdoor pollutants that infiltrate buildings • Evaporation from hot water (e.g., dishwashers, showers) • Construction and building materials, especially materials used in the construction of display cases and storage cabinets; laminated materials • Coatings, sealants, paints and adhesives, some polyvinyl acetate adhesives, oil-based paints • New houses (in older houses off-gassing has decreased significantly or ceased): materials used in cabinet making, doors and plywood subfloors as well as floor assemblies • Materials manufactured with urea formaldehyde, including foam insulation; other formaldehyde-based resins such as phenol formaldehyde wood products • Wood and wood products • Wood-based panel products, especially with urea formaldehyde and melamine formaldehyde binding resins (e.g., pressed wood, composite wood panels, chipboard, particleboard, medium-density fiberboard, parquet) • Other wood-based building materials **Flooring materials** • Cork products • Flooring, linoleum, carpets **Other materials** • Furniture and furniture coatings, varnishes • Consumer and household products, such as hair spray, perfumes and cosmetics, air fresheners, cleaning agents, etc. • Paper and paper products • Finished fabrics (See also sources specific to formic acid and acetic acid, aldehydes, and formaldehyde.)	• **Metal** corrosion: non-noble metals such as **leaded**-bronzes, **copper alloys**; base metals such as **lead**, **copper**, **silver**; corrosion of **cabinetry hardware** coated with cadmium, lead, magnesium, and zinc • Acid hydrolysis of **cellulose** reduces degree of polymerization, which is discernible as embrittlement • Attacks **calcareous materials**: land shells and seashells (i.e., Byne's disease), corals, limestone, calcium-rich fossils • Low-fire **ceramics** • Reacts with **enamel** and **glass**, especially previously damaged and weakened glass, such as weeping glass • Stained glass: corrodes **lead joins** between glass panes
Organic acids **Acetic acid (CH_3COOH)** **Formic acid (HCOOH)** (See also organic carbonyl pollutants.)	***OUTDOOR SOURCES*** • Textile industry effluents and emissions ***INDOOR SOURCES*** • Formaldehyde-free wood composite boards ***Formic-Acid-Specific Sources*** • Oxidation product from reaction of formaldehyde with light ***Acetic-Acid-Specific Sources*** • Degradation of cellulose acetate objects • Silicone sealants	(See at-risk materials under organic carbonyl pollutants.)

Table 2 Major Gaseous Pollutants of Concern to Museums, Galleries, Archives, and Libraries: Sources and At-Risk Materials (*Continued*)

Gaseous Pollutants[a]	**Major Sources and Some Important Minor Sources**	**At-Risk Materials**
Aldehydes **Formaldehyde (HCHO)** **Acetaldehyde (CH_3CHO)** (See also organic carbonyl pollutants and formaldehyde.)	***OUTDOOR SOURCES*** **Industrial processes** • Primary pollutant from vehicles using alcohol fuels (e.g., methanol, gasohol) and ethanol/gasoline fuel blends • Automobile manufacturing, especially painting ***INDOOR SOURCES*** • Combustion by-products, cooking, heating, and tobacco smoke • Artists' linseed oil paints, other drying oils **Construction and building materials** • Terra cotta bricks • Ceramic manufacturing, kiln exposures • Vinyl, laminates, wallpapers, acrylic-melamine coatings • Alkyd paints • Latex and low-VOC latex paints • Secondary pollutants produced by reaction of ozone and some carpet materials	(See at-risk materials under organic carbonyl pollutants.)
Formaldehyde Formaldehyde is easily oxidized to formic acid, which is most likely the aggressive chemical.	***INDOOR SOURCES*** • Natural history wet specimen collections • Consumer products, including decorative laminates, fiberglass products • Dry-process photocopiers • Textiles such as new clothes and fabrics, dry-cleaned clothes, permanent press fabrics, drapery, clothing, carpets, wall hangings, furniture coverings, unfinished fabrics, dyeing process residues, chemical finishes, etc. • Fungicide in emulsion paints and glues (e.g., wheat pastes) • PVC-backed carpeting • Floor finishes	• **Silver** tarnish or surface discoloration • Reacts with unexposed **photographic films** and **photographs**, especially black & white • Cross-links **proteins** (e.g., collagen), resulting in loss of strength in animal hides, leather objects, parchments, etc. (also attacks objects with gelatin, animal glue, or casein binders) • Reacts with **textiles**, **fibers** • Attacks buffered **papers** and reacts with metallic-salt inclusion in paper • Discoloration of **dyes**, fading of **organic colorants** • Chemically changes **inorganic pigments**: insoluble basic copper carbonate (main component of azurite) is converted to soluble copper acetate (See also at-risk materials in organic carbonyl pollutants.)
	Other Potentially Damaging Pollutants	
Ammonia (NH_3) **Ammonium ion ($+NH_4$)** Most damage to museum collections is from the ammonium ion, produced when water and ammonia react.	***OUTDOOR SOURCES*** **Natural sources** • Agriculture, especially fertilization, and animal wastes (animals are the largest global source of ammonia) • Biodeterioration (e.g., landfill gases), underground bacterial activity. **Industrial processes** • Fertilizer production ***INDOOR SOURCES*** • Household cleaning products • Museum visitors • Emulsion adhesives and paints • Alkaline silicone sealants • Concrete	• Blemishes **ebonite**, **natural resins** • Reacts with materials made from **cellulose nitrate**, forming ammonium salts that corrode **copper**, **nickel**, **silver**, and **zinc**

Table 2 Major Gaseous Pollutants of Concern to Museums, Galleries, Archives, and Libraries: Sources and At-Risk Materials (*Continued*)

Gaseous Pollutants[a]	Major Sources and Some Important Minor Sources	At-Risk Materials
Amines (R-NH$_2$) These alkali pollutants are derivatives of ammonia.	***INDOOR SOURCES*** • Amine-based corrosion inhibitors [diethylaminoethanol (DEAE), cyclohexylamine (CHA), and octadecylamine (ODA)] used in humidification systems and ventilation ducts • Atmospheric reactions of nitrogen species and alkali pollutants released from new concrete • Epoxy adhesives	• Causes blemishes on **paintings**, usually when pollutant is dispersed through the ventilation system • Corrosion of **bronze**, **copper**, and **silver** • Darkens **linseed** oil and forms copper amine complexes with **copper pigments** (e.g., malachite) • Blemishes furniture **varnishes**
Fatty acids	***OUTDOOR SOURCES*** • Vehicle exhaust ***INDOOR SOURCES*** • Animal skins, furs, taxidermy specimens, and insect collections (relevant for natural history collections and parchment) • Museum visitors • Combustion: burning candles, cooking • Adhesives • Linoleum	• Yellows **paper** and **photographic** documents • Corrodes **bronze**, **cadmium**, and **lead** • Blemishes **paintings**
Hydrochloric acid (HCl)	***OUTDOOR SOURCES*** • Coal combustion • Oceans, sea mist spray	• HCl is an acidic gas; hence, it attacks **acid-sensitive materials**, especially under high-humidity conditions often present in coastal regions • Increases corrosion rate of metals • Affects tarnishing of **copper** and **silver** by hydrogen sulfide
Water vapor (H$_2$O) Water vapor (i.e., relative humidity) is a critical parameter for museum collections. Besides direct affects of humidity changes on collections, water vapor increases corrosion and decay rates, and is involved in most chemical reactions.	***OUTDOOR SOURCES*** • Atmosphere (high-humidity days) • Bodies of water ***INDOOR SOURCES*** • Fountains • Humidifiers • People • Wet cleaning activities	• Increases hydrolysis reactions on **organic objects**, which usually leads to damage (e.g., hydrolysis of cellulose weakens paper objects) • Increases effect of nitrogen oxides on photographs • Increases hydrogen sulfide corrosion of **copper** and **silver** • Controlling factor in **bronze disease** • Increases deterioration of materials (e.g., **metal** corrosion, efflorescence of calcareous objects, and photo-oxidation of **artists' colorants**) • Increases fading of **dyestuffs** used in textiles and watercolors
Particles (fine and coarse)[b]	• *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 • *Biological and organic compounds*: microorganisms, degradation of materials and objects, visitors and animal danders, construction activities • *Soot (organic carbon)*: burning candles, incense, fires, coal combustion, vehicle exhaust • *Ammonium salts (ammonium sulfate)*: reaction of ammonia with SO$_2$ or NO$_2$ inside or outside or on solid surfaces	• *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 micro irregularities)]; may initiate or increase corrosion processes; may initiate catalysis forming reactive gases • *Soot*: disfiguration of porous surfaces (painting, frescoes, statues, books, textiles, etc.), increases rate of metals corrosion

[a] Source for gaseous pollutants section: Grzywacz (2006).
[b] Source for particle section: Tétreault (2003).

risk. Hydrocarbons and other volatile organic compounds (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 are important, but as the use of alcohol-based fuels increases, organic species, especially formaldehyde and organic acids (Anderson et al. 1996; Schifter et al. 2000), become relatively more important. 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 (Gibson et al. 1997; Grzywacz and Tennent 1994, 1997; Meininghaus et al. 2000).

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 2). 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 (1994, 2003) summary of materials damaged by pollutants can help determine which materials require special care. Brokerhof (1998), Craft et al. (1996), Grzywacz (1999, 2006), Hatchfield (2002), Lavédrine (2003), Ryhl-Svendsen (1999), and Tétreault (1994, 1999, 2003) summarized airborne pollution control strategies for rooms and enclosures.

Damage to artifacts is cumulative and irreversible. All efforts to minimize exposing collections to pollutants are beneficial. Both long-term exposure to low levels of pollutants and short-term exposure to high pollutant concentrations can damage susceptible objects. Not all damage is immediately visible, especially with organic materials (e.g., papers, textiles, animal skins), because damage is loss of strength, brittleness, etc. (Bogaty et al. 1952; Dupont and Tétreault 2000; Graedel and McGill 1986; Oddy and Bradley 1989; Tétreault et al. 1998). Note that concentrations of gaseous pollutants are reported in volumetric units: parts per million (ppm) or parts per billion (ppb), which are temperature and pressure dependent. To standardize reporting, the Compressed Air and Gas Institute (CAGI 2002) recommends using a standard temperature and pressure of 68°F and 14.7 psi. Concentrations of particulate pollutants are reported in gravimetric units [e.g., micrograms per cubic metre ($\mu g/m^3$)], which is temperature and pressure independent.

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.

Organic carbonyl pollutants such as formaldehyde, acetic acid, and formic acid are the most damaging to collections (Brimblecombe et al. 1992; Gibson 1999; Grzywacz 2003; Grzywacz and Tennent 1994, 1997; Hatchfield 2002; Hatchfield and Carpenter 1986; Hopwood 1979; Tétreault 2003). 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, organic materials (see Table 2). Reduced-sulfide compounds such as hydrogen sulfide (H_2S) and carbonyl sulfide (COS) are 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, ≥10 µm) entering the building through air intakes are usually removed effectively by coarse particle filters. However, people (including museum visitors) are a significant source of large particles from skin cell shedding, particles tracked in on shoes, clothing, and the air surrounding them as they pass through exterior doors (Yoon and Brimblecombe 2001). People-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, 1993), Nazaroff and Cass (1991), Nazaroff et al. (1990, 1992, 1993), and Salmon et al. (2005) examined the origin, fate, and concentration of particles in several museums in southern California. 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 onset of perceptible soiling of vertical surfaces is 24 to 86 years.

Some forms of chemical deterioration have been traced to particle deposition. Toishi and Kenjo (1975) extensively covered the risk from new concrete. 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).

“Realistic” 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 can endanger long-term viability of the effort. Insistence on best available technology may also 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.

Risk Management Plans for Collections. Preservation of collections is a tradeoff among many factors. There is not one golden rule; instead, risk management approaches are used (Ashley-Smith 1999; Brimblecombe 2000; Dahlin et al. 1997; Hens 1993; Michalski 1996b; Stock and Venso 1993; Tétreault 2003; Thickett et al. 1998; Waller 1999). Waller and Michalski (2005) report on a preventive conservation software tool to determine appropriate set points and ranges for temperature and relative humidity.

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 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 3 summarizes the probable effects of various specification options, based on the best current knowledge (including all available data, research results, and judgment of conservators). Michalski (1991, 1993, 1995, 1996a, 1996b, 1999) reduced permissible fluctuations 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 AA control has the highest potential for energy consumption and affords no protection to historic buildings in cold climates. Older buildings are at most risk to damage from condensation on windows, walls, and roofs. Therefore, HVAC application in historic buildings must consider the risk to the structure and building envelope. Mecklenburg et al. (2004) discuss the concept of preserving both the collections and the buildings. Class A control has the benefit of some reduction of energy consumption and, with seasonal lowering of the relative humidity set point in the winter, affords some protection to historic buildings in cold climates. Older buildings at these lower temperature and relative humidity specifications are at less risk to damage from condensation on windows, walls, and roofs.

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.

Architectural Considerations. Building envelopes play an important role in controlling moisture migration into the space. Architectural design should include heavy insulation, and consider possible vapor barriers. Control of openings, window materials, and floor slab insulation are critical in the design. Rainwater runoff design should be considered in the HVAC relationship to collection storage and display areas.

Building Envelope Issues

Persily (1999) discusses building envelopes. 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 4 lists the possible classes of fluctuation control possible each class of building. Local climate determines which possibility is most likely. For detailed guidance on air leakage and thermal and moisture performance of building envelopes, refer to Chapters 23, 24, and 30 of the 2005 *ASHRAE Handbook—Fundamentals*.

Airborne Pollutant Targets

Assigning target concentrations for airborne pollutants is a complex task. An object's susceptibility depends on a variety of factors (including historical storage and conservation treatments, and current stability), and is linked to other environmental factors, such as temperature, relative humidity, and light levels (Gibson 1999). The conservator, collection manager, or curator considers all these factors and more.

Principal airborne pollutants for museums, galleries, archives, and libraries are listed in Table 5. Nitrogen oxides, 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), 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.). Wood, construction materials, indoor activities, and artifacts mainly generate organic acids and aldehydes (see Table 2), which can be found at high levels in enclosures. Total VOCs are included; they can be used as a metric for the overall air quality in the area. Table 5 presents suggested concentration limits, action limits, air quality recommendations, natural background and urban concentrations, acute human toxicity levels, U.S. Environmental Protection Agency (EPA) Clean Air Act Limits, and World Health Organization time-weighted average (TWA) limits. Limits in the first four columns are based on Tétreault's (2003) **lowest observable adverse effect dose (LOAED)** and **no observable adverse effect level (NOAEL)**, which combine critical review of detailed in situ observations with laboratory studies and provide substantial quantitative information on adverse effects of pollutants on materials. Extensive sets of LOAED and NOAEL are available in Tétreault (2003).

It is preferable to exclude pollutant sources by properly selecting construction and cleaning products used inside (e.g., not using vinegar-based cleaning products or amine compounds as corrosion inhibitors in humidification systems; see Table 2).

Controlling relative humidity below 60 or 45% for long-term preservation and maintaining temperature at about 65°F can minimize deterioration of collections from airborne pollutants. Cleanliness of the collection is also important, because salts, fatty acids, or metallic dirt may initiate or accelerate some deterioration caused by gaseous pollutants.

For long-term preservation, levels of airborne pollutants should be below 1 ppb for gases and less than 1 μg/m^3 for fine particles. Low levels of airborne pollutants can be achieved in many ways,

Table 3 Temperature and Relative Humidity Specifications for Collections

		Maximum Fluctuations and Gradients in Controlled Spaces			
Type	**Set Point or Annual Average**	**Class of Control**	**Short Fluctuations plus Space Gradients**	**Seasonal Adjustments in System Set Point**	**Collection Risks and Benefits**
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.	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.	**AA** Precision control, no seasonal changes	±5% rh, ±4°F	Relative humidity no change Up 9°F; down 9°F	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.
		A Precision control, some gradients or seasonal changes, not both	±5% rh, ±4°F	Up 10% rh, down 10% rh Up 9°F; down 18°F	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.
			±10% rh, ±4°F	RH no change Up 9°F; down 18°F	
		B Precision control, some gradients plus winter temperature setback	±10% rh, ±9°F	Up 10%, down 10% rh Up 18°F, but not above 86°F	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.
		C Prevent all high-risk extremes	Within 25 to 75% rh year-round Temperature rarely over 86°F, usually below 77°F		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.
		D Prevent dampness	Reliably below 75% rh		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.
Archives, Libraries Storing chemically unstable collections	Cold Store: –4°F, 40% rh	±10% rh, ±4°F			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).
	Cool Store: 50°F 30 to 50% rh	(Even if achieved only during winter setback, this is a net advantage to such collections, as long as damp is not incurred)			Chemically unstable objects usable for a century or more. Such books and papers tend to have low mechanical vulnerability to fluctuations.
Special Metal Collections	Dry room: 0 to 30% rh	Relative humidity not to exceed some critical value, typically 30% rh			

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.

including building design, filtration, maintenance, and operations. If the HVAC system cannot provide the specified protection from contaminants, it may be necessary to place collections in appropriate microclimates.

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

The surface temperature of 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,

Table 4 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).

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 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 some of the most environmentally disruptive elements. The engineer should ensure that loads from these spaces are managed and isolated from 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

Table 5 Current Recommended Target Levels for Key Gaseous Pollutants[a] (in ppb, unless otherwise indicated)

	Suggested Pollutant Limits for Collections[b, c]		Action Limits[d]		Air Quality Recommendations		Reference Concentrations				
Major Outdoor Pollutants in Museums	**Sensitive Materials[e]**	**General Collections**	**High**	**Extremely High**	**Archival Document Storage**	**Libraries, Archives, and Museums**	**Natural Background Levels**	**Urban Areas**	**Health: Acute Toxicity Level for 1 h Exposure[f]**	**EPA Clean Air Act Limits[g]**	**World Health Organization[h] TWA Limits**
Nitrogen dioxide, NO_2	<0.05 to 2.6	2 to 10	26 to 104	>260	Canada: 2.6 USA: 2.6	2.6	0.05 to 4.9	1.6 to 68 USA: 22 to 52 Canada: 16 to 22 Europe: 2 to 34	244 OSHA: 5 ppm[i]	50 (1 y)	104 (1 h) 21 (annual) 62 (8 h)
Nitrogen monoxide,[j] NO, see ozone							0.16 to 1.6	1 to 32	OSHA: 25 ppm		
Acidic nitrogen gases, HNO_2, HNO_3	<0.1	<1.0					0.02 to 0.2	1 to 49			
Ozone, O_3	<0.05	0.5 to 5	25 to 60	75 to 250	Canada: 1.0 USA: 13	2.0	1 to 100	5 to 200 USA: 100 to 120 Canada: 17 to 21 Europe: 65 to 145	90 OSHA: 100	120 (1 h) 80	60 (8 h)
Sulfur dioxide, SO_2	<0.04 to 0.4	0.4 to 2	8 to 15	15 to 57	Canada: 0.4 USA: 0.4	1.0	0.04 to 11 Rural USA: 6 to 10 Europe: 1 to 14	2 to 380 USA: 4 to 6 Canada: 4 to 6 Europe: 2 to 94	251 OSHA: 5 ppm	30 (1 y) 140 (24 h)	190 (10 min) 10 (24 h) 19 (annual)

	Suggested Pollutant Limits		Action Limits		Reference Concentrations				
Major Indoor-Generated Pollutants in Museums	**Sensitive Materials**	**General Collections**	**High**	**Extremely High**	**Natural Background Levels**	**Urban Areas**	**Health: Acute Toxicity Level for 1 h Exposure**	**EPA Clean Air Act Limits**	**World Health Organization TWA Limits**
Hydrogen sulfide, H_2S	<0.010	<0.100	0.4 to 1.4	2.0 to 20	0.005 to 10	0.1 to 5	30 ppm OSHA: 10 ppm		107

Organic Carbonyl Pollutants

		Sensitive Materials	General Collections	High	Extremely High	Natural Background Levels	Urban Areas	Health: Acute Toxicity Level for 1 h Exposure	EPA Clean Air Act Limits	World Health Organization TWA Limits
Organic acids	Acetic acid,[k] CH_3COOH	<5	224 40 to 280	200 to 480	600 to 1000	0.1 to 4	0.1 to 16	OSHA: 10 ppm		
	Formic acid,[l] HCOOH	<5	42 to 78	104 to 260	260 to 780	0.05 to 4	0.05 to 17	OSHA: 5 ppm		
Aldehydes	Formaldehyde, HCHO	<0.1 to 5	10 to 20	16 to 120	160 to 480	0.4 to 1.6	1.6 to 24 New home: 50 to 60	75 OSHA: 750		80 (30 min)
	Acetaldehyde,[m] CH_3CHO	<1 to 20					3 to 17	5 OSHA 200 ppm		
Total VOCs (as hexane)[n]			<100	700	1700		New or renovated building 4500 to 9000			
Fine particles[o] (PM2.5)		<0.1 $\mu g/m^3$	1 to 10 $\mu g/m^3$	10 to 50	50 to 150	1 to 30	1 to 100			

Notes for Table 5

Note: This extrapolation of minimum risk for most collections over an extended period of exposition assumes temperature between 68 and 86°F, collection cleanliness, and less than 60% rh; hypersensitive objects such as lead, vulcanized natural rubber, silver, and most sensitive colorants are excluded and require special control measures.

Source: Grzywacz (2006)

See References:

1. World Health Organization 2000
2. Seinfeld 1986
3. Graedel 1984
4. Tétreault 2003
5. Grosjean 1988
6. Graedel, Kammlott, and Franey 1981
7. Sano 1999
8. Sano 2000
9. Bradley and Thickett 1999
10. Kawamura, Steinberg, and Kaplan 1996
11. Granby and Christensen 1997
12. Grosjean and Williams 1992
13. Hodgson et al. 2000
14. Office of Environmental Health Hazard Assessment 2003
15. Rothweiler, Waeger, and Schlatter 1992
16. Lavédrine 2003
17. National Air Filtration Association (NAFA) 2004

[a] Current standards, based on best available sources; not meant to be absolute and final concentration recommendations. Concentration limits for materials and objects continue to be reviewed. Two sources are CCI (http://www.cci-icc.gc.ca) and the IAQ in Museums and Archives Web site (http://www.IAQ.dk).

[b] Maximum levels allowed to ensure minimum risk to sensitive objects; assumes temperature between 59 and 77°F, clean collection, and less than 60% rh (ideally less than 50%) (Tétreault 2001).

[c] Temperature and relative humidity should always be minimized as well as pollutant concentration to reduce risk.

[d] Mitigation measures should be taken to protect objects in the collection.

[e] Sensitive materials are those that are at risk from the particular gaseous pollutant.

[f] Acute reference exposure levels (RELs) established by U.S. Office of Environmental Health Hazard Assessment (OEHHA 2003).

[g] U.S. Environmental Protection Agency Office of Air and Radiation Clean Air Act limits (EPA 2003).

[h] World Health Organization's maximum exposure recommendations (World Health Organization 2000).

[i] U.S. Department of Labor, Occupational Safety and Health Agency maximum permissible exposure limit (PEL) for 8 h work day.

[j] NO is unstable and breaks down. However, it reacts with ozone to form HNO_2, nitrous acid, which is damaging. Eliminate O_3 to reduce risk from NO.

[k] Acetic acid levels can be as high as 10,000 ppb inside enclosures made with inappropriate materials.

[l] Very little is known about effects of formic acid at various concentrations.

[m] Little damage has been directly attributed to acetaldehyde.

[n] Total VOCs are reported referenced to calibrated gas, such as hexane or toluene.

[o] Adapted from Tétreault (2003).

collection needing 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/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 build-up of gaseous contaminants, they should be made of inert or low-emission materials, or those that emit gases benign to objects in the 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.

These 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 these 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; experienced turnkey or design-build vendors provide the most successful systems (Lavédrine 2003; 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 System. Several systems are available, including direct expansion (DX) cooling, glycol, and central chilled water. Screw compressors are recommended to generate chilled water at 36°F for use in chilled-water coils, which generally have copper fins and tubes. Conventional, DX, and chilled-water systems have a limitation in producing 36°F chilled water; therefore, desiccant systems may be considered instead. Ice storage systems with glycol also could be used.

Heating System. Several systems are available to generate heat, including steam and oil with converter, modular boilers, and scotch marine boilers. Hot water is circulated through heating and reheat coils for temperature and humidity control in the space.

Humidification. Humidification should be provided by steam or deionized 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 (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 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. Humidification methods include electronic steam humidifiers, clean steam humidifiers, evaporative pan humidifiers, spray-coil wetted-element systems, and ultrasonic humidification. All materials in humidification equipment should be selected to minimize microbial growth and degradation of system components.

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 zone humidifiers have 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 wastes 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.

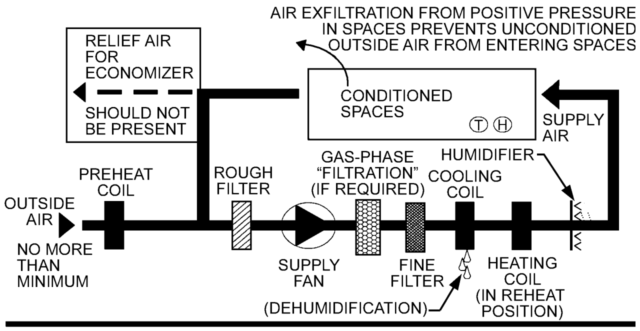


Fig. 6 Primary Elements of Preservation Environment HVAC System

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. Zone reheat is essential to maintaining necessary conditions in the space.

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

- **Low-temperature chilled water**, usually based on a glycol solution, offers familiar operation and stable control but requires glycol management.
- **DX refrigeration** tends to be better for small systems and has lower capital costs, but generally is less reliable, requires more energy, and may require a defrost cycle.
- **Desiccant dehumidifiers** can be quite effective if properly designed, installed, and maintained. Economy of operation is very sensitive to the cost of the regeneration heat source. Liquid desiccant systems eliminate (1) the need to cool the air below the dew point, and (2) reheat, both of which are very important cost factors for sustainability.

Desiccant systems (Figure 7) may be a good solution in many cases that require humidity between 30 and 35% rh year-round. Desiccant regeneration is required. Silica gel and rotary wheel dehumidifiers are commonly used. 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 2004 *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

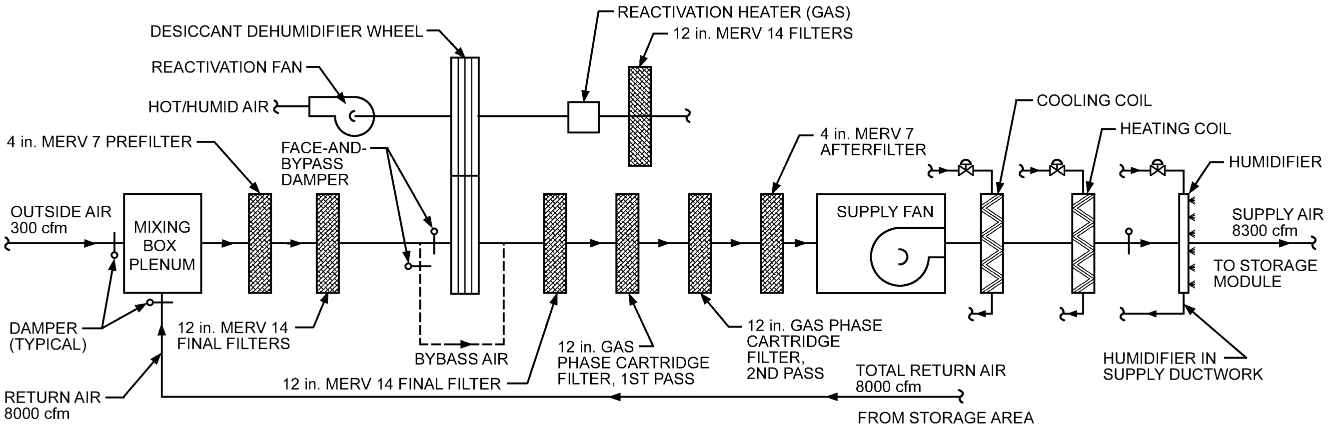


Fig. 7 Packaged Desiccant Dehumidification Unit
(Setty 2006)

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.

Filtration

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

Prefiltration is required for to prevent fouling in cooling coils and build-up of dust in the fan, ductwork, or other HVAC components. It is also required to protect and prolong the functional service life of gas-phase filters and fine-particulate filters. These fouling-sized particles are generally considered to be the MERV E-3 (ASHRAE *Standard* 52.2) range particles or the 3 to 10 µm size range. Achieving at least 50% removal of the E-3 particle size range requires MERV 7 filtration.

Higher efficiencies may be possible with media configurations that operate at lower pressure loss. MERV 11 or higher prefilters can operate at similar or lower pressure drop and provide more protection for HVAC components and gas-phase filters.

Fine-particulate filtration protects artifacts and collections in the facility. This particle size is commonly referred to as the “accumulation” size and falls in the MERV E-1 range of particles (0.3 to 1 µm). Removal efficiencies of a minimum of 85% of the E-1 range are sufficient for preservation of most collections. MERV 15 filters are minimum 85% in the E-1 range, and minimum 90% in both the E-2 (1 to 3 µm) and E-3 (3 to 10 µm) ranges.

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

Framing systems should be able to seal the air filters without bypass air leakage in the housing. Systems design with positive locking mechanisms for filters is a benefit.

High-voltage electrostatic air cleaners should be used with caution because of the potential to generate ozone, which can damage artifacts (see Table 2).

Gas-Phase Filtration. Outside air infiltration of gaseous pollutants, materials offgassing in new construction, and similar offgassing of furnishings and cleaning agents may threaten the stability of some collections. Sensitive collections of valuable holdings (e.g., low-fire ceramics, some metals and alloys, film, rare books) should use active control of gas-phase contaminants.

The primary compounds of concern include acetic acid, formaldehyde, hydrogen sulfide, nitrogen dioxide, ozone, and sulfur dioxide, all of which are removable with molecular filtration. The specific sorbent must be chosen for the various gaseous contaminants indigenous to the facility, because removal and retention properties are not all the same. Some gases are easily removed with activated carbon, whereas others may require treated carbon or potassium permanganate beds.

Careful thought should be given to the service life of molecular filtration media. Much service life testing has focused on the potential weight removal capacity of the sorbent when immersed in a challenge chemical; although this information is important, removal from an airstream may not be achievable even though the sorbent is not spent.

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. Control system design is critical for maintaining precise temperature and humidity control. Consideration should be given to industrial-grade controls for proper temperature and humidity. Control systems should be able to monitor and control humidity, temperatures, airflow, filter pressure drops, water alarms, capacity alarms, and failure scenarios.

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, as do air-handling units. Some systems can provide full control without running any pipes to the zones, but others require two to six pipes to each zone, which often must be run over or in collection areas and are, unfortunately, the pipes most likely to leak. Leaks and maintenance can prevent effective use of spaces and result in lost space efficiency.

Central air-handling stations keep filtration, dehumidification, humidification, maintenance, and monitoring away from the collection. The investment in added space and the expense of the more elaborate duct system provide major returns in reduced disruption to the collection spaces and a dramatically extended service life for the distribution system. 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, and dual-duct. When air handlers are outside collection areas (as recommended), the best choices are constant-volume and multizone with bypass, and dual-duct. 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.

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, humidity-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 (Conrad 1994; Kerschner 1992, 2006), and in many historic buildings in Britain (Staniforth 1984). Maekawa and Toledo (2001) successfully applied humidistatic control in hot, humid climates to minimize microbial growth.

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

This approach is cost-effective in seasonal museums (especially for low-mass wood-frame buildings) in colder climates 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, domestic dehumidifiers can supplement humidistat control.

Hybrid (Load-Sharing) HVAC Systems. This approach involves enhancing preservation in museums and libraries by an optimum collocation of radiant and forced-convection systems. Most of the sensible loads are assigned to radiant panel systems, whereas latent loads and the remaining sensible loads are assigned to forced-convection systems. Decoupling the HVAC functions primarily into sensible and latent heat transfer components enables the designer to select better function-oriented HVAC components and to ensure higher accuracy and precision in control. Additionally, hybrid HVAC seems to satisfactorily balance the needs of preservation and human comfort, while keeping operating costs low. For example, in a library, human comfort could be maintained primarily by thermal radiation, while lowered air temperature increased the expected half-life of the books, with required fan power reduced by almost 50% (Kilkis et al. 1995). Moreover, because the forced-convection system is freed from satisfying most of the sensible heating and cooling loads, more accurate humidity control and faster response to humidity changes may be achieved. Multizoning in a hybrid HVAC system may be easier. Latent and sensible systems can also be integrated into a single HVAC unit called a **hybrid panel** (Kilkis 2002). When hydronic radiant panels, which require piping fluids into exhibition areas, are used, associated risks of damage from liquid leaks and the greater maintenance challenges must be balanced against expected savings. Liquid leakage risk might be minimized by using capillary tubing operated under negative pressure. To eliminate liquid leakage risks, all-air hybrid HVAC systems may be used. More information about panel heating and cooling and hybrid HVAC systems can be found in Chapter 6 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

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 packaged 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.

REFERENCES

Allegrini, I., F. DeSantis, V. Di Palo, and A. Liberti. 1984. Measurement of particulate and gaseous ammonia at a surburban area by means of diffusion tubes (Denuders). *Journal of Aerosol Science* 15(4):465-471.

Anderson, L.G., J.A. Lanning, R. Barrell, J. Miyagishima, R.H. Jones, and P. Wolfe. 1996. Sources and sinks of formaldehyde and acetaldehyde: An analysis of Denver's ambient concentration data. *Atmospheric Environment* 30(12):2113-2123.

Ashley-Smith, J. 1999. *Risk assessment for object conservation*. Butterworth-Heinemann, Oxford.

ASHRAE. 1992. Method of testing general ventilation air-cleaning devices for removal efficiency by particle size. ANSI/ASHRAE *Standard* 52.2-1992.

ASHRAE. 2004. Thermal environmental conditions for human occupancy. ANSI/ASHRAE *Standard* 55-2004.

ASHRAE. 2004. Ventilation for acceptable indoor air quality. ANSI/ASHRAE *Standard* 62.1-2004.

Ayerst, G. 1968. Prevention of biodeterioration by control environmental conditions. In *Biodeterioration of Materials*, pp. 223-241. A.H. Walters and J.J. Elphick, eds. Elsevier, Amsterdam.

Ayres, J.M., H. Lau, and J.C. Haiad. 1990. Energy impact of various inside air temperatures and humidities in a museum when located in five U.S. cities. *ASHRAE Transactions* 96(2):100-111.

Bellan, L.M., L.G. Salmon, and G.R. Cass. 2000. A study on the human ability to detect soot deposition onto works of art. *Environmental Science & Technology* 34(10):1946-1952.

Beuchat, L.R. 1987. Influence of water activity on sporulation, germination, outgrowth, and toxin production. In *Water activity: Theory and applications to food*, pp. 137-152. L.B. Beuchat, and L.R. Rockland, eds. Marcel Dekker, New York.

Bogaty, H., K.S. Campbell, and W.D. Appel. 1952. The oxidation of cellulose by ozone in small concentrations. *Textile Research Journal* 22(2):81-83.

Bovill, C. 1988. Qualitative engineering. *ASHRAE Journal* 30(4):29-34.

Bradley, S. and D. Thickett. 1999. The pollution problem in perspective. *12th Triennial Meeting of ICOM Committee for Conservation*, Lyon, pp. 8-13. J. Bridgland, ed.

Brimblecombe, P. 1990. Particulate material in art galleries, dirt and pictures separated. In *Dirt and pictures separated*, pp. 7-10. United Kingdom Institute of Conservation, London.

Brimblecombe, P. 2000. An approach to air pollution standards in museums. *Third Indoor Air Quality Meeting: Presentation Abstracts and Additional Notes*. Morten Ryhl-Svendsen, ed. Abstract available at http://iaq.dk/iap/iaq2000/2000_01.htm.

Brimblecombe, P., D. Shooter, and A. Kaur. 1992. Wool and reduced sulphur gases in museum air. *Studies in Conservation* 37:53-60.

Brokerhof, A. 1998. Application of sorbents to protect calcareous materials against acetic acid vapours. In *Indoor air pollution—detection and mitigation of carbonyls: Presentation abstracts and additional notes*, pp. 45-54. Lorraine Gibson, ed. Netherlands Institute for Cultural Heritage, Amsterdam. Available at iaq.dk/iap/iap1998/1998_10.htm.

CAGI. 2002. Standard air defined as in ISO standards. Compressed Air and Gas Institute, Cleveland. Available at http://www.cagi.org/toolbox/glossary.asp.

Cass, G.R., J.R. Druzik, J.D. Gros, W.W. Nazaroff, P.M. Whitemore, and C.L. Wittman. 1989. Protection of works of art from atmospheric ozone. *Research in Conservation Series* 5. Getty Conservation Institute, Los Angeles.

CCI/ICC. 2005. *Framework for preservation of museum collections*. Canadian Conservation Institute, Ottawa. Available at http://www.cci-icc.gc.ca/tools/framework/index_e.aspx.

Chang, J.C.S., Z. Guo, and L.E. Sparks. 1998. Exposure and emission evaluations of methyl ethyl ketoxime (MEKO) in alkyd paints. *Indoor Air* 8:295-300.

Conrad, E. 1994. Balancing environmental needs of the building, the collection, and the user. *Preventive Conservation Practice, Theory and Research: Preprints of the Contributions to the Ottawa Congress*, A. Roy and P. Smith, eds. International Institute for Conservation of Historic and Artistic Works (IIC), London.

Conrad, E. 1995. *A table for classification of climatic control potential in buildings*. Landmark Facilities Group, CT.

Craft, M., C. Hawks, J. Johnson, M. Martin, and L. Mibach. 1996. *Preservation of collections: Assessment, evaluation and mitigation strategies.* American Institute for Conservation, Washington, D.C.

Dahlin, E., J.F. Henriksen, and O. Anda. 1997. Assessment of environmental risk factors in museums and archives. *European Cultural Heritage Newsletter on Research (ECHNR)* 10:94-97.

Daly, D. and S. Michalski. 1987. Methodology and status of the lining project, CCI. *ICOM Conservation Committee 8th Triennial Meeting*, Los Angeles, pp. 145-152.

Davies, T.D., B. Ramer, G. Kaspyzok, and A.C. Delany. 1984. Indoor/outdoor ozone concentrations at a contemporary art gallery. *Journal of the Air Pollution Control Association* 31(2):135-137.

Davis, N. 2006. Tracing the evolution of preservation environments in archives, museums, and libraries. *20th Annual Preservation Conference: Beyond the Numbers: Specifying and Achieving an Efficient Preservation Environment*. National Archives, Washington, D.C. Available at http://www.archives.gov/preservation/conferences/2006/presentations.html.

Derrick, M., D. Stulik, and E. Ordonez. 1991. Deterioration of Constructivists sculptures made of cellulose nitrate. *Postprint, Symposium '91: Saving the Twentieth Century*, Ottawa.

Druzik, J.R. and G.R. Cass. 2000. A new look at soiling of contemporary painting by soot in art museums. *Third Indoor Air Quality Meeting, Presentation Abstracts and Additional Notes*, Oxford Brookes University, U.K. Available at http://www.iaq.dk/iap/iaq2000/2000_10.htm.

Druzik, J.R., M.S. Adams, C. Tiller, and G.R. Cass. 1990. The measurement and model predictions of indoor ozone concentrations in museums. *Atmospheric Environment* 24A(7):1813-1823.

Dupont, A.-L. and J. Tétreault. 2000. Study of cellulose degradation in acetic acid environments. *Studies in Conservation* 45.

Eremin, K. and J. Tate. 1999. The museum of Scotland: Environment during object installations. *12th Triennial Meeting of ICOM Committee for Conservation*, Lyon, pp. 46-51. James and James Science, London.

Erhardt, D. and M. Mecklenburg. 1994. Relative humidity re-examined. *Preventive Conservation Practice, Theory and Research: Preprints of the Contributions to the Ottawa Congress*, pp. 32-38. International Institute for Conservation of Historic and Artistic Works, London.

Erhardt, D., M. Mecklenburg, and C.S. Tumose. 1996. New versus old wood: Differences and similarities in physical, mechanical, and chemical properties. *ICOM Conservation Committee 11th Triennial Meeting*, Edinburgh, pp. 903-910. James and James Science, London.

Erlebacher, J.D., E. Brown, C.S. Tumosa, and M.F. Mecklenburg. 1992. The effects of temperature and relative humidity on the rapidly loaded mechanical properties of artists' acrylic paints. In *Materials Issues in Art and Archaeology III*, Paper 267, pp. 359-370.

Fortmann, R., N. Roache, J.C.S. Chang, and Z. Guo. 1998. Characterization of emissions of volatile organic compounds from interior alkyd paint. *Journal of Air & Waste Management Association* 48(10):931-940.

Gibson, L. , ed. 1999. *Indoor Air Pollution Conference: Detection and Mitigation of Carbonyls*. Indoor Air Pollution—Detection and Mitigation of Carbonyls, held at Strathclyde University, Glasgow, p. 77. L. Gibson, ed. Netherlands Institute for Cultural Heritage, Amsterdam. Available at http://www.iaq.dk/iap/iap1998/1998_contents.htm.

Gibson, L.T., B.G. Cooksey, D. Littlejohn, and N.H. Tennent. 1997. Characterisation of an unusual crystalline efflorescence on an Egyptian limestone relief. *Analytica Chimica Acta* 337:151-164.

Graedel, T.E. 1984. Concentrations and metal interactions of atmospheric trace gases involved in corrosion. *Metallic Corrosion*, Toronto, pp. 396-401.

Graedel, T.E. 1994. Mechanisms of chemical change in metals exposed to the atmosphere. In *Durability and change: The science, responsibility, and cost of sustaining cultural heritage*, pp. 95-105. W.E. Krumbein, P. Brimblecombe, D.E. Cosgrove, and S. Stainforth, eds. John Wiley & Sons, London.

Graedel, T.E. and R. McGill. 1986. Degradation of materials in the atmosphere. *Environmental Science & Technology* 20(11):1093-1100.

Graedel, T.E., G.W. Kammlott, and J.P. Franey. 1981. Carbonyl sulfide: Potential agent of atmospheric sulfur corrosion. *Science* 212:663-665.

Granby, K. and C.S. Christensen. 1997. Urban and semi-rural observations of carboxylic acids and carbonyls. *Atmospheric Environment* 31(10): 1403-1415.

Grosjean, D. 1988. Aldehydes, carboxylic acids and inorganic nitrate during NSMCS. *Atmospheric Environment* 22(8):1637-1648.

Grosjean, D. and E.L. Williams, II. 1992. Photochemical pollution at two southern California smog receptor sites. *Journal of the Air & Waste Management Association* 42(6):805-809.

Groom, P. and T. Panisset. 1933. Studies in *Penicillium chrysogenum thom* in relation to temperature and relative humidity of the air. *Annals of Applied Biology* 20:633-660.

Grzywacz, C. 1999. Mitigation—Does it work? Is it always an improvement? *Indoor Air Pollution: Detection and Prevention—Presentation Abstracts and Additional Notes*, pp. 55-57. Netherlands Institute for Cultural Heritage, Amsterdam. Available at http://www.iaq.dk/iap/iap 1999/1999_18.htm.

Grzywacz, C.M. 2006. Monitoring for gaseous pollutants in museum environments. In *Tools in Conservation*, E. Maggio. ed. Getty Conservation Institute, Los Angeles,

Grzywacz, C.M. and A. Gailunas. 1997. *It's inside the stag, not the case: A source of high formaldehyde concentrations: Internal report*. Getty Conservation Institute, Los Angeles.

Grzywacz, C.M. and N.H. Tennent. 1994. Pollution monitoring in storage and display cabinets: Carbonyl pollutant levels in relation to artifact deterioration. *Preventive Conservation Practice, Theory and Research: Preprints of the Contributions to the Ottawa Congress*, pp. 164-170. International Institute for Conservation of Historic and Artistic Works (IIC), London.

Grzywacz, C. and N.H. Tennent. 1997. The threat of organic carbonyl pollutants to museum collections. *European Cultural Heritage Newsletter on Research* (ECHNR). European Commission DG XII Science, Research and Development, Brussels.

Hancock, R.P., N.A. Esman, and C.P. Furber. 1976. Visual response to dustiness. *Journal of the Air Pollution Control Association* 26(1):54-57.

Hatchfield, P.B. 2002. *Pollutants in the museum environment: Practical strategies for problem solving in design, exhibition, and storage.* Archetype Publications, London.

Hatchfield, P.B. and J.M. Carpenter. 1986. The problem of formaldehyde in museum collections. *International Journal of Museum Management and Curatorship* 5:183-188.

Hedley, G. 1988. Relative humidity and the stress/strain response of canvas painting: Uniaxial measurements of naturally aged samples. *Studies in Conservation* 33:133-148.

Hens, H.L.S.C. 1993. Mold risk: Guidelines and practice, commenting the results of the International Energy Agency EXCO on energy conservation in buildings and community systems, Annex 14: Condensation energy. In *Bugs, Mold and Rot III: Moisture Specifications and Control in Buildings*, pp. 19-28. W. Rose and A. Tenwolde, eds. National Institute of Building Sciences, Washington, D.C.

Hermance, H.W., C.A. Russell, E.J. Bauer, T.F. Egan, and H.V. Wadlow. 1971. Relation of air-borne nitrate to telephone equipment damage. *Environmental Science & Technology* 5:781-789.

Hodgson, A.T., A.F. Rudd, D. Beal, and S. Chandra. 2000. Volatile organic compound concentrations and emission rates in new manufactured and site-built houses. *Indoor Air* 10(3):178-192.

Hopwood, W.R. 1979. Choosing materials for prolonged proximity to museum objects. *American Institute for Conservation of Historic and Artistic Works, Preprints of the 7th Annual Meeting*, Washington, D.C., pp. 44-49.

Howie, F.M.P. 1992. Pyrite and marcasite. In *The care and conservation of geological materials*, pp. 70-84. F.M.P. Howie, ed. Butterworth-Heinemann, London.

IPI. 2006. *Preservation calculator.* Image Permanence Institute, Rochester Institute of Technology (RIT) College of Imaging Arts and Sciences. Available at http://www.imagepermanenceinstiute.org/shtml_sub/dl_prescalc.shtml.

Kawamura, K., S. Steinberg, and I.R. Kaplan. 1996. Concentrations of monocarboxylic and dicarboxylic acids and aldehydes in southern California wet precipitations: Comparison of urban and nonurban samples and compositional changes during scavenging. *Atmospheric Environment* 30(7):1035-1052.

Kerschner, R.L. 1992. A practical approach to environmental requirements for collections in historic buildings. *Journal of the American Institute for Conservation* 31:65-76.

Kerschner, R.L. 2006. Providing safe and practical environments for cultural properties in historic buildings . . . and beyond. *20th Annual Preservation Conference: Beyond the Numbers: Specifying and Achieving an Efficient Preservation Environment.* National Archives, Washington, D.C. Available at http://www.archives.gov/preservation/conferences/2006/kerschner.pdf.

Kilkis, B.I. 2002. Modeling of a hybrid HVAC panel for library buildings. *ASHRAE Transactions* 108(2):693-698.

Kilkis, B.I., S.R. Suntur, and M. Sapci. 1995. Hybrid HVAC systems. *ASHRAE Journal* 37(12):23-28.

LaFontaine, R.H. 1979. Environmental norms for Canadian museums, art galleries, and archives. *CCI Technical Bulletin* 5, Canadian Conservation Institute, Ottawa.

LaFontaine, R.H. 1982. Humidistically-controlled heating: A new approach to relative humidity control in museum closed for the winter season. *Journal of the International Institute for Conservation: Canadian Group* 7(1,2):35-41.

LaFontaine, R.H., and S. Michalski. 1984. The control of relative humidity—Recent developments. *ICOM Conservation 7th Triennial Meeting*, Copenhagen, pp. 33-37.

Lavédrine, B. 2003. *A guide to the preventive conservation of photographic collections*. Getty Conservation Institute, Los Angeles.

Ligocki, M.P., H.I.H. Liu, G.R. Cass, and W. John. 1990. Measurements of particle deposition rates inside southern California museums. *Aerosol Science and Technology* 13:85-101.

Ligocki, M.P., L.G. Salmon, T. Fall, M.C. Jones, W.W. Nazaroff, and G.R. Cass. 1993. Characteristics of airborne particles inside southern California museums. *Atmospheric Environment, Part A: General Topics* 27(5): 697-711.

Lull, W.P. 1990. *Conservation environment guidelines for libraries and archives*. New York State Library.

Lull, W. and L. Harriman. 2001. Museums, libraries and archives. In *Humidity Control Design Guide for Commercial and Institutional Buildings*, L. Harriman, G.W. Brundrett, and R. Kittler, eds. ASHRAE.

Maekawa, S. and F. Toledo. 2001. Sustainable climate control for historic buildings in hot and humid regions. *Renewable Energy for a Sustainable Development of the Built Environment: Proceedings of the 18th International Conference on Passive and Low Energy Architecture,* F.O.R. Pereira, R. Rüther, R.V.G. Souza, S. Afonso, and J.A.B. da Cunha Neto, eds.

Marcon, P.J. 1987. Controlling the environment within a new storage and display facility for the governor general's carriage. *Journal of the International Institute for Conservation: Canadian Group* 12:37-42.

Mecklenburg, M.F. and C.S. Tumosa. 1991. Mechanical behaviour of paintings subjected to changes in temperature and relative humidity. In *Art in Transit*, pp. 173-216. M.F. Mecklenburg, ed. National Gallery of Art, Washington, D.C.

Mecklenburg, M.F., C.S. Tumosa, and D. Erhardt. 1998. Structural response of wood panel paintings to changes in ambient relative humidity. In *Painted Wood: History and Conservation*, pp. 464-483. Getty Conservation Institute, Los Angeles.

Mecklenburg, M.F., C.S. Tumosa, and J.D. Erlebacher. 1994. Mechanical behavior of artist's acrylic emulsion paints under equilibrium conditions. In *Polymers in Museums '94 Symposium: Polymer Preprints*, pp. 297-298.

Mecklenburg, M.F., C.S. Tumosa, and A. Pride. 2004. Preserving legacy buildings. *ASHRAE Journal* 46(6):S18-S23.

Mecklenburg, M.F., C.S. Tumosa, and D. Erhardt. 2005. The changing mechanical properties of aging oil paints. *Art and Archeology, Materials Research Society* 852.

Meininghaus, R., L. Gunnarsen, and H.N. Knudsen. 2000. Diffusion and sorption of volatile organic compounds in building materials—Impact on indoor air quality. *Environmental Science & Technology* 34(15):3101-3108.

Michalski, S. 1991. Paintings, their response to temperature, relative humidity, shock and vibration. In *Works of Art in Transit*, pp. 223-248. M.F. Mecklenburg, ed. National Gallery, Washington, D.C.

Michalski, S. 1993. Relative humidity in museum, galleries and archives: Specification and control. *Bugs, Mold and Rot III: Moisture Specification and Control in Buildings*, pp. 51-61. W. Rose and A. Tenwolde, eds. National Institute of Building Science, Washington, D.C.

Michalski, S. 1995. *Wooden artifacts and humidity fluctuation: Different construction and different history mean different vulnerabilities*. Chart, Version 3.0. Canadian Conservation Institute, Ottawa.

Michalski, S. 1996a. *Environmental guidelines: Defining norms for large and varied collections*. American Institute for Conservation, Washington, D.C.

Michalski, S. 1996b. Quantified risk reduction in the humidity dilemma. *APT Bulletin* 37:25-30.

Michalski, S. 1998. Climate control priorities and solutions for collections in historic buildings. *Forum* 12(4):8-14.

Michalski, S. 1999. *Relative humidity and temperature guidelines for Canadian archives*. Canadian Council of Archives and Canadian Conservation Institute, Ottawa.

NAFA. 2004. *Recommended practice: Guidelines—Libraries, archives and museums*. National Air Filtration Association, Virginia Beach.

Nazaroff, W.W. and G.R. Cass. 1991. Protecting museum collections from soiling due to the deposition of airborne particles. *Atmospheric Environment* 25A(5/6):841-852.

Nazaroff, W.W., L.G. Salmon, and G.R. Cass. 1990. Concentration and fate of airborne particles in museums. *Environmental Science & Technology* 24(1):66-76.

Nazaroff, W.W., M.P. Ligocki, L.G. Salmon, G.R. Cass, T. Fall, M.C. Jones, H.I.H. Liu, and T. Ma. 1992. *Protection of works of art from soiling due to airborne particulates*. Getty Conservation Institute, Marina del Rey, CA.

Nazaroff, W.W., M.P. Ligocki, L.G. Salmon, G.R. Cass, T. Fall, M.C. Jones, H.I.H. Liu, and T. Ma. 1993. *Airborne particles in museums.* Getty Conservation Institute. Marina del Rey, CA.

NBS. 1983. *Air quality criteria for storage of paper-based records*. NBSIR 83-2795. National Institute of Standards and Technology, Gaithersburg, MD.

Nishimura, D.W. 1993. The IPI storage guide for acetate film. *Topics in Photographic Preservation* 5:123-137.

Oddy, W.A. and S.M. Bradley. 1989. The corrosion of metal objects in storage and on display. *13th International Symposium on the Conservation and Restoration of Cultural Property*, pp. 225-244. Tokyo National Research Institute of Cultural Property.

Office of Environmental Health Hazard Assessment. 2003. Air—Hot spots—Chronic RELS: All chronic reference exposure levels developed by the OEHHA. Available at http://www.oehha.org/air/chronic_rels/index.html.

Ohtsuki, T. 1990. Studies on *Eurotium tonophilium Ohtsuki*: Minimum humidity for germination and characterization of yellow pigments produced by this fungus. *Kobunkazai No Kagaku* 35(December):28-34.

Oreszczyn. T., M. Cassar, and K. Fernandez. 1994. Comparative studies of air-conditioned and non-air-conditioned museums: Preventive conservation practice, theory and research. *Preprints of the Contributions to the Ottawa Congress*, pp. 144-148. International Institute for Conservation of Historic and Artistic Works, London.

Padfield, T. and P. Jensen. 1996. Low energy climate control in stores: A postscript. *ICOM Conservation Committee, 9th Triennial Meeting*, Dresden, pp. 596-601.

Perera, D.Y. and D. Vanden Eynde. 1987. Moisture and temperature induced stresses (hygrothermal stresses) in organic coatings. *Journal of Coatings Technology* 59(5):55-63.

Persily, A.K. 1999. Myths about building envelopes. *ASHRAE Journal* 41(3):39-45.

Raychaudhuri, M.R. and P. Brimblecombe. 2000. Formaldehyde oxidation and lead corrosion. *Studies in Conservation* 45(4):226-232.

Reilly, J.M. 1993. *IPI storage guide for acetate film.* Image Permanence Institute, Rochester, NY.

Rothweiler, H., P.A. Waeger, and C. Schlatter. 1992. Volatile organic compounds and some very volatile organic compounds in new and recently renovated buildings in Switzerland. In *Atmospheric Environment, Part A: General Topics*.

Ryhl-Svendsen, M. 1999. Pollution in the photographic archive: A practical approach to the problem. *IAQ in Museums and Archives.* Available at http://www.iaq.dk/papers/iada1999.htm.

Salmon, L.G., P.R. Mayo, G.R. Cass, and C.S. Christoforou. 2005. Airborne particles in new museum facilities. *Journal of Environmental Engineering* 131(10):1453-1461.

Sano, C. 1999. Indoor air pollutants in museum—Carboxylic acid concentrations and their detective methods: Case studies. *Hozon Kagaku* 3823-3830.

Sano, C. 2000. Indoor air quality in museums: Their existing levels, desirable conditions and countermeasures. *Kuki Seijo* 38(1):20-26.

Seinfeld, J.H. 1986. *Atmospheric chemistry and physics of air pollution*. John Wiley & Sons, Toronto.

Schifter, I., L. Díaz, E. Lopez-Salinas, and S. Avalos. 2000. Potential impacts of compressed natural gas in the vehicular fleet of Mexico City. *Environmental Science & Technology* 34(11):2100-2104.

Scott, D.A. 1990. Bronze disease: A review of some chemical problems and the role of relative humidity. *Journal of the American Institute of Conservation* 29:193-206.

Sebor, A.J. 1995. Heating, ventilating, and air-conditioning systems. In *Storage of natural history collections: Ideas and practical solutions*. C.L. Rose, C.A. Hawks, and H.H. Genoways, eds. Society for the Preservation of Natural History Collections, Washington D.C.

Selwitz, C. 1988. *Cellulose nitrate used in conservation*. Getty Conservation Institute, Los Angeles.

Snow, D., M.H.G. Crichton, and N.C. Wright. 1944. Mould deterioration of feeding stuff in relation to humidity of storage. *Annals of Applied Biology* 31:102-110.

Staniforth, S. 1984. Environmental conservation. In *Manual of curatorship*, pp. 192-202. J.M.A. Thompson, ed. Butterworths, London.

Stock, T.H., and E.A. Venso. 1993. The impact of residential evaporative air cooling on indoor exposure to ozone. *Indoor Air '93: Proceedings of the 6th International Conference on Indoor Air Quality and Climate*, Helsinki, pp. 251-256. M. Jantunen, P. Kalliokoski, E. Kukkonen, K. Saarela, O. Seppänen, and H. Vuorelma, eds.

Tétreault, J. 1994. Display materials: The good, the bad, and the ugly. *Exhibition and Conservation SSCR*, pp. 21-22. Scottish Society for Conservation and Restoration (SSCR), Edinburgh.

Tétreault, J. 1999. Summary of control procedures to prevent damages caused by contaminants. *Indoor Air Pollution: Detection and Prevention—Presentation Abstracts and Additional Notes*, pp. 53-55. Netherlands Institute for Cultural Heritage, Amsterdam. Available at http://www.iaq.dk/iap/iap1999/1999_17.htm.

Tétreault, J. 2001. *Material damages caused by airborne pollutants; survey from the literature.* Canadian Conservation Institute, Ottawa, ON.

Tétreault, J. 2003. *Airborne pollutants in museums, galleries and archives: Risk assessment, control strategies and preservation management.* Canadian Conservation Institute, Ottawa, ON.

Tétreault, J., J. Sirois, and E. Stamatopoulou. 1998. Studies of lead corrosion in acetic acid environments. *Studies in Conservation* 43:17-32.

Thickett, D., S.M. Bradley, and L.R. Lee. 1998. Assessment of the risks to metal artifacts posed by volatile carbonyl pollutants. *Metal 98: Proceedings of the International Conference on Metals Conservation*, pp. 260-264. W. Mourey and L. Robbiola, eds. James and James Science, London.

Thomson, G. 1994. *The museum environment (conservation and museology)*, 2nd ed. Butterworth-Heinemann, Oxford, U.K.

Toishi, K. and T. Kenjo. 1975. Some aspects of the conservation of works of art in buildings of new concrete. *Studies in Conservation* 20:118-122.

USDA. 1999. *Wood handbook*. U.S. Department of Agriculture, Washington, D.C.

Volent, P. and N.S. Baer. 1985. Volatile amines used as corrosion inhibitors in museum humidification systems. *International Journal of Museum Management and Curatorship* 4:359-364.

Walker, J.T., V.P. Aneja, and D.A. Dickey. 2000. Atmospheric transport and wet deposition of ammonium in North Carolina. *Atmospheric Environment* 34(20):3407-3418.

Waller, R. 1992. Temperature- and humidity-sensitive mineralogical and petrological specimens. In *The Care and Conservation of Geological Material*, pp. 25-50. F. Howie, ed. Butterworth-Heinemann, London.

Waller, R. 1999. Internal pollutants, risk assessment and conservation priorities. *12th Triennial Meeting of ICOM Committee for Conservation,* Lyon, pp. 113-118. J. Bridgland, ed.

Waller, R., and S. Michalski. 2005. A paradigm shift for preventive conservation, and a software tool to facilitate the transition. *14th Triennial Meeting, ICOM Committee for Conservation*, The Hague, pp. 733-738. I. Verger, ed.

Watts, S. 1999. Hydrogen sulphide levels in museums: What do they mean? *Indoor Air Pollution: Detection and Prevention—Presentation Abstracts and Additional Notes*, pp. 14-16. Netherlands Institute for Cultural Heritage, Amsterdam. Available at http://www.iaq.dk/iap/iap1999/1999_04.htm.

Watts, S. and M. Libedinsky. 2000. Measurements from a museum case. *Third Indoor Air Quality Meeting: Presentation Abstracts and Additional Notes*. Available at http://www.iaq.dk/iap/iaq2000/2000_13.htm.

Wilhelm, H. 1993. *The permanence and care of color photographs: Traditional and digital color prints, color negatives, slides, and motion pictures*. Preservation Publishing, Grinnell, Iowa.

World Health Organization. 2000. *Air quality guidelines for Europe*, 2nd ed. World Health Organization *European Series* 91, Regional Office for Europe, Copenhagen.

Yoon, Y.H. and P. Brimblecombe. 2001. The distribution of soiling by coarse particulate matter in the museum environment. *Indoor Air* 11(4): 232-240.

BIBLIOGRAPHY

ASHRAE. 1992. Gravimetric and dust-spot procedures for testing air-cleaning devices used in general ventilation for removing particulate matter. *Standard* 52.1-1992.

CAGI. 2006. *Toolbox: Metric to standard converter calculator.* Compressed Air and Gas Institute, Cleveland. Available at http://www.cagi.org/toolbox/metric.asp.

Larsen, R. 1997. Deterioration and conservation of vegetable tanned leather. *European Cultural Heritage Newsletter on Research, EC Research Workshop—Effects of the Environment on Indoor Cultural Property* 10 (June):54-61.

Tennent, N.H., B.G. Cooksey, D. Littlejohn, B.J. Ottaway, S.E. Tarling, and M. Vickers. 1993. Unusual corrosion and efflorescence products on bronze and iron antiquities stored in wooden cabinets. *Conservation Science in the U.K.; Preprints of the Meeting held in Glasgow, May 1993*, pp. 60-66. N.H. Tennent, ed. James and James Science, London.

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