

## Guidelines for the Museum Climate

David Erhardt, Marion F. Mecklenburg, Charles S. Tumosa, and Mark McCormick-Goodhart, Conservation Analytical Laboratory, Smithsonian Institution, Washington, DC 20560, USA.

### 1. Introduction

The museum environment has a number of components, including temperature, relative humidity, light, vibration, pollutants, and particulates. Of these factors, the optimal value for vibration, pollutants, and particulates is zero. If objects are light sensitive, then light should be reduced to the minimum amount of visible light required for proper viewing (and preferably only during viewing). Temperature and relative humidity differ from the other environmental factors in that they are interdependent, and their effects are much more varied and complex. A temperature or relative humidity acceptable for one object may be disastrous for another. Since temperature and relative humidity must be optimized rather than eliminated, satisfactory values or ranges must be determined and maintained.

Values for temperature in the general museum area (as opposed to storage) are restricted to the relatively narrow range in which people are comfortable. Thus relative humidity is the major variable of the museum environment for which there is no obvious optimal value or range.

Relative humidity affects the preservation of objects in many ways. It affects physical, chemical, structural, and optical properties, and even the physical state of materials. It determines the rate of many chemical reactions, and whether biological attack might occur. It affects the rate at which pollutants or contaminants can attack a material. It even affects the building structure itself if temperature differences cause condensation within the external fabric of the building. Changes in relative humidity also have effects, producing dimensional changes in hygroscopic materials which can result in strains, stresses, plastic deformation, or fracture.

Each of these factors may be more or less important for a specific type of material, and each material will be affected differently. As a result, considerations of different individual factors may suggest different optimal values or ranges of relative humidity, even for the same material. Research into the different effects of relative humidity leads not to an ever more accurate determination of the one optimal value, but to more or less overlapping, or even conflicting, recommendations [1]. Thus, no matter what value or range of relative humidity is chosen for the general museum environment, there always will be some objects which require either tighter control or separate and different conditions. Conditions other than those of the general environment can be provided through the maintenance of appropriate microenvironments.

This paper presents some of the considerations relating to the determination of suitable conditions of relative humidity in the general museum environment. In addition, some considerations relating to specialized storage environments also are presented.

## 2. Classes of materials

Materials in the museum can be roughly separated into four different classes: those which are insensitive to relative humidity, those which require low relative humidity (possibly below a critical value), those which require RH values within a specific range, and those which respond to differences in RH throughout the RH range.

### 2.1 Materials insensitive to RH

The class of materials which are insensitive to RH includes many inorganic materials: most ceramics and glasses and some metals. These materials are dimensionally stable with changes in RH, and are either chemically unreactive under any reasonable conditions or reaction is so slow as to be negligible. For example, some ceramics theoretically can re-hydrate, but do so very slowly so that changes can be ignored.

### 2.2 Materials requiring low RH

Degradation processes of a number of materials start or speed up as the RH is raised. Such processes include the corrosion of metals such as iron and bronze, and the oxidation or hydrolysis of minerals such as pyrite. In some cases, reaction stops or is negligible below certain values of RH. For example, Scott found that the corrosion process of chloride contaminated bronze known as "bronze disease" is inactive below about 46% RH [2]. Waller determined that the rate of oxidation of pyrite speeds up with increases of RH within the range 10 to 60% RH, above which the rate levels off. At values below about 30%, the reaction rate eventually slowed and approached zero [3]. Some alkaline glasses are sensitive to RH, with sodium and potassium hydroxides forming and leaching from the glass (eventually to form carbonates by reaction with carbon dioxide in the air) under typical museum conditions. Low RH slows the process, but it is not clear whether keeping the glass below 44% RH (to keep the carbonates from deliquescing [4]) or even 5% RH (to keep the hydroxides from deliquescing [4]) will totally prevent the process of degradation.

Many materials are impregnated with deliquescent salts. These may have been introduced deliberately (some textiles were salted and worked at high RH where they are soft and lubricated as a result of the presence of salt solutions), or acquired unintentionally as the result of burial or submersion. If the RH is above the value at which such salts deliquesce, they absorb water vapor from the air to form mobile electrolytic solutions. The presence of such solutions can contribute to reactions such as corrosion [5] or hydrolysis, or increase the susceptibility to pollutants [6].

For materials described in this section, low RH is required. Some materials require an environment as dry as possible, while others are unreactive and insensitive to RH and dimensionally stable as long as the RH is below a certain value. Many such materials, however, require drier conditions than are suitable for general collections. Such materials are best kept in separate low RH areas, or in dry microenvironments.

In addition to exhibited and stored objects, the museum building itself may require an RH below a certain value. If the outside temperature is below the dewpoint of the interior air, then condensation may occur in the exterior fabric of the building. This can result in rotting, staining, rusting, spalling, dripping, and other problems. Ideally, the dewpoint of the interior air should be below the temperature of the exterior air. This would result in extremely low interior RH values during cold weather in temperate and cold climates, however. Approaches to the problem include strategies such as vapor barriers, reduced interior temperatures and pressures, and other measures to minimize problems while still maintaining acceptable interior humidities.

Another factor, mold growth, places an upper boundary on RH. Mold growth is likely above about 75% RH, but ceases to be a factor below about 60% RH [7].

### **2.3 Materials requiring a specific RH range**

The number of materials requiring a specific RH range is quite small, restricted mainly to mineral hydrates which incorporate water into their crystalline lattice. These minerals are stable only within certain compound-specific RH ranges, losing water and powdering at lower RH, or gaining water and decomposing or dissolving at higher RH. For example, magnesium sulfate can exist as the anhydride, or as the mono-, di-, tetra-, penta-, hexa-, or heptahydrate, depending on the RH. Waller has compiled the stability ranges for a number of minerals [8]. Such materials must be kept in separate microenvironments if the overall RH is not maintained within their range of stability.

### **2.4 Materials responsive to RH throughout the RH range**

Most organic materials are sensitive to differences in RH throughout the RH range. This can be illustrated by a typical moisture absorption isotherm for cellulose shown in Figure 1. There is no range over which the moisture content remains constant. Any change in RH produces a change in moisture content. This leads to changes in chemical reactivity, structural and physical properties, and dimension. These effects in turn can result in changes in stress and strain, possibly leading to plastic deformation or fracture. Any attempt to determine an optimal value or range for such a material (or composites which incorporate it) must take all of these factors into account. The RH range chosen often is a compromise.

Cellulose, which is the structural component of a large number of museum objects, provides an example of the way these factors can be taken into account in determining an appropriate or optimal range for hygroscopic materials. The first step is considering the nature of absorbed water in hygroscopic materials.

#### **2.4.1 Water in cellulose**

Cellulose contains a large proportion of polar, reactive groups, specifically the hydroxyl groups of the glucose molecules which are the building blocks of cellulose. These groups can form hydrogen bonds to, and bind very tightly with, water molecules. Cellulose at very low RH contains little or no water, but as the RH is raised cellulose rapidly picks up water.

This accounts for the steep curve of the isotherm at low RH in Figure 1. This "bound" water absorbed at low RH is held very tightly by the reactive groups, and in fact can be regarded as part of the structure of the cellulose "matrix". The isotherm curve flattens out once the reactive sites are covered, and cellulose absorbs water at a much slower rate as the RH is raised through the middle range, i.e. cellulose is less responsive to RH change in this region. As the RH is raised further, capillary absorption increases and the rate of absorption with RH change increases. Capillary absorption in fact occurs throughout the RH range, but is most important at higher RH (above about 50%). Water absorbed through capillary action, so-called "free" water, is not tightly bound, is mobile, reactive, and behaves much more like liquid water. Bound and free water can be differentiated by methods such as thermodynamic studies of the heat of absorption of water. Figure 2 separates the isotherm of Figure 1 into bound and free water.

#### 2.4.2 Reactivity of cellulose vs RH

The main reaction of cellulose under "normal" conditions is the hydrolysis of the cellulose chain. This process involves the reaction of water with cellulose to split the cellulose chain between glucose units. This type of reaction is dependent on RH. In Figure 3 the rates of several such reactions are plotted vs RH, along with curves fit to the data [10]. It can be seen that the rates of the reactions correlate with the amount of free water from Figure 2, which is also plotted. Thus the hydrolysis of cellulose can be reduced to minimal levels by reducing the relative humidity.

At low RH, crosslinking of cellulose occurs. This is due at least in part to the uncovering of the reactive groups with the loss of bound water. In addition, the loss of bound or structural water can lead to collapse of the pore structure and inter-fibrillar interstices of materials such as paper and wood, along with reductions in reactivity as accessibility of the cellulose molecules is reduced. Changes induced by severe drying are only partly reversible, and are less so if crosslinking is allowed to continue for a long time.

Thus, the reactivity of cellulose is minimized by reducing the RH to the point at which most of the free, reactive water is removed, but enough bound water remains to cover the reactive groups and prevent crosslinking and structural collapse. This minimum occurs somewhere around 30% RH (isotherms vary depending on factors such as percent crystallinity and processing of the cellulose). Since the isotherm is relatively flat just above this point, though, the RH can be raised up to 50% or so without significantly increasing the reactivity of the cellulose ("significantly" being a relative term, in this case a factor of two or three, as compared to the large increases which occur at very high RH). Thus, considerations of the chemical reactivity of cellulose lead to a recommended range of 30-50% RH, which is the relatively flat portion of the isotherm.

#### 2.4.3 Physical properties of cellulose versus RH

Of the basic physical properties which are important in determining how easy it is to cause damage at constant RH, three can vary with changes in RH. These are the modulus (stiffness), strain-to-yield (deformation required to cause permanent distortion), and strain-to-

failure (deformation required to cause fracture or breakage). Absorbed water affects these properties by acting as a plasticizer. Figure 4 plots the modulus of tulip poplar in the cross-grain (primarily tangential) direction. The modulus is relatively constant up to about 50% RH, then falls off rapidly, losing two-thirds of its maximum value by 100% RH. This behavior indicates that it is primarily the free absorbed water which acts as a plasticizer and affects the stiffness. This material exhibits relatively little change in stiffness in the range below 50% RH, which includes the 30-50% RH range suggested from the considerations of chemical reactivity. In this relatively flat portion of the isotherm, there is little change in water content, thus little change in these properties.

Similar conclusions result from a consideration of the strain required for failure. Figure 5 plots both the strain-to-failure and strain-to-yield of cottonwood in the (primarily) tangential direction. The strain-to-failure (amount of stretching required to cause fracture) is relatively constant (between 1 and 2%) up to about 80% RH, above which it increases dramatically. Again, there is relatively little difference in a wide range which includes the 30-50% RH range. However, the prevention of total failure is not stringent enough a goal. Permanent distortion can be avoided by not exceeding the strain-to-yield, which is relatively constant at about 0.004 (0.4%). Deformations less than this are elastic, with the material returning to its original shape and size once the deforming force is released. Absorbed water seems to have little if any effect on this property.

These data dispel one myth, which is that materials are necessarily brittle and/or stiff at all low RH values. This idea may have resulted from the fact that the crosslinking of materials stored at very low RH (less than 20-30%) can result in reduced strain-to-break, which can be interpreted as brittleness. In fact, as long as very low RH is avoided, important physical properties are relatively insensitive to RH within the flat portion of the isotherm.

#### **2.4.4 Effects of RH fluctuations on hygroscopic materials**

Cellulosic materials absorb and desorb water and consequently change dimension as the relative humidity changes. If a material is unrestrained, this absorption and desorption is reversible in a reasonable range of relative humidity, and a material simply expands and contracts with changes in relative humidity. It is only when a material is restrained, either internally or externally, that this tendency to change dimension can cause stresses and resulting damage. If the relative humidity is reduced, wood will try to shrink. If it is held in a rigid metal frame and prevented from shrinking, stresses develop. If these stresses are large enough, they result in permanent deformation or breakage.

Figure 6 shows stress-strain curves for a piece of cottonwood at various relative humidities. Such data is typical for the many materials that have been tested by the authors. Applying a force (moving up the vertical axis) stretches the sample (moving to the right along the horizontal axis). Changes in dimension also can be produced simply by changing the RH with no force involved. This involves moving along the horizontal (zero stress) axis, which is why the stress-strain curves for different values of RH start at different positions along the horizontal axis. The curves are separated by the change in length due solely to changes in RH. The beginning of each curve is linear. This linear section of the curve represents a

region in which deformation is reversible and elastic.

How do these tests, conducted at constant RH, relate to effects caused by changes in RH? Figure 7 is a detail of Figure 6. The worst case assumption is that a sample is fully restrained and not allowed to change dimension or respond to changes in RH. If the RH is reduced from 48%, the sample tries to shrink, but cannot. Stress develops. This is equivalent to moving vertically, staying the same length but with increasing stress. If the RH is reduced to 23%, the plot ends up at a point on the 23% RH stress-strain curve. This demonstrates a fundamental principle found to be true for all of the materials tested [12]. The stress in a sample is a function of the final conditions of strain and RH; the path to a specific condition does not matter. Keeping the dimension constant and lowering the RH results in the same stress as allowing the sample to shrink freely as the RH is lowered, and then stretching it to the original length. This means that the effects of RH changes can be calculated from a series of stress-strain tests conducted at constant, but different, values of RH. The only additional information required is the change in dimension caused by changes in RH. Measurements of the changes in dimension caused by RH changes, as well as the amount a material can be reversibly stretched, allows the calculation of the RH fluctuations which can be allowed without irreversible deformation or fracture [11-22].

An example of a plot of allowable RH fluctuations (for cottonwood) is illustrated in Figure 8. These calculations are for the worst case, i.e. full restraint and full response to the change in RH. If the material is not restrained, or the exposure to the RH extremes is not long enough for full response of at least the outer layer to occur, then even greater fluctuations are required to produce damage. The rate of the change in RH does not affect these allowable fluctuations. Rapid fluctuations (within the allowable range) which allow less than full response do not produce stresses and strains which exceed the elastic limit. As shown in the plot, stress-free cottonwood at equilibrium at 50% RH can be restrained and then exposed to conditions with the RH as low as about 31% or as high as about 68% RH without producing damaging strains and stresses. Fracture does not occur until the RH is lowered to below 15%. An interesting feature of the plot is that the allowable fluctuations are not uniform, but depend on the starting relative humidity. Not surprisingly, the greatest allowable fluctuations are in the 30-60% RH range, the flat portion of the isotherm where the wood is least responsive to changes in relative humidity. If there is no response, there is no mechanism for environmental mechanical damage. Similar measurements and calculations for a wide range of materials (not just cellulose) yield similar results, with allowable fluctuations of around  $\pm 15\%$  or more in the moderate RH range. These calculations refute another myth, that objects at high RH can more readily "equilibrate" to RH changes. In fact, allowable fluctuations are small at high RH because hygroscopic materials are very responsive to RH changes in that region. Any so-called "equilibration" at high RH to other than small changes likely involves irreversible plastic deformation (damage).

#### 2.4.5 Effects of RH changes on composite materials

If the material properties of the components of a composite structure are known, similar calculations of the overall response of the composite, and the strains and stresses induced at each point, can be made [11,17-22]. Figure 9 shows the swelling coefficients of the layers

of a typical panel painting. In the moderate (30-60% RH) range, the materials respond to RH changes similarly, and the materials shrink or swell together, producing little or no stress in the individual layers. At low (below 30%) or high (above 70%) RH, the wood and gesso layers respond much more to changes in RH than do the other layers. The massive wood layer controls the response of the composite. At high RH, the wood swells and stretches the paint layer, while at low RH the wood shrinks and compresses the paint. Thus, RH-induced cracking of the paint, if it occurs at all, is caused not by low RH, but by high RH, while low RH can result in buckling and cupping of the paint layer. A more detailed discussion of such calculations can be found in the references [11,20-21]. In general, the allowable fluctuation of a composite is at least as great as that of the most RH-responsive material. Most materials have at least a  $\pm 15\%$  RH allowable fluctuation when equilibrated to moderate RH. A collection equilibrated to 45% RH can be allowed to fluctuate between 30 and 60% RH. Other considerations, such as chemical stability, favor keeping the RH at the low end of this range. Again, it must be emphasized that these calculations of allowable fluctuations are based on worst case considerations, and many materials and objects can be subjected to even greater fluctuations without sustaining mechanical damage.

### 3. Conditions other than room temperature

An underlying assumption is that museum collections, with few exceptions, are stored, exhibited, and studied at room temperature. This is unfortunate, because the increases in the chemical stability of most organic materials possible with cold storage are much greater than those which can be achieved by modifying the relative humidity within a reasonable range. For instance, Figure 3 shows that lowering the RH from 60 to 30% can reduce the rate of degradation of paper by a factor of three to five times. In the same study, a determination of the activation energies of these reactions showed that their rates could be approximately halved by each 5° C reduction in temperature [10]. Lowering the storage temperature from room temperature (20° C) to -15° C (a temperature achievable with standard single-stage mechanical refrigeration) produces over a hundred-fold increase in expected chemical stability.

Physical considerations are the main factor in determining whether a material or object can safely be stored at low temperature. Temperature changes produce dimensional changes, and therefore are capable of producing strains and stresses much as changes in RH. An approach similar to that used in determining the mechanical and physical effects of changing the relative humidity can be used to evaluate the effects of temperature [14-15, 18-19, 21-22]. Measurements of properties such as the thermal expansion coefficient, and modulus, strain-to-break, and strain-to-yield as a function of temperature can be used to calculate the effects of temperature changes. Other subtle factors also must be considered. These include glass transitions which can change physical properties, and shifts in the isotherm which can change the equilibrium moisture content even at constant RH. The complex relationship between temperature, pressure, relative humidity, and moisture content was demonstrated by a study of the behavior of photographic gelatin [23].

Deviations from "room temperature" are practical only in storage areas or specialized microclimate exhibit cases. Cold storage also presents challenges of design and access.

Nevertheless, cold storage can be integrated effectively with overall museum energy cost objectives and reasonable policies which balance the conflict between preservation and access.

#### 4. General recommendations for RH settings

It is clear from the previous discussion that there is no one ideal RH for the general museum environment. This is made clear in Figure 10, adapted from [1], which provides a comparison of the ranges suggested by various factors. An environment maintained between 30-50% RH may be the best general compromise. The RH could be allowed to vary (at any rate) within this region with little risk of damage. However, any overall setting must be a compromise, and there will always be exceptions which will have to be treated separately, either buffered to reduce RH fluctuations or housed in a microenvironment with a different RH. As shown in the section on RH fluctuations, objects conditioned to high RH are susceptible to damage if exposed to low RH environments. Metals such as bronze and iron should be kept in the dry end of the 30-50% RH range, if not drier.

The costs of maintaining both the general and specialized environments also must be considered. The installation and running costs of equipment and facilities designed to maintain "constant" conditions can be prohibitive. Allowing both short-term and seasonal fluctuations in the environment can greatly reduce costs. For example, allowing the RH to drop to 30% in the winter and rise to 50% (or even 60%) in the summer may reduce the running costs of humidification and dehumidification, and may even eliminate the need for large capacity or multiple stage systems.

Setting the RH range and determining the exceptions requires an understanding of the effects of RH as well as a thorough knowledge of the materials in a collection, the ability to determine which objects and materials must be treated differently, and an understanding of the costs and problems involved in maintaining specific environments.

#### References

1. Erhardt, D., and M. Mecklenburg, "Relative Humidity Re-examined", Preventive Conservation: Practice, Theory and Research, Preprints of the Contributions to the Ottawa Congress, 12-16 September 1994, The International Institute for Conservation of Historic and Artistic Works, 32-38.
2. Scott, D., "Bronze disease: A review of some chemical problems and the role of relative humidity", Journal of the American Institute for Conservation Vol. 29 (1990) 193-206.
3. Waller, R., "Pyrite oxidation studies", CCI Newsletter (1989) 10.
4. Meites, L., ed., Handbook of Analytical Chemistry, 1st edition, McGraw Hill Book Company, New York (1963).



5. Evans, U. R., The Corrosion and Oxidation of Metals: Scientific Principles and Practical Applications, Edward Arnold Ltd., London (1960).
6. Padfield, T., and D. Erhardt, "The Spontaneous Transfer to Glass of an Image of Joan of Arc", ICOM Committee for Conservation, 8th Triennial Meeting, Sydney (1987) 909-913.
7. Michalski, S., "Relative humidity: A discussion of correct/incorrect values", ICOM Committee for Conservation, 10th Triennial Meeting, Washington (1993) 624-629.
8. Waller, R., "The preservation of mineral specimens", Preprints of papers presented at the 8th annual meeting, The American Institute for Conservation of Historic and Artistic Works, San Francisco (1980) 116-128.
9. Urquhart, A. R., "Sorptions Isotherms", Moisture in Textiles, J. W. S. Hearle and R. H. Peters, eds., Textile Book Publishers, Inc., New York (1960), 14-32.
10. Erhardt, D., and M. Mecklenburg, "Accelerated vs Natural Aging: Effect of Aging Conditions on the Aging Process of Paper", Materials Issues in Art and Archaeology IV, Materials Research Society Symposium Proceedings Vol. 352 (1995) 247-270.
11. Erhardt, D., M. F. Mecklenburg, C. S. Tumosa and M. McCormick-Goodhart, "The Determination of Allowable RH Fluctuations", Western Association for Art Conservation Newsletter, Vol. 17(1), (1995) 19-23.
12. Mecklenburg, M. F., C. S. Tumosa and M. H. McCormick-Goodhart, "A General Model Relating Externally Applied Forces to Environmentally Induced Stresses in Materials", Materials Issues in Art and Archaeology IV, Materials Research Society Symposium Proceedings Vol. 352 (1995) 285-292.
13. Mecklenburg, M. F., C. S. Tumosa and N. Wyplosz, "The Effects of Relative Humidity on the Structural Response of Selected Wood Samples in the Cross-Grained Direction", Materials Issues in Art and Archaeology IV, Materials Research Society Symposium Proceedings Vol. 352 (1995) 305-324.
14. Mecklenburg, M. F., C. S. Tumosa and M. H. McCormick-Goodhart, "A General Method for Determining the Mechanical Properties Needed for the Computer Analysis of Polymeric Structures Subjected to Changes in Temperature and Relative Humidity", Materials Issues in Art and Archaeology III, Materials Research Society Symposium Proceedings Vol. 267, (1992) 337-358.
15. Erlebacher, J. D., E. Brown, C. S. Tumosa and M. F. Mecklenburg, "The Effects of Temperature and Relative Humidity on the Rapidly Loaded Mechanical Properties of Artists' Acrylic Paints", Materials Issues in Art and Archaeology III, Materials Research Society Symposium Proceedings Vol. 267, (1992) 359-370.

16. Mecklenburg, M. F., "Some Mechanical and Physical Properties of Gilding Gesso", Gilded Wood Conservation and History, D. Bigelow, E. Cornu, G.J. Landrey, and C. van Horne, Eds., Sound View Press, Madison Conn., (1991) 163-170.
17. Mecklenburg, M. F., and C. S. Tumosa, "An Introduction into the Mechanical Behavior of Paintings under Rapid Loading Conditions", Art in Transit: Studies in the Transport of Paintings, M. F. Mecklenburg, ed., National Gallery of Art, Washington (1991), 137-172.
18. Mecklenburg, M. F., and C. S. Tumosa, "Mechanical Behavior of Paintings Subjected to Changes in Temperature and Relative Humidity", Art in Transit: Studies in the Transport of Paintings, M. F. Mecklenburg, ed., National Gallery of Art, Washington (1991), 173-216.
19. Mecklenburg, M. F., M. McCormick-Goodhart and C. S. Tumosa, "Investigation into the Deterioration of Paintings and Photographs Using Computerized Modeling of Stress Development", Journal of the American Institute for Conservation, Vol. 33(2), (1994) 153-170 .
20. Mecklenburg, M. F., C. S. Tumosa and D. Erhardt, "Structural Response of Wood Panel Paintings to Changes in Ambient Relative Humidity", Painted Wood: History and Conservation, proceedings of the symposium Painted Wood: History and Conservation held at Williamsburg, VA, November, 1994, in press.
21. Richard, M., M. F. Mecklenburg, and C. S. Tumosa, "Technical Considerations for the Transport of Panel Paintings", The Structural Conservation of Panel Paintings, Getty Conservation Institute, in press.
22. Mecklenburg, M. F., and C. S. Tumosa, "The Relationship of Externally Applied Stresses to Environmentally Induced Stresses", submitted for the First International Conference on Composites in Infrastructure, NSF and University of Arizona, 1996.
23. McCormick-Goodhart, M. H., "Moisture content isolines of gelatin and the implications for accelerated aging tests and long term storage of photographic materials", Journal of Imaging Science and Technology, Vol. 39 (1995) (in press).

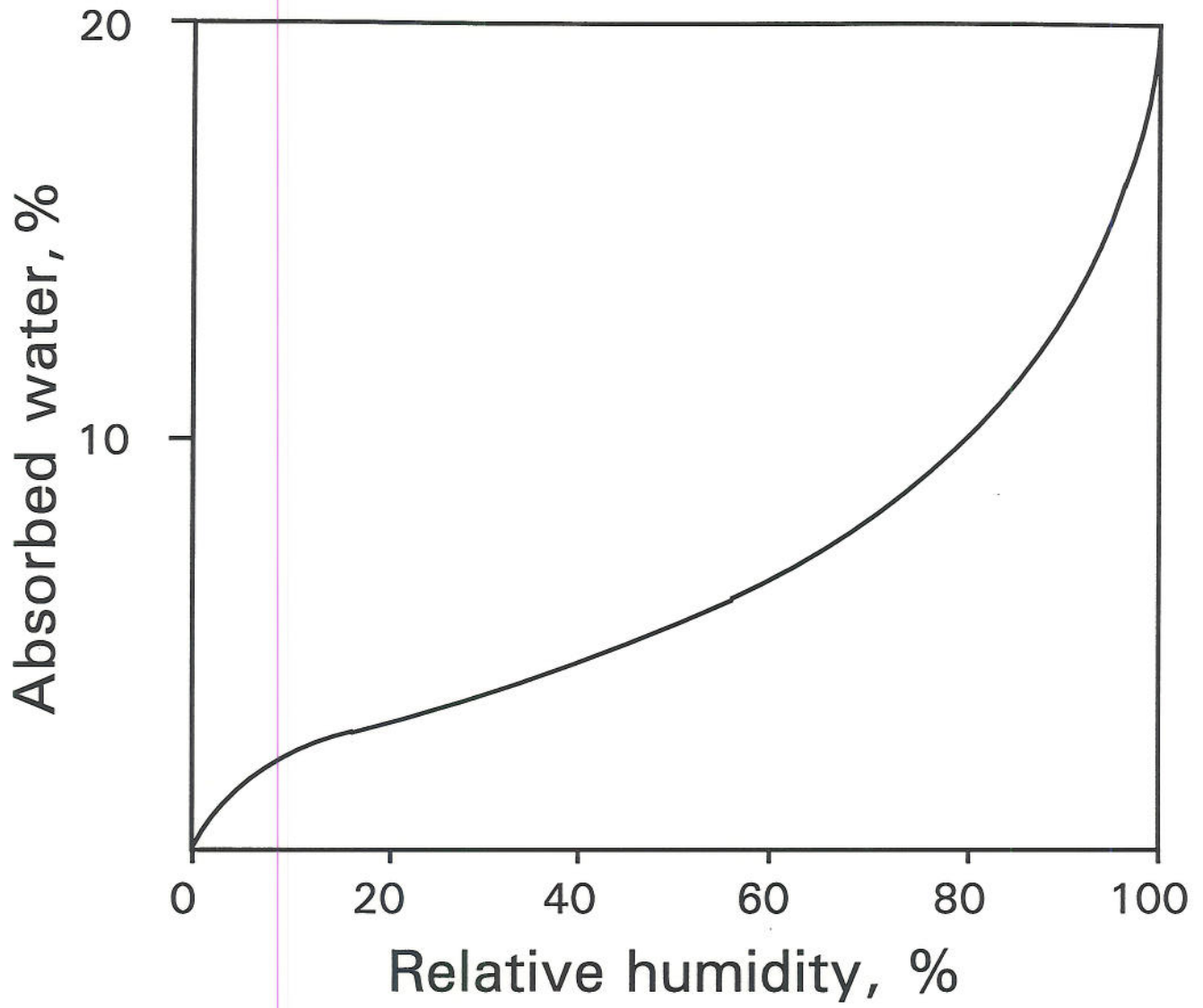


Figure 1. Moisture absorption isotherm of cotton. From [9].

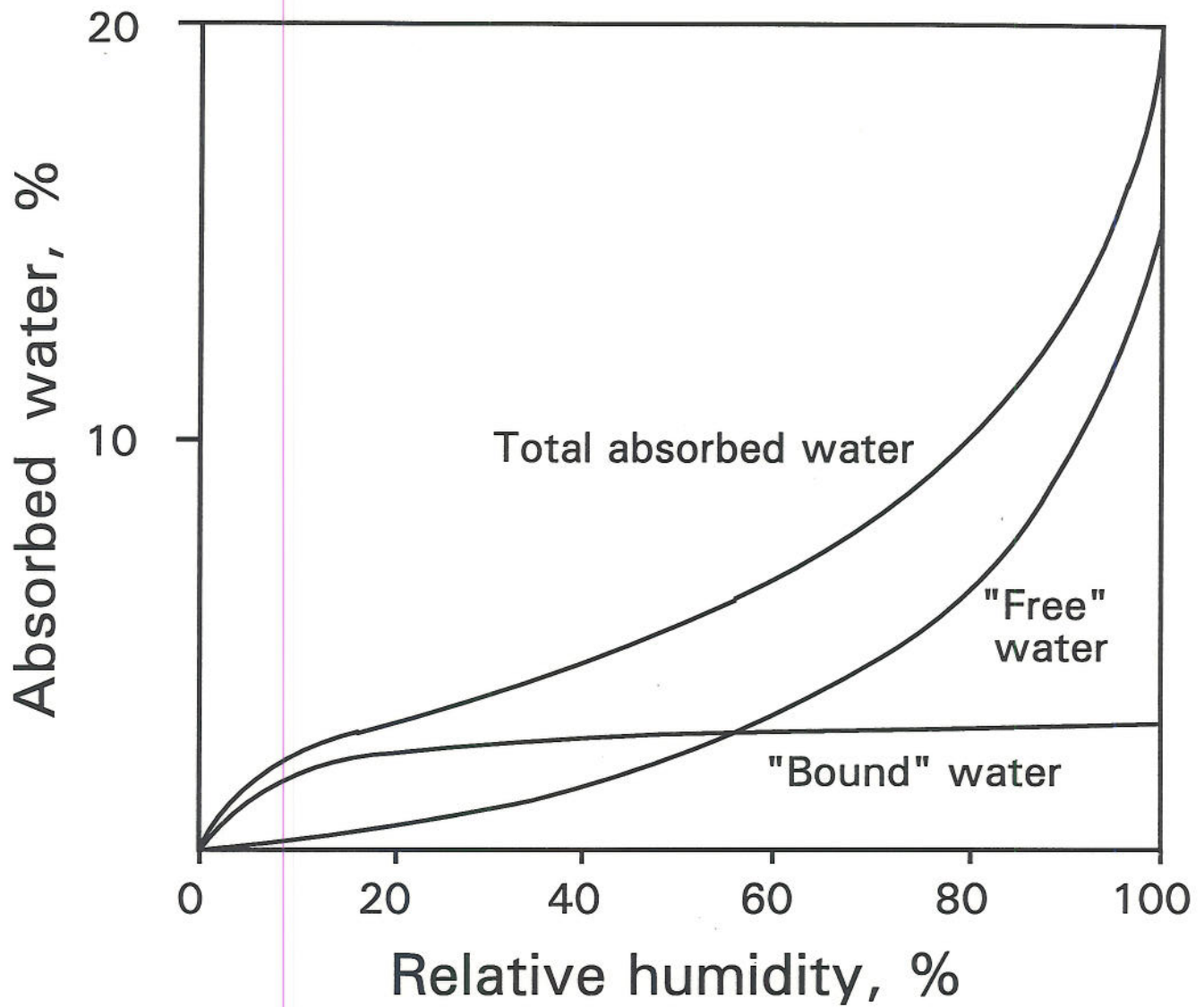


Figure 2. "Bound" and "free" water absorption of cotton. From [9].

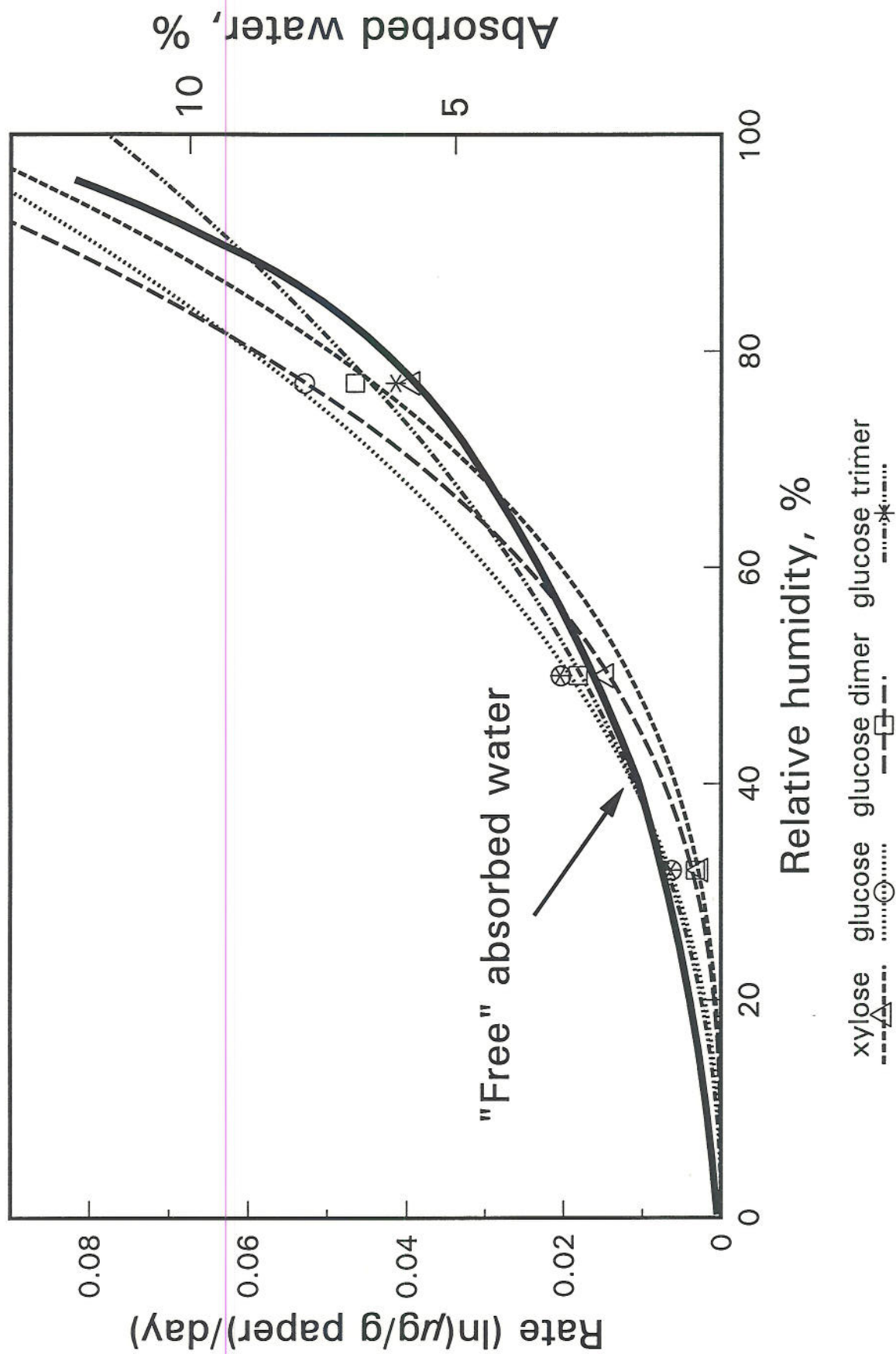


Figure 3. Rates of cellulose reactions at 80° C correlated with "free" absorbed water. Reaction data from [10].

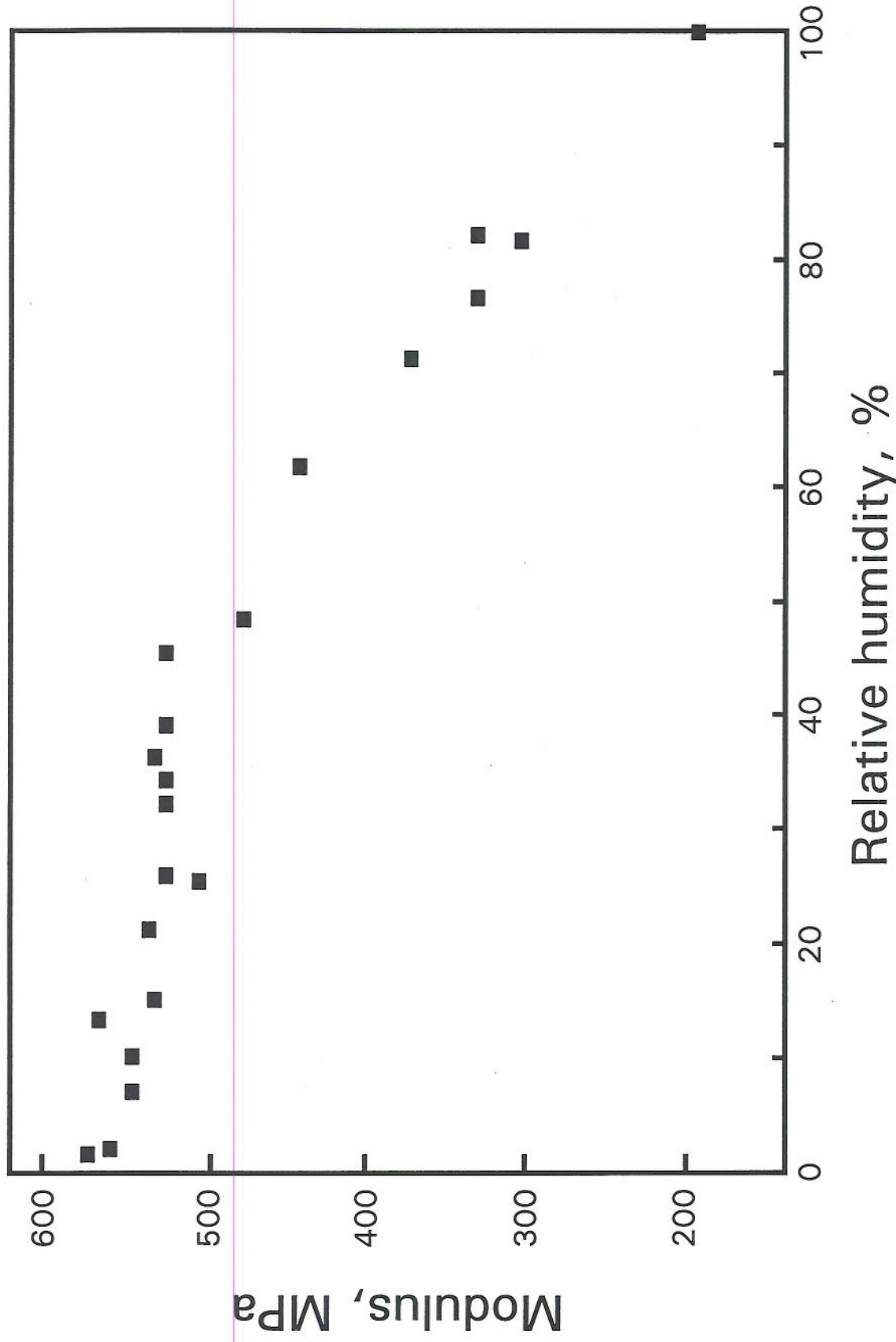


Figure 4. Modulus (stiffness) of tulip poplar as a function of relative humidity.

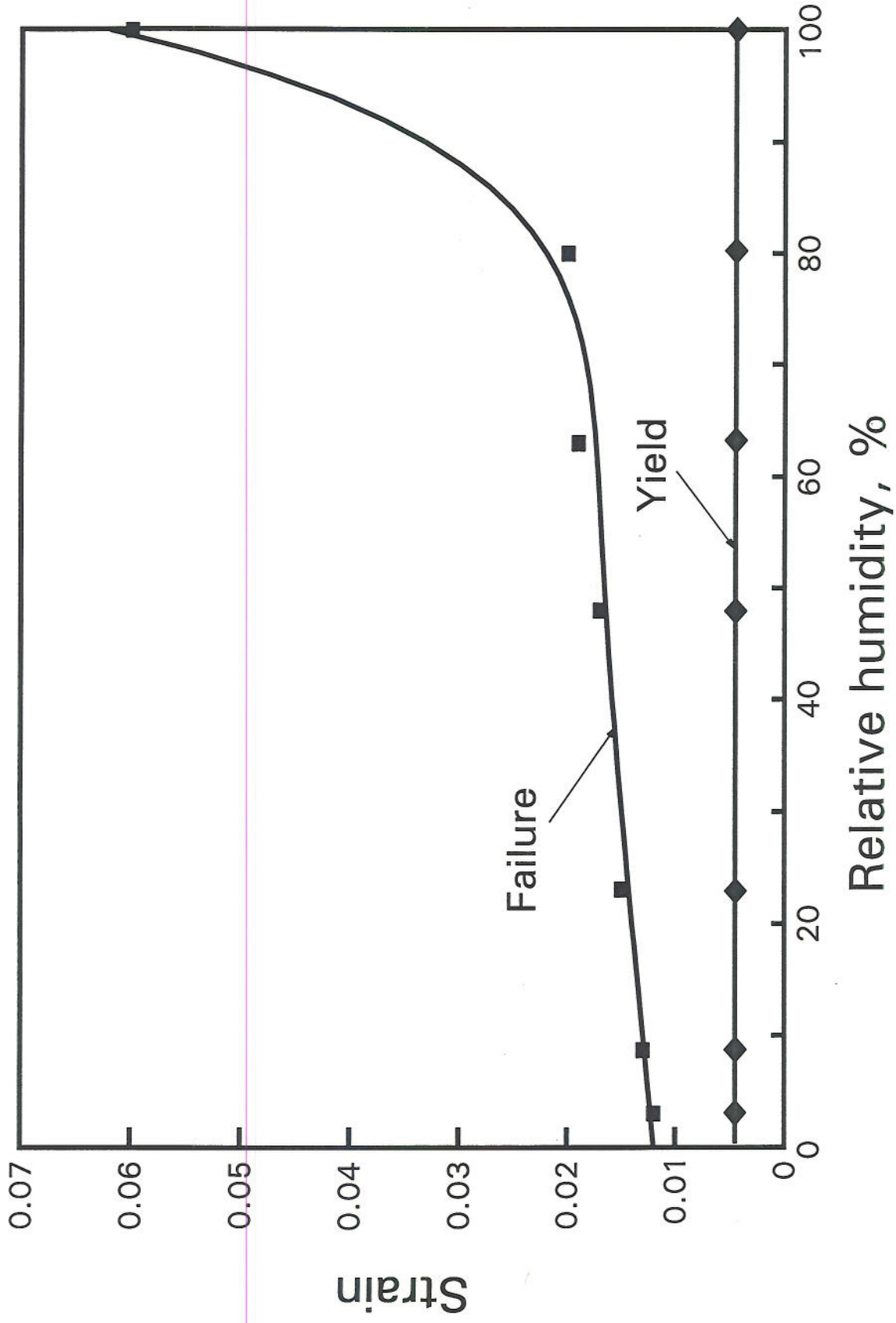


Figure 5. Strain to yield and strain to failure for cottonwood in the tangential direction as a function of relative humidity.

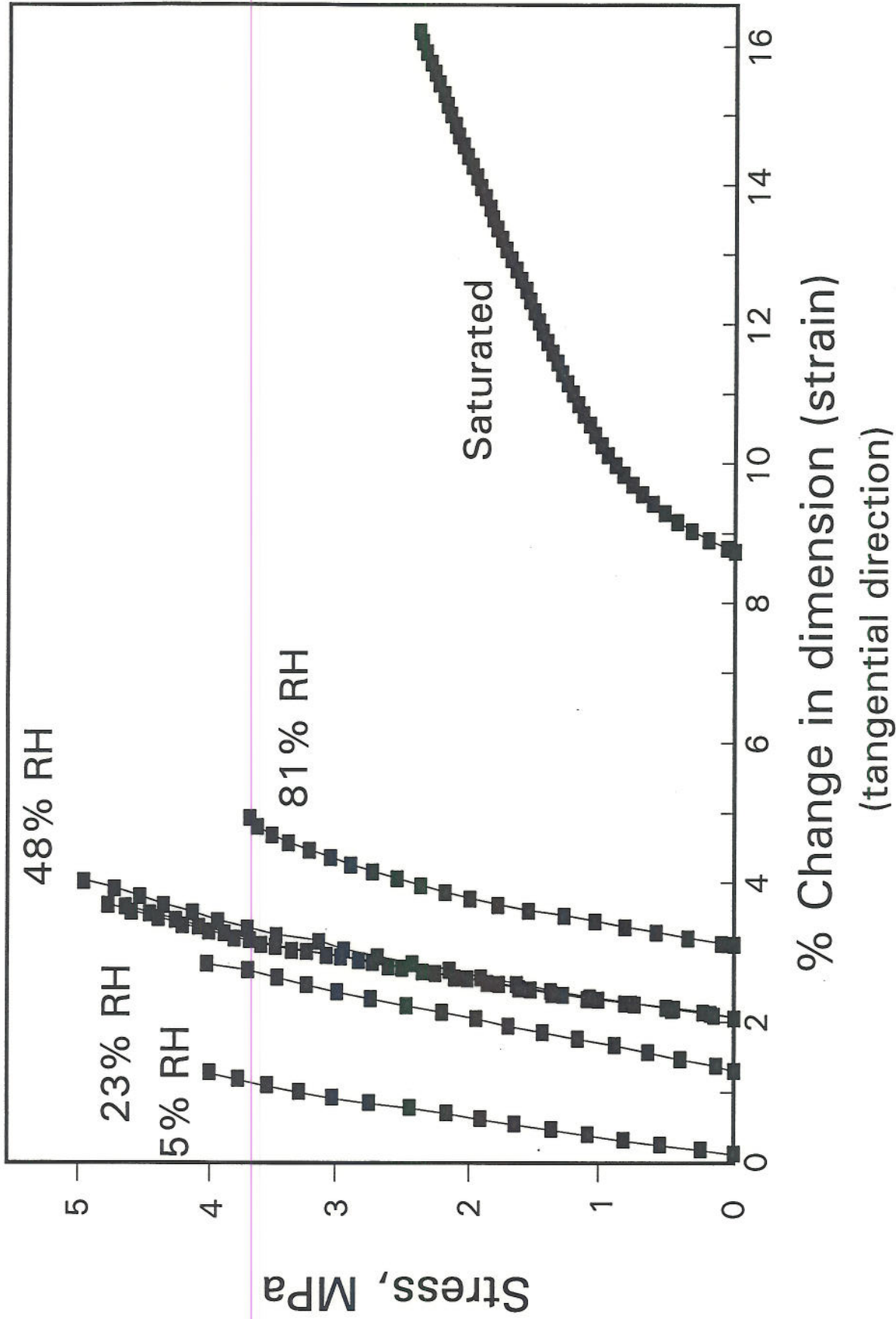
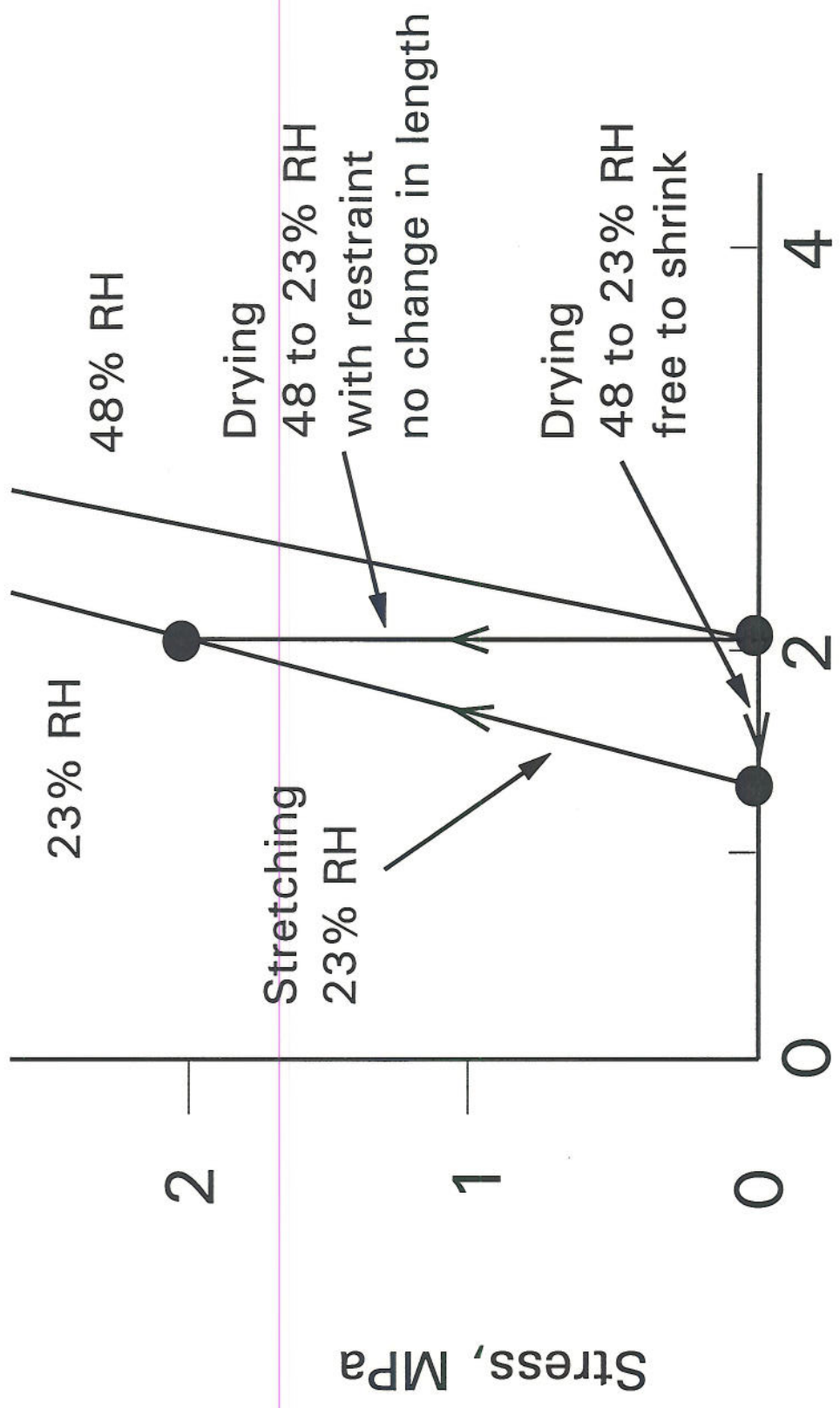


Figure 6. Stress-strain curves for cottonwood at various relative humidities. The curves are displaced on the X axis by changes in dimension due to RH. From [11].





% Change in dimension (strain)  
(tangential direction)

Figure 7. Detail of Figure 6. Drying while held at constant length produces the same stress as when allowed to shrink during drying and then stretched to the original length. From [11].

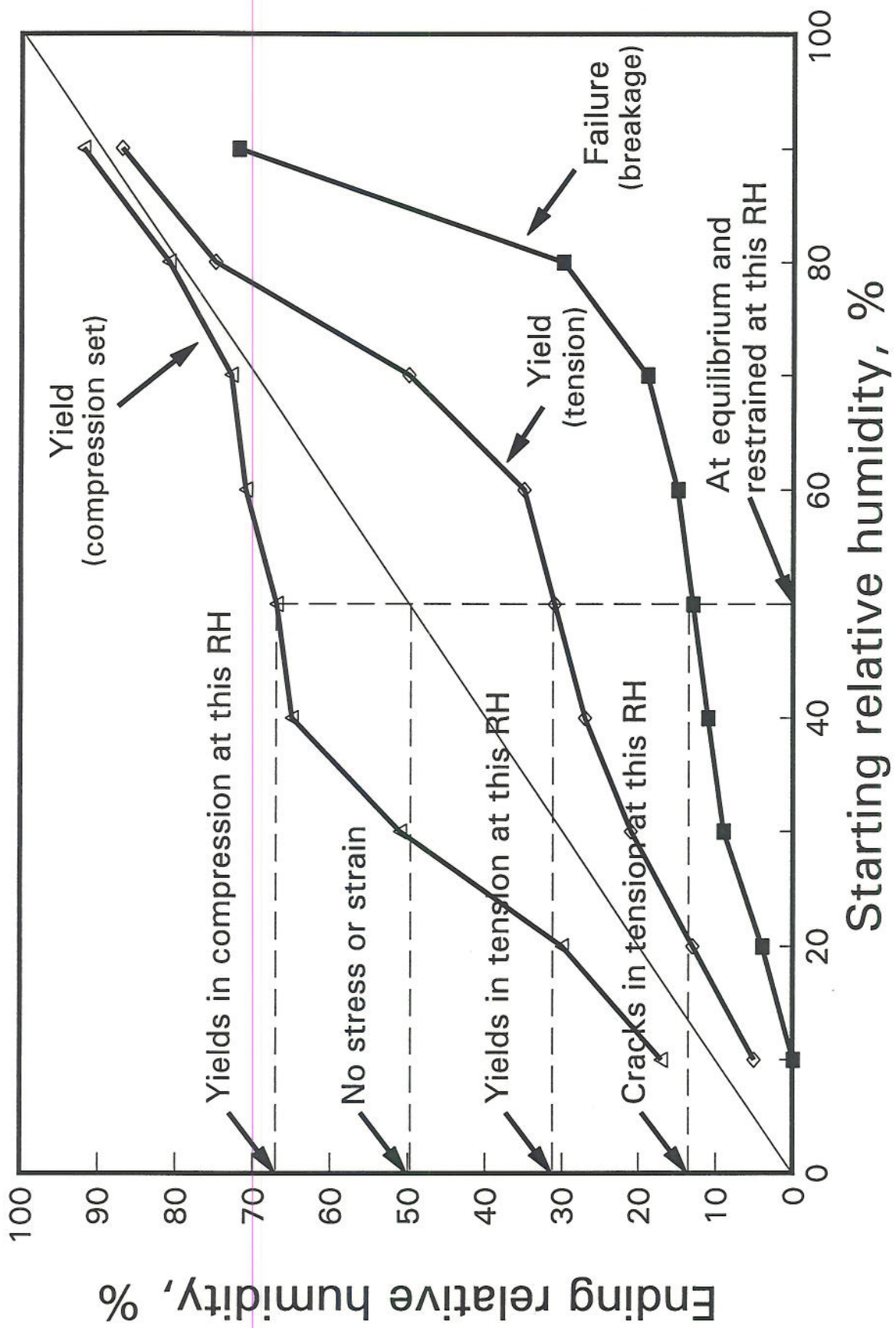


Figure 8. Allowable fluctuations for cottonwood as a function of starting relative humidity. A stress-free sample restrained at 50% RH can be raised or lowered to 68 or 31% RH without permanent deformation, and lowered to 13% before failure. From [11].

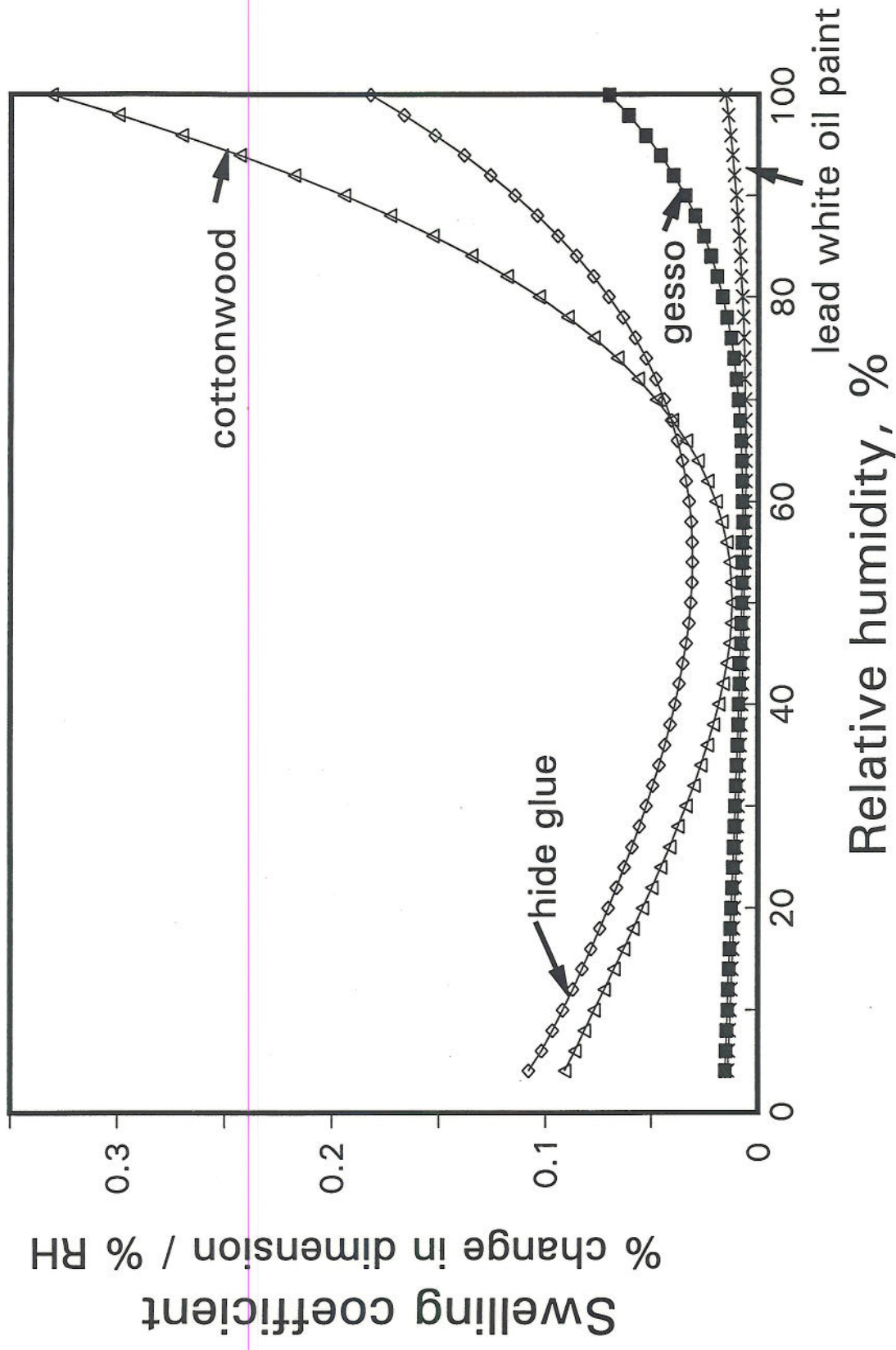


Figure 9. Responsiveness to RH changes of typical layers of a panel painting. The layers have a similar low response at moderate RH, but the wood (tangential direction) and glue swell or shrink much more at high or low RH. The wood has negligible response along the grain. From [11].

# RELATIVE HUMIDITY STABILITY ZONES

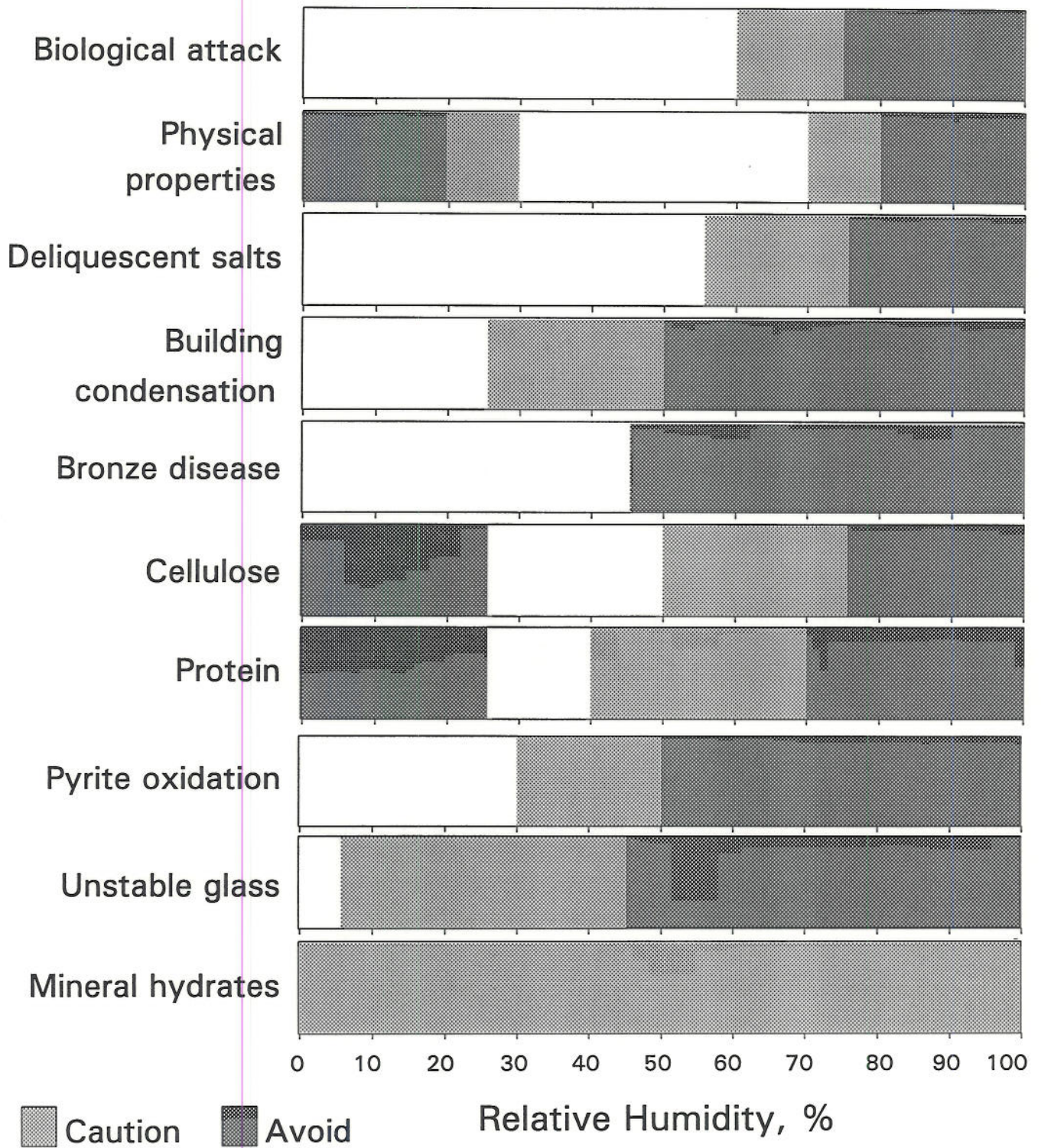


Figure 10. Ranges of relative humidity suggested by consideration of various factors. Adapted from [1].