

RELATIVE HUMIDITY RE-EXAMINED

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ABSTRACT

The determination of an optimal value of relative humidity for the preservation of museum objects is more complex than for other environmental factors. Relative humidity affects the preservation of objects in many ways, and effects vary for different types of object. Relative humidity affects the rates of chemical reactions, and the values of physical properties such as size, strength and stiffness. Extremes of either low or high relative humidity can be damaging. Changing the relative humidity may decrease damage due to one factor while increasing damage due to others. This paper examines ways in which relative humidity affects the degradation processes of different types of material, the limits each factor places on allowable values of relative humidity, and how each factor influences preservation within the allowable range. The type of collection, its use, and constraints imposed by the building housing the collection are also considered. The "optimal" relative humidity is not a specific value upon which all considerations converge, but a range chosen as a compromise in an attempt to minimize the total effect of numerous reactions and processes.

1 INTRODUCTION

The most important factor in the preservation of collections is the maintenance of proper environmental conditions. What are the appropriate conditions for museum objects? The museum environment has a number of components, including temperature, relative humidity, light, vibration, pollutants and particulates. Suitable values or limits must be determined for each. This is straightforward for some factors, even if it is not practical to achieve the value. For example, vibration, pollution and particulates are all damaging and unnecessary and should be reduced to the lowest practical levels.

Light is a more complex subject. Light, although damaging, is necessary for viewing objects. Even the specifications for light, however, can be reduced to the basic principle of using the minimum amount of visible light required to view an object properly. The problems of determining how much light is required by viewers and providing the correct spectral distribution of visible light, while excluding infrared and ultraviolet wavelengths, are largely technical and practical rather than theoretical.

Temperature and relative humidity differ from other environmental factors. They are interdependent and their effects on objects are more varied and complex than those of the other factors. A temperature or relative humidity that is acceptable for one object may be disastrous for another. Temperature and relative humidity cannot be eliminated; instead, satisfactory values for each must be determined. Objects are also affected by the rate and magnitude of changes in temperature and relative humidity, making it insufficient simply to specify an average value for these factors. Relative humidity is a function of temperature, and the practical range within which it can be controlled is dependent on temperature.

The range of temperatures suitable for museums, except for special situations or long-term storage areas, is restricted to temperatures at which people are comfortable. This range is relatively narrow, at most 5 or 10°C. Therefore, relative humidity is the major variable of the museum environment for which there is no obvious optimal value or range.

2 PRESENT STANDARDS FOR RELATIVE HUMIDITY

The title of this section is misleading. There are currently no universal official museum standards for relative humidity (RH). There are commonly accepted values, and general guidelines for certain types of objects. Many museums in the USA maintain 50% RH in general collection areas. European museums often use 55-60% as better replicating the local climate. Museums in colder climates tend toward lower values such as 40-45%, since

higher values are difficult to maintain in heated buildings during extremely cold weather. Exceptions to these values are sometimes made for objects such as panel paintings (higher values) and corroded metal (the lower the better) because of their reported sensitivity to extremes of, or changes in, RH.

Such values are often mentioned without justification or references. Michalski traced the derivation of the generally recommended values, and showed that they originally were determined more by mechanical feasibility and the local climate than by any research designed to determine a value of relative humidity that minimized damage [1]. Early work led to settings in the range of 50-60% RH. In 1960, a survey by the International Council of Museums (ICOM) found that most of the curators, conservators and scientists who responded favored RH control either in or overlapping the 50-60% range [2], with exceptions for materials such as corroded metals. This 50-60% range probably is accepted even more widely today.

Effects of relative humidity on individual objects or types of material have been studied, but few reports have attempted to derive an optimal value or range of values for either general or specific types of collection. Many references to an optimal value of relative humidity cite *The Museum Environment* by Thomson [3]. Thomson selected 55% RH as midway between an upper limit of 65-70% to prevent mold growth and a lower limit of 40-45% for the failure of materials such as wood and ivory. He emphasized that the relative humidity must be held stable, while acknowledging that there was little evidence as to how stable it must be.

The widespread, if unofficial, acceptance of values of relative humidity in the range 50-60% is because visible damage (cracking, flaking, distortion, mold) is greatly reduced by controlling the relative humidity in this range. However, the reduction of damage is at least partially due to the stabilization of relative humidity and the avoidance of damaging extremes, rather than to the specific value of relative humidity.

3 EFFECTS OF RELATIVE HUMIDITY

3.1 Consideration of specific effects

Many aspects of the degradation of museum objects are affected by relative humidity. Each factor should be considered in any attempt to determine an optimal overall value. A discussion of some factors affected by relative humidity follows.

3.2 Biological attack

Mold and mildew grow only at high relative humidity. Michalski concluded from an analysis of the literature that an upper limit of 60% RH should prevent all mold growth, with a real danger of mold growth above 75% RH [1]. Other forms of biological attack do not affect these limits. Bacterial growth requires even higher RH, while insects can survive all but extremely dry conditions [3]. In Figure 1, the caution and danger zones for mold growth are shaded light and dark, respectively.

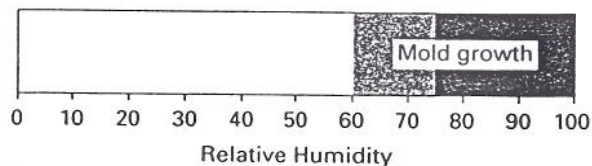


Fig. 1 Relative humidity zones of possible and probable mold growth, shaded light and dark, respectively.

3.3 Mechanical damage

The role of relative humidity in mechanical damage is complex. Changes in relative humidity produce changes in the dimensions and mechanical properties of organic materials and can lead to damage directly. At high RH, above about 80%, hide glue softens and loses adhesive strength [4]. Materials shrink and stiffen at low RH. This stiffening may be accompanied by fracture sensitivity or embrittlement. If the RH is stable, an object at equilibrium will experience damage only if components such as glue are too soft for proper adhesion or support, or so brittle that vibration or handling causes damage. Within an RH range in which an object is otherwise mechanically stable, most mechanical damage is due to RH fluctuations. Moderate changes in relative humidity produce minimal problems in materials that are free to expand and contract. Larger changes cause problems in objects, even those fully free to expand or contract, because moisture diffusion into or out of materials is not instantaneous, nor is it the same in different materials. Partial or differential moisture penetration results in the dry or less hygroscopic part of the object acting as a swelling restraint to the more moisture-reactive sections. The construction of an object tends to restrain the movement of its components, inducing stresses in the object. If changes in RH are severe enough, the induced stresses exceed the strength of the materials, resulting in cracking and flaking.

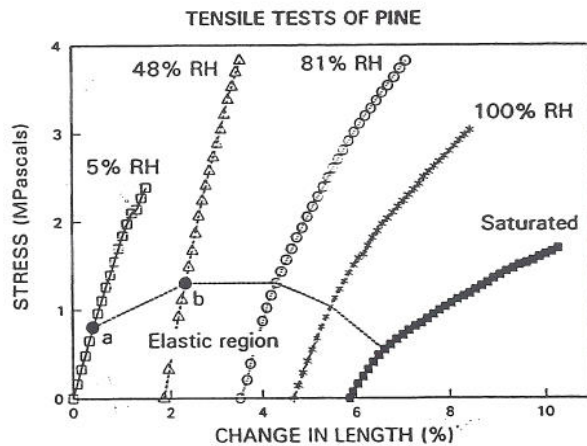


Fig. 2 Stress-strain behavior of pine as a function of RH.

3.3.1 Effects of RH fluctuation

The behavior of wood illustrates these principles. Figure 2 plots stress against change in length for pine tested in a largely radial direction. The strength (maximum stress) rises as the RH is lowered until very low RH is reached. At 5% RH the wood is weaker and liable to fracture, because the strength has dropped from 3.79MPa at 48% RH to 2.41MPa at 5% RH. The ability to deform (maximum change in length) increases with increasing relative humidity. This increase in deformation allows the dramatic bending of wet and steamed wood for decorative furniture. Reversible, or elastic, stretching occurs during the initial linear portion of the plots. Plastic flow, or irreversible stretching, occurs at higher extensions. Its onset is indicated by curvature of the plot. Fracture can be prevented by avoiding the conditions at the ends of the plots, while irreversible deformation can be avoided by staying within the elastic zone indicated by the curved line connecting the plots.

The plots for each RH are separated on the x-axis by the differences in length due solely to changes in RH (with no restraint or stress applied). Moving along the x-axis from the 5% to the 48% RH plot shows an increase in length of 1.8% due solely to the change in RH. The 5% RH stress-strain test shows that the specimen breaks if stretched more than 1.5%. If a speci-

men of pine were restrained at 48% and desiccated to 5% RH, it would break, because it is being held at a length that exceeds that to which it can be stretched at 5% RH without breaking. A pine table-top, restrained by its frame, would be likely to split if subjected to a change in RH of this severity. Such data allow limits to be set that avoid breakage of pine objects. Narrower limits are required to avoid irreversible deformation, plastic flow and compression set.

3.3.2 Calculation of allowable RH fluctuations

The data suggest that the elastic limit, or yield point, is about one-third the maximum stress of the pine at each of the tested environments. The maximum stress that can occur without permanent deformation is therefore about one-third the measured breaking stress at all environments. This is shown in Figure 2 as the dotted line connecting the plots. The changes in length associated with these stresses are a function of the mechanical properties of the pine at each environment. At 5% RH the maximum allowable stress and its associated stretch is 0.79MPa at 0.42% extension (point a); at 48% RH, the allowable stress/stretch is 1.27MPa/0.45% (point b).

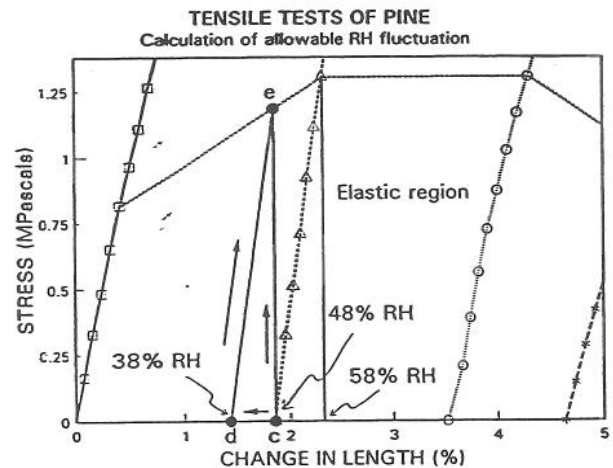


Fig. 3 Calculation of maximum RH fluctuations within the elastic region.

A drop of 10% RH from a starting point of 48% RH produces a shrinkage of approximately 0.44% in unrestrained pine. This is equivalent to moving from point c to point d in Figure 3, an expanded section of Figure 2. If the same pine is restrained and not allowed to shrink as the RH is lowered to 38%, it develops stresses (moving from point c to point e). These stresses are the same as if it were allowed to shrink freely at 38% RH (points c to d) and then stretched 0.44% (points d to e) at this new environment. The resulting stress would be around 1.17MPa (in tension) for the specimen at 38% RH, which is within the elastic region. Conversely, if the RH is raised by 10% to 58%, with restraint, stresses are produced equivalent to those required to compress unrestrained pine at 58% to the size it is at 48%. These compressive stresses would be about 1.27MPa, within the elastic range for 58% RH. The key to setting safe limits of RH fluctuation is to avoid stresses that exceed the yield point for a specific environment and that would produce plastic or irreversible deformation.

These data show that, at 48% RH, a piece of stress-free, restrained pine can experience fluctuations of $\pm 10\%$ without exceeding the yield points for these environments. This allowable fluctuation is not the same for all woods, or even necessarily for different starting relative humidities for the same wood. For pine the allowable fluctuation does remain constant at about $\pm 10\%$ RH over most of the RH range. Red oak, even though it

can sustain considerably higher stresses, has approximately the same allowable fluctuation as pine because it has a greater dimensional response to moisture. Spruce has allowable fluctuations in RH that are three or four times greater than either pine or red oak. Spruce has a smaller moisture response, and a larger elastic region, than the other two woods.

More complex analysis is required for objects such as furniture with inlays and veneers of various woods. Initial calculations show that the glue used in adhering the inlays and veneers is the component that determines the allowable limits. Adhesives are often more responsive than wood to RH. A similar analysis of the properties of sound rabbitskin-glue films shows that they can withstand fluctuations of $\pm 15\%$ RH at 50% RH, but only $\pm 8\%$ at 35% RH. Like many organic materials, the moisture response of glue is relatively flat at moderate (40-60%) RH, reducing both its response to RH fluctuations and the resulting stresses. Such analyses can be extended to composite materials whose properties are known. Calculations using data collected for a 13-year-old lead white pigmented oil-paint film indicate a tolerance to fluctuations of $\pm 30\%$ at 50% RH.

The magnitude of RH-induced stresses depends on several critical factors. These include the dimensional response to RH (the moisture coefficient of expansion), the change in stiffness as measured by the modulus of the material, the degree to which the material is restrained (the construction of the object), and the magnitude and rate of the change in relative humidity. The rate of change determines the depth of moisture penetration into a given material and the stress gradient resulting from the uneven moisture content. The potential for cracking is determined by the strength of the material, its ability to deform, the presence of defects in the material and the fracture sensitivity of the material.

By assuming conditions of full restraint and full equilibration as above, allowable RH fluctuations can be developed for materials for which appropriate data exist, and for composite objects that include these materials. The presence of degraded materials and existing flaws will certainly require a reduction in the allowable fluctuations. But calculations such as those above allow the development of rational guidelines, based on the measured physical and mechanical properties of the materials and the assembly of the object.

3.3.3 RH limits

The RH limits suggested by the above discussion are illustrated in Figure 4. The upper limit of 80% is determined by the softening of materials such as glue, with a value of 70% providing a margin of safety. Below 30-40%, materials such as glue become increasingly stiff and require increasingly tight RH control to prevent cracking. These limits assume that objects are at equilibrium and relatively stress-free at some moderate RH. Objects assembled at or acclimatized to very low RH may survive quite well at, and even require, drier conditions.

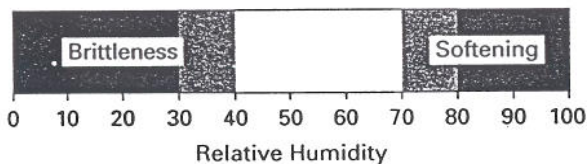


Fig. 4 Relative humidity zones of possible and probable mechanical damage, shaded light and dark, respectively.

3.4 Deliquescent salts

Most properties of hygroscopic materials change smoothly over a range of relative humidities. Other changes, such as the deliquescence of salts, can occur over a very narrow RH range. Each deliquescent salt is stable up to a specific RH, above which it

absorbs water vapor from the air and dissolves to form a solution. Common salt (sodium chloride) deliquesces at 76% RH. If the ambient RH is above 76%, then salt exists as an aqueous solution rather than a solid. If the RH varies over a range containing the deliquescence point, then the salt will alternately dissolve and crystallize. This can result in movement of the salt (crystallization on the surface is seen as efflorescence), or disruption and damage if the salt crystallizes within an object. Many objects, especially archaeological or previously submerged or buried materials, contain such salts, and examples are common [5]. Salt solutions can cause chemical damage. Their presence may increase the rate of corrosion of metals [6], or make a material more susceptible to damage by pollutants [7].

The deliquescence points of many pure salts are known [8]. A mixture of salts may deliquesce at a lower RH than either pure salt [8]. Hygroscopic materials impregnated with a deliquescent salt may absorb excess water at a relative humidity below the deliquescence point of the pure salt and form mobile ionic solutions of the salt. For example, silk containing 2.4% by weight of sodium chloride gained excess weight and increased in electrical conductivity when the RH exceeded about 55% [7].

Some salts deliquesce at very low RH (lithium chloride at 15%, calcium chloride at 32% [8]). To prevent the deliquescence of salts in museum objects, the RH should be as low as possible. Other factors may rule out very low RH, but the deliquescence of sodium chloride, at least, can be prevented. To achieve this, the RH *must* be kept below 76%, the deliquescence point of the pure salt, and preferably below about 55%, a point at which the salt can form solutions in hygroscopic organic materials (Fig. 5).

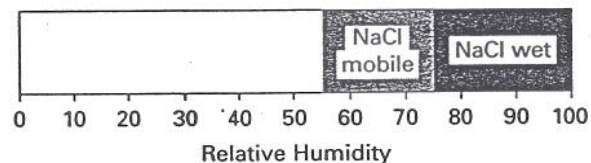


Fig. 5 Relative humidity zones of salt deliquescence and mobility, shaded dark and light, respectively.

3.5 Mineral hydrates

Mineral collections contain deliquescent salts and hydrates. If deliquescence is the sole concern, the RH need only be kept sufficiently low. Mineral hydrates are solid compounds that incorporate water in the crystalline lattice. Hydrates may be stable only within a specific range of relative humidity, losing water at lower RH or gaining water at higher RH. Magnesium sulfate exists as the mono-, di-, tetra-, penta-, hexa- and heptahydrates, as well as the anhydrous form, depending on the RH [9]. Microenvironments must be maintained for collections containing minerals whose ranges of stability do not overlap. Waller compiled the stability ranges for a number of minerals [9]. Such a list shows that there is no value of RH at which all minerals are stable (Fig. 6).

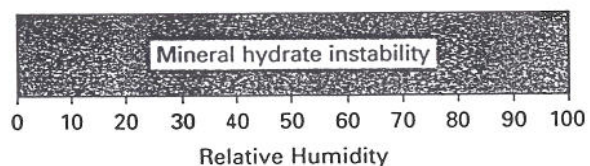


Fig. 6 For any relative humidity, there are mineral hydrates that are unstable.

3.6 Building damage

Damage due to an inappropriate RH is not limited to objects. Condensation can occur in historic buildings that house objects if

the outside temperature falls too low. With indoor conditions of 20°C and 50% RH, condensation can occur in exterior walls if the outside temperature falls below 10°C. Such condensates can cause damage, especially if they freeze. At 20°C, indoor relative humidities would have to be maintained at less than 10% to keep the dew-point above the winter temperatures of colder climates. It is difficult to prevent condensation within exterior walls. Effective vapor barriers are difficult to achieve in new buildings and almost impossible in old ones. Maintaining a negative pressure within the building may cause other problems. The construction of the building and the local climate determine the safe upper RH limit for a building, often no more than 50% in temperate climates and possibly much lower during cold weather (Fig. 7). The interior RH may be allowed to vary seasonally, depending on other factors such as the RH range that the collection will tolerate. A year-long cycle through a limited RH range should cause little, if any, damage.

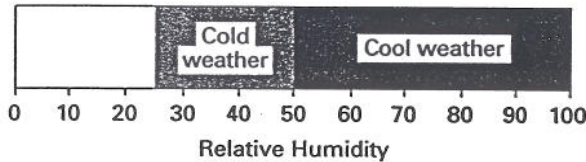


Fig. 7 The colder the external temperature, the lower the internal relative humidity must be to reduce the possibility of condensation within the building structure.

3.7 Chemical degradation

Many chemical processes depend on, or are accelerated by, the presence of water. Water may be present as absorbed water or may be incorporated from the vapor phase as a reaction proceeds. The amount of absorbed water increases as the RH increases. This added water is more available for chemical reactions, since each successive layer of water molecules is less tightly held.

Chemical degradation processes affected by relative humidity involve most types of material, including metals, glasses, inorganic and organic materials. The following examples will demonstrate the considerations involved in minimizing damage.

3.7.1 Metals

The corrosion of many metals is accelerated by high humidity, especially if corrosion or contaminants such as salts are present [6]. One example is bronze disease, in which small amounts of chlorides initiate the conversion of metallic copper to unstable copper chlorides and hydrated copper hydroxychlorides. Bronze disease is active at high RH, and slow or inactive at low RH. Low relative humidities are preferable for all metals that can corrode, especially those that already exhibit corrosion or that may contain salts due to burial or submersion. There is no lower limit on RH for the storage of metal objects. Scott found an upper safe limit of 46% RH for bronze disease [10] (Fig. 8). Lower values would provide a greater margin of safety and help to prevent other corrosion reactions, such as the rusting of iron, that might have lower RH limits.

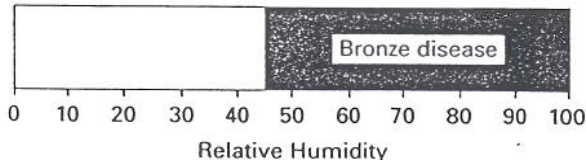


Fig. 8 Bronze disease can be active above 46% RH.

3.7.2 Glass

Certain highly alkaline glasses may decompose at all but very low relative humidities. Sodium and potassium ions leach from

the glass to form alkali hydroxide solutions. These solutions pick up carbon dioxide from the atmosphere. The resulting sodium and potassium carbonates either crystallize out and cause delamination and flaking if the RH is below their deliquescence points (91% for sodium carbonate and 44% for potassium carbonate [11]), or appear as droplets on so-called 'weeping glass' at relative humidities above the lower deliquescence point. At high RH the glass may appear sound, with carbonate solution filling in the pores and spaces between delaminations. The glass looks normal while it rapidly decomposes. Relative humidities below the deliquescence point of the carbonates yield a less visually desirable (opaque) glass, yet still may not be low enough to prevent the leaching of sodium and potassium ions from the glass (Fig. 9). Sodium and potassium hydroxide both have extremely low deliquescence points, respectively 6% and 5% RH [11], values impractical to maintain in a general environment. Available data are inadequate to determine the RH at which such alkaline glass would be stable.

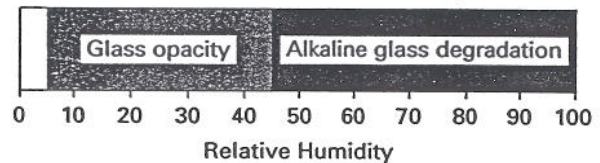


Fig. 9 Alkaline glass becomes wet and deteriorates at high relative humidity, but deterioration may continue even down to very low values of RH.

3.7.3 Minerals

Some inorganic materials react with water to form new compounds, rather than simply dissolving or changing hydration state. One example is barium sulfide, which reacts with water to form barium hydroxide and hydrogen sulfide. Others may undergo reactions more quickly in the presence of water. At high RH, pyrite (ferrous disulfide) oxidizes in air more quickly to form ferrous and ferric sulfates. Waller found that the rate rose exponentially as RH increased from 10 to 60%, but the rise was less drastic and approached a limiting value above 60% RH [12]. This work also indicated that the rate eventually slowed and approached zero when the RH was below 30%; above 50% RH the reaction would continue until the pyrite was consumed. Low RH, certainly below 50% and preferably below 30%, is required for pyrite (Fig. 10). Though there are few, if any, such studies for other similarly reactive minerals, it is obvious that, in this case, the RH should be maintained as low as is practical.

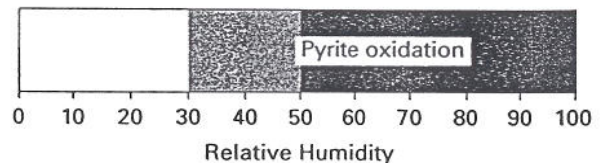


Fig. 10 Pyrite continues to oxidize indefinitely at high relative humidity, and requires very low RH for stability.

3.7.4 Organic materials

Most organic materials are hygroscopic, gaining and losing water with increases and decreases in RH so that their water content is a smooth (though not linear) function of RH. The effects of RH on the nature and rate of chemical reactions generally vary gradually with changes in RH, with no specific limiting values that determine whether or not a reaction occurs. Most of the RH-dependent reactions of organic materials will proceed, however slowly, at all practical values of relative humidity. The goal

becomes one of minimizing, rather than eliminating, their effect. The degradation of organic materials is often slow, gradual, and more subtle than that of inorganic materials. Changes in inorganic materials, such as corrosion, dissolution and conversion to another compound, are more obvious and more easily measured than changes such as fading, loss of strength, crosslinking or hydrolysis in organic materials. Some changes were not measurable until recent developments in instrumentation. The relationship of relative humidity to the chemical degradation of organic materials was not obvious, and often was not considered when setting the RH. The effects of relative humidity on two common organic materials derived from plants and animals, respectively — cellulose and protein — will demonstrate.

3.7.4.1 Cellulose

The effects of relative humidity on the aging of cellulose (in the form of paper) were examined perhaps most thoroughly in the study by Graminski, Parks and Tech [13]. They found that effects on the aging of paper varied smoothly, increasing from 0 to 75% RH. Michalski re-examined their data and concluded that relative humidity has an effect down to 2-3% RH [1]. The hydrolysis of cellulose has been studied in this laboratory by measuring increases in the amount of free glucose in paper [14]. Hydrolysis continues, however slowly, even during dry oven aging. The temperature range of the study, 90 to 150°C, implies RH values of <2% to <1%, respectively. During water extraction of soluble reaction products from the samples, it was noticed that longer aging made samples more resistant to pulping, indicating that crosslinking was occurring. Samples aged at 90°C in air in sealed vessels containing water (high RH) developed much higher concentrations of glucose, and remained pulpable. This indicated that hydrolysis, rather than crosslinking, was the predominant reaction at high RH. Layers of absorbed water surround the cellulose fibers at high RH, inhibit the fibers from reacting with one another, and accelerate hydrolysis. The moisture absorption of cotton levels off above about 50% RH [15], when water has covered most of the absorptive active surface sites of the cellulose fibers. Maintaining the RH above 25% should ensure the presence of enough water to inhibit crosslinking reactions between fibers.

The rate of hydrolysis is minimized by reducing the RH to as low a value as possible, while crosslinking reactions are probably minimized by maintaining the RH above 25% (Fig. 11). Insufficient data exist to determine a range of relative humidity in which the total rate of change is minimized, but it is probably somewhere in the range 25-50%.

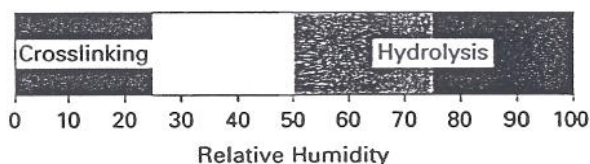


Fig. 11 Lowering the relative humidity reduces the rate of hydrolysis of cellulose, but the rate of crosslinking increases if the RH falls too low.

3.7.4.2 Proteins

Hansen, Lee and Sobel investigated the effects of relative humidity on the physical properties of vellum, reviewed relevant literature on the effects of RH on leather, and proposed an optimum RH range for the storage of leather and related protein-based materials [16]. Studies of the gelatinization (hydrolysis) of collagen in the range 40-100% RH showed that rates increased with increasing RH. The rate of gelatinization should slow further below 40% RH. Highly desiccated collagen does not

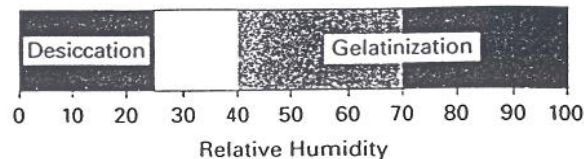


Fig. 12 Gelatinization of collagen accelerates with increasing relative humidity, while irreversible desiccation occurs at very low RH.

completely rehydrate. This probably does not occur unless the RH is reduced below 25%. Above this value, strongly water-absorbing groups (those that might otherwise interact with each other to prevent rehydration) are saturated with water. The important reactions of collagen affected by RH therefore mirror those for cellulose: hydrolysis and crosslinking. For these and other reasons, Hansen *et al.* recommended a value of 30% RH as the optimum for the storage of materials composed of collagen, with outer limits of 25 and 40% (Fig. 12).

3.8 Type of collection

The purpose and use of the collection must also be considered.

3.8.1 Active collections

Section 3.3 examined environmentally induced static stresses. For a collection in active use, with objects moved on and off display, subjected to study or otherwise handled or moved with some frequency, the effects of RH on more dynamic processes such as vibration and impact must be considered. At low RH, materials lose ductility and are less able to withstand deformation, even though they might be stronger. Many materials become fracture-sensitive and prone to breakage, behaving more like a glass or ceramic. An impact that briefly distorts a painting at 50% RH might cause cracking at 15% RH. Pre-existing defects and cracks, present in most museum objects, represent sites of intense stress concentration from where further cracking or flaking can propagate.

Shock and vibration generated by different forms of transport have been characterized [17], and the results applied to the transport of art [18]. Transport without proper packing protection is a hazard at any environment, but especially at low RH. Maintaining an RH above 40% should provide a reasonable margin of safety during transport.

Other sources of serious impact include accidents and improper handling within the museum. As with transport, moderate RH environments reduce the potential for damage during handling. Both extremes — flexible but weak at high RH and strong but brittle at low RH — should be avoided for collections in active use. Minimizing damage due to handling thus leads to the same RH limits as does minimizing damage from mechanical problems in general (Fig. 13).

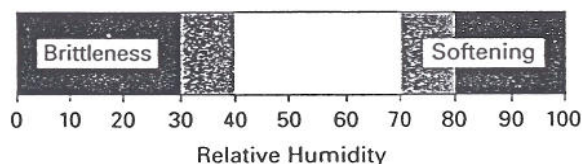


Fig. 13 For active collections, both the extremes — flexible but weak at high relative humidity and strong but brittle at low relative humidity — should be avoided.

3.8.2 Archival collections

Collections in which objects are infrequently moved from storage are less subject to damage by handling. Permanence is more important than durability and resistance to breakage. For objects that are not handled, brittleness caused by low RH is acceptable

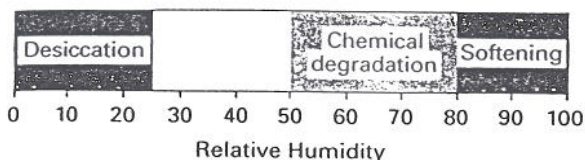


Fig. 14 For archival collections, lowering the relative humidity reduces most types of chemical degradation. Only very low values of RH that promote crosslinking or irreversible desiccation or induce intolerable stresses should be avoided.

as long as stresses generated by low RH are not enough to cause direct damage. Objects can be slowly conditioned to moderate RH for the rare occasion when the object is to be handled or moved. High RH, and the resulting softening that leads to deformation due to the weight of the object, still should be avoided. Once mechanical damage is reduced or eliminated, chemical degradation is the major remaining concern. As discussed earlier, many chemical processes are slower at low RH, and only very low relative humidity (less than about 25-30%) should be avoided (Fig. 14). Many long-term storage facilities maintain low temperatures to slow down chemical degradation processes. Low-temperature storage is beyond the scope of this paper, however, since it results in changes in the physical properties of materials that further complicate matters and may affect the choice of RH. For example, the effects of changes in temperature and RH on paintings have been examined [19].

4 OVERALL RELATIVE HUMIDITY

In Figure 15, the values and ranges in Figures 1 and 4-14 are collected and arranged in groups relevant to general collections, to special cases, and to specific types of collection. It is obvious that there is no 'ideal' RH for museums. Examining the effects of

RELATIVE HUMIDITY STABILITY ZONES

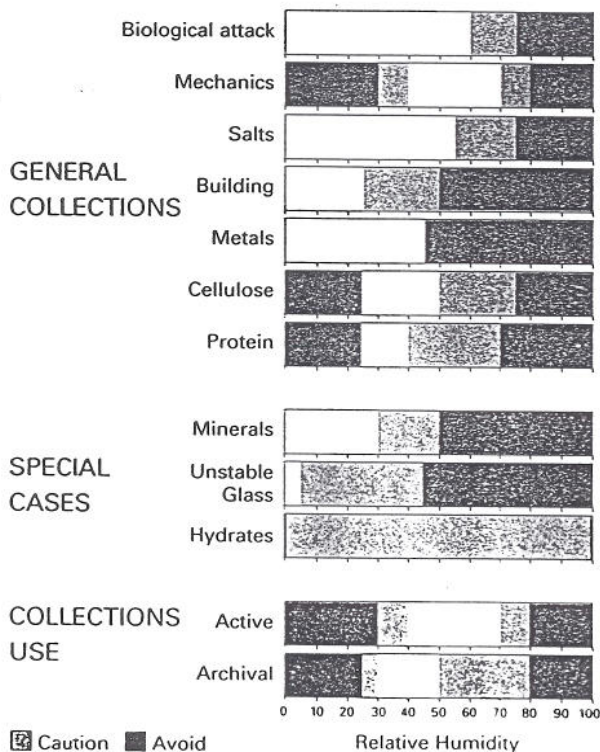


Fig. 15 The ranges of relative humidity suggested by consideration of various factors. No one RH is ideal, and any value chosen must be a compromise.

relative humidity does not lead to convergence on an ideal RH, but to a set of values and ranges (i) that may be more or less precise or accurate, (ii) that may apply only to specific types of material or object, and (iii) at which different types of damage may stop, start, increase or decrease. These values and ranges may or may not overlap, and often are in conflict. To choose an overall RH set-point for a collection it is necessary to determine the relevant factors, assess their importance, and select a value that is the best compromise in terms of minimizing overall effects. This may require separate macro- or microenvironments for some collections or objects, and special precautions in handling and conditioning if objects are kept at low RH. Costs and capabilities of available heating and air-conditioning equipment must also be considered.

The RH settings most common in museums, those in the range 40-60%, minimize biological attack, mechanical damage and the efflorescence of common salt. It is interesting to note that these are the most visible, and often the fastest, forms of damage seen in museums (other than for materials known to require separate treatment, such as corroded metals, weeping glass and mineral hydrates). It is easy to see how RH values around 50% have become so widely accepted. It is only when less obvious forms of damage are considered, such as the slow but continuous degradation of organic materials, that lower values of relative humidity seem more desirable. In fact, the reduction of mechanical damage is the only major factor that would seem to argue against all but the lowest values of relative humidity, those below 25-30%. This conflict — mechanical damage versus chemical degradation, form versus content — is the main consideration in choosing a suitable RH, and one for which there is no obvious resolution.

5 CONCLUSIONS

There is no one 'ideal' relative humidity for museums, only values and ranges that minimize specific types of change in materials and objects. Extreme values and rapid or large changes in RH should be avoided. Within the range of moderate RH values (30-60%), high RH tends to minimize mechanical damage and low RH tends to minimize chemical change. Some objects will require, or would benefit from, separate microenvironments no matter what RH set-point is chosen.

REFERENCES

- Michalski, S., 'Relative humidity: a discussion of correct/incorrect values' in *ICOM Committee for Conservation 10th Triennial Meeting*, Washington (1993) 624-629.
- Pfenderleith, H.J., and Philippot, P., 'Climatology and conservation in museums', *Museum* 13 (1960) 242-289.
- Thomson, G., *The Museum Environment*, Butterworths, London (1978).
- Mecklenburg, M.F., and Tumosa, C.S., 'An introduction into the mechanical behavior of paintings under rapid loading conditions' in *Art in Transit: Studies in the Transport of Paintings*, ed. M.F. Mecklenburg, National Gallery of Art, Washington (1991) 137-171.
- FitzHugh, E.W., and Gettens, R.J., 'Calcite and other efflorescent salts on objects stored in wooden museum cases' in *Science and Archaeology*, ed. R.H. Brill, MIT Press, Cambridge, MA (1971) 91-102.
- Evans, U.R., *The Corrosion and Oxidation of Metals: Scientific Principles and Practical Applications*, Edward Arnold Ltd, London (1960).
- Padfield, T., and Erhardt, D., 'The spontaneous transfer to glass of an image of Joan of Arc' in *ICOM Committee for Conservation 8th Triennial Meeting*, Sydney (1987) 909-913.
- Weast, R.C., ed., *Handbook of Chemistry and Physics*, 54th edn, CRC Press, Cleveland, OH (1973).
- Waller, R., 'The preservation of mineral specimens' in *Preprints of Papers Presented at the 8th Annual Meeting*, American Institute for Conservation, Washington (1980) 116-128.

- 10 Scott, D., 'Bronze disease: a review of some chemical problems and the role of relative humidity', *Journal of the American Institute for Conservation* 29 (1990) 193-206.
- 11 Meites, L., ed., *Handbook of Analytical Chemistry*, 1st edn, McGraw Hill Book Company, New York (1963).
- 12 Waller, R., 'Pyrite oxidation studies', *CCI Newsletter* (1989) 10.
- 13 Graminski, E.L., Parks, E.J., and Toth, E.E., 'The effects of temperature and moisture on the accelerated aging of paper', *NBSIR 78-1443*, prepared for the National Archives and Records Service by the Polymer Division, Institute for Materials Research, National Bureau of Standards, US Department of Commerce, March 1978.
- 14 Erhardt, D., Von Endt, D., and Hopwood, W., 'The comparison of accelerated aging conditions through the analysis of extracts of artificially aged paper' in *Preprints of Papers Presented at the 15th Annual Meeting*, American Institute for Conservation, Washington (1987) 43-55.
- 15 Morton, W.E., and Hearle, J.W.S., *Physical Properties of Textile Fibres*, Heineman, London (1975).
- 16 Hansen, E.F., Lee, S.N., and Sobel, H., 'The effects of relative humidity on some physical properties of modern vellum: implications for the optimum relative humidity for the display and storage of parchment', *Journal of the American Institute for Conservation* 31 (1992) 325-342.
- 17 Ostrem, F.E., and Godshall, W.D., 'An assessment of the common carrier shipping environment', *General Technical Report FPL 22*, Forest Products Laboratory, USDA, Madison (1979).
- 18 Marcon, P.J., 'Shock, vibration, and the shipping environment' in *Art in Transit: Studies in the Transport of Paintings*, ed. M.F. Mecklenburg, National Gallery of Art, Washington (1991) 121-132.
- 19 Mecklenburg, M.F., and Tumosa, C.S., 'Mechanical behavior of paintings subjected to changes in temperature and relative humidity' in *Art in Transit: Studies in the Transport of Paintings*, ed. M.F. Mecklenburg, National Gallery of Art, Washington (1991) 173-216.

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