paper presented at the Symposium on the
Structural Conservation of Panel Paintings,
April 24-28, 1995, GCI, Marina del Rey.

TECHNICAL CONSIDERATIONS FOR THE TRANSPORT OF PANEL PAINTINGS

M. J. Richard, National Gallery of Art, Washington, D.C.
M. F. Mecklenburg, and C. S. Tumosa, Smithsonian Institution, Washington, D.C.

INTRODUCTION

Panel paintings have suffered damage over the years as a result of accidents, natural catastrophes, improper handling, dramatic environmental changes, and misguided conservation treatments. Once damaged, repairs to panel paintings can be difficult. For these and other reasons, many museum professionals and collectors are hesitant to transport panels unless absolutely necessary. Some institutions have even adopted policies that forbid their loan. Panel paintings are not indemnified by the Arts and Artifacts Indemnity program in the United States, which is a government program that provides insurance for international exhibitions designated as being in the national interest.

Indeed, some paintings on wood supports are very fragile and should not be loaned. Even an ideal packing case cannot protect a painting in poor condition. Many panel paintings are very stable, however, and can be safely packed and transported.

A thorough technical examination of panel paintings considered for loan is probably the most important aspect of the loan process. The usefulness of this examination is enhanced if condition and treatment records have been maintained for many years. Paintings that have recurring problems, such as flaking paint, are poor candidates for loans unless the cause of the insecurity of the paint is clearly understood and controllable.

There are four environmental conditions that should be considered when evaluating any painting for loan: relative humidity (RH), temperature, shock, and vibration. The safety of a painting during transit is reflected in its potential response to these conditions; this response must be evaluated in terms of what a panel painting is able to withstand and what protection the proposed transport is able to provide. For example, a very fragile painting might suffer impact poorly and no packing condition can provide the protection needed to ensure safe transport. Under these conditions, transport of the painting is not recommended. In contrast, if the painting can sustain moderate fluctuations in RH and temperature (and these can be easily controlled during transport) and the panel can safely resist the anticipated levels of shock and vibration, then the panel is a potential candidate for loan.

There are several things to consider when contemplating a possible loan. The size of the painting, its materials and construction, the condition of the design layers (the paint and ground layers), and wood supports are all factors that must be considered during an examination. Small paintings usually present fewer difficulties than large paintings. They are frequently made of a single piece of wood, are lightweight, and easily moved. Large panels are heavier and more subject to bending moments during handling operations simply because of their own weight and width. Bending (or flexing) can result from impact and vibration, which will increase the stress throughout the panel, but will have particularly adverse effects on poorly glued joints and existing cracks in wood panels.

There is considerable anecdotal evidence that some panels have been exposed to extensive environmental fluctuations for years without apparent damage, while others subjected to similar conditions have suffered. Some paintings have remained stable for centuries, perhaps only because their environment has been relatively stable. If subjected to a different environment, some of these paintings may develop damage rapidly. Until recently, the only way to check this effect was to change the environment and see what occurs. Obviously this is a destructive test. Damage has been reported when paintings have been moved from relatively damp churches to drier and even well-controlled environments in museums or private homes. Similar problems also have developed when central heating systems without humidification have been installed in buildings that were normally cold and damp. These reports have led institutions to become cautious when considering the safety of lending a panel painting. Lenders to exhibitions frequently require that borrowers maintain environmental RH levels closely matching the conditions where their paintings are exhibited.

Battens or cradles often are added to the reverse of panels either to reinforce the panel or reduce warping. Such restoration treatments have limited success and often lead to additional problems since these devices tend to restrain RH and temperature-related movement in the crossed-grained direction of the panel. This restraint can lead to excessive stresses (either compressive or tensile) if the RH or temperature seriously deviates from the conditions present when the battens or cradle were applied.

The issue, then, becomes one of the ability to assess the effects of changes in temperature and RH as well as the events of impact and vibration on panel paintings and to recognize the limitations of controlling these factors during transport. The short duration of transport usually precludes chemical damage to paintings, but on occasion there have been biological problems such as mold growth. For the most part, determining the risks inherent to the transport of a panel painting is an engineering problem and requires a knowledge of the mechanics of artists' materials; this discipline is an important part of current research and a summary of materials behavior is a significant focus of this paper.

RELATIVE HUMIDITY AND MOISTURE CONTENT

All of the materials typically found in panel paintings are hygroscopic; they adsorb water when the RH increases and desorb water when the RH decreases. These materials include the wood supports, hide glues, gesso layers, paints, and varnishes. When these materials are unrestrained, changes in their moisture content result in their expansion and contraction. It is noteworthy that panel materials respond differently to the gain and loss of water vapor. For example, oil paints and gessos show relatively little dimensional response to moisture compared to pure hide glue or wood in the tangential direction. Wood cut in the radial direction shows about one-half of the dimensional response compared to wood cut in the tangential direction.[1] The dimensional response of wood in the parallel-to-grain direction is between 1/50th to 1/80th of that in the tangential direction. In the tangential direction, some woods -- such as cottonwood (*Populus sp.*) and white oak (*Quercus sp.)* -- can swell as much as 7% when subjected to changes from 5% RH to 95% RH. Other woods -- such as spruce (*Picea sp.*) and mahogany *(Swietenia Macrophylla sp.*) -- swell only 3.5% under similar conditions. The rate of dimensional change with respect to RH is usually called the moisture coefficient of expansion and it is cited in units of strain per percent RH (in./in./%RH or, mm/mm/%RH). It is of critical importance to recognize that free-swelling dimensional changes are stress-free strains. It is only when they are restrained that hygroscopic materials subjected to RH changes develop strains that are associated with stress. These are mechanical strains in the truest sense of the word.

A coefficient of expansion is often considered to be a constant, but the moisture coefficients for the materials of interest are not only variable but highly nonlinear. In Figure 1, the moisture coefficients for four materials are plotted versus RH. These materials include a sixteen-year-old flake white oil paint, gesso with a pigment volume concentration (PVC) of 81.6%, hide glue, and a sample of white oak in the tangential direction. In this plot the longitudinal direction of the white oak (or any wood) would plot almost along the zero line. In Figure 1, all of the materials have very low rates of dimensional response with respect to RH in the 40% to 60% RH range. Outside this range, the wood and glue show dramatic increases in the rate of dimensional response with respect to RH and there is a significant deviation of the wood and glue responses in relation to the paint and gesso responses. This mismatch in the coefficients is indicative of the source of many but not all of the problems associated with environmental changes. Wood in the longitudinal direction responds much less to the environment than the paint and gesso. This means that different environmentally induced responses are occurring to the layers of the painting in the two perpendicular directions of the panel. The responses of the materials to RH can be studied alone or as part of a composite construction.

A material that is allowed to expand and contract freely can be repeatedly subjected to a fairly wide range of RH without damage. In addition, woods (e.g., white oak) show a dramatic hysteresis when the unrestrained dimensional response is measured over a very large range of humidity. The increasing RH path tends to stay lower than the decreasing RH path. If the measurements are taken at between 25% and 75% RH, then the increasing and decreasing paths are almost the same.

A structural problem arises when there is either full or partial restraint. This restraint can result from defects such as knots in the wood, cross-grain construction often found in furniture, or with battens attached to the reverse of a panel. If battens and cradles restrict the dimensional movement of the wood, stresses and strains develop perpendicular to the grain with changes in RH. Internal restraint can develop when the outer layers of a massive material respond more quickly than the interior layer.

Research has shown that there are reversible levels of stress and strain. For a fully restrained material, such as white oak in the tangential direction, there are changes in RH that can occur without ill effect to the wood.[2] Organic materials such as wood, paints, glue and gesso have yield points. These yield points are levels of strain below which strains are fully reversible and above which there occurs a plastic, or permanent, deformation. For woods, paints, and glues the initial yield points are approximately 0.004 when measured by an axial mechanical test. These materials can strain harden and there can be substantial increases in the yield points. For a brittle gesso found in a traditional panel painting the yield point is approximately 0.0025. If the gessos are richer in glue, both the yield points and the strains at failure increase significantly. The magnitudes of yield points do not appear to be appreciably affected by RH, but, in general, the strains to breaking increase significantly with increases in RH. Finally, RH and temperature-related events are biaxial and triaxial events. This means that yielding can occur at significantly higher strain levels than indicated by axial testing. In this paper, the lowest axially measured strain level of 0.004 will be used for all materials except gesso, which yields at 0.0025. These yield points will be used as criteria for determining the maximum allowable RH fluctuations in panels. This criteria is a fairly conservative approach to assessing the effects of RH and temperature on panel paintings and should be considered accordingly. It also should be noted here that while materials yield at strains of 0.004 or greater between 35% and 65% RH, strains of 0.009 or greater are necessary to cause failure. The strains at failure in seriously degraded materials are often lower because degradation usually reduces the strength of materials. When the failure strains approach the yield strains in magnitude, the materials of the panel painting are fragile and will most likely be difficult to handle because the materials break in an elastic region rather than plastically deform.

<u>Responses of Restrained Wood to RH: The Tangential Direction</u>

Research[3] has shown that the moisture coefficient of a material can be used to calculate the RH change required to induce both yielding and failure strains in a restrained material. The equation used for calculating these mechanical strains as a function of RH is Equation 1 below. Using this equation, the strain change, $\Delta\epsilon$, for any RH change can be calculated by integrating from one RH point to another as:

$$\Delta\epsilon = \int \alpha \; dRH \qquad \text{Eq. 1}$$

where: $\alpha = d\epsilon/dRH$, the moisture coefficient of expansion.

The yield point for white oak is about 0.004 at all RH levels and its breaking strains increase with increasing RH. These strain values are shown in Figure 2. The failure strains are small at low RH and increase dramatically with increases in RH.

Using the information from Figure 1, Figure 2, and Equation 1, it is possible to develop a picture of the effects of RH on the strains of white oak fully restrained in the tangential direction. This hypothetical example is a worst possible condition and, fortunately, few objects in collections are actually fully restrained. The plotted results of calculating Equation 1 are shown in Figure 3. In this plot, the calculated results show what would occur if white oak in the tangential direction were restrained at 50% RH, then subjected to RH changes. A decrease in RH to approximately 33% results in a tensile yielding of the wood. Further, decreasing the RH to 21% could cause the wood to crack. Increasing the RH from 50% to approximately 64% causes the wood to begin compression yielding. As long as the RH remains between approximately 33% and 64%, the wood can respond dimensionally without altering its structure. However, if the RH increases above approximately 64% it can result in "compression set," which is a permanent deformation of the wood. Compression set also re-initializes the wood to a new, higher RH environment. The wood now behaves like wood acclimated to a higher RH.

The plots in Figure 4 were obtained by recalculating Equation 1 for a fully restrained, white oak panel that has been acclimated to 70% RH. It doesn't matter whether the panel has always been maintained at 70% or whether it was temporarily stored in a damp location. It can even happen when a painting is removed from exhibition and placed in a packing case that has been stored in a very damp environment. Whatever the circumstances, the panel is now "acclimated" to a higher ambient RH. A problem is apparent when desiccation of the panel is attempted. A drop from 70% to 62% RH causes tensile yielding and a drop to approximately 38% RH could cause cracking of the wood. Increasing the RH to approximately 74% induces yielding in compression. The panel cannot tolerate the much larger variations in RH that are possible with a panel equilibrated to 50% RH, as seen in Figure 3. This narrow range of RH must be considered when evaluating the risks of lending panel paintings acclimated to high RH.

In the past, panels have been treated with water or large amounts of water vapor in an attempt to flatten them. Battens or cradles were often attached to the reverse while the panel was still wet. The net effect of this treatment is to restrain the panel while it is still acclimated at an extremely high RH. As the panel dries, the adhesive hardens and the point where the panel is fully restrained could easily be at a moisture content equivalent to acclimation of the wood at 75% RH. If this is the case, this panel will yield in tension at around 68% RH and could quite possibly crack at approximately 45% RH. If a restrained panel were to be subjected to a flood, such as occurred in Florence, Italy, in 1966, the simple act of drying is almost certain to cause wood support damage unless all of the panel restraint is removed before drying.

Figure 5 shows the results of RH fluctuations on a typical white oak panel restrained and equilibrated at 35% RH. In this case, the panel will yield in compression at approximately 53% RH and tension at 25% RH. The net effect here is to simply change the reversible environment for the painting support panels to a lower RH.

For comparison purposes, the moisture coefficient of expansion for a 100-year-old white oak sample was measured in the tangential direction. This measurement allows for a comparison of the strain development in new and aged oak. Figure 6 shows that when using the same yield criterion, 0.004, the 100-year-old oak appears to be able to sustain slightly greater RH variations, particularly at the extreme ranges of the RH spectrum. Many other woods used as painting supports have less dimensional response to moisture than white oak, and the allowable fluctuations will be significantly greater even in the tangential grain direction.

Response of Restrained Wood to RH: The Radial Direction

The moisture coefficient of expansion in the radial direction is about one-half that of the tangential direction. If a wood panel support is made so that the two primary directions of the wood are longitudinal and radial, the panel can sustain significantly greater variations in humidity. See Figure 7 for a comparison of the calculated RH changes required to reach yield in both the radial and tangential directions for a 100-year-old white oak. If the panels had been restrained at 50% RH as shown in Figure 7, the RH change required to cause yielding in tension is from 50% to 31% in the tangential direction and from 50% to 23% in the radial direction. With increases in RH, a change from 50% to 65% causes compressive yielding in the tangential direction and a change from 50% to 75% causes compressive yielding in the radial direction. Clearly, woodworkers were aware of the benefits of using wood that was cut in the radial direction, for the increase in the allowable changes in RH is substantial. This cutting direction is important for woods acclimated and restrained at high RH. In Figure 8 the restrained panels are shown as equilibrated to 70% RH. In the radial direction the wood can sustain a drop in RH to 40% before yielding in tension and an increase in RH to 86% before compression set begins. In the tangential direction, the panel is restricted to a range of between 55% and 79% RH. The implications of the results for woods in these two directions are clear: panels cut in the tangential direction present a significantly greater risk to movement, particularly if they have been acclimated to a high RH. In contrast, restrained panels cut in the radial direction are low risks even if they have been acclimated to 70% RH.

The above examples help illustrate the response of wood to RH. Knowing the history, type of wood, treatment record, and grain orientation of a panel painting is extremely useful in helping to determine its potential risk from changes in RH and therefore its potential for safe travel. This study used extremely conservative yield criteria and assumptions of worst-case full restraint.

<u>Response of the Design Layers to RH</u>

Until now, only the wood panel has been discussed. It is also important to examine other components of the panel, such as gesso and oil paint layers. Since paint and gesso have very similar dimensional responses to changes in RH over most of the RH range, similar effects will occur when these layers are considered as coatings on both restrained and unrestrained panels (i.e., no restraint from battens, cradles, or framing techniques). The primary difference between the two is that paint will be assumed to yield at a strain of 0.004 and gesso at a strain of about 0.0025. While gesso and paint have similar dimensional response to changes in RH, the gesso will yield sooner to those changes than will the paint. As we saw with the wood, once the paint or gesso is beyond the yield point, nonreversible strains occur. Depending on the environment to which the panel is acclimated, damage can be anticipated if the equilibrated RH deviations are well in excess of those causing yielding. Not all paintings have gesso layers; often oil paint was applied directly to a prepared panel. The following will distinguish between the effect of RH on panels having both gesso and paint layers and those having paint directly applied to the wood.

Unrestrained wood panels in the tangential direction will exhibit substantial dimensional fluctuations with RH changes. If the swelling coefficients of expansion of all materials applied to the wood panel are the same as the wood, then RH variations induce no stresses in the attached layers. If the swelling coefficients differ, there will be resulting mechanical stresses and strains as a result of RH changes. For example, in the longitudinal direction of a panel painting, the wood is minimally responsive to RH. The paint and gesso coatings are responsive, but the wood restrains these layers from shrinking and swelling with changes in RH. In the tangential direction the wood is much more responsive to RH variations than the gesso or paint. This also creates stresses and strains in the design layers. In effect, the wood is overriding the response of the design layers.

The mechanical strains in the paint and gesso layers can be calculated using Equation 2. This equation can be used for any material applied to any substrate if the substrate is substantially thicker than the applied layers. To check this equation, assume that the coefficient of expansion for the substrate is zero; Equation 2 then simplifies to Equation 1. Equation 2 is:

$$\Delta\epsilon_p = [(1-\int\alpha_s dRH) - (1-\int\alpha_p dRH)]/(1-\int\alpha_s dRH) \qquad \text{Eq. 2}$$

Where: α_s is the swelling coefficient of the substrate, which is thick relative to any attached layers, and α_p is the swelling coefficient of the coatings, either flake white paint or gesso. In our examples, white oak is the substrate.

<u>Response of the Design Layer to RH: Panels Cut in the Tangential Direction</u>

In Figure 9, the calculated mechanical strains for flake white oil paint and gesso (calcium carbonate and hide glue) on an unrestrained white oak panel are plotted versus RH. The paint, gesso, and wood support panel are considered to be equilibrated to 50% RH with initial stresses and strains of zero. The strains are plotted versus RH in both the tangential and longitudinal directions of the wood panel support. In the longitudinal direction, the wood acts as a full restraint to the applied coatings (paint and gesso) and strains remain low over most of the RH range. The oil paint and gesso are minimally responsive to moisture and the plot shows that, for the paint, it is possible to desiccate from 50% RH to 8% RH before tensile yielding occurs. Compressive yielding in the paint occurs when the RH is raised from 50% to approximately 95%. Note that the paint is yielding but not breaking. However, in the gesso, which yields at a lower strain, the range for acceptable RH is narrower. Tensile yielding will occur at approximately 19% RH and compressive yielding will occur at approximately 83% RH. This indicates that fairly large RH variations can occur without yielding in the design layer. However, it is well-known that cracks do develop perpendicular to the grain of the wood (meaning that the stresses and strains were parallel to the grain). This study indicates that these cracks are not likely to occur as a result of moderate RH changes. As will be discussed later, drops in temperature are can cause these types of cracks.

In the tangential direction, Equation 2 was used with the white oak coefficient plotted in Figure 1. The wood substrate responds to the moisture changes and significantly affects the mechanical strains in both the paint and gesso layers. With desiccation, the strains of the design layers actually become compressive because the wood is shrinking at a greater rate than either the paint or gesso. At 33% RH the gesso yields and at 27% RH the paint yields. Further desiccation from the yield points cause permanent deformation in both layers. If the desiccation continues below 15% RH and the gesso ground is not firmly attached, crushing and cleavage can occur. Cleavage ridges will develop running parallel to the grain of the wood.

Raising the RH above 50% causes a different kind of problem. At approximately 62% RH, the gesso begins to yield in tension and at about 65% RH the paint begins to yield in tension. At about 75% RH or above, strains in the design layer can be sufficiently high to begin crack initiation in a brittle gesso layer. This cracking of the gesso can induce cracking in the paint film applied above it. These cracks will be parallel to the grain of the wood support panel. If no gesso layer is present, paint cracking would not initiate until well above 85% RH.

Diagrams similar to Figure 9 will be used to demonstrate the response of gesso and paint layers attached to the panel when they are equilibrated to RH levels different than 50%. Figure 10 shows the calculated resulting strains developed in the paint and gesso when the panel painting has been equilibrated to 64% RH. To effect a shift of the equilibration at higher RH, the RH changes needed to cause compression yielding in the paint and gesso should be about 6% higher than when first equilibrated to 50% RH. Tensile yielding in the paint now occurs at about 43% RH, again higher than when the painting was acclimated to 50% RH. At 53% RH the gesso yields in tension. A 14% variation (50% RH to 64% RH) in the equilibrium environment has a major effect on the dimensional response of the panel. This panel is restricted to some degree to a narrower and higher environment compared to a panel equilibrated to 50% RH. If, however, the equilibrium environment is higher, about 70% RH, greater differences occur in the response of the panel to the environment. This is illustrated in Figure 11, which shows the calculated strains of the design layers applied to a panel equilibrated to 70% RH. Under the conditions in this example, the gesso layer will yield with a drop in RH from 70% to 64% and the paint will yield when the RH drops to 60%. Crushing or cleavage of the design layer could occur at about 35% RH if the gesso ground is not sound. A panel equilibrated to a high level of RH will suffer some permanent deformation when subjected to the well-controlled environments found in many institutions. In addition, a smaller increase in RH, only about 6% to 8%, is needed to cause tensile yielding when compared to 50% RH equilibration.

How realistic is the example above? At such a high RH level there is a very high potential for biological attack that should have been observed and noted. For a panel to equilibrate to a high annual RH mean, RH levels during the more humid periods of the year must be high. Evidence of mold damage could be an important indication that a panel painting may have equilibrated to an excessively high humidity and is therefore a less-than-suitable candidate for shipment.

If a panel painting has equilibrated to an environment lower than 50%, the RH changes needed to cause yielding are not significantly affected. Figure 12 shows the calculated results for a painting equilibrated to 36% rather than 50% RH. Note that when there is a 14% downward shift in the equilibrium environment, there is only about a 6% downward shift in the RH change necessary to attain compressive yielding in both the gesso and paint layers. The panel painting equilibrated to this low RH environment can still sustain significant deviations in the mid-RH range without yielding. In addition, the painting has to drop to 26% RH to cause yielding in the gesso and 22% RH to cause yielding in the paint.

Response of the Design Layer to RH: Panels Cut in the Radial Direction

If a panel paintings was executed on radially-cut wood the risks during transport are reduced. The layers applied to the panel are much less likely to suffer RH-related damage. Figure 13 illustrates the different responses of the design layer to the unrestrained movement in the tangential and radial directions of 100-year-old white oak panels. Assume that the panels were equilibrated to 50% RH. In the longitudinal direction there is little difference whether the panels are tangentially or radially prepared and the strains in the gesso and paint layers are similar to those shown in Figure 9. As assumed before, the yield strains are assumed to be 0.004 for the paint and 0.0025 for the gesso.

In a panel cut in the radial direction and acclimated to 50% RH, compressive yield in the gesso occurs at 22% and tensile yield in the gesso occurs at 79%. In a panel cut in the tangential direction, the gesso yields at 33% RH and 63% RH. If there is no gesso layer, only paint layers, the paint film attains compressive yielding at 13% RH and tensile yielding at 86% RH. These RH values are not substantially reduced from the RH yield points of the paint in the longitudinal direction. The difference is that with desiccation, the paint and gesso experience compression in the crossed-grained direction and tension in the longitudinal direction, and with increases in humidity the opposite occurs. Both the wood and the design layers are more stable on a radially cut panel.

Of significant interest is the response of the design layers that have been applied to radially cut oak and equilibrated to high RH. In Figure 14 the calculated strains in the paint and gesso layers applied to radially cut oak and equilibrated to 70% RH are given. When desiccation occurs, compressive yielding occurs in the gesso at 32% RH and in the paint at 19% RH. Upon humidification to 50% RH, tensile yielding in the gesso occurs at 85% RH and in the paint at 90% RH. This is a substantial improvement over the strains that developed in the design layers that were applied to tangentially cut wood. Panels cut tangentially and equilibrated to high RH are at serious risk if desiccated. Panels cut radially are at considerably less risk, even when equilibrated to a high RH and desiccated. The discussion above offers an explanation as to why panels with paint applied directly to the wood without gesso layers seem to be more stable.

A plywood panel is made entirely of restrained, tangentially cut wood and it will fare poorly when exposed to RH fluctuations in comparison to a radially cut panel painting that is either restrained or unrestrained.

The RH of a panel painting equilibrium environment establishes its risks for transport. Knowing what the equilibrium RH is allows for the development of environmental guidelines for both the transit case and new temporary exhibition space. Tangentially cut panels acclimated to high RH are at risk. This risk can occur when warped panels have been flattened with moisture before the addition of battens or cradles. A warped panel is often thinned, moistened on the reverse, and finally, has had battens or a cradle attached to forcibly hold the panel flat. As a result, considerable tensile stress can build up as the wood dries because the battens or constricted cradles can restrict the return to warpage.

Thinning panels create other consequences. Decreasing the thickness reduces the bending stiffness of a panel and makes it more flexible. The reduction in stiffness is inversely proportional to the cube of the thickness of the panel.[4] This thinning makes the panel prone to buckling when restrained. At high RH, a panel with a locked-in cradle is subjected to high RH-induced compressive stresses in the spans between the cradle supports. These stresses are not uniform due to the presence of the cradle and cause out-of-plane bending or buckling of thinned panels.

During the examination of panel paintings it is important to assess whether the panel's movement is restricted. In some instances, this assessment may be difficult. Panels having battens or cradles locked up by friction present higher risks for transport if there is a crack in the panel[5] or if the panel has equilibrated to a very high RH environment. In addition, the results of research suggest that an unrestrained panel with a gesso layer equilibrated to a high RH environment is at greater risk to damage upon desiccation than a sound, restrained, uncracked panel. This risk occurs because the gesso layer is subject to compression cleavage due to panel contraction with the desiccation of an unrestrained panel. Almost all of the panel paintings of the fifteenth and sixteenth century Italian Renaissance have gesso grounds. This gesso layer and the wood panel itself should be considered the crucial components when contemplating the movement of such paintings.

Oil paintings on copper supports seem to have fared fairly well over the centuries. Research shows that oil paint responds only moderately to changes in RH, particularly if extremely high RH is avoided. Copper is dimensionally unresponsive to RH fluctuations. When these two materials have been combined, the result is a painting that is durable with respect to changes in atmospheric moisture.

Contemporary panel paintings having wood supports and either acrylic or alkyd design layers may also be analyzed using the criteria above. Figure 15 shows the coefficients for swelling of alkyd and acrylic emulsion paints compared to oil paint. All of these paints have dried for fifteen or more years under normal drying conditions. In comparison to oil paint, both the alkyd and the acrylic emulsion paints are much less dimensionally responsive to moisture. When acrylic paints are applied to a wood panel, RH changes will have very little effect in the longitudinal direction of the wood. In the tangential direction, however, the movement of the wood in an unrestrained panel will almost totally control what happens to the paint. Therefore the environmental change needed to develop yield in alkyd or acrylic paints will be approximately 2% to 3% RH less than the change needed for oil paint on wood panels to develop yield.

<u>Controlling the Transport RH</u>

RH levels may also vary during transport, but, fortunately, this problem can be solved with proper packing. The RH levels in trucks depend largely on weather conditions. If the weather is hot and humid, the RH inside the truck may be very high, even when the cargo area is air-conditioned. If the weather is very cold, the RH in the truck will be low because of the drying effects of the cargo-area heating system. Because of low pressure and temperature of the outside air at high altitudes, the RH in a heated and partially pressurized aircraft is always low -- often 10% to 15%. If panel paintings are exposed to this extreme desiccation for the duration of even an average flight, there could be damage. This desiccation can be avoided by wrapping the painting in a material that functions as a moisture barrier. Wrapping panel paintings will be further discussed in the section on packing cases.

TEMPERATURE EFFECTS

The dimensional response of wood panels to temperature variations has been largely ignored by many conservators because temperature has been considered to have a much smaller effect on wood than RH, which is true if one considers only the relative dimensional response of wood to temperature as compared to moisture. It would take several hundred degrees in temperature change to induce the same dimensional change in wood that can be caused by a large change in RH. Panel paintings are rarely exposed to such temperature extremes and are usually exhibited or stored where temperature variations are relatively small. The problem, however, is not the response of only the wood, but rather the response of the gesso and paint layers on the wood panel. When considering the effect of temperature, it is necessary to understand the mechanical properties of the different paint media as well as their dimensional response. In the temperature ranges most likely encountered, the thermal coefficients of expansion of the materials found in panel paintings can easily be considered as constants. Some values for these materials are given in Table 1.

Table 1. Thermal Coefficients of Expansion of selected painting materials

Material	Thermal Coefficient of Expansion
White Oak Longitudinal	0.0000038/°C
White Oak Tangential	0.0000385/°C
White Oak Radial	0.00003/°C
Oil Paint	0.000052/°C
Gesso	0.00002/°C
Hide glue	0.000025/°C
Copper	0.000017/°C

To determine the effect of temperature on paint or gesso applied to different substrates, it is again possible to use Equation 2. Note that changes in temperature will change the moisture content of materials even when the ambient RH is held constant. At constant RH, heating desiccates materials somewhat and cooling increases the moisture content. The following discussion does not include these effects. Figure 16 plots the calculated mechanical strains of flake white oil paint directly applied to panels in the longitudinal, tangential, and radial directions of the wood and to a copper panel as well. Because the thermal coefficient of expansion of the paint is greater than the thermal coefficient of wood in any direction, the paint responds to drops in temperature by developing tensile strains. The shrinkage of the wood in the tangential and radial directions relieves a considerable amount of the paint strain since the coefficients in these directions more closely match those of the paint. In the longitudinal direction of the wood the coefficient is the smallest and the strain relief to the paint is the least. Hence, the greatest mechanical strain increase in the paint occurs in the direction parallel to the grain of the wood. Unfortunately, as the temperature drops, the paint may pass through its glass transition temperature, T_G. At approximately this temperature, the paint undergoes a transition from a ductile to a very brittle and glassy material. Below the T_G the paint is very fracture sensitive and prone to crack in the presence of low stresses and strains. In this example, the paint could crack when the strains reach levels as low as 0.002. In the longitudinal direction of a wood panel painting, cracking occurs if the temperature drops from 22°C to approximately -19°C. A copper panel painting, however, requires a temperature drop to -35°C to produce the same strain level.

Cracking in varnish and polyurethane coatings on wood have, in fact, been recorded when the temperature dropped from 24°C to -20°C. In the radial and tangential directions of the wood, the temperature must drop to well below -50°C to produce similar strains in the oil paint layers.

It is unlikely that cracks in oil paint layers could occur perpendicular to the grain of the wood because of RH variations. When considering the effects of temperature, however, it is likely that even moderate subfreezing temperatures will crack oil paint in this direction. Low temperature is less likely to cause cracking in the paint parallel to the grain, unless the wood support panel is fully restrained from thermal movement during the temperature drop. As Figure 16 shows, oil paint layers applied to copper can survive a substantial drop in temperature. Note that embrittlement of the paint layer is far more severe when exposed to low temperature at moderate RH than to low RH at room temperature.

Other paint media suffer similar embrittlement to oils, but at higher temperatures. A T_G of approximately -5°C occurs with alkyd paints; with acrylic paints it occurs at approximately +5°C. While unlikely, it is possible for the temperature inside packing cases to drop to +5°C in the cargo holds of aircraft, while cases sit on the airport tarmac, or inside an unheated truck. These transition temperatures should be considered the lowest temperature for safe environments as other factors such as shock and vibration can also damage brittle materials.

The effect of temperature on gesso applied to wood panel paintings is different than the effect of temperature on paint applied to wood panels. In general, gesso has a low thermal coefficient of expansion that is higher than that of white oak in the longitudinal direction and lower than the oak coefficients in the radial and tangential directions. Figure 17 plots the calculated temperature related mechanical strains in the three grain orientations for a gesso coating applied to a white oak panel. The first observation is that the developed mechanical strains are minimal, even at -40°C. In the longitudinal direction the gesso strains are tensile and in the tangential and radial directions they are compressive. Thus, it appears that temperature has a significantly smaller effect on gesso than it does on oil paint.

In the panel itself, the most probable damage would occur in the tangential direction if the wood was fully restrained and subjected to a drop in temperature. The tangential direction has the highest thermal coefficient of expansion and the lowest strength. However, even in this direction a drop in temperature from 22°C to -40°C causes a mechanical strain of only 0.00246, which is not a serious concern for wood.

Excessive heat can cause undue softening of paint and varnish layers and is to be avoided. In the transport environment, temperature changes can be great enough to cause damage to the paint (and varnish) layers. Therefore, precautions must be taken to avoid exposing panel paintings to extremely hot or cold environments.

Temperature variations are inevitable in most transport situations.[6,7,8] Although variations are minimal during a local move in a climate-controlled vehicle, they can be extreme during a long trip by truck during harsh winter months. In the northern Unites States and Canada, for example, winter lows of -20°C are typical and temperatures of -40°C are possible. These extremely low temperatures can cause damage to panel paintings and must be avoided. In the summer, temperatures of 40°C to 50°C can be found in many parts of the world, and the temperature inside a stationary vehicle can be even higher because of solar heating. Due to softening of the paint, high temperatures are less likely to cause cracking in panel paintings. However, varnishes can become tacky at high temperatures and wrapping materials can adhere to the panel surface. Using climate-controlled vehicles for transporting works of art is the best way to minimize temperature variations, but contingency plans should be made in case of mechanical problems with the vehicle or its climate-control system. Should a problem occur, insulation in packing cases will slow the rate of temperature change inside packing cases but for only a short while.[9]

Temperature variations also occur in the cargo holds of aircraft because the ambient temperatures at high altitudes are always low. The cargo holds of all modern commercial aircraft have heating systems, and, barring mechanical failure, the temperature should not fall below 5°C. Acrylic paintings are at high risk at these lower temperatures, but sound oil paintings on panel are not.

SHOCK

Accidents caused by handling and environmental variations can add sufficient stress to a panel structure to permanently deform its wood, propagate cracks, separate joints, and cause paint loss.

Shocks in the transport environment are derived from three basic sources: handling before a work is packed, handling of the packing cases, and the motion of the vehicles carrying packing cases. Shock levels in trucks and planes are low if the packing cases are properly secured to the vehicle. In contrast, handling operations "are generally considered as imposing the most severe loads on packages during shipment."[10] "Packaging designers have achieved reasonable success in preventing shipment losses due to shock by designing packages and cushioning systems according to the presumption that shocks received during handling operations will be the most severe received by the packages during the entire shipment."[11]

Old panel paintings are fragile and the shock level to which they are exposed must be minimized. The *fragility factor* or *G factor* is a measure of the amount of force required to cause damage and is usually expressed in G's. Mass-produced objects are destructively tested to measure their fragility but this is not possible with works of art. Until recently, no attempt has been made to determine the fragility factor range for panel paintings. Art packers have relied on estimates. Conservatively, a packing case should ensure that a panel painting is not subjected to an edge drop shock level greater than 40 G's. The edge drop, however, is not the greatest concern.

One of the most serious accidents can occur when a painting that is resting upright on the floor and leaning against a wall slides away from the wall and impacts the floor. Another accident possibility is when a case topples over. In both of these "handling" incidents a panel painting is at serious risk due to inertially induced bending forces applied to the panel. The bending stresses induced in a panel are the most potentially damaging. The thinner the panel the greater the risk. While a thin panel weighs less (has a lower mass), for a given action the bending stresses increase as a function of the inverse square of the thickness of the panel. For example, consider a sound, one inch (2.5 cm) thick white oak panel painting measuring forty inches (102 cm) in the direction perpendicular to the grain and sixty inches (152 cm) in the direction parallel to the grain. If this panel painting is supported in a frame and is bowed, it is very likely that the support is along the two long edges (Fig. 18). If this painting were to topple so that the rotation were along one of the long edges, there would be bending stresses in the wood perpendicular to the grain. These stresses can be calculated by first determining the effective loading that results to the panel at the time of impact. If the impact were 50 G's, the maximum bending stresses would be approximately 708 pounds per square inch (psi) (4.66 Mega Pascals [MPa]). This stress is calculated by first determining the shear (Fig. 19), and bending (Fig. 20), resulting from the impact forces. White oak has a specific gravity of approximately 0.62, which means that it has a density of approximately 0.023 pounds/cubic inch (0.171 kg/cm^3). At 50 G's, the density of the wood is 1.15 pounds/cubic inch (0.032 kg/cm^3) along the impact edge and diminishes to zero at the rotating edge. For a one-inch(2.54 cm) thick panel, the loading for every inch of width of the panel at the impact edge is 1.15 pounds/cubic inch (0.032 kg/cm^3) and tapers to zero at the other edge (Fig. 18). From the bending moment diagram, the bending stresses can be calculated from the equation:

$$\sigma = Mc/I \qquad \text{Eq. 3}$$

where: σ are the bending stress, in either tension or compression, at the outer surfaces of the panel. M is the bending moment calculated and shown in Figure 20. c is one-half the thickness of the panel. I is the second area moment of the cross section of the panel segment under consideration, and $I = 1/12\ bd^3$ where b is the width of the panel section and d is the thickness of the panel.

The calculated bending stresses resulting from a 50 G topple impact to a one-inch thick, forty inch by sixty inch (102 cm x 152 cm) oak panel are shown in Figure 21. The maximum stresses occur at approximately station 23 (23 in. [58.4 cm] from the rotating edge) and reach 708 psi (4.88 MPa). This amount is slightly more than half the breaking strength of structurally sound oak in the tangential direction.

If the same event occurred to an oak panel, that is one-half inch (1.27cm) thick with the other two dimensions the same, the bending stresses would be 1,417 psi (9.8 MPa). Even though the one-half inch panel weighs half as much as the one-inch panel, it incurs twice the stress. The measured breaking stress of white oak at room temperature and 50% RH is approximately 1,300 psi (8.9 MPa). The thinner panel will likely crack in a 50 G topple accident. The one-inch thick panel would require a 100 G topple impact to crack it. If either panel was supported continuously around the edges, the risk of damage decreases by a factor of five.

Figure 22 shows the calculated bending stresses of oak panels of different sizes and thicknesses subjected to 50 G topple impacts. These panels are assumed to be supported on the parallel to grain edges only and the topple is a rotation of one of those edges. For this test, it is also assumed that there are no battens or cradles attached to the reverse since they provide a certain degree of bending protection.

Panels constructed of lighter woods such as pine (*Pinus sp.*; specific gravity of .34) will develop lower bending stresses when subjected to a 50 G topple impact. However, the strength of the lighter wood is also lower and the result is that the risk for damage is greater than for denser woods. Figure 23 illustrates the results of the calculated bending stresses for different thicknesses of forty inch by sixty inch (102 cm x 152 cm) oak and pine panels subjected to 50 G topple impacts. The breaking stress of the pine in the tangential direction is only 450 psi (3.10 MPa). As was the case with white oak the thinner pine panels are at greater risk and the pine panels must be thicker than oak panels to prevent failure under the same topple conditions.

The implications are that a <u>single packing criterion</u> is <u>not</u> sufficient for the impact protection of panel paintings. Larger and thinner panel paintings need greater protection than those that are smaller and thicker. In addition, in this analysis it is assumed that the panel is sound, that is free of cracks. Existing cracks in panels reduce their total strength. Panel paintings should be supported continuously around the edges in a way that allows them to expand and contract with RH and thermal fluctuations. Special care should be taken to prevent topple accidents; one way to do this is to pack more than one painting in a case which effectively increases the width of the case and reduces the possibility of a topple.

Often, panel paintings in the forty inch by sixty inch (102 cm x 152 cm) size will be greater than one inch in thickness.

Those that are less than one inch thick are probably supported by either battens or cradles. On the other hand, a one-inch (2.54 cm) thick oak panel that is fifty inches (127 cm) wide or greater will fail in a 50 G topple. Based on this information, a 30 G maximum impact criterion for topple should be considered reasonable.

It should not be difficult to provide 30 G topple protection for larger panels. For an edge drop, the risk is much less. It is not difficult to provide 40 G protection for edge drop heights of thirty inches (76 cm), or less, using foam cushioning materials. The use of foam cushioning to reduce shock is discussed later in this paper.

VIBRATION

The primary sources of vibration in the transit environment are the vehicles used for transport. "Trucks impose the severest vibration loads on cargo with the railcar next, followed by the ship and aircraft."[12] In trucks, the main sources of vibration are the natural frequencies of the engine, tires, drive train, suspension system, and the truck body. The properties of the road surface are also a factor. The vibration levels in vehicles are all relatively low and random in nature. The human body is very sensitive to vibration, and vehicles are designed to minimize the vibration levels to which the operator and passengers are subjected.

Low levels of vibration are unlikely to damage panel paintings unless sustained vibrations create resonant vibrations in the panel; the random nature of vibration makes this unlikely. In addition, the resonant frequencies of panel paintings are high and those vibrations are easily attenuated by packing cases.[13]

PACKING CASE DESIGN

There are many packing case designs suggested for the transport of panel paintings. It is essential that all cases provide adequate protection against shock, vibration, and environmental fluctuations. Protection against shock and vibration is usually achieved through the use of foam cushioning materials. Although various cushioning materials are available for the transport of works of art, the most commonly used are polyethylene and polyurethane foams. These foam products, along with polystyrene foam, can also function as thermal insulation. The proper use of these materials and information concerning the principles of case design is available in many publications[14] and will be only summarized here.

Packing Case Construction

Packing cases for panel paintings should be rigid to ensure that panels do not flex or twist during handling and transport. Rigidity can be accomplished by using quality construction techniques and relatively stiff materials. It is recommended that glue be used in the joinery of the cases because it increases the strength and stiffness of the joints. Case joints held together with only nails or screws perform poorly when dropped. "A case having edges and corners that are well-joined can have over ten times the strength and one-hundred times the rigidity of a case that has corners and edges that are poorly joined."[15]

Compared to single packing case designs, double packing cases provide significantly better protection for panel paintings. An inner case adds rigidity to the structure. An inner case also increases the quantity of thermal insulation and reduces the likelihood of damage should the outer case be punctured by a sharp object, such as the blade of a forklift.

Figure 24 depicts a double packing case design commonly used at the National Gallery of Art, Washington. The polyester urethane foam functions not only as a cushioning material but also provides thermal insulation. The entire case is lined with a minimum of two inches (5 cm) of foam, which is adequate insulation for most transport situations when temperature-controlled vehicles are used. A packing case for a typical easel-size painting has a thermal half-time of two to three hours (Fig. 25).[16] The foam thickness should be increased to at least four inches (10 cm) when extreme temperature variations are anticipated. Increasing the thickness of the insulation increases the thermal half-time to approximately four to five hours. However, thermal insulation only slows the rate of temperature change within the case. When paintings are transported in extreme climates, the only way to maintain temperature levels that will not damage paintings is through the use of temperature-controlled vehicles.

Foam Cushion Design

In the packing case design depicted in Figure 24, the polyester urethane foam also provides shock protection for the painting. The painting should be firmly secured within the inner case. There are two procedures that are commonly used: (1)secure the painting's frame to the inner case with metal plates and screws; (2)hold the frame in place with strips of foam. Shock protection in a double case design is provided by foam cushions fitted between the inner and outer cases. When a packing case is dropped, the foam cushions compress on impact, allowing the inner case to move within the outer case. While the acceleration of the outer case is quickly halted on impact with the floor, the acceleration of the inner case is halted much more slowly. If the packing system functions properly, the outer case may sustain a few hundred G's on impact while fewer than 50 G's are transmitted to the inner case and the painting inside.

It is easy to attain 50 G protection for panel paintings when packing cases are dropped less than a meter. In fact, when careful attention is given to the proper use of foam cushioning materials, 25 G protection can be attained. The shock-absorbing properties of cushioning materials are provided in graphs known as *Dynamic Cushioning Curves* (Fig. 26). These curves plot the G forces transmitted to a packed object as a function of the static load of the cushioning material. The curves vary with different materials, thicknesses, and drop heights. Dynamic cushioning curves for many materials are published in the Military Standardization Handbook,[17] and more accurate cushioning curves for specific products are usually available from the manufacturers. The use of these curves has been extensively discussed in several publications.[18]

Two cushioning curves for polyester urethane foam (density = two pounds/cubic foot; 33 kg/m^3) are shown in Figure 26. Both are for a drop height of thirty inches (75 cm). Note that increasing the foam thickness has a dramatic effect on the cushioning properties of the material. The lowest point on each curve corresponds to the optimal performance for a given thickness of the material. Therefore, in looking at Figure 26, the optimal static load for four inch (10 cm) thick, polyester urethane foam is 0.36 pounds per square inch (0.025 kg/cm^2) (point A, Fig. 26). The static load is the weight of the object divided by the area in contact with the foam cushioning. At this static load, a painting packed with four inch (10 cm) thick cushions of polyester urethane foam will sustain a shock force of approximately 22 G's if the packing case is dropped from a height of thirty inches (75 cm). If a packing case has cushions that are two inches (5 cm) thick, the optimal static load would be 0.22 pounds per square inch (0.016 kg/cm²) and a force of 45 G's would be anticipated in a 75 cm drop (point B, Fig. 26). Because of the dramatic improvement in the performance of the four inch (10 cm) thick foam, as compared to the two inch (5 cm) thick foam, it is highly recommended that foam cushions at least four inches (10 cm) thick be used in packing cases built for the transport of panel paintings.

It is not possible to predict accurately the fragility of all panel paintings although the methods described here can give a good estimate for reasonably sound objects. Due to cracks and unseen defects, panel paintings will always be more and never less fragile than calculated. Manufacturing companies that sell mass-produced items destructively test a few to ascertain their fragility. In this way, the company can design the least expensive package that usually provides adequate protection. While a small percentage of the items will be damaged, the expense incurred due to loss is less than the cost of more complex and expensive packing cases. Obviously, panel paintings cannot be destructively tested and in the absence of accurate fragility information, it is recommended that packing cases provide at least 40 G protection for small panel paintings and 30 G protection for larger panel paintings. Ideally, the foam cushions should be at least four inches (10 cm) thick and the static load on the foam should be calculated, using dynamic cushioning curves, to provide optimal performance.

Wrapping Materials for Paintings

Wrapping paintings in moisture barrier materials is one way to control their moisture content during transport.[19] Relatively thick polyethylene films that are well-sealed with packaging tape work effectively. Unfortunately, the quality of commercial polyethylene film materials vary considerably. They often are made from recycled materials. Grease, oil, chemical additives, and various powders also may be added to polyethylene during the manufacturing process. It is important, therefore, to know the quality of polyethylene film materials. Better moisture barrier materials are also available but they provide few advantages over high-quality, polyethylene sheeting. The better materials would be advantageous when wrapped paintings are stored for many weeks in an inappropriate environment.

Conservators and packers are often concerned that wrapping paintings in a moisture barrier will result in condensation. Condensation problems can occur in packing cases that contain large volumes of air relative to the mass and surface area of hygroscopic materials packed inside. However, when a typical panel painting is wrapped in polyethylene, the volume of air is very small relative to the mass and surface area of the painting and frame. In this case, experimental evidence indicates that condensation will not occur unless a painting is acclimated to a very high RH level, at least 70%, and is exposed to a rapid and extreme temperature drop in a non insulated packing case. The most likely cause of condensation is unpacking and unwrapping a cold painting in a warm room. (Anyone who wears eyeglasses has experienced condensation problems when they walk indoors on a cold winter day.) This problem can be avoided simply by allowing several hours for the painting to acclimate to the higher temperature while it is still in the insulated case.

Wrapping paintings in polyethylene, or an alternate moisture barrier material, is particularly important when there is uncertainty about the environment where packing cases will be stored. Most packing cases contain hygroscopic materials. If they are stored in environments having an unusually high or low RH, they will become acclimated to that environment. Unless sufficient time, usually a week or two, is allowed for the cases to reacclimate to the proper RH before packing, inappropriate microenvironments will exist in the cases. Similar problems can occur when packing cases are constructed from wood that has not been acclimated to the proper RH. A moisture barrier film that surrounds the painting will reduce the potential of damaging effects from an inappropriate environment.

To improve the microclimate inside packing cases, buffering materials such as silica gel can be added. Additional buffering materials will slow the rate of moisture content variation in the painting should it be subjected to extreme variations of RH for an extended period of time. The greatest risk in adding silica gel to a packing case is the possibility of using improperly conditioned silica gel. Even if the gel is carefully conditioned by the lending institution, it is always possible that it will become improperly conditioned during the period when the packing cases are in storage. Therefore, if silica gel is used, it is essential that it be checked for proper conditioning each time it is packed with a painting.

Silica gel can also be used in a microclimate display case that remains on the painting while it is on exhibition. Properly made microclimate display cases provide very stable environments for panel paintings. They are particularly useful when a painting is accustomed to an environment that cannot be provided at the borrowing institution. A panel acclimated to 65% RH, for example, could be placed in a microclimate display case when lent to a borrowing institution that can only maintain 35% RH during the winter. However, mold growth can develop inside microclimate display cases that are acclimated to a high RH.

Hand Carrying Panel Paintings

Due to concerns about their fragility, panel paintings are often hand carried. In certain situations, there are advantages to hand carrying works of art. The work remains in the possession of the courier at all times; this is not possible when works are sent as cargo on an aircraft. The painting will be subjected to smaller variations in temperature if the courier is conscientious about time spent in unusually cold or warm locations. However, there are some risks associated with hand carrying works of art. It is important that the painting fit into a sturdy but light weight case that is easily carried and small enough to fit in a safe location on an aircraft, ideally, under the seat. Overhead compartments should not be used because the work could accidentally fall to the floor should the compartment door open during the flight. If necessary, the case can be placed in a coat closet on an aircraft, but it must be secured so that no movement can occur.

Another risk with hand carrying works of art is theft. High-value materials that are carried are a potential target for well-informed thieves. Although this problem has been extremely rare, it is a concern that must be considered. While couriers may feel more secure because they are never separated from their packing cases, as is the case with cargo shipments, this doesn't mean that the work is actually safer.

There are many ways to pack a panel painting for hand carrying on an aircraft. Metal photographic equipment cases have proven very successful. These cases come in various sizes and shapes, the smaller ones fitting conveniently under aircraft seats. Packing a painting in these cases is straightforward. The procedure often used at the National Gallery of Art, Washington, is as follows: the framed panel painting is either wrapped directly in polyethylene that is sealed with waterproof tape or it is placed in an inner case that is then wrapped in polyethylene. Unframed panels are always fit into an inner case so that nothing touches the surface of the painting. The metal photography case is filled with polyester urethane foam, with a minimum of one inch of foam on all sides of the painting with a cavity cut into the foam to accept the wrapped painting or the inner case. In this procedure, the polyester urethane foam functions as a cushioning material and thermal insulation.

CONCLUSION

Most panel paintings that are in good condition and free to respond dimensionally to environmental variations can be safely transported as long as they are properly packed. There are circumstances when some paintings are at greater risk than others. All panels should be carefully examined and an assessment should be made of RH and temperature-related stresses that may develop because of improper framing techniques or restraint imposed by cradles or battens. Existing cracks in the design layers usually act as expansion joints, but cracks in panels are a potential problem, especially if the painting is subjected to impact.

It is also important to compare the RH levels where the painting normally hangs to the RH levels at the borrowing institution. If there is a large discrepancy in the RH, a microclimate display case could be used. Tables 2-4 summarize the relative RH-related risks for sample paintings of different construction and grain orientation. For example, in Table 2, it can be seen that it is risky to transport a restrained, tangentially cut, white oak panel, that has been equilibrated to 70% RH or higher.

In Tables 3 and 4, we see that it is potentially hazardous to ship a panel painting that has been equilibrated to 70% RH or higher and has a gesso ground or paint directly applied to the wood, particularly if the wood support is tangentially cut and <u>not restrained</u>.

Summary Table 2. Maximum allowable RH ranges and relative risks for sound, uncracked and restrained white oak panels in different grain orientations

PANEL GRAIN ORIENTATION	EQUILIBRIUM RH (%)	ALLOWABLE RH RANGE TO YIELD (%)	RELATIVE RISK
TANGENTIAL	36	25-54	MEDIUM
TANGENTIAL	50	33-63	LOW
TANGENTIAL	70	62-73	HIGH
RADIAL	50	23-75	LOW
RADIAL	70	40-85	LOW

Table 3. Maximum allowable RH ranges and relative risks for well-attached gesso applied to unrestrained white oak panels in different grain orientations

PANEL GRAIN ORIENTATION	EQUILIBRIUM RH (%)	ALLOWABLE RH RANGE TO YIELD (%)	RELATIVE RISK
LONGITUDINAL	50	20-86	LOW
RADIAL	50	22-79	LOW
TANGENTIAL	50	33-62	MEDIUM
LONGITUDINAL	64	29-93	LOW
RADIAL	64	33-87	LOW
TANGENTIAL	64	53-68	**HIGH**
LONGITUDINAL	70	32-96	LOW
RADIAL	70	32-84	LOW
TANGENTIAL	70	65-73	**VERY HIGH**
LONGITUDINAL	36	12-75	LOW

RADIAL	36	15-71	LOW
TANGENTIAL	36	26-54	MEDIUM

Table 4. Maximum allowable RH ranges and relative risks for well-attached oil paint applied to unrestrained white oak panels in different grain orientations.

PANEL GRAIN ORIENTATION	EQUILIBRIUM RH (%)	ALLOWABLE RH RANGE TO YIELD (%)	RELATIVE RISK
LONGITUDINAL	50	8-95	LOW
RADIAL	50	13-86	LOW
TANGENTIAL	50	27-65	MEDIUM
LONGITUDINAL	64	16-95	LOW
RADIAL	64	20-92	LOW
TANGENTIAL	64	43-71	MEDIUM
LONGITUDINAL	70	17-95	LOW
RADIAL	70	19-90	LOW
TANGENTIAL	70	61-75	**VERY HIGH**
LONGITUDINAL	36	4-92	LOW
RADIAL	36	8-88	LOW
TANGENTIAL	36	22-60	MEDIUM

To maintain stable moisture contents of paintings, they should be wrapped in moisture barrier materials, provided the paintings are not conditioned to an unusually damp environment. Condensation could occur when paintings acclimated to very high RH are transported in extremely cold weather and mold growth could develop.

Temperature variations during transit should be minimized using climate-controlled vehicles and thermal insulation inside packing cases. Table 5 below gives the typical glass transition temperatures for three types of paint. Paintings should never be subjected to temperatures as low as these values but should stay above 10°C.

Table 5. The approximate glass transition temperatures for

selected paints

MATERIAL	GLASS TRANSITION TEMPERATURE, T_g (°C)
OIL PAINT	-10
ALKYD PAINT	-5
ACRYLIC PAINT	+5

Careful attention should be given to the selection and proper use of cushioning materials in the packing cases to ensure that paintings are not exposed to edge drops resulting in forces exceeding approximately 40 to 50 G's.

For panel paintings, topple accidents can cause more severe damage than edge drops. The edges of panel paintings should be supported continuously around the edges when in the frame and during transport. The panel must be free to move in response to changes in temperature and RH. See Table 6 for the approximate topple accident G levels that will break sound, uncracked panels of different dimensions and woods. This table assumes that there is no auxiliary support such as battens or cradles attached to the panels and the wood is cut in the tangential direction. Woods cut in the radial direction are approximately 40% stronger than the examples provided in Table 6.

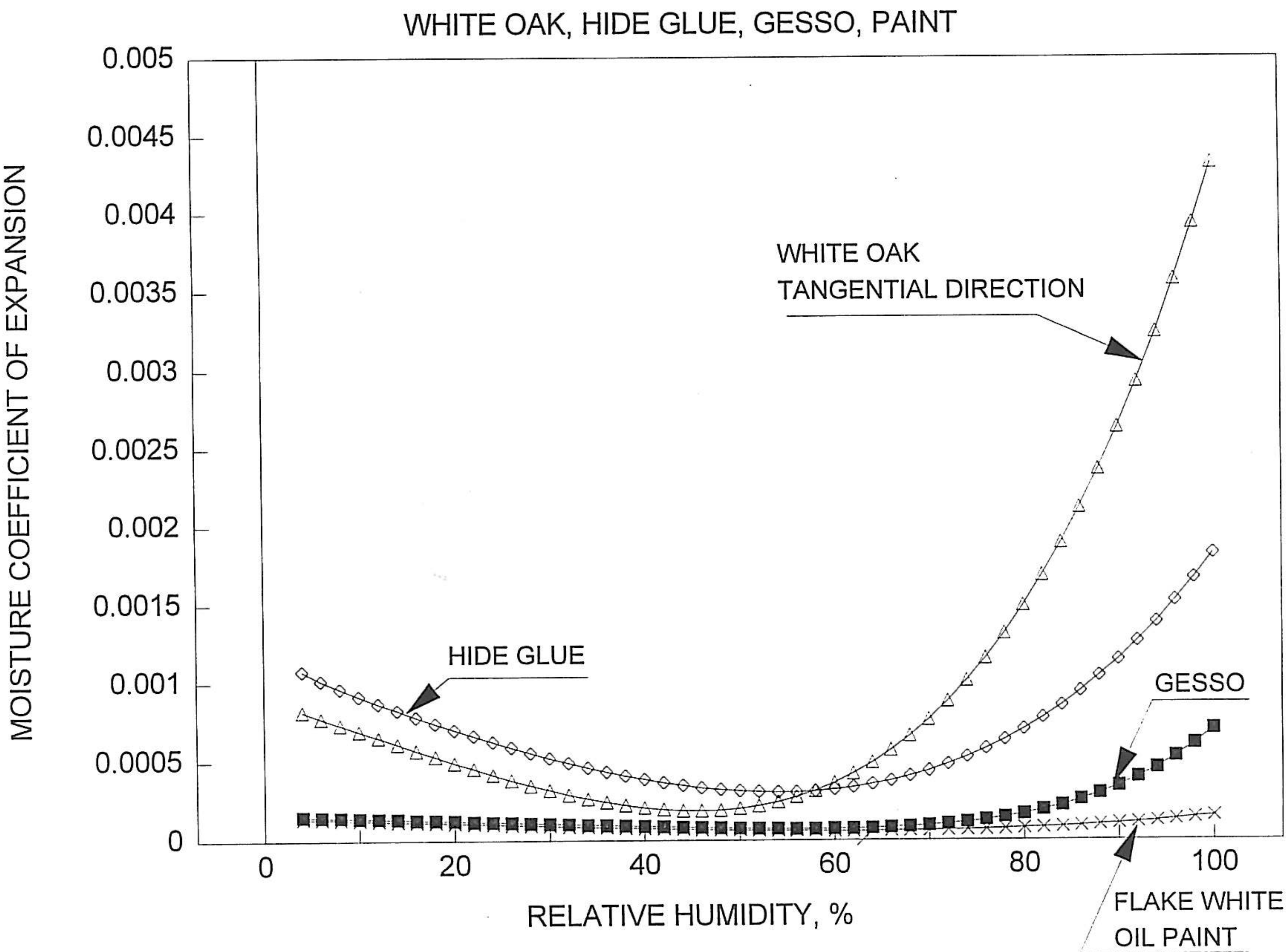
Table 6. Topple accident G levels required to break selected wood panels cut in the tangential directions and supported along the two parallel to grain directions

PANEL WIDTH INCHES (CM)	PANEL THICKNESS INCHES (CM)	TOPPLE G AT FAILURE WHITE OAK	TOPPLE G AT FAILURE PINE
50 (127)	0.50 (1.25)	29	19
50 (127)	0.75 (1.90)	44	28
50 (127)	1.00 (2.53)	59	37
40 (102)	0.50 (1.25)	46	29
40 (102)	0.75 (1.90)	69	44
40 (102)	1.00 (2.53)	92	58

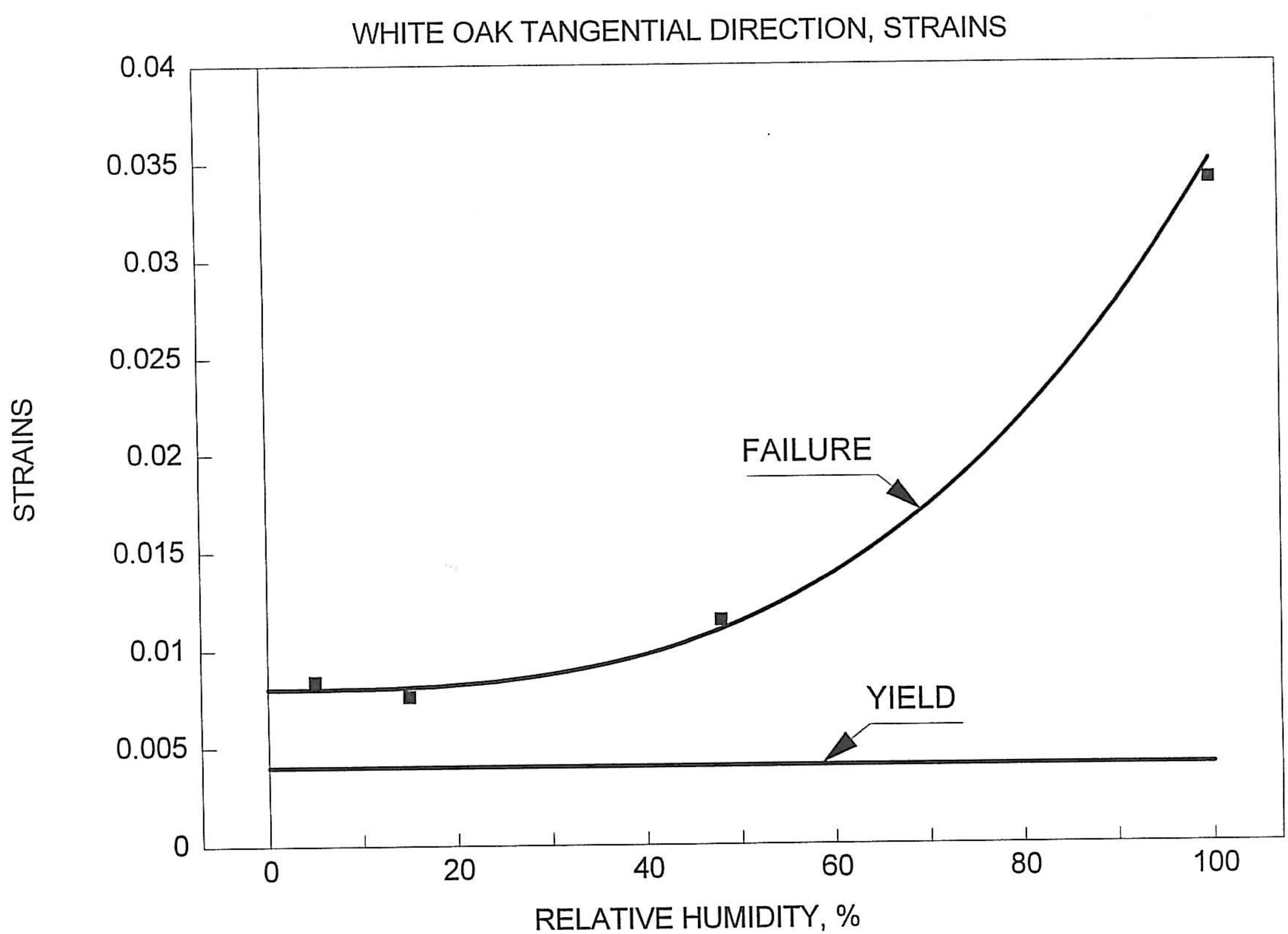
30 (76)	0.50 (1.25)	82	52
30 (76)	0.75 (1.90)	122	77
30 (76)	1.00 (2.53)	163	103

Low temperatures can severely reduce the effectiveness of foam cushions in reducing impact G levels.

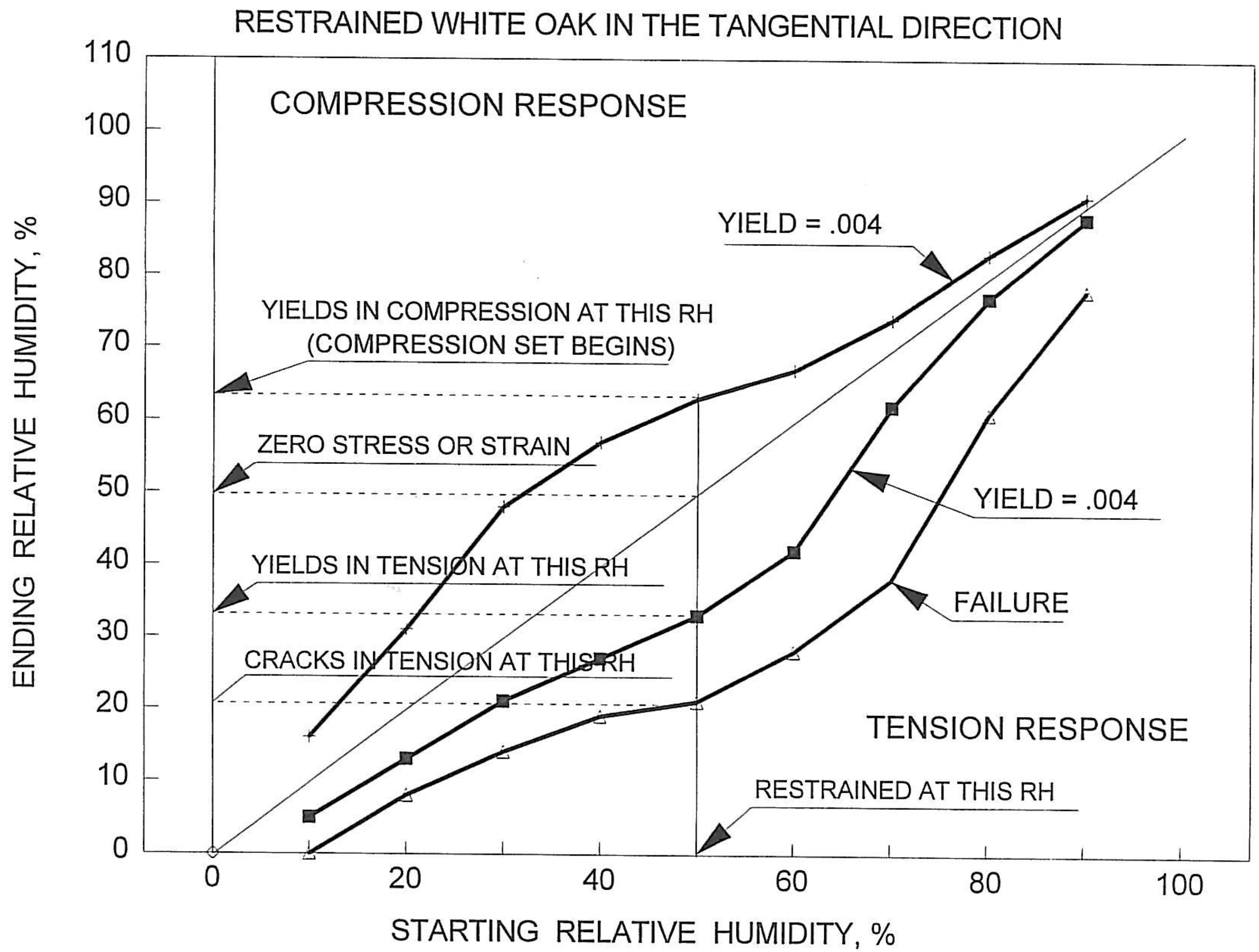
Transit vibration in panel paintings can normally be successfully attenuated by the foam cushions used to protect the painting from impact damage.

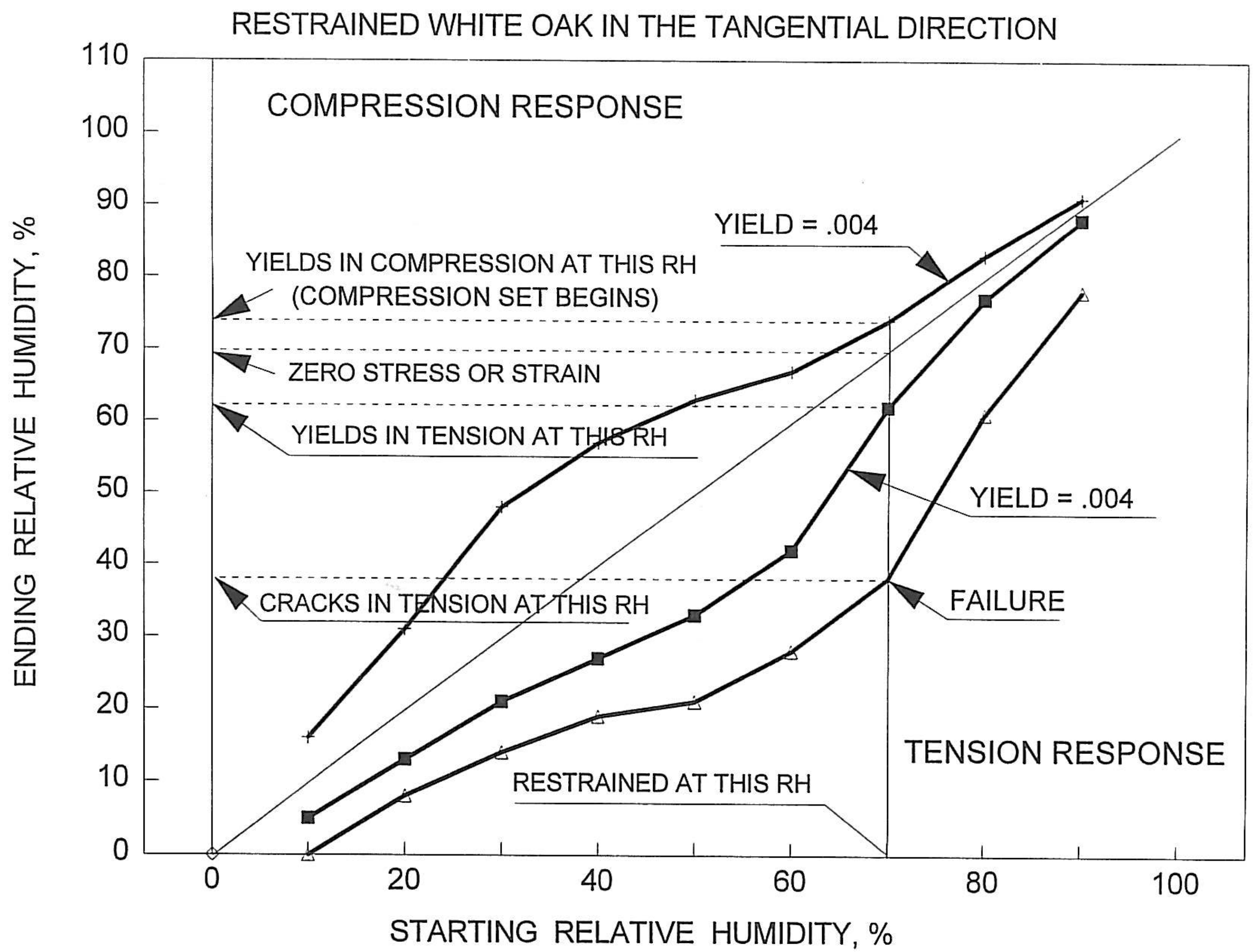


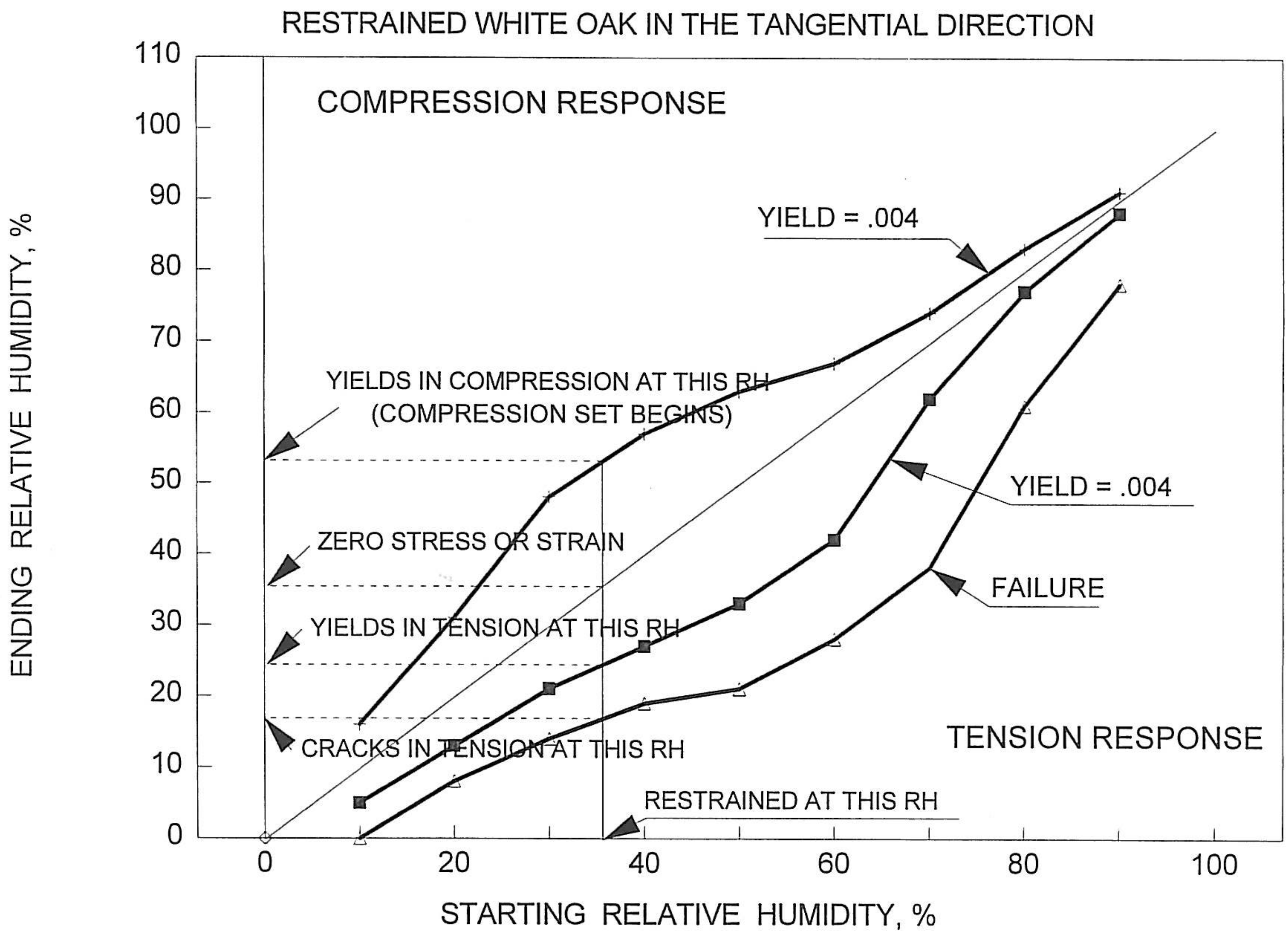
WHITE OAK, HIDE GLUE, GESSO, PAINT
MOISTURE COEFFICIENT OF EXPANSION
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0
20
40
60
80
100
RELATIVE HUMIDITY, %
WHITE OAK
TANGENTIAL DIRECTION
HIDE GLUE
GESSO
FLAKE WHITE
OIL PAINT


WHITE OAK TANGENTIAL DIRECTION, STRAINS
STRAINS
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
FAILURE
YIELD
0
20
40
60
80
100
RELATIVE HUMIDITY, %

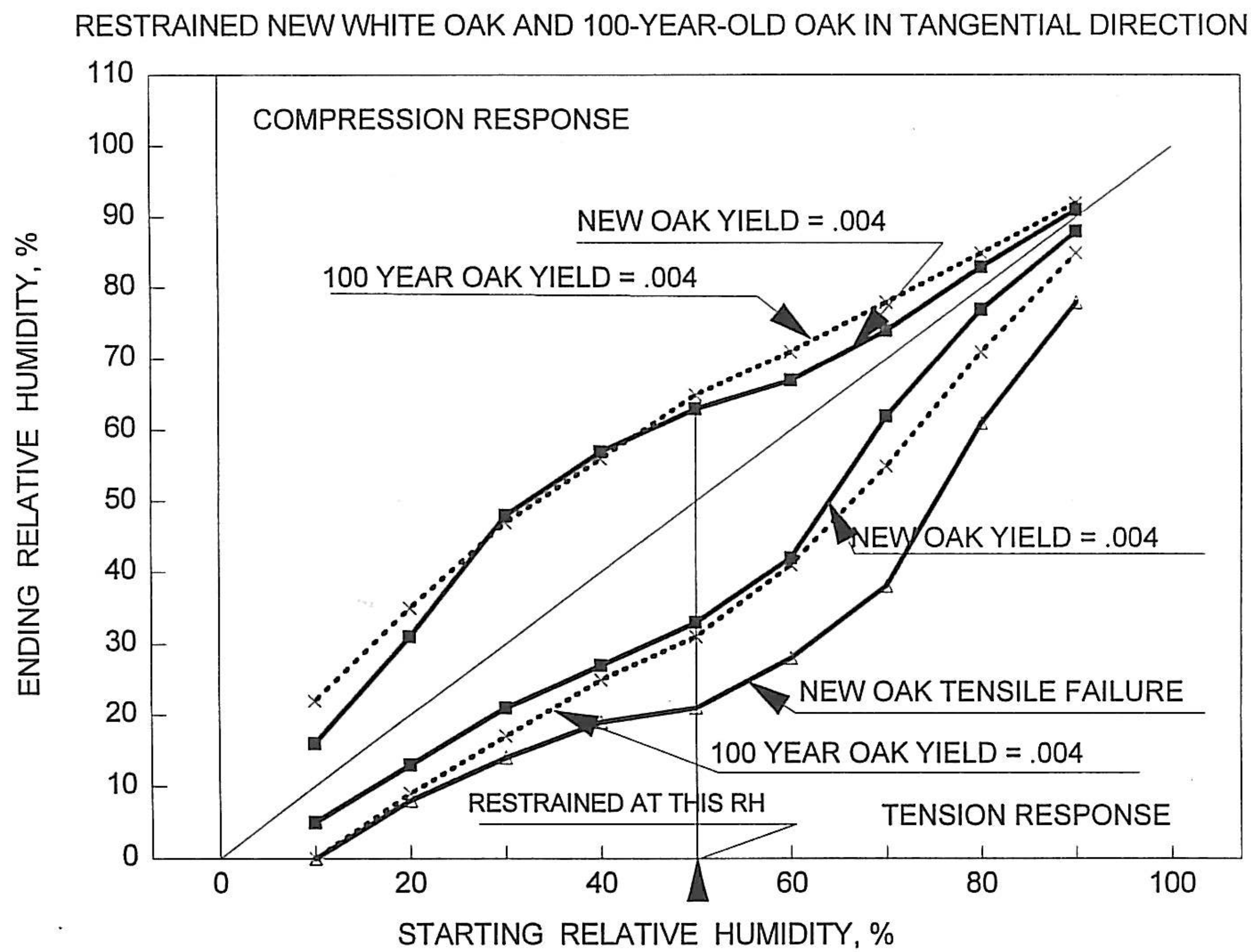
2


RESTRAINED WHITE OAK IN THE TANGENTIAL DIRECTION
COMPRESSION RESPONSE
YIELD = .004
YIELDS IN COMPRESSION AT THIS RH
(COMPRESSION SET BEGINS)
ZERO STRESS OR STRAIN
YIELDS IN TENSION AT THIS RH
CRACKS IN TENSION AT THIS RH
YIELD = .004
FAILURE
TENSION RESPONSE
RESTRAINED AT THIS RH
ENDING RELATIVE HUMIDITY, %
110
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
STARTING RELATIVE HUMIDITY, %

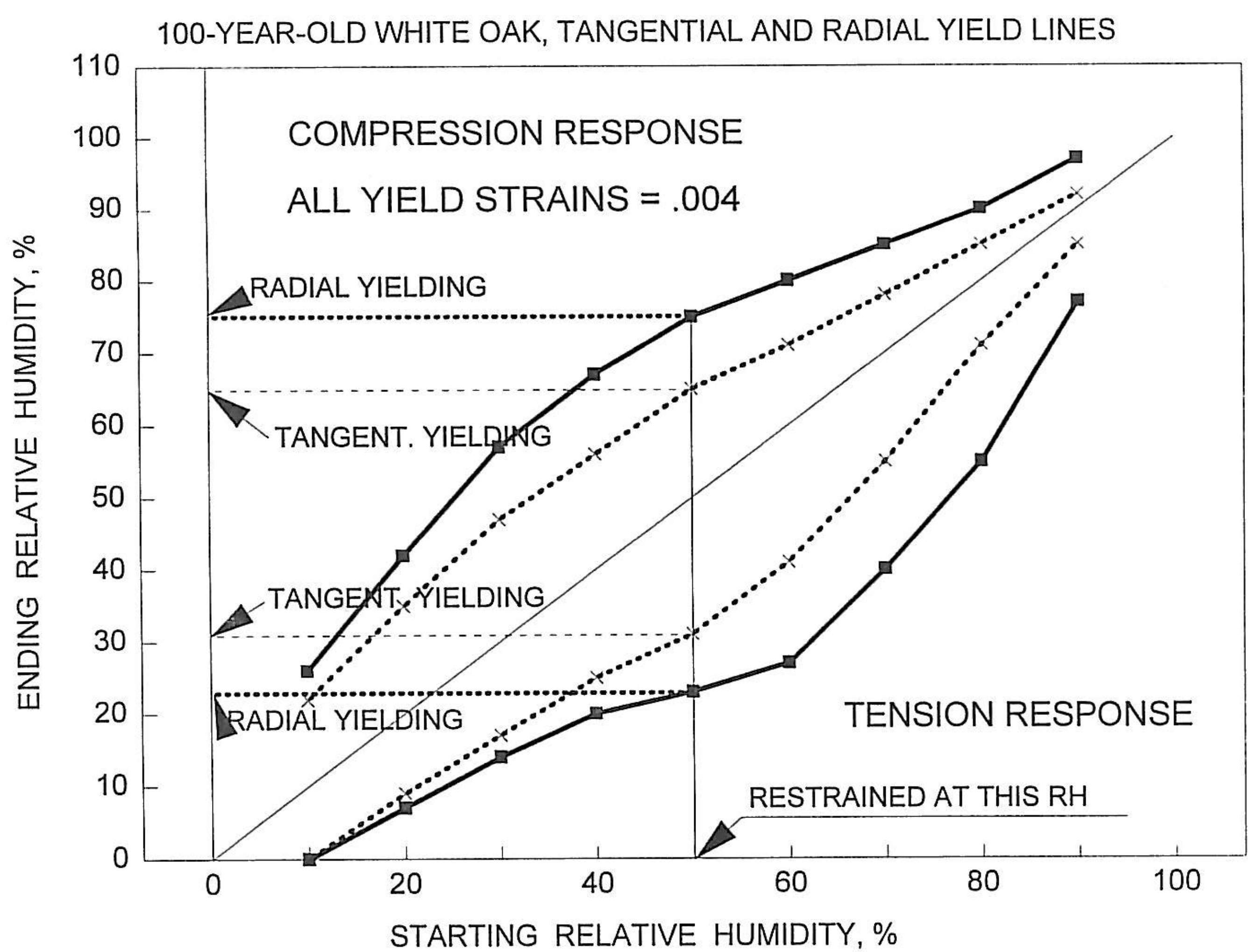

RESTRAINED WHITE OAK IN THE TANGENTIAL DIRECTION
COMPRESSION RESPONSE
YIELD = .004
YIELDS IN COMPRESSION AT THIS RH
(COMPRESSION SET BEGINS)
ZERO STRESS OR STRAIN
YIELDS IN TENSION AT THIS RH
YIELD = .004
CRACKS IN TENSION AT THIS RH
FAILURE
TENSION RESPONSE
RESTRAINED AT THIS RH
ENDING RELATIVE HUMIDITY, %
STARTING RELATIVE HUMIDITY, %
0
10
20
30
40
50
60
70
80
90
100
110


RESTRAINED WHITE OAK IN THE TANGENTIAL DIRECTION
COMPRESSION RESPONSE
TENSION RESPONSE
YIELD = .004
YIELD = .004
FAILURE
YIELDS IN COMPRESSION AT THIS RH
(COMPRESSION SET BEGINS)
ZERO STRESS OR STRAIN
YIELDS IN TENSION AT THIS RH
CRACKS IN TENSION AT THIS RH
RESTRAINED AT THIS RH
ENDING RELATIVE HUMIDITY, %
STARTING RELATIVE HUMIDITY, %
0
10
20
30
40
50
60
70
80
90
100
110
0
20
40
60
80
100

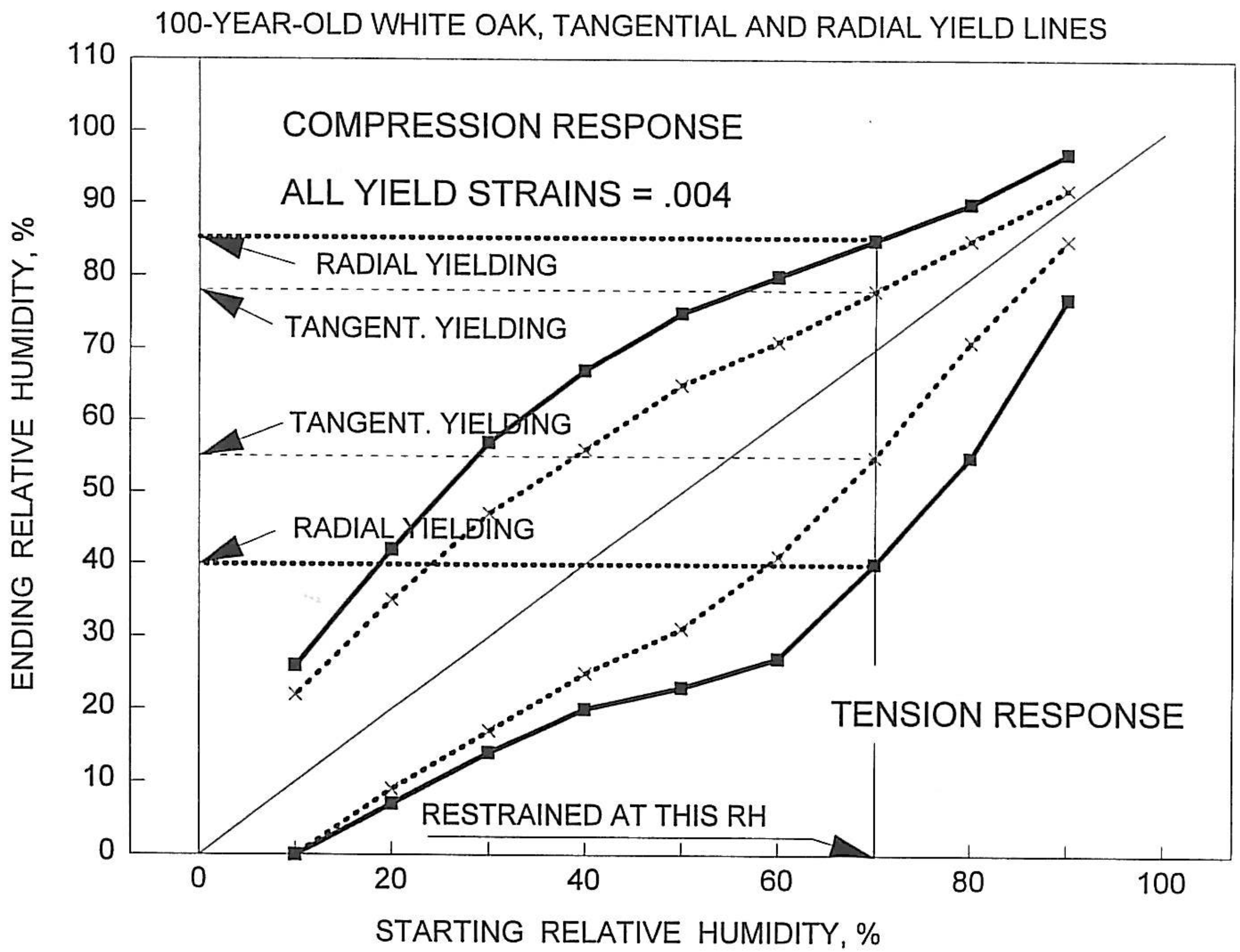
5

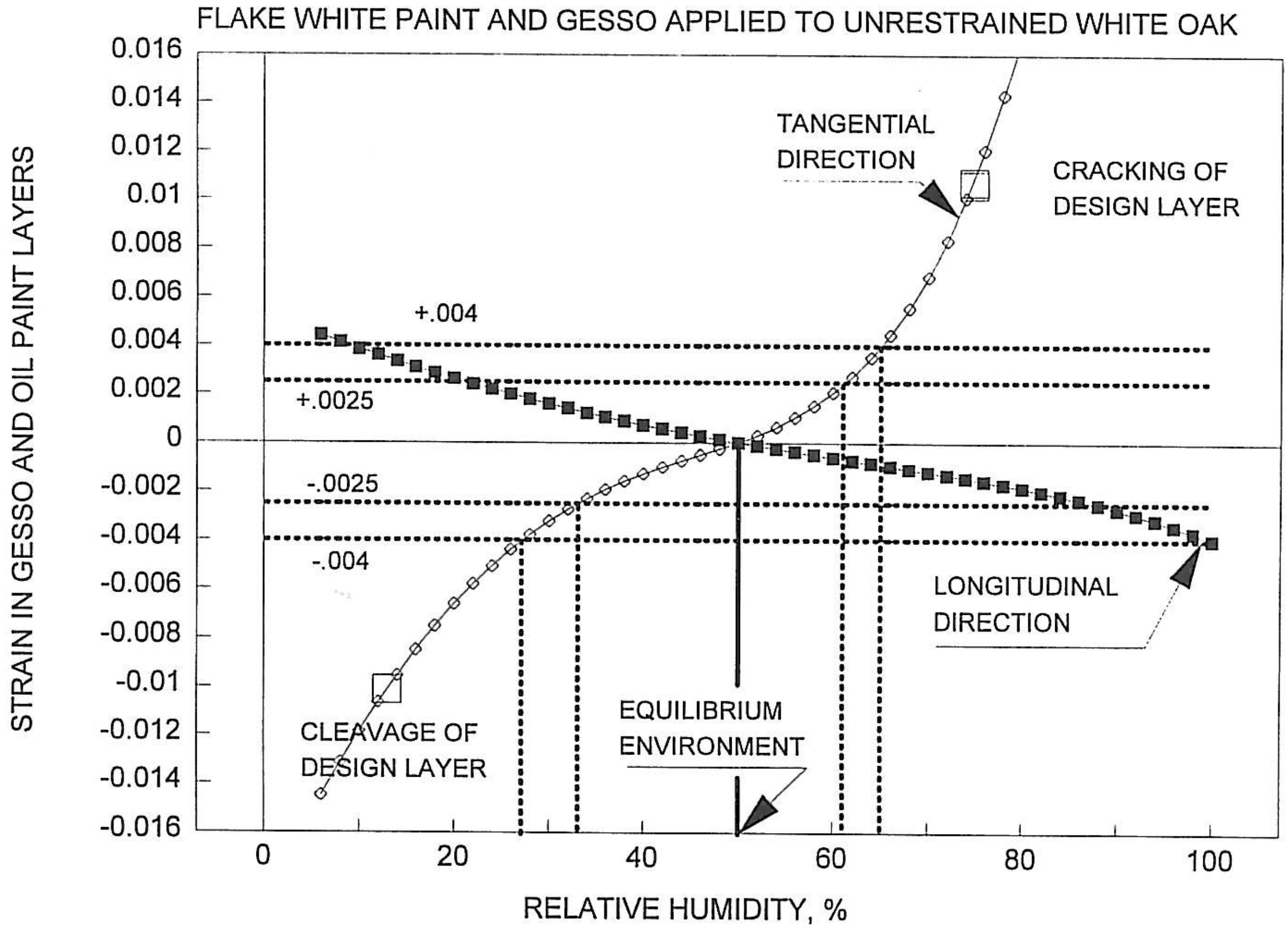

RESTRAINED NEW WHITE OAK AND 100-YEAR-OLD OAK IN TANGENTIAL DIRECTION
COMPRESSION RESPONSE
NEW OAK YIELD = .004
100 YEAR OAK YIELD = .004
NEW OAK YIELD = .004
NEW OAK TENSILE FAILURE
100 YEAR OAK YIELD = .004
RESTRAINED AT THIS RH
TENSION RESPONSE
ENDING RELATIVE HUMIDITY, %
STARTING RELATIVE HUMIDITY, %
0
10
20
30
40
50
60
70
80
90
100
110
0
20
40
60
80
100

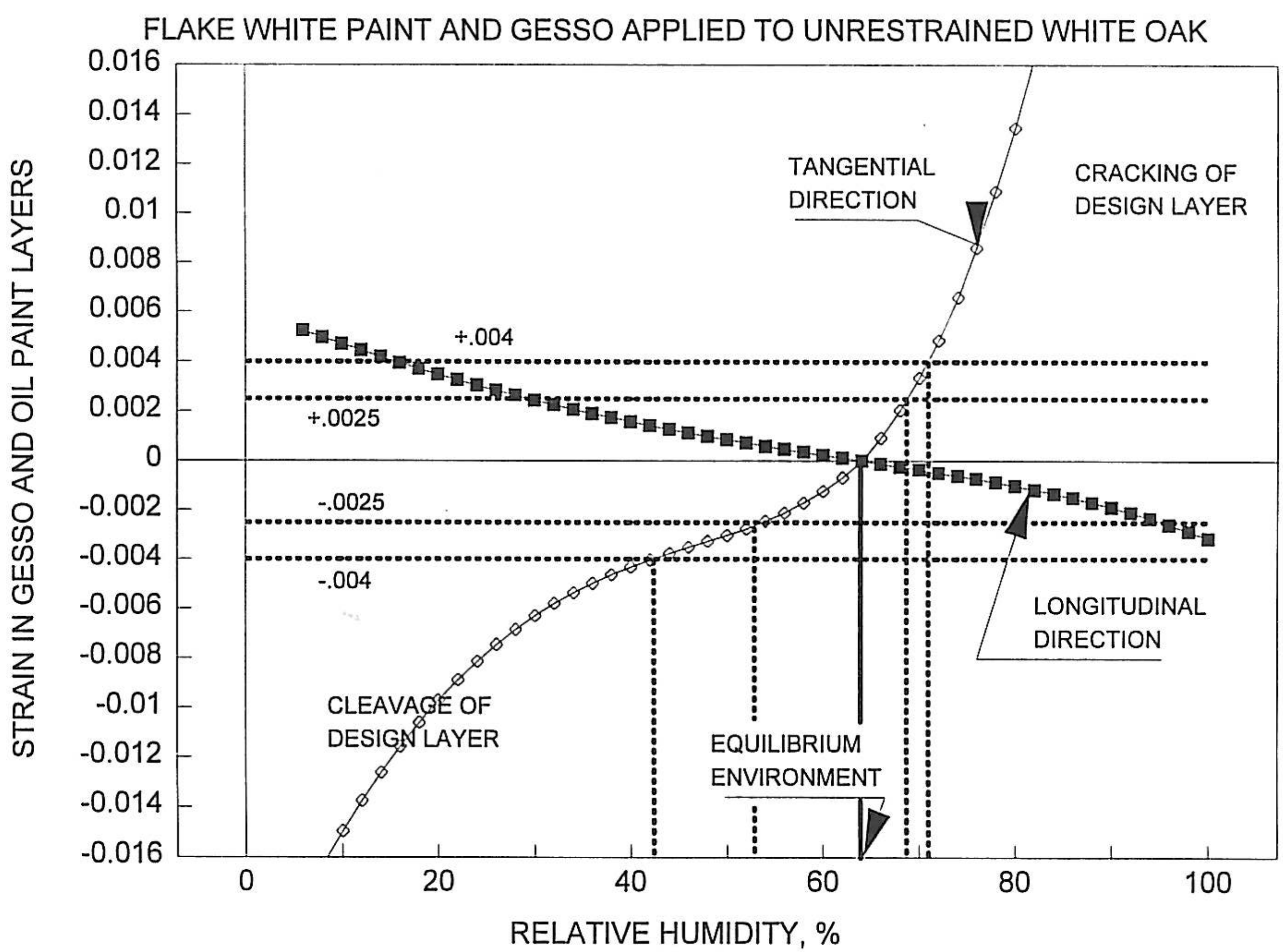
6


100-YEAR-OLD WHITE OAK, TANGENTIAL AND RADIAL YIELD LINES
COMPRESSION RESPONSE
ALL YIELD STRAINS = .004
RADIAL YIELDING
TANGENT. YIELDING
TANGENT. YIELDING
RADIAL YIELDING
TENSION RESPONSE
RESTRAINED AT THIS RH
ENDING RELATIVE HUMIDITY, %
STARTING RELATIVE HUMIDITY, %
0
10
20
30
40
50
60
70
80
90
100
110
0
20
40
60
80
100

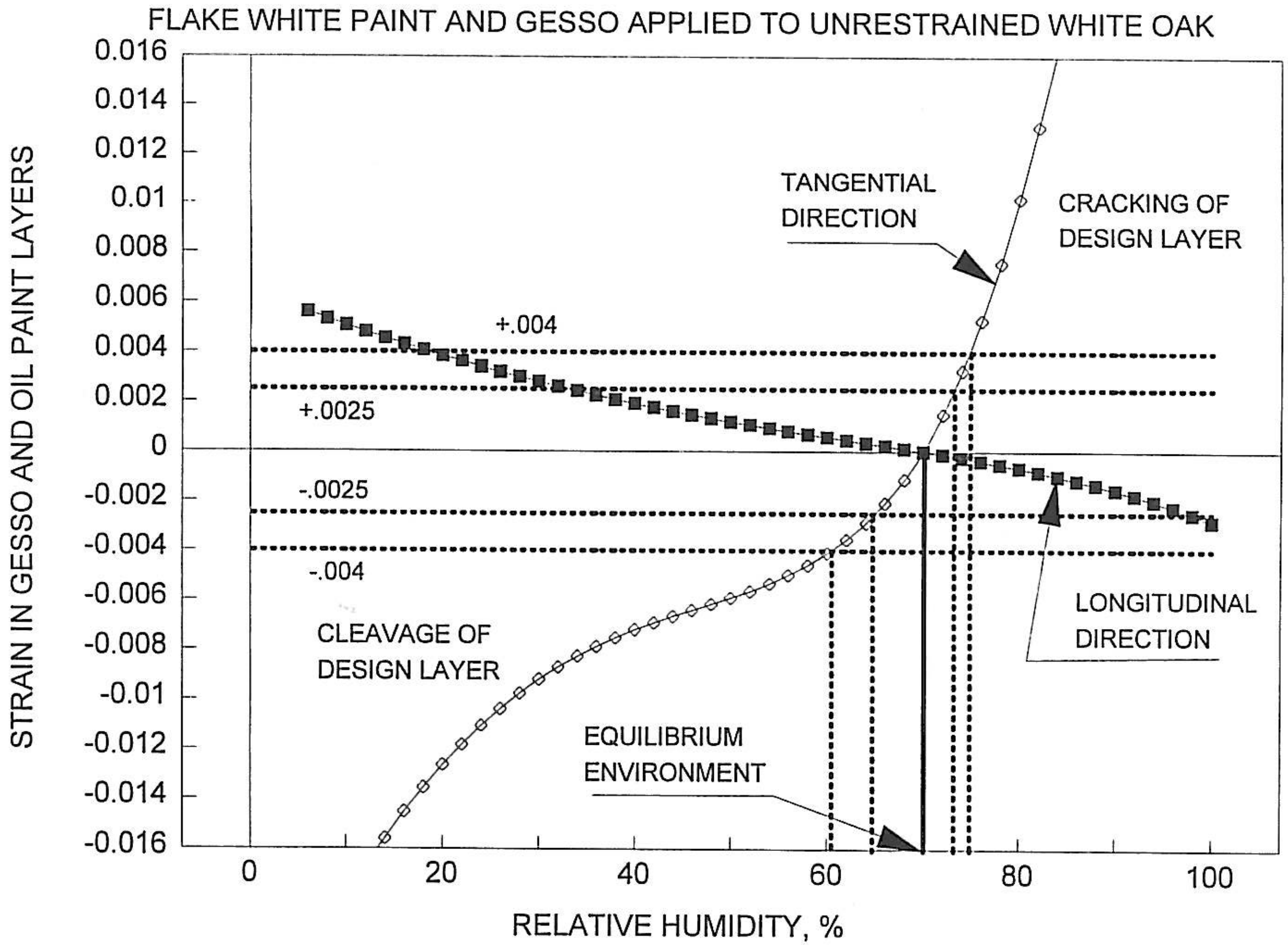
7


100-YEAR-OLD WHITE OAK, TANGENTIAL AND RADIAL YIELD LINES
COMPRESSION RESPONSE
ALL YIELD STRAINS = .004
RADIAL YIELDING
TANGENT. YIELDING
TANGENT. YIELDING
RADIAL YIELDING
TENSION RESPONSE
RESTRAINED AT THIS RH
ENDING RELATIVE HUMIDITY, %
STARTING RELATIVE HUMIDITY, %
0
10
20
30
40
50
60
70
80
90
100
110
0
20
40
60
80
100

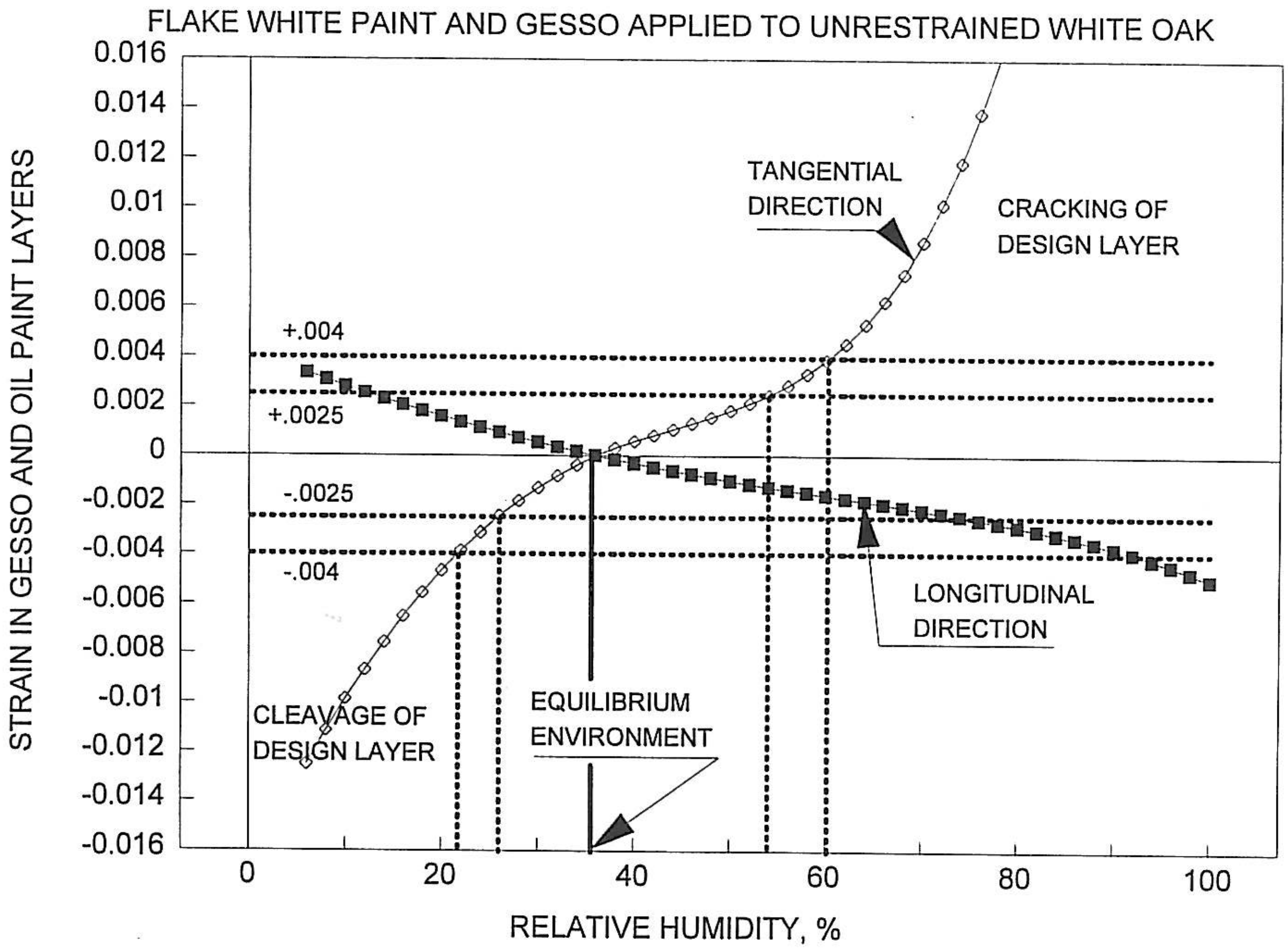

FLAKE WHITE PAINT AND GESSO APPLIED TO UNRESTRAINED WHITE OAK
STRAIN IN GESSO AND OIL PAINT LAYERS
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
0
20
40
60
80
100
RELATIVE HUMIDITY, %
+.004
+.0025
-.0025
-.004
TANGENTIAL DIRECTION
CRACKING OF DESIGN LAYER
LONGITUDINAL DIRECTION
EQUILIBRIUM ENVIRONMENT
CLEAVAGE OF DESIGN LAYER

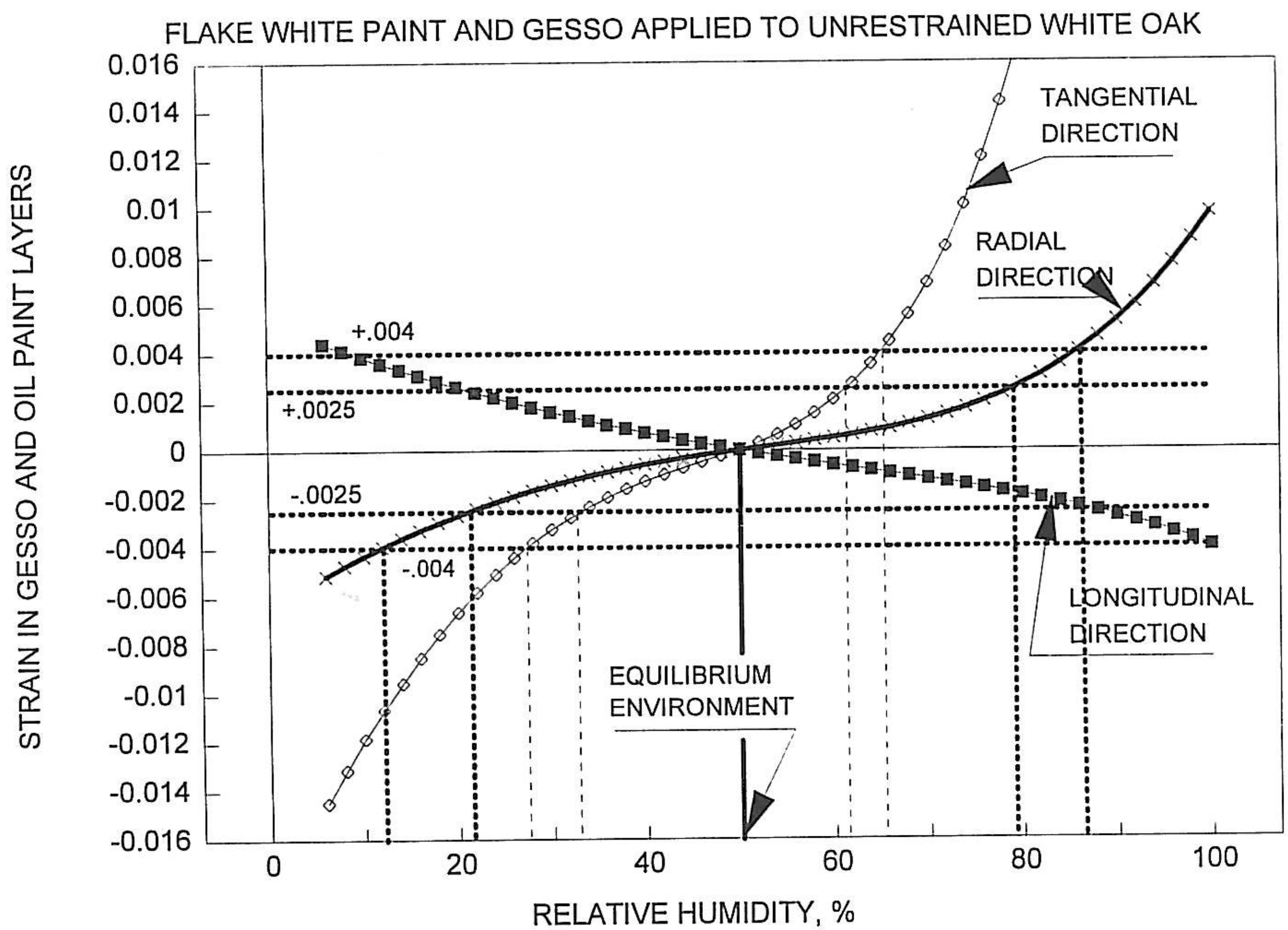

FLAKE WHITE PAINT AND GESSO APPLIED TO UNRESTRAINED WHITE OAK
STRAIN IN GESSO AND OIL PAINT LAYERS
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
0
20
40
60
80
100
RELATIVE HUMIDITY, %
+.004
+.0025
-.0025
-.004
TANGENTIAL DIRECTION
CRACKING OF DESIGN LAYER
LONGITUDINAL DIRECTION
CLEAVAGE OF DESIGN LAYER
EQUILIBRIUM ENVIRONMENT

10

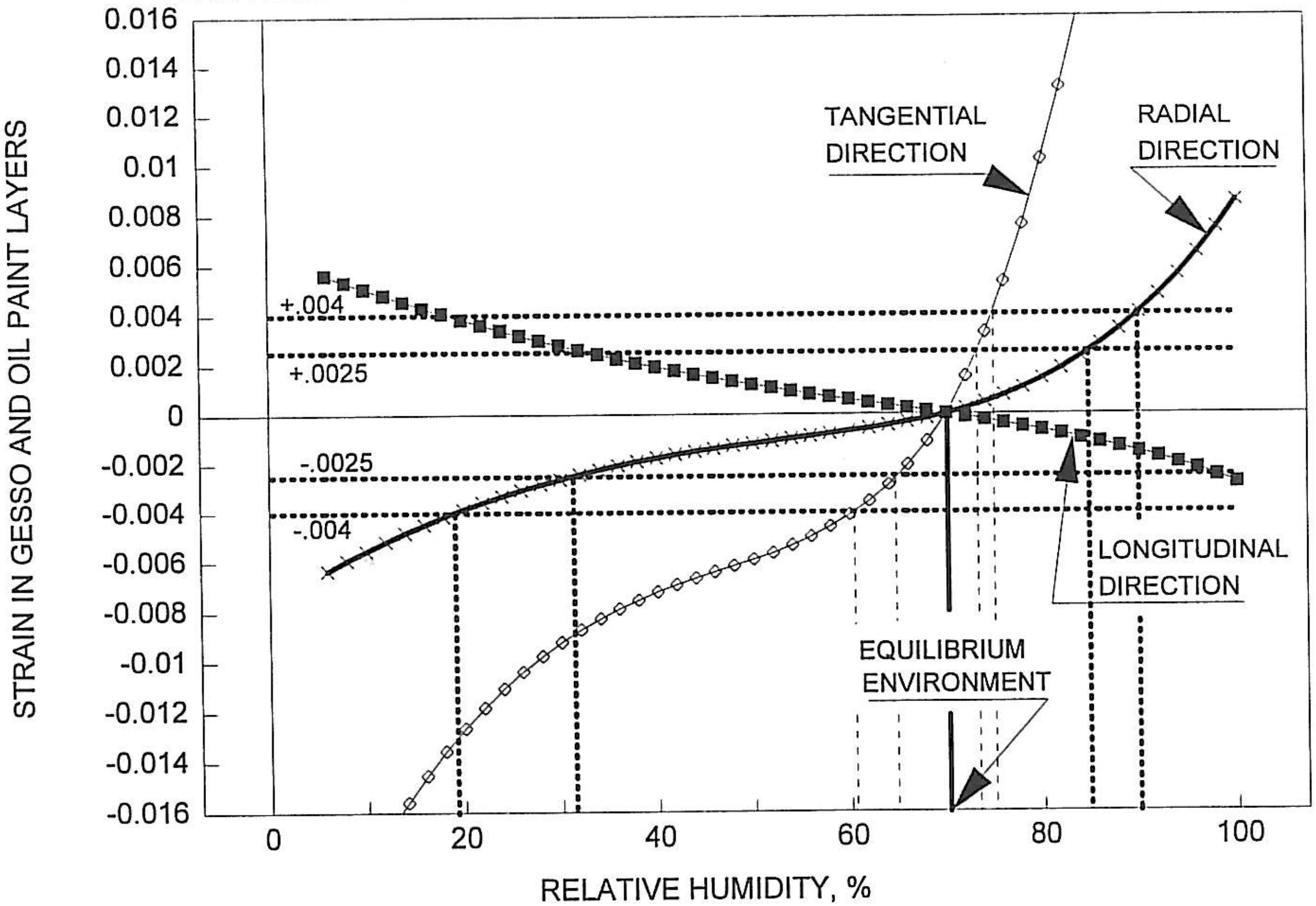

FLAKE WHITE PAINT AND GESSO APPLIED TO UNRESTRAINED WHITE OAK
STRAIN IN GESSO AND OIL PAINT LAYERS
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
0
20
40
60
80
100
RELATIVE HUMIDITY, %
+.004
+.0025
-.0025
-.004
TANGENTIAL DIRECTION
CRACKING OF DESIGN LAYER
LONGITUDINAL DIRECTION
CLEAVAGE OF DESIGN LAYER
EQUILIBRIUM ENVIRONMENT

11

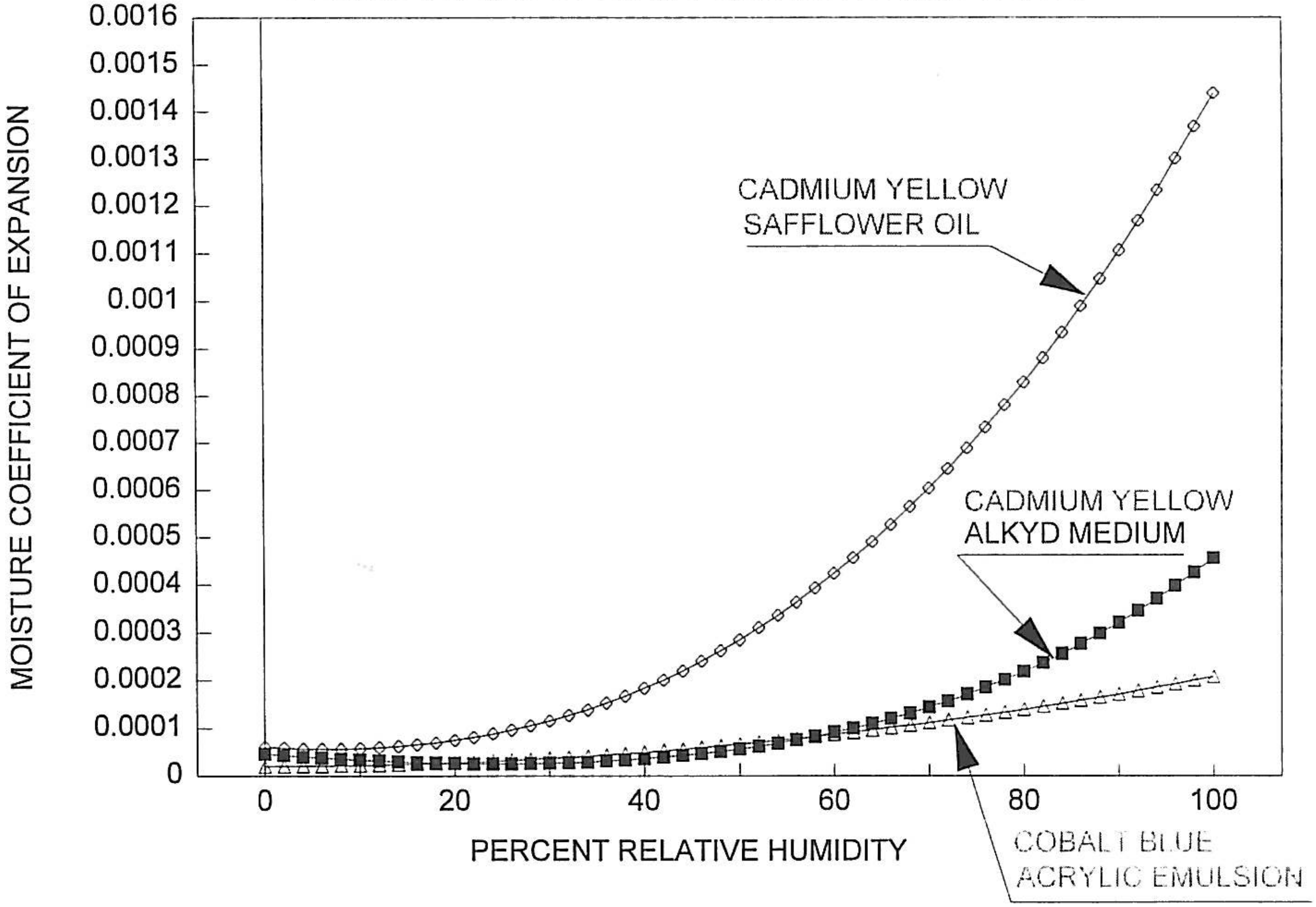

FLAKE WHITE PAINT AND GESSO APPLIED TO UNRESTRAINED WHITE OAK
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
STRAIN IN GESSO AND OIL PAINT LAYERS
+.004
+.0025
-.0025
-.004
TANGENTIAL DIRECTION
CRACKING OF DESIGN LAYER
LONGITUDINAL DIRECTION
CLEAVAGE OF DESIGN LAYER
EQUILIBRIUM ENVIRONMENT
0
20
40
60
80
100
RELATIVE HUMIDITY, %

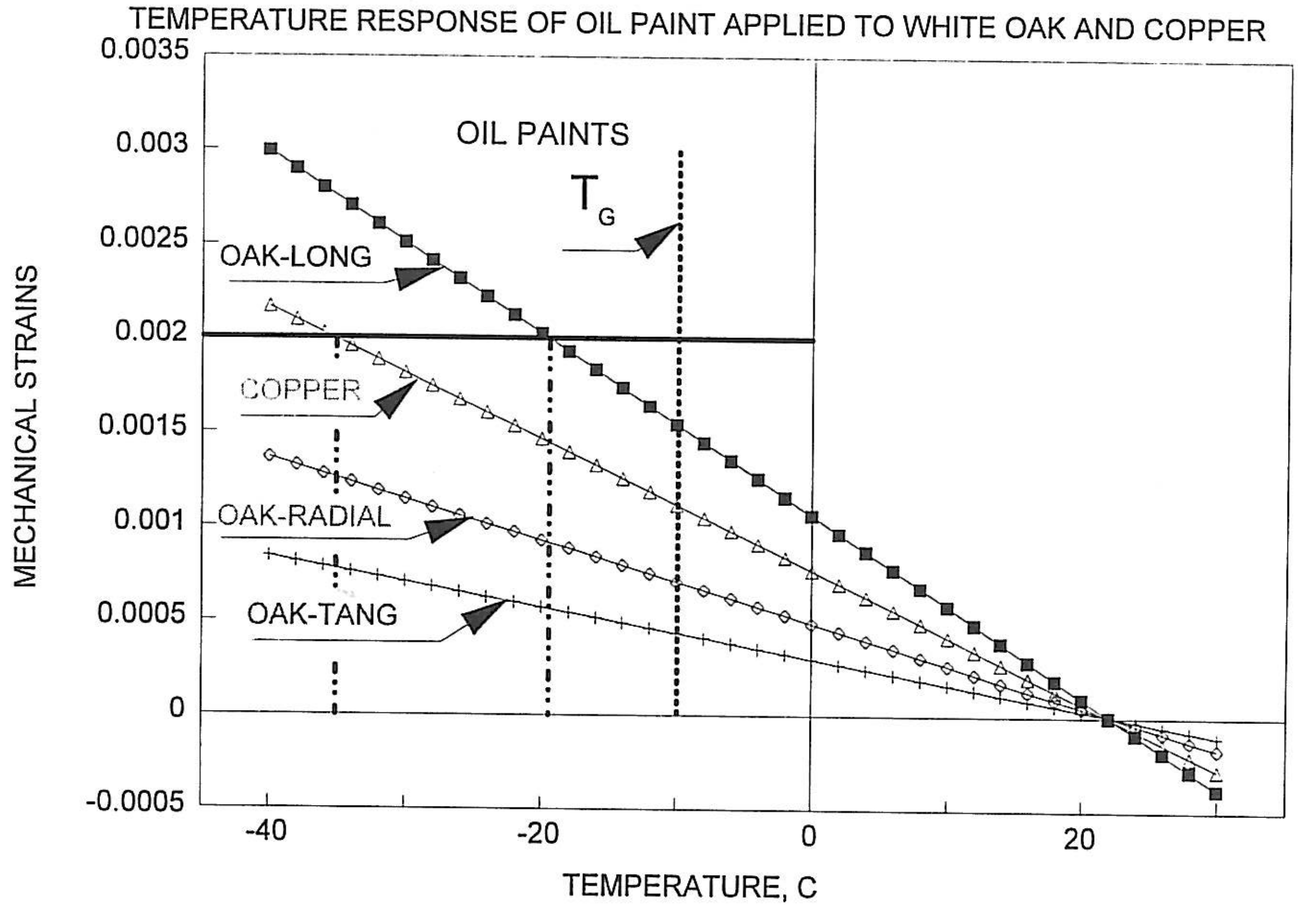

FLAKE WHITE PAINT AND GESSO APPLIED TO UNRESTRAINED WHITE OAK
STRAIN IN GESSO AND OIL PAINT LAYERS
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
0
20
40
60
80
100
RELATIVE HUMIDITY, %
TANGENTIAL DIRECTION
RADIAL DIRECTION
LONGITUDINAL DIRECTION
EQUILIBRIUM ENVIRONMENT
+.004
+.0025
-.0025
-.004

FLAKE WHITE PAINT AND GESSO APPLIED TO UNRESTRAINED WHITE OAK

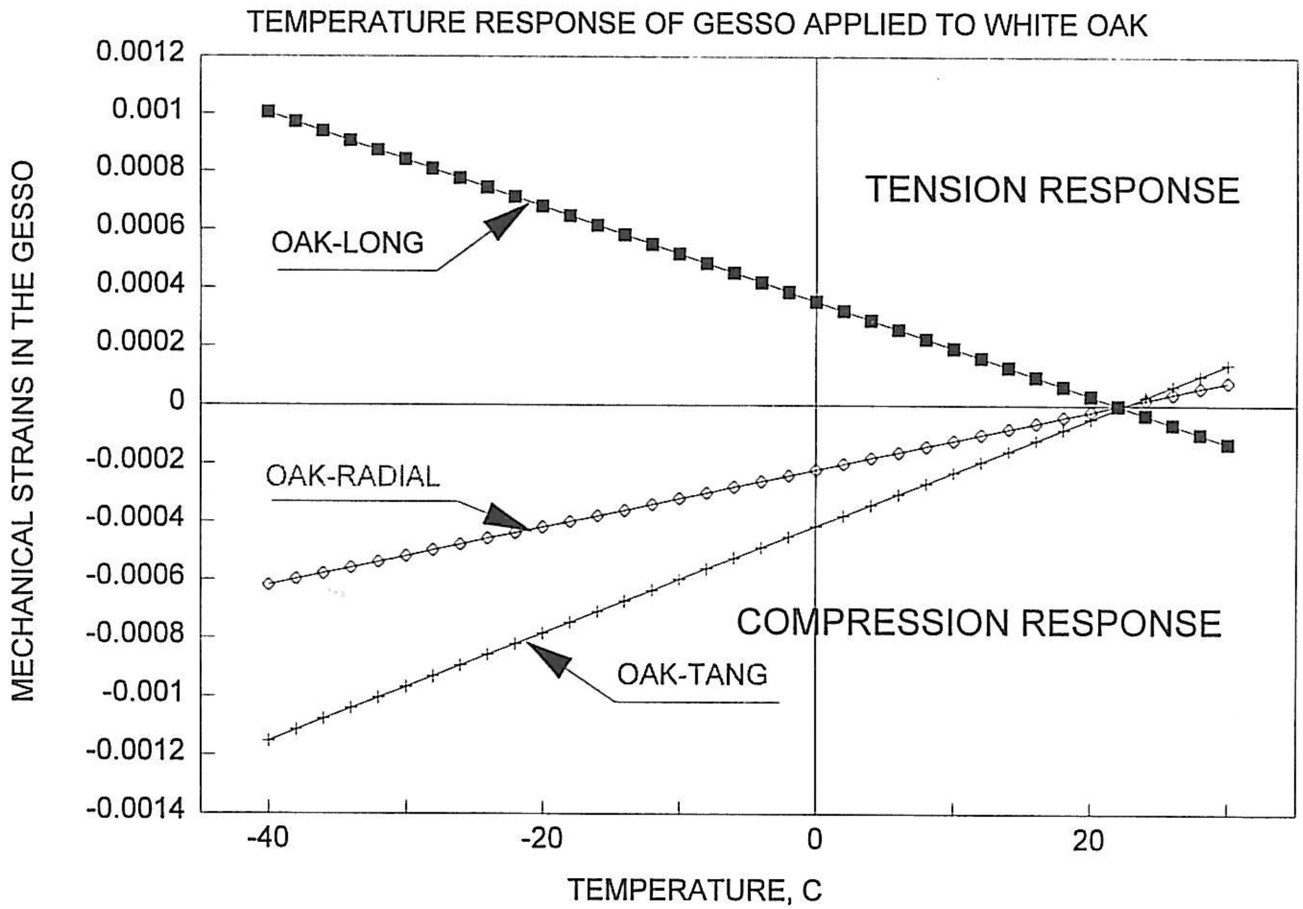


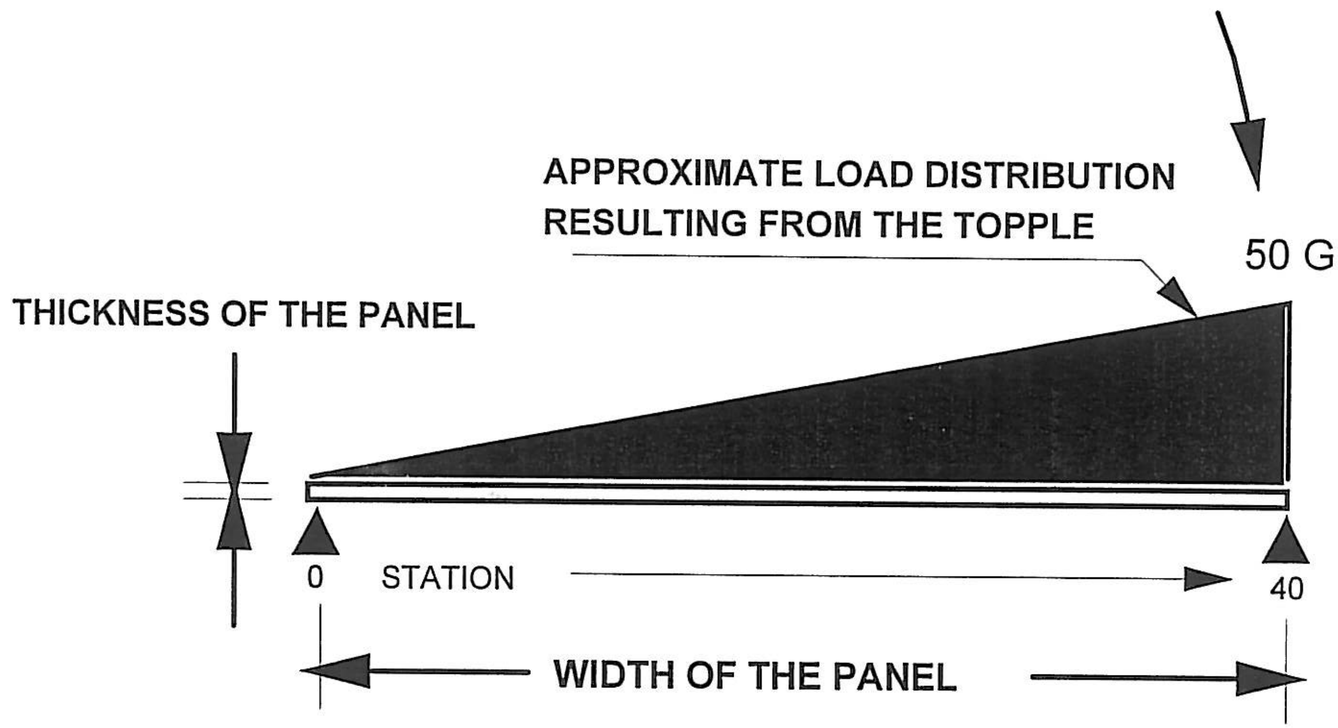
SWELLING RATES OF ALKYD, OIL, AND ACRYLIC PAINTS

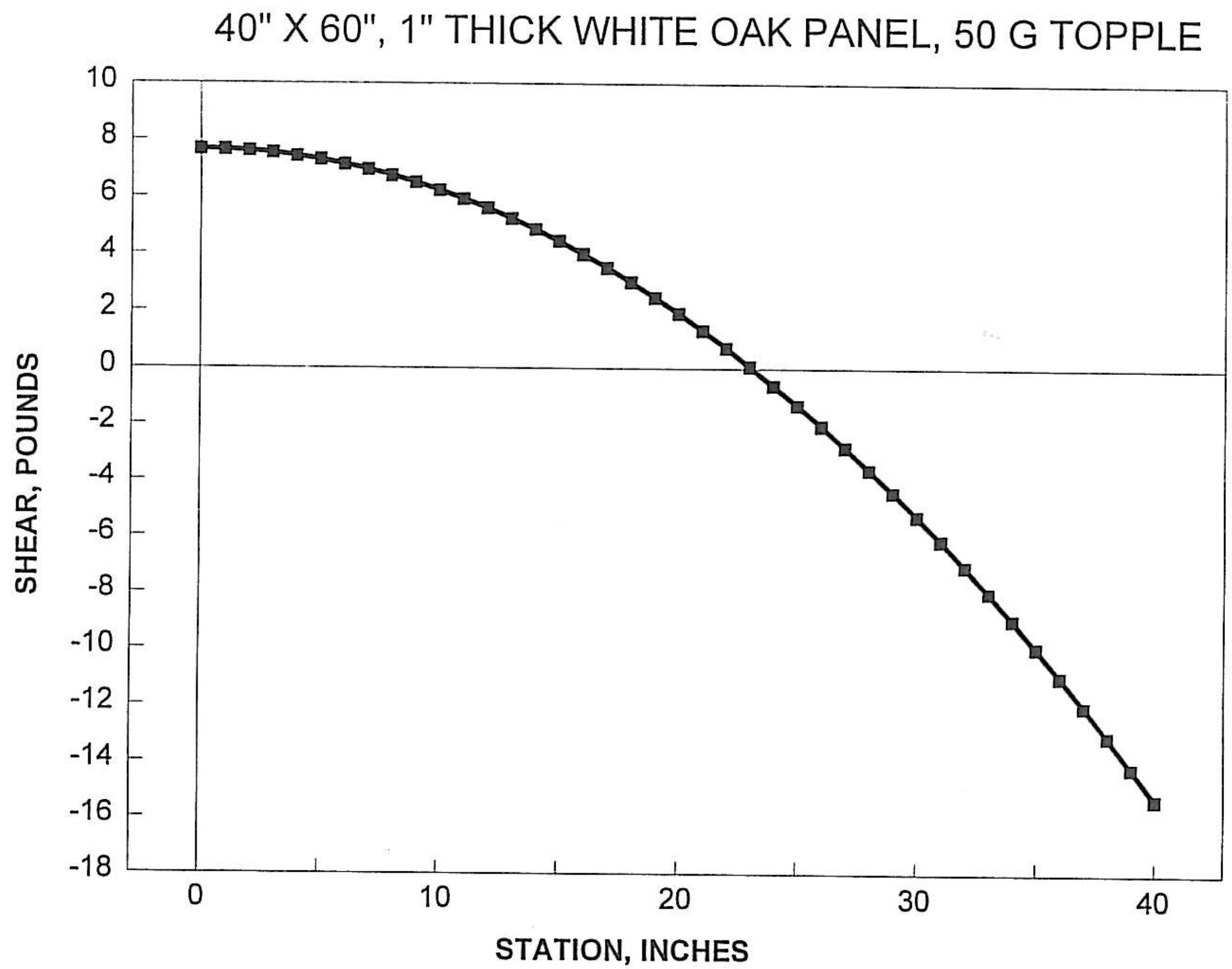



TEMPERATURE RESPONSE OF OIL PAINT APPLIED TO WHITE OAK AND COPPER
MECHANICAL STRAINS
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
-0.0005
OIL PAINTS
T_G
OAK-LONG
COPPER
OAK-RADIAL
OAK-TANG
-40
-20
0
20
TEMPERATURE, C

16

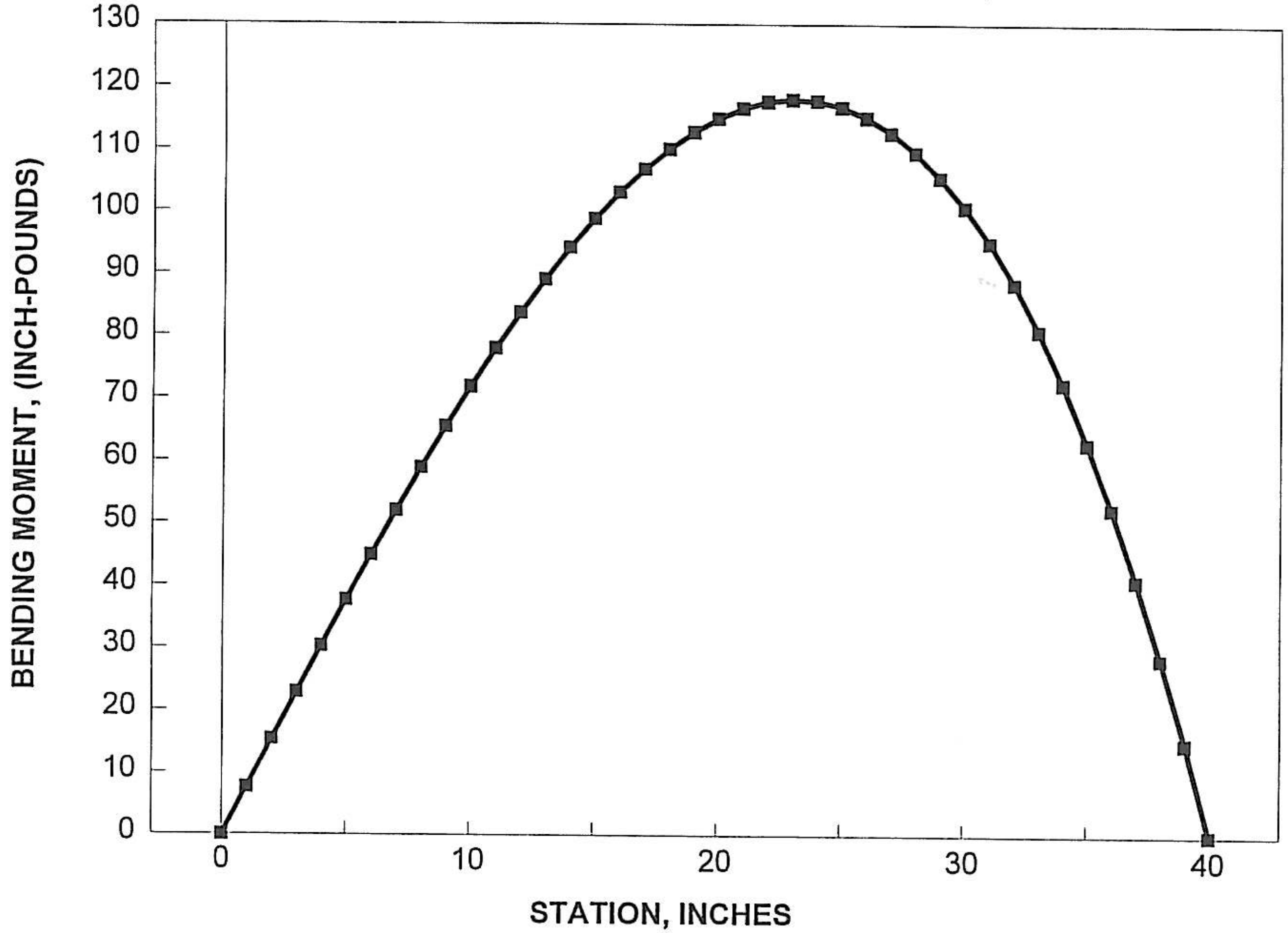

TEMPERATURE RESPONSE OF GESSO APPLIED TO WHITE OAK
MECHANICAL STRAINS IN THE GESSO
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
-0.0008
-0.001
-0.0012
-0.0014
TENSION RESPONSE
COMPRESSION RESPONSE
OAK-LONG
OAK-RADIAL
OAK-TANG
-40
-20
0
20
TEMPERATURE, C


APPROXIMATE LOAD DISTRIBUTION
RESULTING FROM THE TOPPLE
50 G
THICKNESS OF THE PANEL
0
STATION
40
WIDTH OF THE PANEL


40" X 60", 1" THICK WHITE OAK PANEL, 50 G TOPPLE
SHEAR, POUNDS
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
0
10
20
30
40
STATION, INCHES

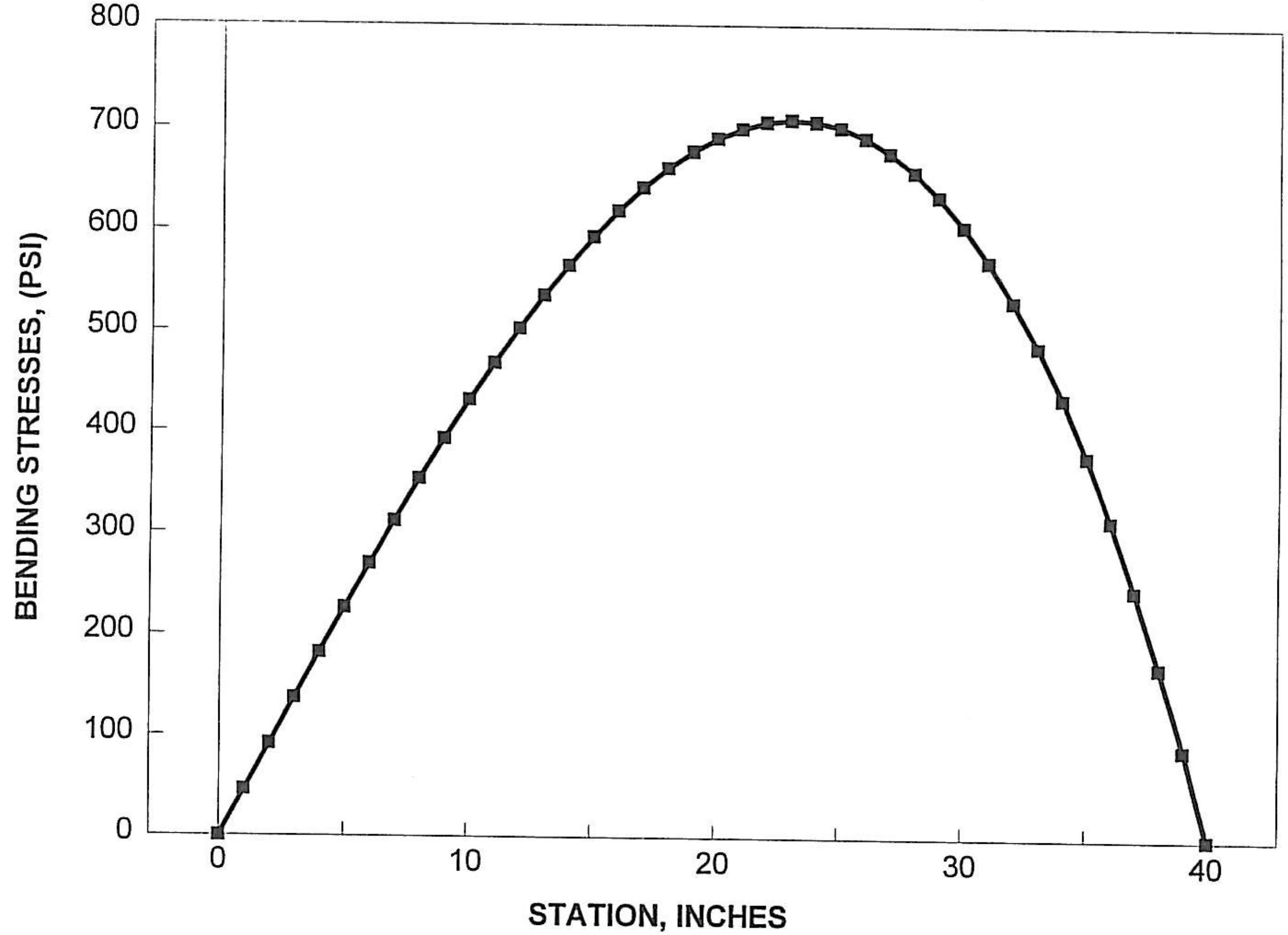
19

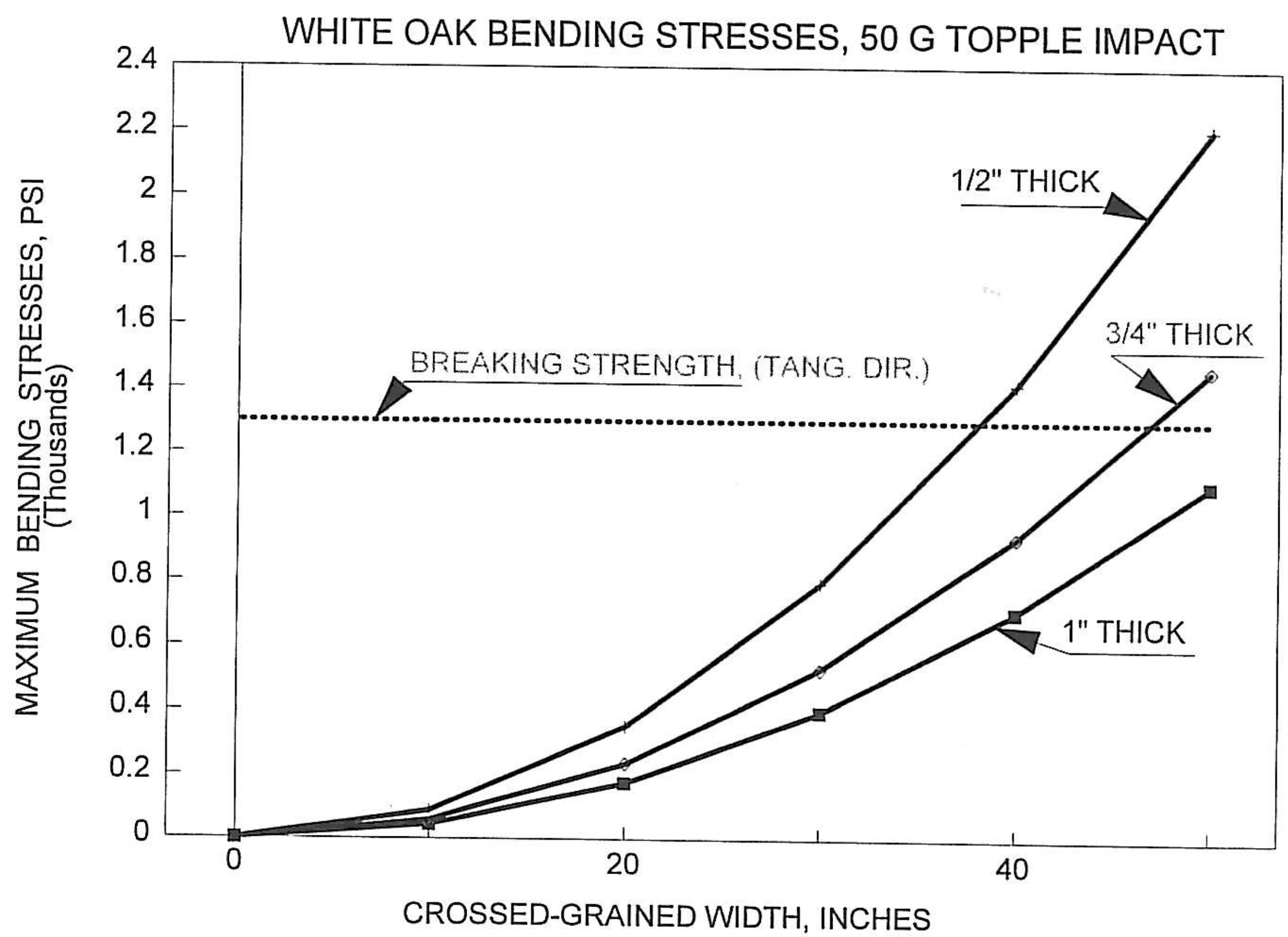
40" X 60", 1" THICK WHITE OAK PANEL, 50 G TOPPLE



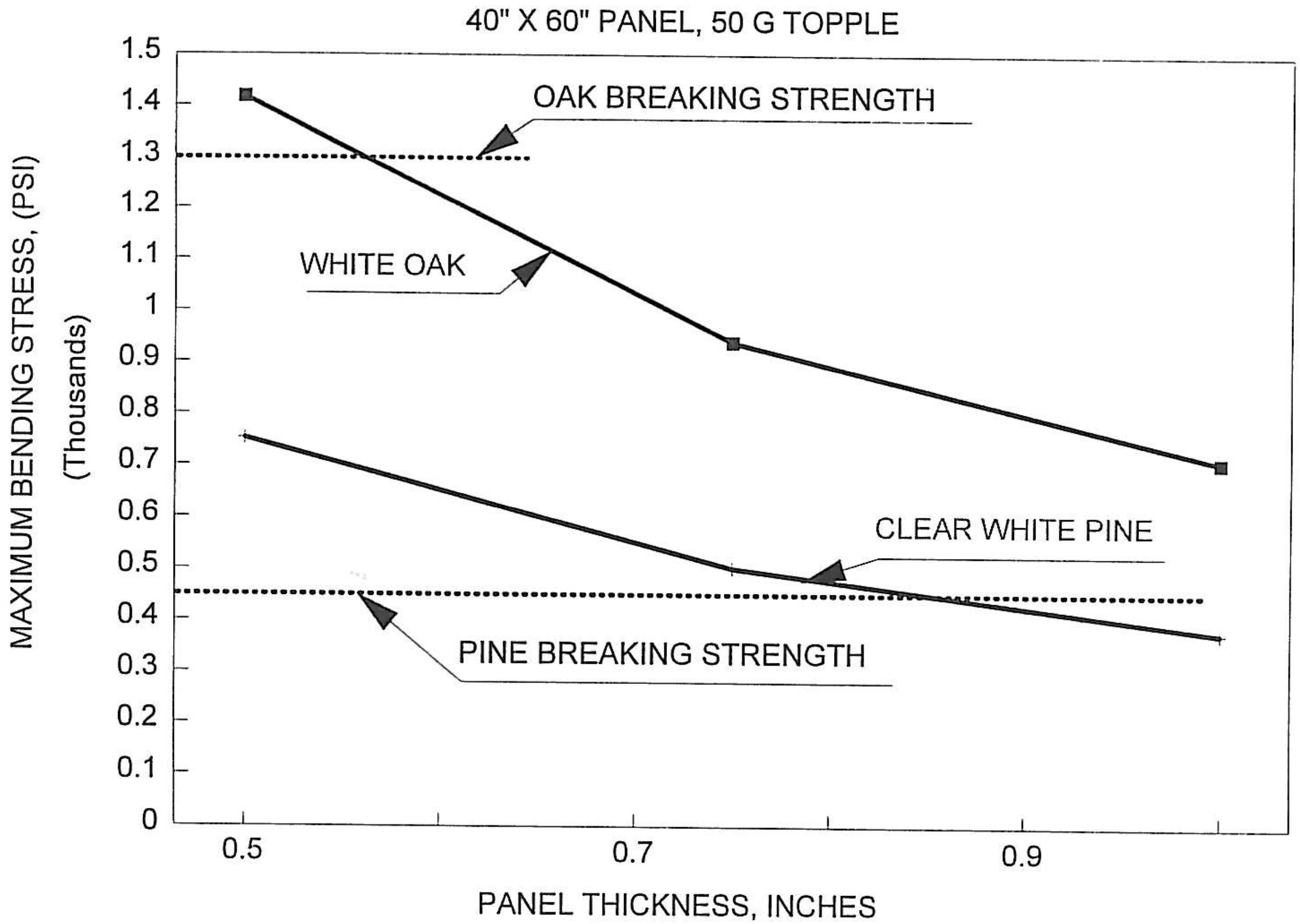
.20

40" X 60", 1" THICK WHITE OAK PANEL, 50 G TOPPLE



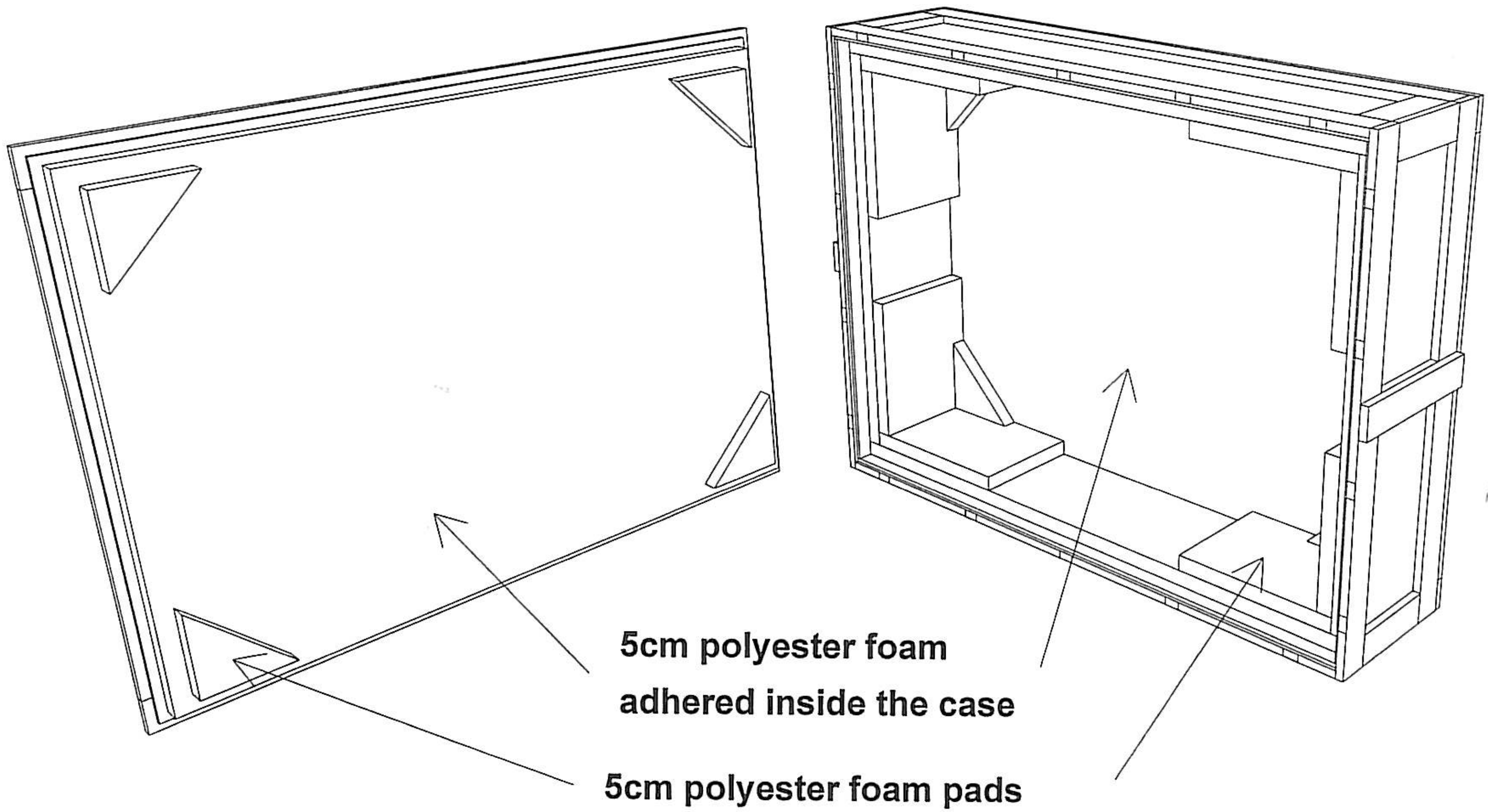

WHITE OAK BENDING STRESSES, 50 G TOPPLE IMPACT
MAXIMUM BENDING STRESSES, PSI
(Thousands)
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
BREAKING STRENGTH, (TANG. DIR.)
1/2" THICK
3/4" THICK
1" THICK
0
20
40
CROSSED-GRAINED WIDTH, INCHES

2'2

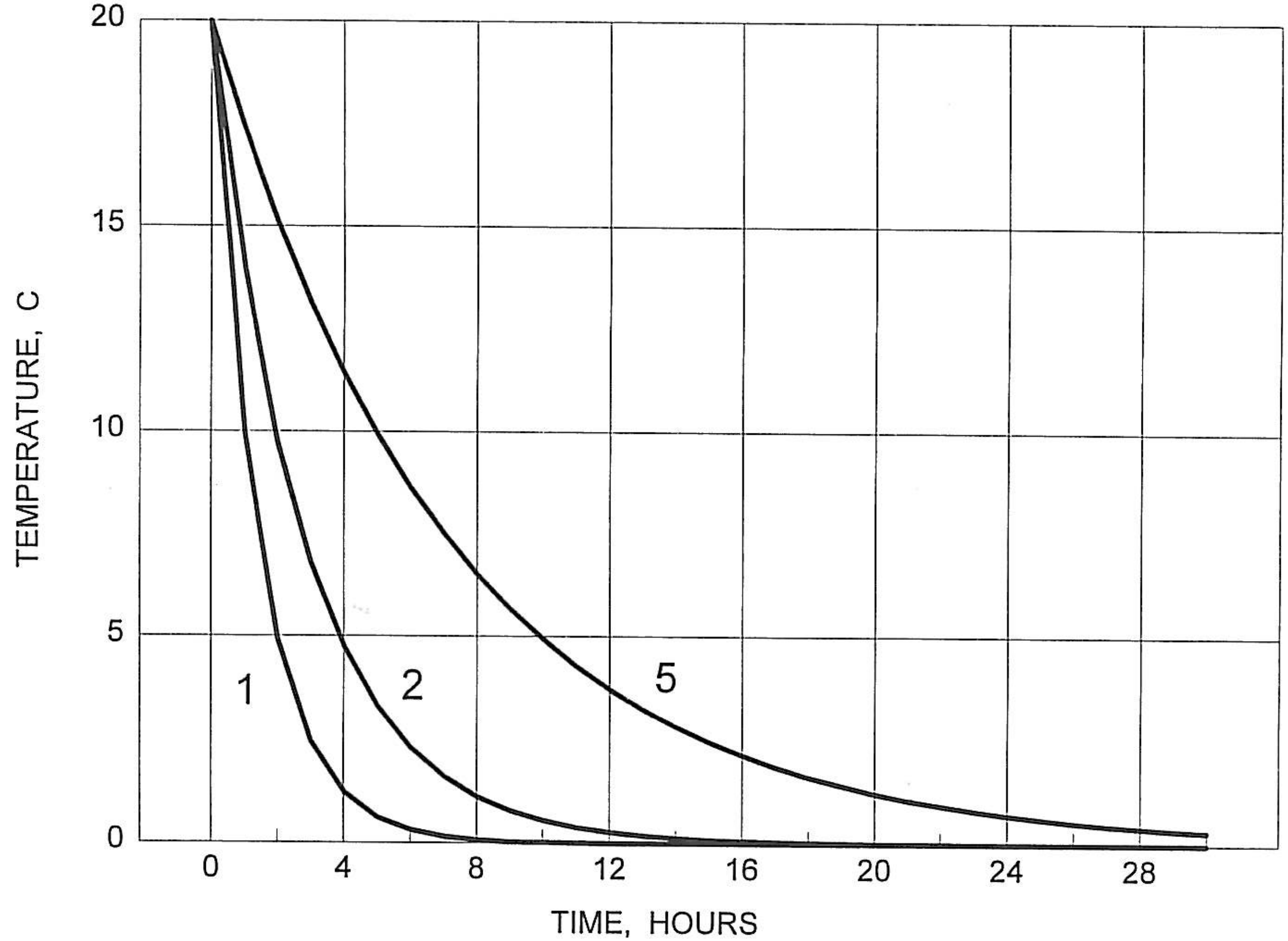

40" X 60" PANEL, 50 G TOPPLE
OAK BREAKING STRENGTH
WHITE OAK
CLEAR WHITE PINE
PINE BREAKING STRENGTH
MAXIMUM BENDING STRESS, (PSI)
(Thousands)
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
0.7
0.9
PANEL THICKNESS, INCHES

Painting Case

(Double Case Design)



EXAMPLES OF 1, 2, AND 5 HOUR HALF-TIME RESPONSES



DYNAMIC CUSHIONING CURVE

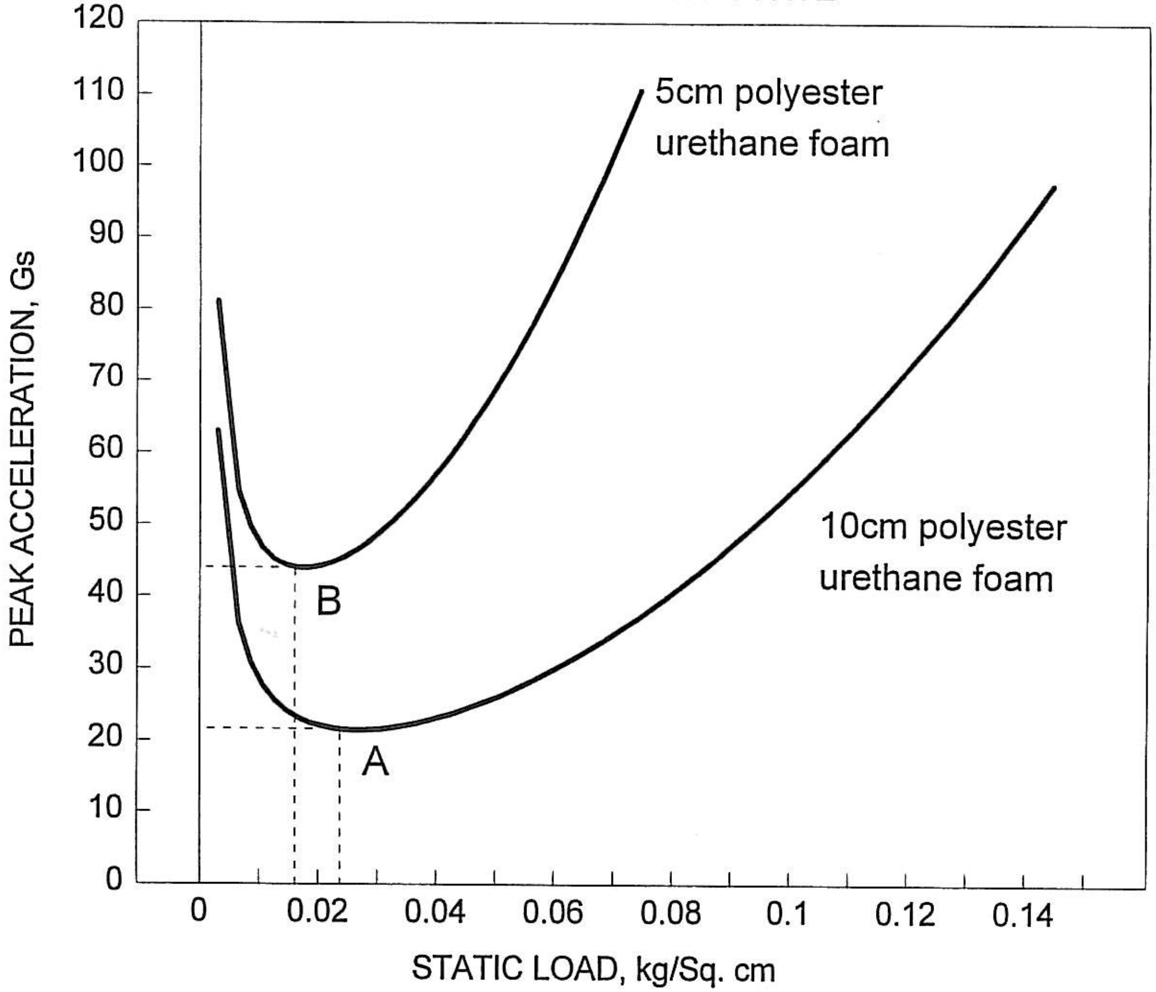


Figure Captions

Figure 1. Moisture coefficients of expansion for white oak in the tangential direction, hide glue, gesso, and 15-year-old flake white oil paint versus RH. The radial direction coefficient for the white oak is approximately one-half of the tangential and the longitudinal direction coefficient is about one tenth of the tangential direction. The swelling rate is the lowest in the mid-range RH levels.

Figure 2. Measured yield and breaking strains of tangential direction white oak versus RH, measured using an axial tensile test.

Figure 3. Calculated reversible RH range of fully restrained, tangentially cut white oak versus ambient RH. A yield value of 0.004 was used as the limiting criteria in both tension and compression. The values of the dotted lines are for wood that has been fully equilibrated to, and is stress free, at 50% RH.

Figure 4. Calculated reversible RH range of fully restrained, tangentially cut white oak versus ambient RH. A yield value of 0.004 was used as the limiting criteria in both tension and compression. The wood has been fully equilibrated to 70% RH. The allowable RH range has been severely reduced.

Figure 5. Calculated reversible RH range of fully restrained, tangentially cut white oak versus ambient RH. A yield value of 0.004 was used as the limiting criteria in both tension and compression. The wood has been fully equilibrated to 36% RH. The allowable RH range is still fairly large but it has been shifted to lower values.

Figure 6. Calculated reversible RH range of fully restrained, new, tangentially cut white oak versus ambient RH compared to 100-year-old oak. A yield value of 0.004 was used as the limiting criteria in both tension and compression. It is assumed that the wood has been fully equilibrated to 50% RH.

Figure 7. Calculated reversible RH range of fully restrained, 100-year-old, radially cut white oak versus ambient RH compared to 100 year old tangentially cut oak. A yield value of 0.004 was used as the limiting criteria in both tension and compression. It is assumed that the wood has been fully equilibrated to 50% RH. The significant increase of the allowable RH in the radial

direction demonstrates the advantages of preparing panel supports in that direction.

Figure 8. Calculated reversible RH range of fully restrained, 100 year old, radially cut white oak versus ambient RH compared to 100 year old tangentially cut oak. A yield value of 0.004 was used as the limiting criteria in both tension and compression. It is assumed that the wood has been fully equilibrated to 70% RH. The significant increase of the allowable RH in the radial direction demonstrates the advantages of preparing panel supports in that direction. This is particularly important in the case of panels equilibrated to high RH levels.

Figure 9. Calculated strains of gesso and flake white oil paint applied to an unrestrained, tangentially cut white oak panel versus RH. The panel painting is assumed to be equilibrated to 50% RH. Both the gesso and paint have fairly large allowable RH fluctuations even in the tangential direction of the wood.

Figure 10. Calculated strains of gesso and flake white oil paint applied to an unrestrained, tangentially cut white oak panel versus RH. The panel painting is assumed to be equilibrated to 64% RH. The paint still has a fairly large allowable RH fluctuation even on the tangentially cut wood, but the gesso is now confined to a more restricted RH range.

Figure 11. Calculated strains of gesso and flake white oil paint applied to an unrestrained, tangentially cut white oak panel versus RH. The panel painting is assumed to be equilibrated to 70% RH. Both the paint and gesso are now confined to a very restricted RH range in the tangential direction. This painting would be at serious risk if subjected to low RH levels.

Figure 12. Calculated strains of gesso and flake white oil paint applied to an unrestrained, tangentially cut white oak panel versus RH. The panel painting is assumed to be equilibrated to 36% RH. Both the paint and gesso have large allowable fluctuations of RH even in the tangential direction. This painting would not be at risk unless it is subjected to RH levels above 55%.

Figure 13. Calculated strains of gesso and flake white oil paint applied to unrestrained, radially and tangentially cut white oak panels versus RH. The panel paintings are assumed to be equilibrated to 50% RH. Both the paint and gesso have large

allowable fluctuations of RH even in the tangential direction but the radial direction shows a significant increase in the allowable fluctuations over the tangential cut.

Figure 14. Calculated strains of gesso and flake white oil paint applied to unrestrained, radially and tangentially cut white oak panels versus RH. The panel paintings are assumed to be equilibrated to 70% RH. Both the paint and gesso have very small allowable fluctuations of RH in the tangential direction but the radial direction shows a significant increase in the allowable fluctuations over the tangential. Where the tangentially cut panel is at risk when equilibrated to high RH, the radially cut panel can still sustain large RH fluctuations.

Figure 15. Moisture coefficients of expansion versus RH for oil, alkyd, and acrylic paints. The dimensional responses of the alkyd and acrylic paints are substantially lower than the oil paint.

Figure 16. Calculated temperature related strains of flake white oil paint when applied to white oak and copper. The paint strains in the longitudinal direction are the highest and failure can most likely occur when the temperature drops below the glass transition temperature, T_G. This type of failure results in cracks in the oil paint perpendicular to the grain of the wood.

Figure 17. Calculated temperature-related strains of gesso when applied to white oak. The gesso strains in the longitudinal (tensile) and cross-grained (compressive) directions are never very high and failure is not likely to occur even if the temperature drops significantly.

Figure 18. Approximate loading that occurs to a panel painting subjected to a 50 G topple accident. In this case, it is assumed that the panel is supported only along the two parallel to grain directions. It is always better to support the panel continuously around the edges.

Figure 19. Shear, in pounds, for a one inch wide strip of a one inch thick, 40" x 60" panel subjected to a 50 G topple accident.

Figure 20. Bending moment diagram for a one inch wide strip of a one inch thick, 40" x 60" panel subjected to a 50 G topple accident. The bending moments of panels subjected to topples can be quite high.

Figure 21. Distribution of the calculated bending stresses for a one inch wide strip of a one-inch thick, 40" x 60" panel subjected to a 50 G topple accident. The bending stresses of panels subjected to topples can be quite high and in this case they reach about one-half the breaking stress of oak in the tangential direction. Thinner panels are at even greater risk.

Figure 22. Calculated maximum bending stresses for white oak panels of different thicknesses and sizes when subjected to 50 G topple accidents. These stresses assume that the panels are supported only on the two parallel-to-grain edges.

Figure 23. Calculated maximum bending stresses for 40" x 60" white oak and pine panels subjected to 50 G topple accidents versus panel thickness. These stresses assume that the panels are supported only on the two parallel-to-grain edges. Even though the pine is a lighter wood, its substantially lower strength puts panels made from this wood at serious risk in the event of a topple.

Figure 24. Interior view of an outer packing case of a double case packing system.

Figure 25. Thermal half-times for three different case designs. The cases was initially conditioned at 20°C and placed in a 0°C environment. The half times shown are 1 hour, 2 hours, and 5 hours. Even for a well insulated case such as the 5 hour half-time example, there is not a lot of time available before the case equilibrates to a new temperature.

Figure 26. Dynamic cushioning curves for two thicknesses of polyester urethane foam. The curves show the distinct advantage of using the thicker material.

Endnotes

1. *Wood Handbook: Wood as an Engineering Material*, USDA Agricultural Handbook No. 72 (Madison: Forest Products Laboratory, 1987), 3-12.

2. Mecklenburg, M.F., C.S. Tumosa, and D. Erhardt, "Structural Response of Wood Panel Paintings to Changes in Ambient Relative Humidity," *Proceedings of the Painted Wood Symposium*, Williamsburg, Va. (Los Angeles: Getty Conservation Institute, 1994), (in press).

3. 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, 1995) (in press).

4.Weaver, W. and J.M. Gere, *Matrix Analysis of Framed Structures*, Second Edition, (New York: Van Nostrand, 1965), 115-117.

5. 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*, ed. M.F. Mecklenburg (Washington: National Gallery of Art, 1991), 187-188.

6. Saunders. D., "Temperature and Relative Humidity Conditions Encountered in Transportation," *Art in Transit: Studies in the Transport of Paintings*, ed. M.F. Mecklenburg (Washington: National Gallery of Art, 1991), 299-310.

7. Ostrem, F.E, and W.D. Godshall, *An Assessment of the Common Carrier Shipping Environment*, USDA General Technical Report No. 22, (Madison: Forest Products Laboratory, 1979).

8. Ostrem, F.E. and B. Libovicz, *A Survey of Environmental Conditions Incident to the Transportation of Materials*, GARD Report No. 1512-1 (Niles, Illinois: General American Research Division, 1971).

9. Richard, M., "Control of Temperature and Relative Humidity in Packing Cases," *Art in Transit: Studies in the Transport of Paintings*, ed. M.F. Mecklenburg (Washington: National Gallery of Art, 1991), 279-398.

10. Marcon, P., "Shock, Vibration, and the Shipping Environment," *Art in Transit: Studies in the Transport of Paintings*, ed. M.F. Mecklenburg (Washington: National Gallery of Art, 1991), 123.

11. *Military Standardization Handbook, Package Cushioning Design*, U. S. Department of Defense Handbook No. MIL-HDBK-304B (Washington: Department of Defense, 1978), 9.

12. Ostrem, F.E, and W.D. Godshall 1979, 29.

13. Marcon, P., "Shock, Vibration, and Protective Package Design," *Art in Transit: Studies in the Transport of Paintings*, ed. M.F. Mecklenburg (Washington: National Gallery of Art, 1991) 112.

14. *Art in Transit: Studies in the Transport of Paintings*, ed. M.F. Mecklenburg (Washington: National Gallery of Art, 1991); Piechota, D, and G. Hansen, "The Care of Cultural Property in Transit: A Case Design for Traveling Exhibitions," *Technology and Conservation*, (Winter 1982) 32-46; *Art in Transport: Handbook for Packing and Transporting Paintings*, eds. M. Richard, M. F. Mecklenburg, and R. Merrill (Washington: National Gallery of Art, 1991); Stolow, N., *Conservation Standards for Works of Art in Transit and on Exhibition*, (Paris: UNESCO, 1979); Stolow, N., *Controlled Environments for Works of Art in Transit* (London: Butterworths, 1966); Stolow, N., *Conservation and Exhibition: Packing, Transport, Storage, and Environmental Considerations* (London: Butterworths, 1987)

15. *Art in Transport: Handbook for Packing and Transporting Paintings*, eds. M. Richard, M. F. Mecklenburg, and R. Merrill (Washington: National Gallery of Art, 1991) 1-4.

16. Richard, M., "Control of Temperature and Relative Humidity in Packing Cases," Art in Transit: Studies in the Transport of Paintings, ed. M. F. Mecklenburg (Washington: National Gallery of Art, 1991), 279-297.

17. Military Standardization Handbook.

18. Piechota, D., and G. Hansen, "The Care of Cultural Property in Transit: A Case Design for Traveling Exhibitions," *Technology and Conservation*, (Winter 1982) 32-46; Richard, M., "Foam Cushioning Materials: Techniques for their Proper Use," *Art in Transit: Studies in the Transport of Paintings*, ed. M.F.

Mecklenburg (Washington: National Gallery of Art, 1991) 269-278.

19. Hackney, S., "The Dimensional Stability of Paintings in Transit," *Preprints of the ICOM Committee for Conservation*, 8th Triennial Meeting, Sydney, Australia (Los Angeles: Getty Conservation Institute, 1987), 597-600.