

Technical Considerations for the Transport of Panel Paintings

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OVER THE YEARS, panel paintings have suffered damage from a wide range of causes—accidents, natural catastrophes, improper handling, dramatic environmental changes, and misguided conservation treatments. Once damaged, panel paintings can be difficult to repair. Due to this risk, many museum professionals and collectors are hesitant to transport panels unless absolutely necessary. Some institutions have even adopted policies that forbid their loan. In the United States, panel paintings are not indemnified by the Arts and Artifacts Indemnity program, 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 transported or loaned to other institutions. Even the most ideal packing case cannot protect a painting in very 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 crucial aspect of the loan process. This examination is especially useful 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 possible loan: relative humidity (RH), temperature, shock, and vibration. The overall safety of a painting during transit is gauged by any expected response to these conditions; this response must then be evaluated in terms of what the painting will be 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 would be able to provide the protection needed to ensure safe transport. If this is the particular case, transport of the painting is not recommended. However, if the painting can sustain moderate fluctuations in RH and temperature (factors easily controlled during transport), and the panel can safely resist the anticipated levels of shock and vibration, then the panel is a more likely candidate for loan.

There are several things to consider about the painting itself when contemplating a possible loan, including the following: the size of the painting, its materials and construction, the condition of the design (paint and ground) layers, and the condition of the wood supports. Small

paintings usually present fewer difficulties than large paintings, since they are lightweight, easily moved, and frequently made of a single piece of wood. Large panels are heavier and more subject to bending moments during handling operations, because of their own weight and width. Bending or flexing can also result from impact and vibration, which will increase the stress throughout the panel and have particularly adverse effects on poorly glued joints and existing cracks in the wood.

Considerable anecdotal evidence shows 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, probably only because their environment has also remained relatively stable. If subjected to a different environment, the same paintings might rapidly develop problems.

Until recently, the only way to verify and observe this effect was to change the environment to see what occurs. Obviously, this test can prove destructive: damage has been reported when paintings have been moved from relatively damp churches to drier and better-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 advisability 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 have often been added to the reverse of panels, either to reinforce the panels or to reduce warping. Usually 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 cross-grain direction of the panel. This restraint can lead to excessive stresses (either compressive or tensile) if the RH or temperature significantly deviates from the conditions present when the battens or cradle were applied.

The issue, then, lies in assessing the effects of changes in temperature and RH, as well as the events of impact and vibration on panel paintings, and recognizing the limitations of controlling these factors during transport. The typically short duration of transport usually precludes chemical damage to paintings, but occasionally biological problems, such as mold growth, arise. For the most part, determining the risks inherent to the transport of a panel painting is an engineering problem that requires a knowledge of the mechanics of artists' materials. This particular discipline is an important part of the authors' current research, and a summary of materials' behavior is a significant focus of this article.

RH and Moisture Content

All 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 and paint layers, and varnishes. When these materials are unrestrained, changes in their moisture content result in expansion and contraction. It should be noted that panel materials respond differently to the gain and loss of water vapor. Oil paints and gessos show relatively little dimensional response to moisture, for example, as compared to pure hide glue or to wood cut in the tangential direction. Wood cut in the radial direction

shows about one-half of the dimensional response of wood cut in the tangential direction (U.S. Department of Agriculture 1987). The dimensional response of wood in the parallel-to-grain direction is 0.05–0.08% of that in the tangential direction. In the tangential direction, some woods (e.g., cottonwood [*Populus* spp.] and white oak [*Quercus* spp.]) can swell as much as 7% when subjected to changes from 5% to 95% RH. Other woods (e.g., spruce [*Picea* spp.] 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 is cited in units of strain per percentage RH (mm/mm/% RH). It is of critical importance to recognize that free-swelling dimensional changes are stress-free strains. It is only when under restraint that hygroscopic materials subjected to RH changes develop stress-associated strains. These are called mechanical strains, in the truest sense of the word.

A coefficient of expansion is often considered to be a constant; however, the moisture coefficients for these materials are not only variable but highly nonlinear as well. In Figure 1, the moisture coefficients for four materials are plotted versus RH. These materials are a fifteen-year-old flake white oil paint, gesso with a pigment volume concentration 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 of any wood) would factor 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 40–60% 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 most of the problems associated with environmental changes. Wood in the longitudinal direction responds much less to the environment than do the paint and gesso, which essentially means that different responses are occurring to the painting's layers in the two perpendicular directions of the panel. The responses of the materials to RH can be studied either 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 RH range 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; therefore, if the measurements are taken at 25–75% RH, the increasing and decreasing paths are almost the same.

A structural problem arises when either full or partial restraint is present. This restraint can result from defects such as knots in the wood, cross-grain construction (often found in furniture), or battens that are 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. In the case of a fully restrained material (white oak in the tangential direction, for example), some changes in RH can occur without ill effect to the wood (Mecklenburg, Tumosa, and Erhardt 1998). Organic materials (i.e., wood, paints, glue, gesso) have *yield points*, which are levels of strain

below full reversibility and above permanent deformation. Measured by an axial mechanical test, the initial yield points for woods, paints, and glues are approximately 0.004. These materials can, however, harden under strain, a process that creates substantial increases in their yield points. For a brittle gesso found in a traditional panel painting, the yield point is approximately 0.0025. If gessos are richer in glue, both their yield points and their strains at failure increase significantly. The magnitudes of yield points do not appear to be appreciably affected by RH, but generally the strains to breaking will increase parallel to 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 axial testing would indicate. In this article, 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 to determine the maximum allowable RH fluctuations in panels. This approach is a fairly conservative one to assessing the effects of RH and temperature on panel paintings, and it 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 the process of degradation usually reduces strength. When the magnitude of the failure strains approaches that of the yield strains, the materials of the panel painting are considered fragile and probably difficult to handle, as they will break in an elastic region rather than plastically deform.

Response of restrained wood to RH: Tangential direction

Research 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 (Mecklenburg, Tumosa, and McCormick-Goodhart 1995). Equation 1 shows how these mechanical strains can be calculated as a function of RH. Using this equation, the strain change ($\Delta\Sigma$) for any RH change can be calculated by integrating from one RH point to another as

$$\Delta\Sigma = \int \partial dRH \quad (1)$$

where: $\partial = d\Sigma/dRH$, 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 a low RH and increase dramatically as RH increases.

With the information from Figures 1 and 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 is a hypothetical example of the worst condition possible; fortunately, few objects in collections are actually fully restrained. The plotted results of calculations made using 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 to approximately 33% RH would result in tensile yielding of the wood. Further decreasing, to 21% RH, could cause the wood to crack. Increasing the RH from 50% to approximately 64% would cause the wood to begin

Figure 1

Moisture coefficients of expansion versus RH for four materials: white oak in the tangential direction, hide glue, gesso, and fifteen-year-old flake white oil paint. The radial-direction coefficient for white oak is approximately one-half of the tangential, and the longitudinal-direction coefficient is about one-tenth of the tangential. The swelling rate is the lowest in the midrange RH levels.

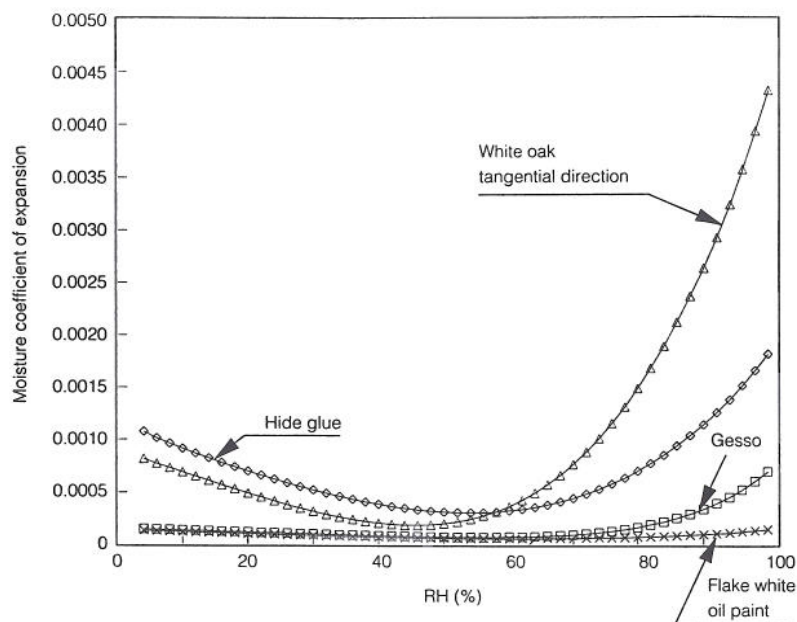
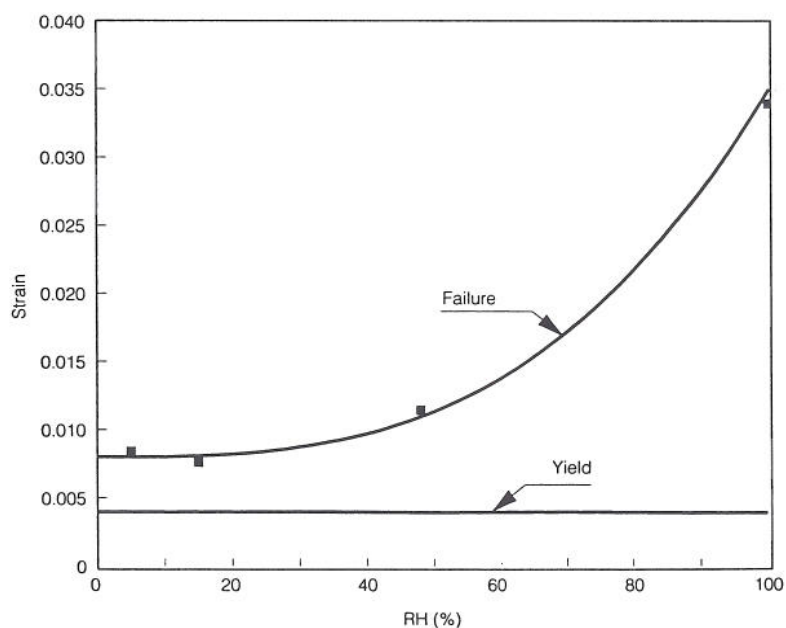


Figure 2

Measured yield and breaking strains of tangential-direction white oak versus RH (axial tensile test).



compression yielding. As long as the RH remains between approximately 33% and 64%, the wood can respond dimensionally without its structure being altered. However, if the RH increases above approximately 64%, *compression set* may occur, which is a permanent deformation of the wood. Compression set also re-initializes the wood to a new, higher RH environment, causing the wood to behave like one acclimated to a higher RH.

The plots in Figure 4 were obtained by recalculating Equation 1 for the fully restrained white oak panel, now acclimated to 70% RH (the circumstances under which the panel acclimated to a higher ambient RH are irrelevant—it does not matter whether the painting has always been maintained at 70% or whether it was temporarily stored in a damp location).

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 criterion in both tension and compression. The values of the dotted lines are for stress-free wood that has been fully equilibrated to 50% RH.

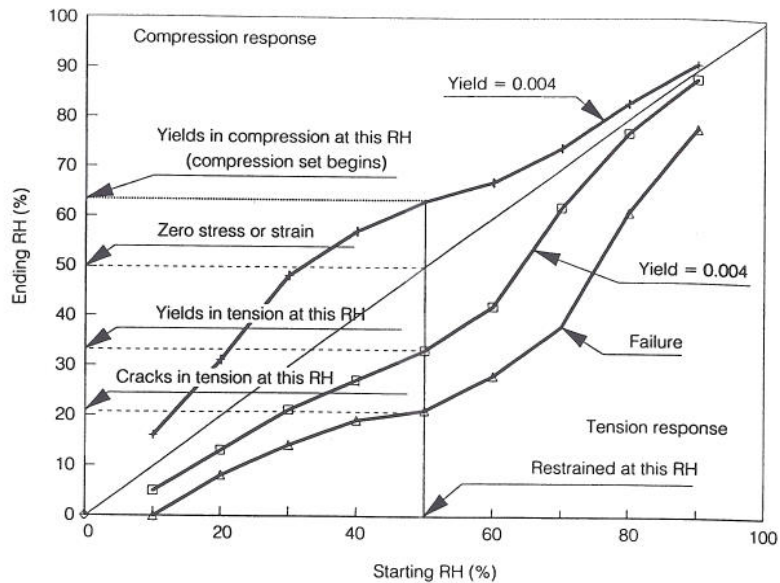
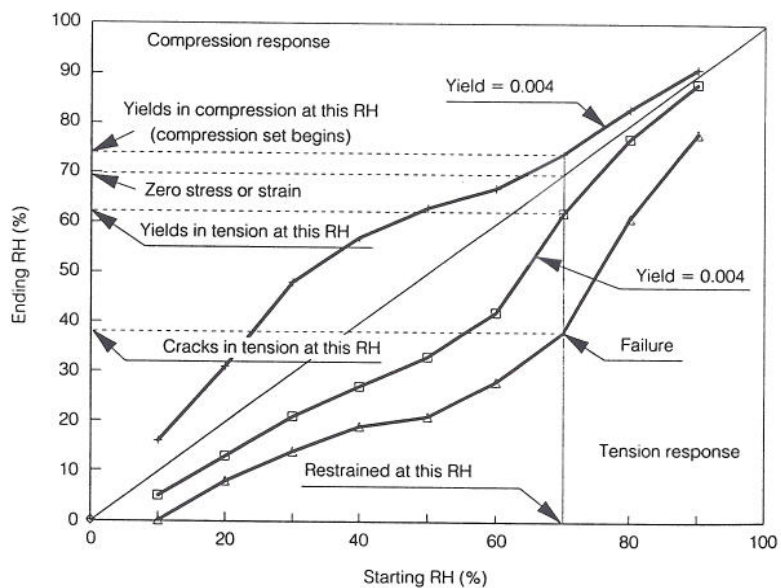


Figure 4

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 criterion in both tension and compression. The wood has been fully equilibrated to 70% RH. The allowable RH range has been severely reduced in comparison to wood equilibrated to 50% RH.

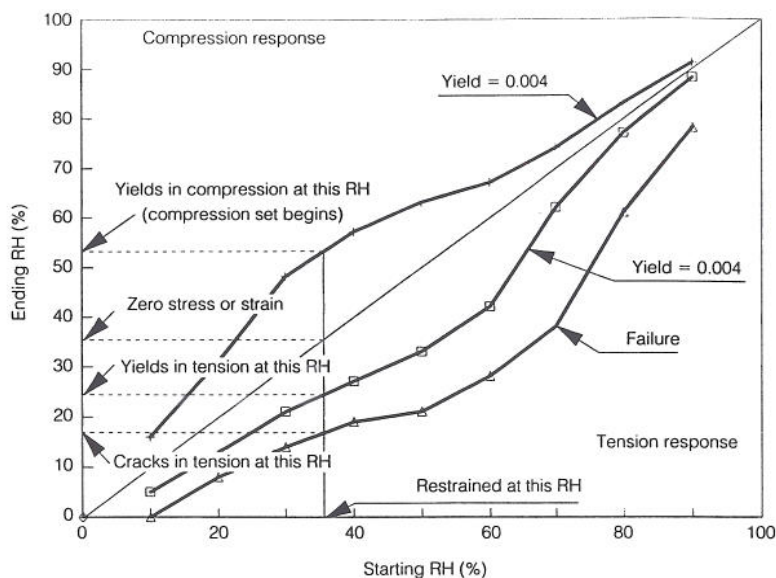


A problem becomes apparent when desiccation of the panel is attempted. A drop from 70% to 62% RH causes tensile yielding, and a drop to approximately 38% RH can cause cracking of the wood. Increasing the RH to approximately 74% induces yielding in compression. The panel cannot tolerate the much larger 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, some panels have been treated with water or large amounts of water vapor in an attempt to flatten them. Battens or cradles

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 criterion in both tension and compression. The wood has been fully equilibrated to 36% RH. The allowable RH range is still fairly broad, but it has been shifted to lower values.



were often attached to the reverse while a panel was still wet. The effect of this treatment was to restrain the panel while it was still acclimated at an extremely high RH. As the panel dries, the adhesive hardens, and the point of full restraint could easily have 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 in 1966), the simple act of drying would be almost certain to cause wood-support damage unless all of the restraint were removed before drying.

Figure 5 shows the results of RH fluctuations on a typical white oak panel restrained and equilibrated at 36% RH. In this case the panel will yield in compression at approximately 53% RH and in tension at 25% RH. The effect is to simply ensure that the reversible environment for the painting support panels is changed 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 the same yield criterion (0.004) is used, 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, so their allowable fluctuations will be significantly greater, even in the tangential grain direction.

Response of restrained wood to RH: 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 than if a primary direction were tangential. Figure 7 shows a comparison of the

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 criterion in both tension and compression. It is assumed that the wood has been fully equilibrated to 50% RH.

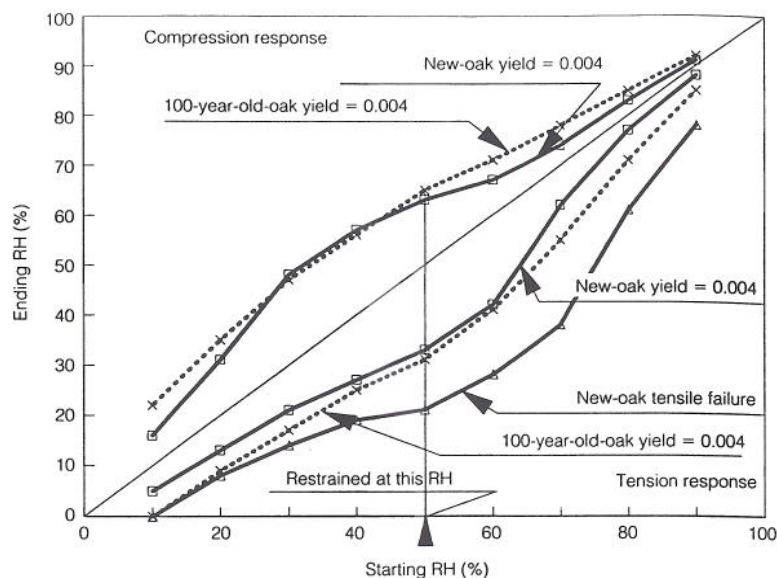
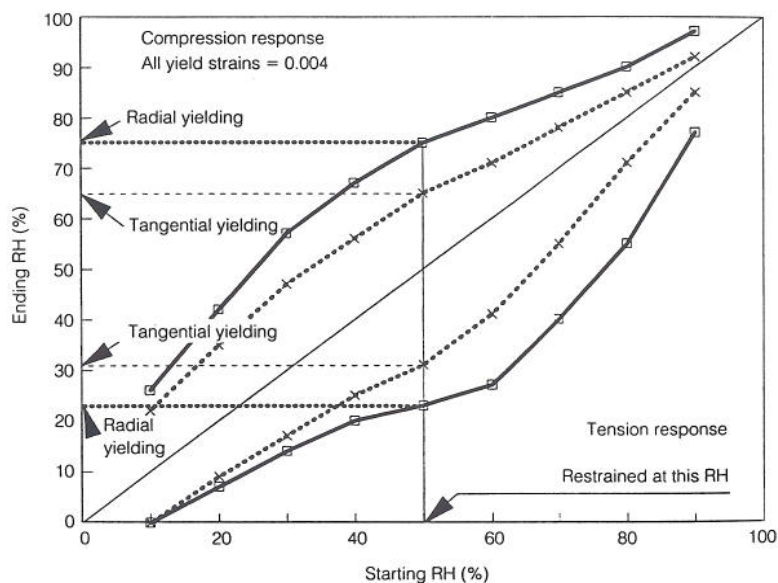


Figure 7

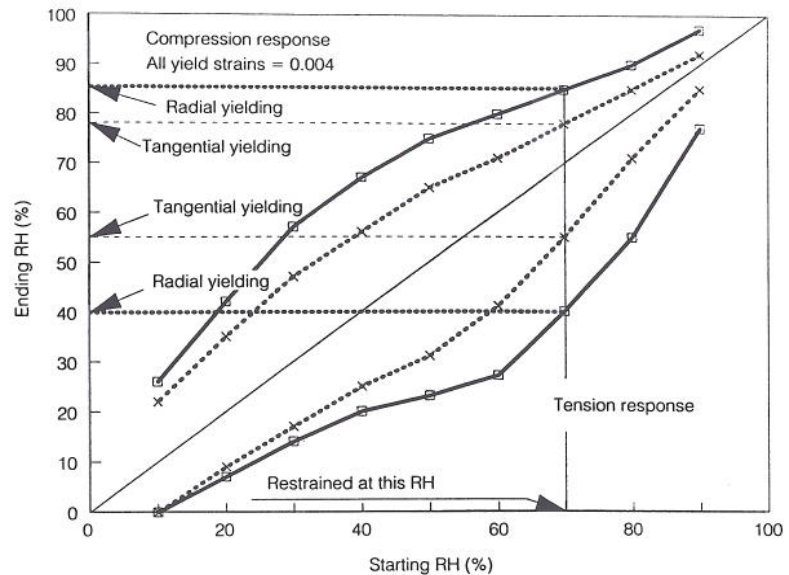
Calculated reversible RH range of fully restrained, 100-year-old, radially cut white oak versus ambient RH, compared to 100-year-old tangentially cut oak. A yield value of 0.004 was used as the limiting criterion in both tension and compression. It is assumed that the wood has been fully equilibrated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



calculated RH changes required to reach yield in both the radial and tangential directions for 100-year-old white oak. If it is assumed that the panels had been restrained at 50% RH, the RH change required to cause yielding in tension is a decrease to 31% in the tangential direction and to 23% in the radial direction. An increase in RH to 65% would cause compressive yielding in the tangential direction; an increase in RH to 75% would cause compressive yielding in the radial direction. Because of its substantial increase in the allowable changes in RH, radial cutting is an important consideration for woods that are to be 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 would be capable of sustaining a drop to

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 criterion in both tension and compression. It is assumed that the wood has been fully equilibrated to 70% RH. The significant increase of allowable RH in the radial direction demonstrates the advantages of preparing panel supports in that direction. This consideration is particularly important in the case of panels equilibrated to high RH levels.



40% RH before yielding in tension, and capable of sustaining an increase to 86% RH before compression set begins. In the tangential direction, the panel is restricted to a range of 55–79% RH. The implications of these results are clear: panels cut in the tangential direction present a significantly greater risk of movement, particularly if acclimated to a high RH. In contrast, restrained panels cut in the radial direction are low risk, even if they have been acclimated to 70% RH.

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

Response of the design layers to RH

Until now, only the wooden panel has been discussed. However, 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 panels that are both restrained and unrestrained (i.e., without battens, cradles, or framing techniques).

The primary difference between the two materials is that paint will be assumed to yield at a strain of 0.004 and gesso at a strain of about 0.0025. Therefore, while gesso and paint do have similar dimensional responses to changes in RH, the gesso will yield sooner to those changes than will the paint. As was seen with the wood, once 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. Since not all paintings have gesso layers, the following comments will

distinguish between the effect of RH on panels having both gesso and paint layers and the effect on panels having paint directly applied to the wood.

Unrestrained wooden panels in the tangential direction 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 those of the wood, then RH variations will induce no stresses in the attached layers. If the swelling coefficients differ, mechanical stresses and strains will develop 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, however, the wood is much more responsive to RH variations than the gesso or paint. The responsiveness of the wood 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, provided 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 would then simplify to Equation 1.) Equation 2 is

$$\Delta \Sigma_p = [(1 - \int \alpha_s dRH) - (1 - \int \alpha_p dRH)] / (1 - \int \alpha_s dRH) \quad (2)$$

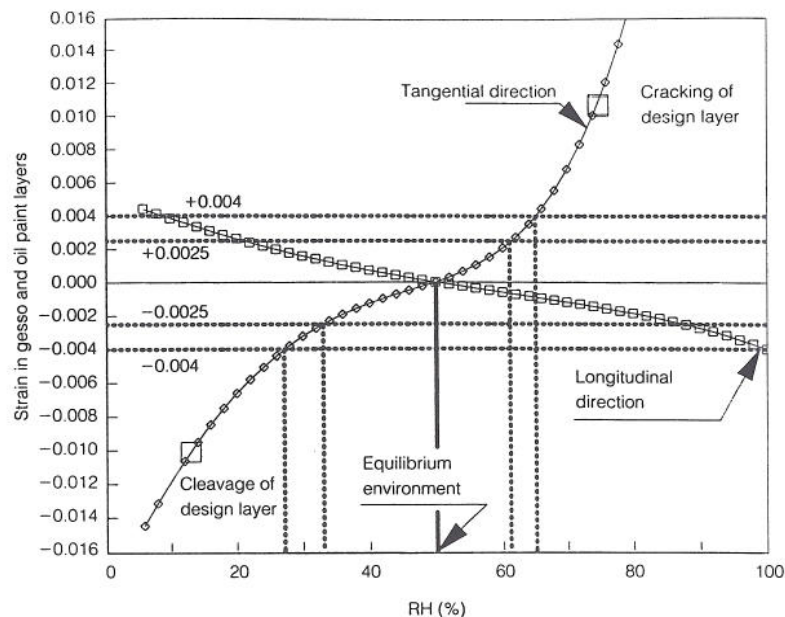
where: α_s is the swelling coefficient of the substrate, which is thick relative to any attached layers; and α_p is the swelling coefficient of the coatings, either flake white paint or gesso. In our examples white oak is the substrate.

Response of the design layers to RH: Panels cut in the tangential direction

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 wooden 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 wooden 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—for the paint, the plot shows that it is possible to desiccate from 50% 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, not breaking). However, in the gesso (which yields at a lower strain), the range for acceptable RH is narrower. In this case, tensile yielding will occur at approximately 19% RH, and compressive yielding at approximately 83% RH. This indicates that fairly large RH variations can occur without yield in the design layer. However, it is well known that cracks do develop perpendicular to the grain of the wood, indicating that the stresses and strains are parallel to the grain. This study shows that these cracks do not usually occur as a result of moderate RH changes. Drops in temperature are more likely to cause these types of cracks, as will be discussed below.

Figure 9

Calculated strains in 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.



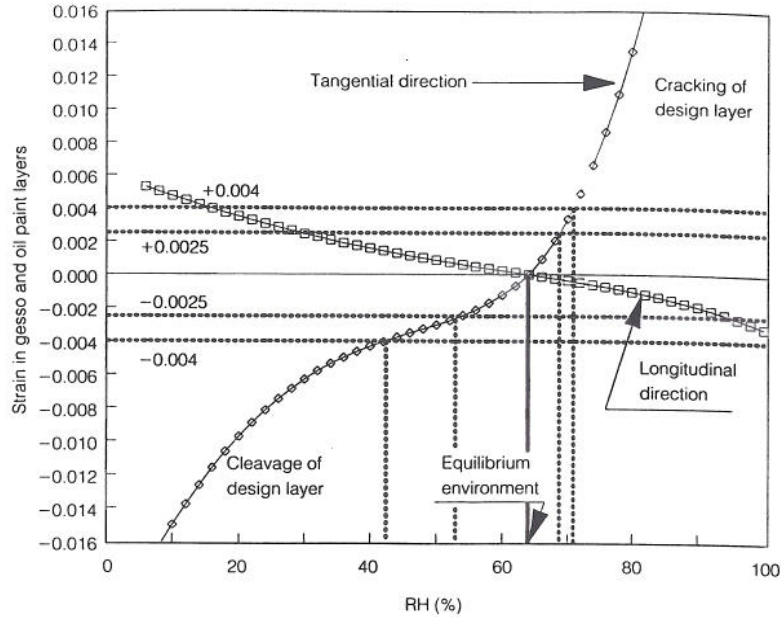
As it responds to the moisture changes, the wooden substrate significantly affects the mechanical strains in both the paint and the gesso layers. The strains of the design layers actually become compressive with desiccation, because the wood shrinks at a greater rate than either the paint or gesso—the gesso yields at 33% RH, and the paint yields at 27% RH. Further desiccation from the yield points causes permanent deformation in both layers. If the desiccation continues below 15% RH and the gesso ground is not firmly attached, crushing may occur, and cleavage ridges will develop parallel to the grain.

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

Diagrams similar to that in Figure 9 demonstrate the response of gesso and paint layers attached to the panel when they are equilibrated to RH levels other 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. Tensile yielding in the paint now occurs at about 43% RH (higher than when the painting was acclimated to 50% RH). At 53% RH the gesso yields in tension. A 14% variation (50–64% RH) in the equilibrium environment will have a major effect on the dimensional response of the panel. This panel is to some degree restricted to a narrower and higher environment, as compared to a panel equilibrated to 50% RH. If, however, the equilibrium environment is higher (e.g., about 70%), greater differences will 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 condi-

Figure 10

Calculated strains in 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.



tions 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 if subjected to the well-controlled environments found in many institutions. In addition, a smaller increase in RH, (6–8%), is needed to cause tensile yielding when compared to a panel equilibrated to 50% RH.

How realistic is the example above? At such a high RH level, there is a strong potential for biological attack that should be observed and noted. For a panel's RH to equilibrate to a high annual mean, RH levels during the more humid periods of the year must also be high. Evidence of

Figure 11

Calculated strains in 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 gesso and paint 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.

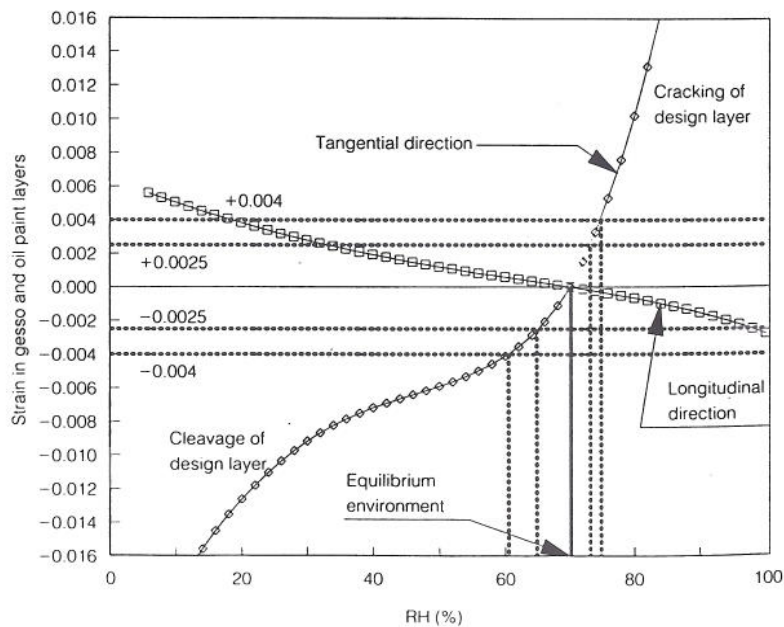
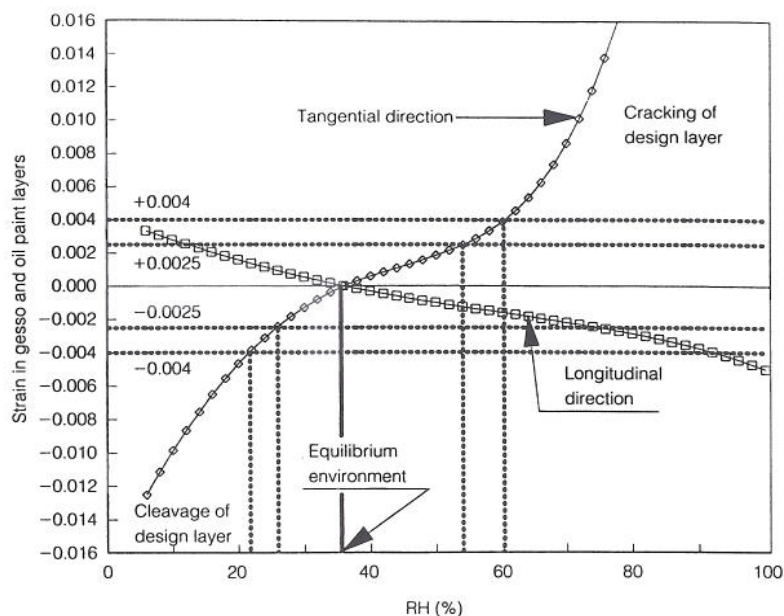


Figure 12

Calculated strains in 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 gesso and paint have large allowable fluctuations of RH, even in the tangential direction. This painting would not be at risk unless it were subjected to RH levels above 55%.



mold damage could be an important indication that a panel painting may have equilibrated to an excessively high humidity and therefore is 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 with a 14% downward shift in the equilibrium environment, only about a 6% downward shift in the RH is necessary to attain compressive yielding in both the gesso and the 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 for yielding in the gesso to occur, and to 22% RH for yielding in the paint to occur.

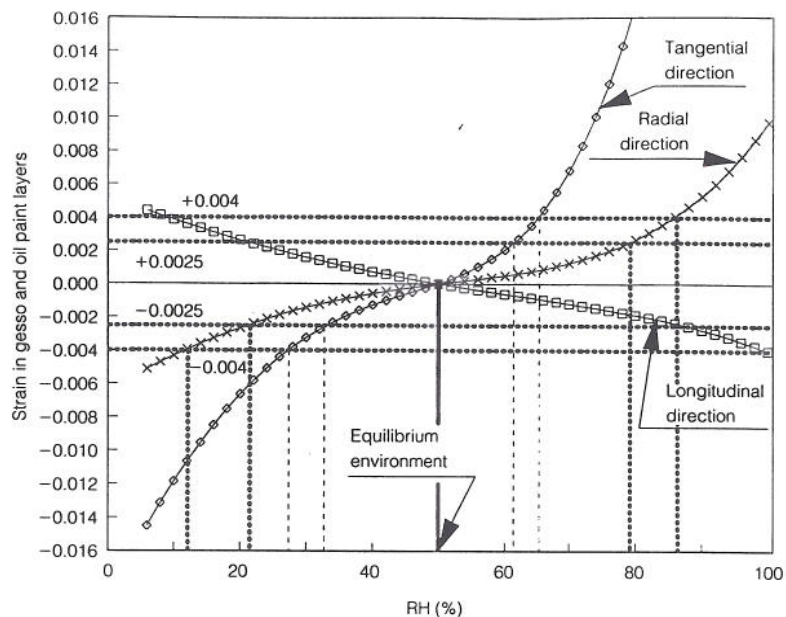
Response of the design layers to RH: Panels cut in the radial direction

Paintings executed on radially cut wooden panels are at reduced risk during transport, and the layers applied to such panels are far less likely to suffer RH-related damage. Figure 13 illustrates the different responses of the design layer to the unrestrained movement of white oak. In the longitudinal direction, there is little difference between tangentially and radially prepared panels, and the strains in the gesso and paint layers are similar to those shown in Figure 9. (As before, the assumed yield strains are 0.004 for the paint and 0.0025 for the gesso.)

In a panel cut in the radial direction and acclimated to 50% RH, gesso shows compressive yielding at 22% and shows tensile yielding at 79%. In a panel cut in the tangential direction, the gesso shows compressive yielding at 33% RH and tensile yielding at 63% RH. If there is no gesso layer, 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

Figure 13

Calculated strains in 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 gesso and paint 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.

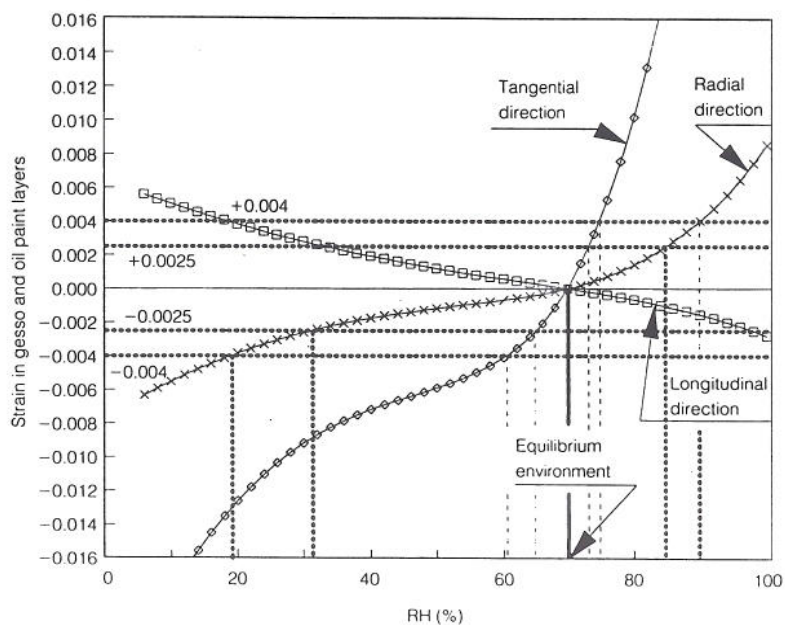


difference is that with desiccation, the paint and gesso experience compression in the cross-grain direction and tension in the longitudinal direction, while increases in humidity induce the opposite reaction. Both the wood and the design layers are more stable on a radially cut panel.

Of significant interest is the response of the design layers that have been applied to radially cut oak and equilibrated to a 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 equilibration to 50% RH, tensile yielding in the gesso occurs at 85% RH and in the paint at 90% RH. This is a sub-

Figure 14

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



stantial improvement over the strains that developed in the design layers that were applied to tangentially cut wood. Panels cut tangentially and equilibrated to a high RH are at serious risk if desiccated. Panels cut radially are at considerably less risk, even when desiccated and equilibrated to a high RH. For example, paintings on plywood panels that are made entirely of restrained, tangentially cut wood fare poorly when exposed to RH fluctuations, as compared to paintings on radially cut panels, whether restrained or not.

The equilibrium RH of a panel painting's environment establishes its risks for transport. Knowing the equilibrium RH allows for the development of environmental guidelines for both the transit case and the 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. In such instances a warped panel is often thinned, moistened on the reverse, and finally attached to battens or a cradle to forcibly hold the panel flat. As a result, considerable tensile stress can build up as the wood dries, since the battens or constricted cradles can restrict the return to warpage.

When panels are thinned, there are 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 (Weaver and Gere 1965:115-17). This thinning makes the panel prone to buckling when restrained. At a high RH, a panel with a locked-in cradle is subjected to high RH-induced compressive stresses in the spans between the cradle supports, and because of the cradle, such stresses are not uniform. They cause out-of-plane bending or buckling of thinned panels.

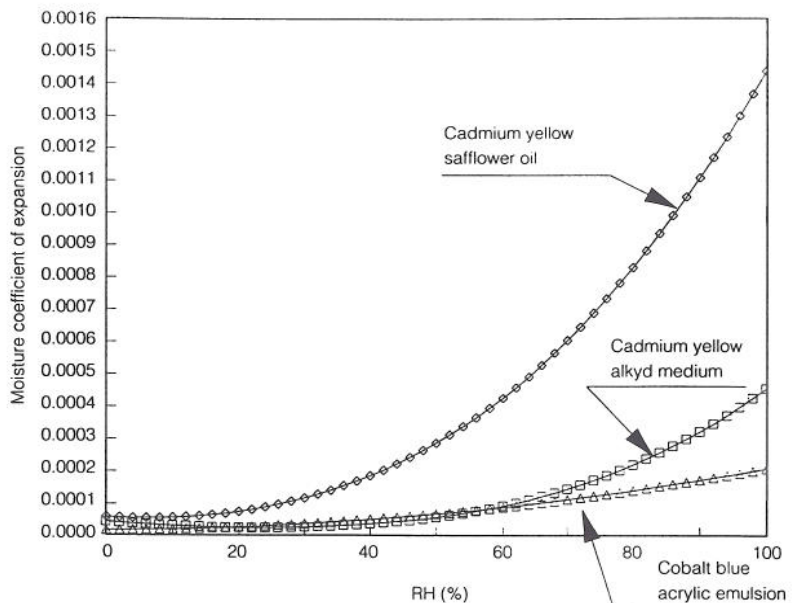
It is important to assess whether a panel's movement is restricted—an assessment that may be difficult in some cases. Panels with battens or cradles that have locked up by friction present higher risks for transport if they are cracked or if the panel has equilibrated to a very high RH environment (Mecklenburg and Tumosa 1991:187-88). In addition, research suggests that an unrestrained panel with a gesso layer equilibrated to a high-RH environment is at greater risk of damage upon desiccation than is a sound (free of cracks), restrained panel. This risk occurs because the gesso layer is subject to compression cleavage when an unrestrained panel contracts from desiccation. Almost all 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 the movement of such paintings is contemplated.

In contrast, oil paintings on copper supports seem to have fared well over the centuries. Research shows that oil paint responds only moderately to changes in RH, particularly if extremely high RH levels are avoided. Additionally, copper is dimensionally unresponsive to RH fluctuations. The combination of these two materials results in a painting that is durable with respect to changes in atmospheric moisture.

Contemporary panel paintings having wooden supports and either acrylic or alkyd design layers may also be analyzed in relation to the criteria discussed above. Figure 15 shows the coefficients for swelling of alkyd and acrylic emulsion paints compared to those of oil paint. All of these paints have dried for fifteen years or more under normal drying conditions. Both the alkyd and the acrylic emulsion paints are much less dimensionally responsive to moisture than is oil paint. When acrylic paints are

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 those of the oil paint.



applied to a wooden panel, RH changes have very little effect in the longitudinal direction of the wood. In the tangential direction, the movement of the paint is almost totally dictated by the movement of an unrestrained wooden panel. However, the RH change needed to develop yield in alkyd or acrylic paints will be approximately 2–3% less than the change needed for oil paint on wooden panels because the moisture coefficient of expansion of the oil paint is higher.

Control of transport RH

RH levels may also vary during transport, but fortunately this problem can be solved with proper packing. Since the RH levels in trucks depend largely on weather conditions, the RH inside even an air-conditioned truck may be very high on a hot, humid day. If the weather is very cold, the RH in the truck may be low because of the drying effects of the cargo-area heating system. At high altitudes, the RH in a heated and partially pressurized aircraft cargo space is always low—often as low as 10–15%. Panel paintings exposed to this extreme desiccation for the duration of an average flight could be damaged. This desiccation can be avoided if the painting is wrapped in a material that functions as a moisture barrier (wrapping of panel paintings is discussed further below).

Temperature Effects

The dimensional response of wooden 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 has RH. This precept holds true if one considers only the relative dimensional response of wood to temperature as compared to its response to moisture. It would take a change of several hundred degrees in temperature 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 they are usually exhibited or stored where temperature variations are relatively small. The problem, however, is not so much the response of the

Table 1 Thermal coefficients of expansion of selected painting materials

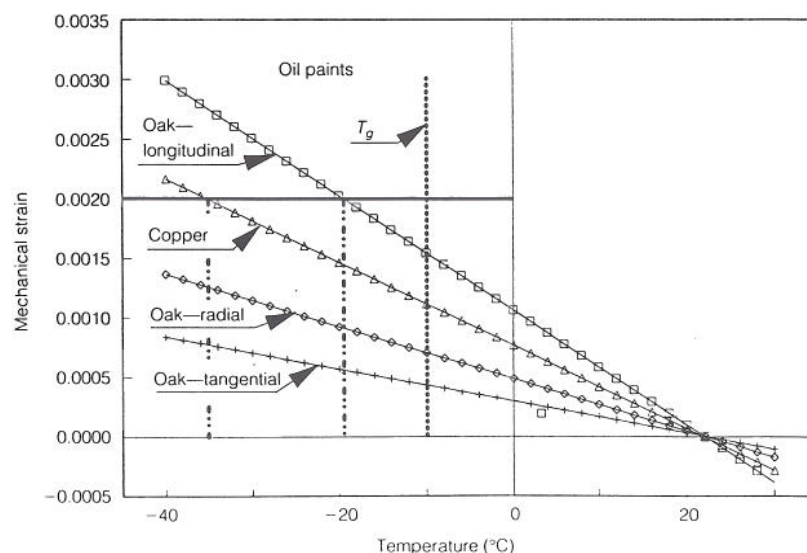
| Material | Thermal coefficient of expansion |
|------------------------|----------------------------------|
| White oak—longitudinal | 0.000038/°C |
| White oak—tangential | 0.000385/°C |
| White oak—radial | 0.00003/°C |
| Oil paint | 0.00052/°C |
| Gesso | 0.00002/°C |
| Hide glue | 0.000025/°C |
| Copper | 0.000017/°C |

wood as it is the response of the gesso and paint layers. Therefore, when the effects of temperature are considered, it is also necessary that the mechanical properties of the different paint media, as well as their dimensional responses, are understood. In the temperature ranges most likely to be encountered, the thermal coefficients of expansion for the materials found in panel paintings can easily be considered as constants. Some values for these materials are given in Table 1.

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 a constant RH, heating will desiccate materials somewhat, and cooling will increase their moisture content. The following discussion does not take these effects into account. 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 wood's shrinkage 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 strain relief to the paint the lowest. Hence, the greatest mechanical strain increase in the paint occurs in the direction parallel to the grain of the wood. As the temperature drops, the paint may pass through its glass-transition temperature (T_g). At this approximate temperature, the paint undergoes a transition from ductile to very brittle and glassy. Below T_g , the paint is very fracture sensitive and prone to crack under low stresses and strains. In this example, cracks could result when the strains reach levels as low as 0.002. In the longitudinal direction of a wooden 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.

Figure 16

Calculated temperature-related strains in 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.



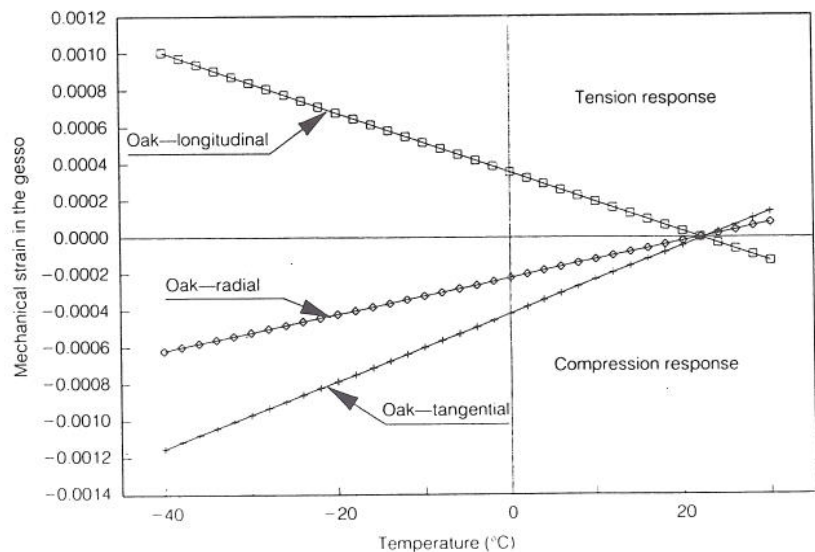
Cracking in varnish and polyurethane coatings on wood has, in fact, been recorded when the temperature has dropped from 24 °C to -20 °C. In the radial and tangential directions of the wood, the temperature must drop to well below -50 °C to produce similar strains in the oil paint layers.

It is unlikely that cracks in oil paint layers could occur perpendicular to the grain of the wood because of RH variations. However, with regard to temperature, even moderate subfreezing temperatures can crack oil paint in this direction. Low temperatures are less likely to cause cracking of paint parallel to the grain, unless the wooden 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 resultant embrittlement of the paint layer is far more severe when it is exposed to low temperature at moderate RH than when exposed to low RH at room temperature.

Other paint media suffer embrittlement similar to that suffered by oil paint, but at higher temperatures. With alkyd paints, a T_g occurs at approximately -5 °C, while 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, on the airport tarmac, or inside an unheated truck. T_g should be considered the lowest allowable temperature for a safe environment, because embrittled materials are more vulnerable to damage.

The effect of temperature on gesso applied to wooden panel paintings is different from the effect of the same temperature on paint applied to wooden panels. In general, gesso has a low thermal coefficient of expansion that is higher than that of the longitudinal direction of white oak and lower than the oak coefficients in the radial and tangential directions. Figure 17 plots the calculated temperature-related mechanical strains in the three different grain orientations for a gesso coating applied to a white oak panel. First, 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

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



appears that temperature has a significantly smaller effect on gesso than it has on oil paint.

In the panel itself, the most probable damage would occur in the tangential direction if the wood were 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 therefore is to be avoided. In the transport environment, temperature changes can be great enough to cause damage to the paint (and varnish) layers. Thus, precautions must be taken to avoid exposing panel paintings to extremes of hot or cold environments.

Temperature variations are inevitable in most transport situations (Saunders 1991; Ostrem and Godshall 1979; Ostrem and Libovicz 1971). Although variations are usually minimal during a local move in a climate-controlled vehicle, they can grow extreme during a long truck trip during harsh winter months. In the northern United 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 40-50 °C can be found in many parts of the world; because of solar heating, temperatures inside stationary vehicles can be even higher. High temperatures are less likely to cause cracking in panel paintings, since heat softens the paint. However, varnishes can become tacky at high temperatures, causing wrapping materials to adhere to the panel surface. The use of 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 vehicles or with their climate-control systems. Should a problem occur, insulation in packing cases will slow the rate of temperature change inside packing cases, but for only a short while (Richard 1991a).

Temperature variations can also occur in the cargo holds of aircraft. Cargo holds of all modern commercial aircraft now have heating systems, however, 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

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

Shocks in the transport environment are derived from three basic sources: handling before a work is packed, handling of the packing case, and the motion of the vehicle carrying the packing case. Shock levels in trucks and planes are low if 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" (Marcon 1991:123). "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" (U.S. Department of Defense 1978:9).

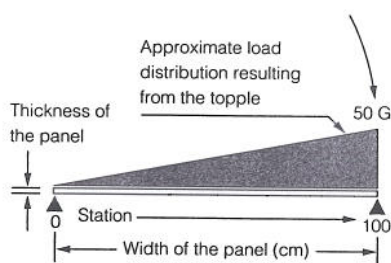


Figure 18

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.

Because old panel paintings are fragile, 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 Gs. Mass-produced objects are destructively tested to measure their fragility, but obviously this test is not possible with works of art. Until recently, no attempt has been made to determine the fragility-factor range for panel paintings. Instead, 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. The edge drop, however, is not the greatest concern.

One of the most serious accidents can occur when a painting resting upright on the floor and leaning against a wall slides away and falls to the floor. Another possible accident involves a case toppling over. In both of these handling situations, a panel painting is at serious risk because of inertially induced bending forces applied to the panel. The bending stresses induced in a panel are potentially the most damaging, and the thinner the panel, the greater the risk. While a thin panel has a low weight (low 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, 2.54 cm thick white oak panel painting measuring 100 cm in the direction perpendicular to the grain, and 150 cm in the direction parallel to the grain. If this panel painting is bowed and supported in a frame, 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 on the panel that results at the time of impact. If the impact were 50 G, the maximum bending stresses would be approximately 4.66 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 0.171 kg cm^{-3} . At 50 G, the density of the wood is 0.032 kg cm^{-3} along the impact edge and diminishes to zero at the rotating edge. For a 2.54 cm thick panel, the loading for every 2.54 cm of width of the panel at the impact edge is 0.032 kg cm^{-3} , and the loading tapers to zero at the other edge (Fig. 18). From the bending moment diagram, the bending stresses can be calculated from the equation

$$\sigma = M_c / I \quad (3)$$

where: σ is 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 $I = bd^3/12$, 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 $100 \times 150 \times 2.54$ cm thick oak panel are shown in Figure 21. The maximum stresses are stationed approximately 58 cm from the rotating edge and reach 4.88 Mpa. This amount is slightly more than half the breaking strength of structurally sound oak in the tangential direction.

Figure 19

Shear in newtons (N) for a 2.54 cm wide strip of a $100 \times 150 \times 2.54$ cm thick panel subjected to a 50-G topple accident.

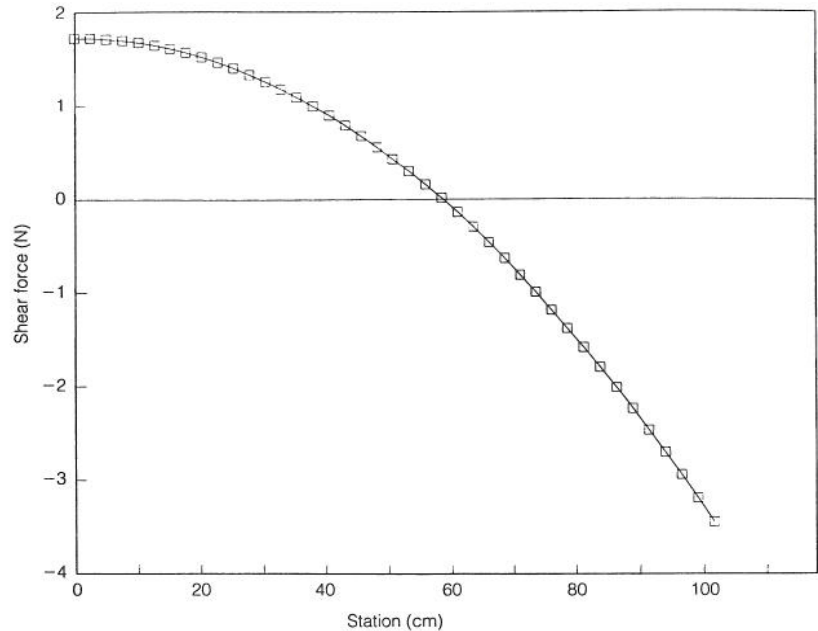
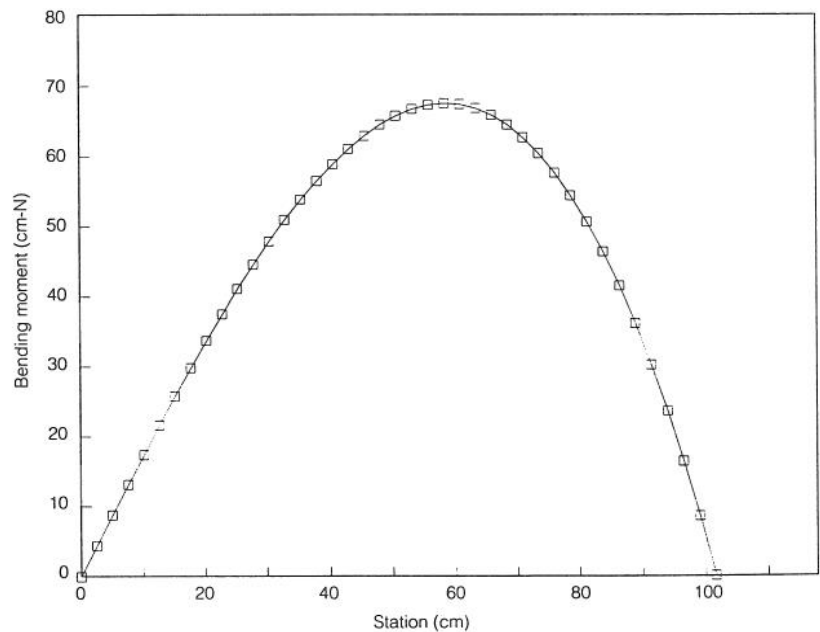


Figure 20

Bending-moment diagram for a 2.54 cm wide strip of a $100 \times 150 \times 2.54$ cm thick panel subjected to a 50-G topple accident. The bending moments of panels subjected to topples can be quite high.



If the same event occurred to an oak panel 1.25 cm thick (with the other two dimensions the same), the bending stresses would be 9.8 Mpa. Even though the 1.25 cm thick panel weighs half as much as the 2.54 cm one, it incurs twice the stress. The measured breaking stress of white oak at room temperature and 50% RH is approximately 8.9 Mpa. The thinner panel will likely crack in a 50-G topple accident. The 2.54 cm thick panel would require a 100-G topple impact to crack it. If either panel were supported continuously around the edges, the risk of damage would decrease by a factor of five.

lighter wood is also lower, and the result is that the risk of damage is greater than for denser woods. Figure 23 illustrates the results of the calculated bending stresses for different thicknesses of oak and pine panels of 100×150 cm subjected to 50-G topple impacts. The breaking stress of the pine in the tangential direction is only 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.

This implies that a single packing criterion is not sufficient for the impact protection of panel paintings. Larger and thinner panel paintings obviously need greater protection than those that are smaller and thicker. In addition, in this analysis it is assumed that the panel is sound, since existing cracks reduce the 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, effectively increasing the width of the case and reducing the possibility of a topple.

Panel paintings in the size range of 100×150 cm will often be thicker than 2.54 cm, and those that are thinner are probably supported by either battens or cradles. Yet a 2.54 cm thick oak panel that is 125 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.

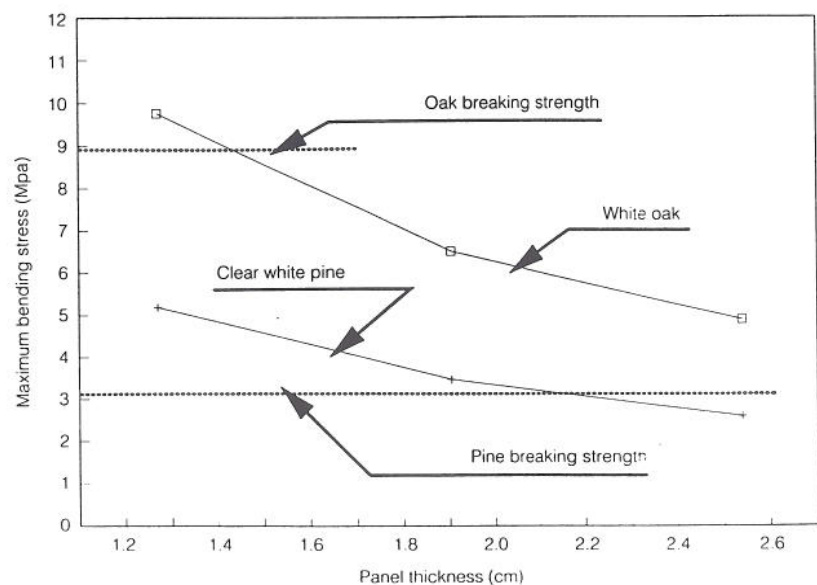
It should not be difficult to provide 30-G topple protection for larger panels. For one thing, the risk for an edge drop is much lower. It is fairly easy to provide 40-G protection for edge drop heights of 75 cm or less, using foam cushioning materials (the use of foam cushioning to reduce shock will be discussed below).

Vibration

The primary sources of vibration in the transit environment come from the vehicles used for transport. "Trucks impose the severest vibration loads on cargo with the railcar next, followed by the ship and aircraft"

Figure 23

Calculated maximum bending stresses for 100×150 cm 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, because of its substantially lower strength, panels made from it are at serious risk in the event of a topple.



(Ostrem and Godshall 1979:29). In trucks, the main sources of vibration are the natural frequencies of its body, engine, tires, drive train, and suspension system. The properties of the road surface are also a factor. The vibration levels in vehicles are all relatively low and random in nature, as vehicles are usually designed for passenger comfort.

Low levels of vibration are unlikely to damage panel paintings unless sustained vibrations create resonant vibrations in the panel; the random nature of vehicle vibration makes this unlikely. In addition, the resonant frequencies of panel paintings are high, and those vibrations are easily attenuated by packing cases (Marcon 1991:112).

Packing Cases

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 the first two stresses 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 polyester urethane foams. These foam products, along with polystyrene foam, can additionally function as thermal insulation. The proper use of these materials and information concerning the principles of case design are available in many publications (Mecklenburg 1991; Piechota and Hansen 1982; Richard, Mecklenburg, and Merrill 1991; Stolow 1966, 1979, 1987) and will only be 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 the use of relatively stiff materials and quality construction techniques. 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" (Richard, Mecklenburg, and Merrill 1991).

Compared to single packing-case designs, double packing cases provide significantly better protection for panel paintings because an inner case adds rigidity to the structure. An inner case also increases the level 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 in Washington, D.C. The polyester urethane foam not only functions as a cushioning material but also provides thermal insulation. The entire case is lined with a minimum of 5 cm of foam, which proves adequate insulation for most transport situations if temperature-controlled vehicles are used. A packing case for a typical easel-sized painting has a thermal half-time of two to three hours (Fig. 25) (Richard 1991a). The foam thickness should be increased to at least 10 cm if extreme temperature variations are anticipated. However, thermal insulation only slows the rate of temperature change within the case: increasing the thickness of the insulation increases the thermal half-time to approximately four to five hours.

Figure 24

Interior view of the outer packing case of a double-case packing system.

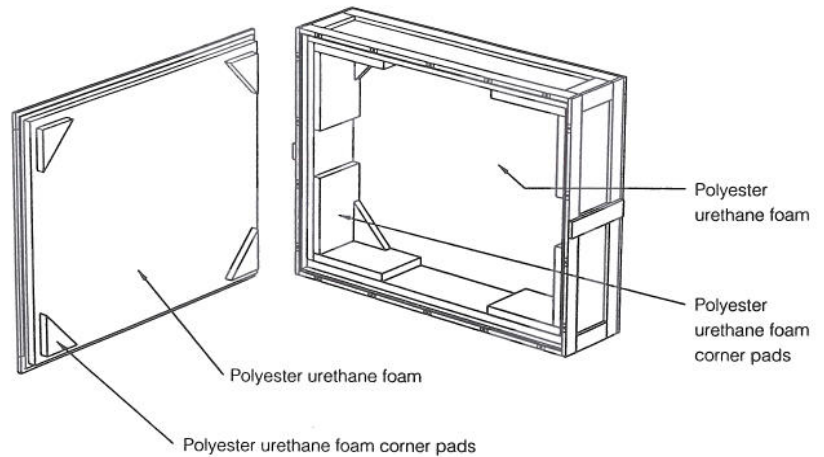
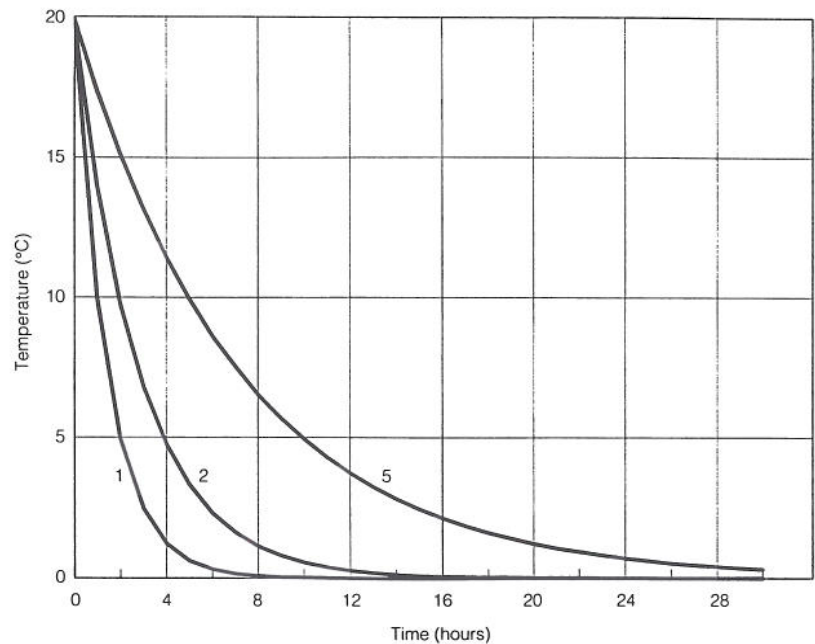


Figure 25

Thermal half-times for three different case designs. The cases were initially conditioned at 20 °C environment. The half-times shown are 1, 2, and 5 hours. Even for a well-insulated case (such as the 5-hour half-time example), little time is available before the case equilibrates to a new temperature.



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

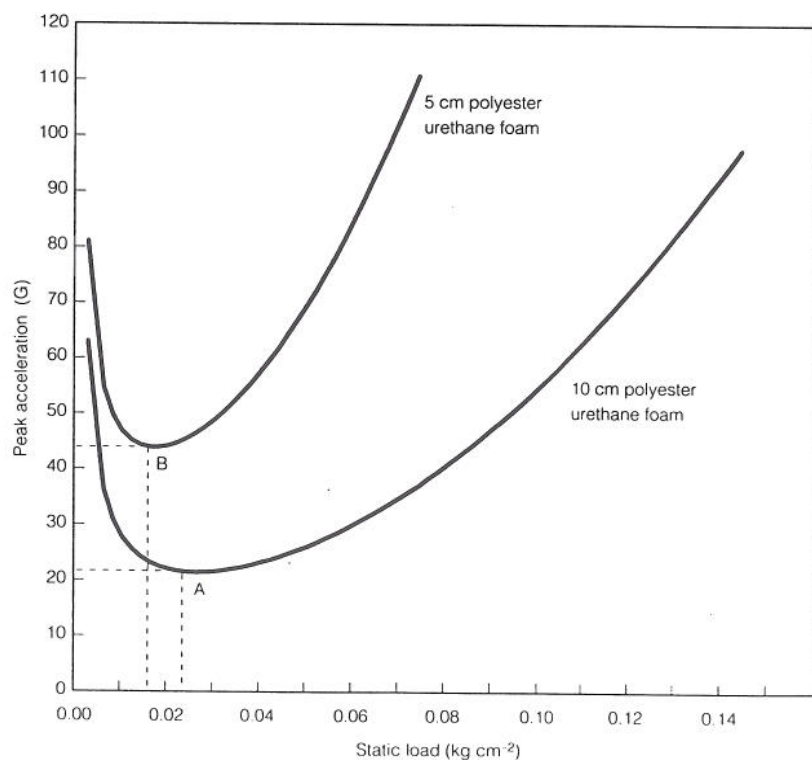
In the packing-case design depicted in Figure 24, the polyester urethane foam provides shock protection for the painting. The painting should be firmly secured within the inner case. There are two procedures that are commonly used: (1) the painting's frame is secured to the inner case with metal plates and screws, or (2) the frame is held 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 Gs on impact, while fewer than 50 G 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 1 m. In fact, if 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* (U.S. Department of Defense 1978). 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 (Piechota and Hansen 1982; Richard 1991b).

Two cushioning curves for polyester urethane foam with a density of 33 kg m^{-3} are shown in Figure 26. Both are calculated for a drop height of 75 cm. Note that an increase in foam thickness dramatically effects 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, as seen in Figure 26, the optimal static load for 10 cm thick polyester urethane foam is approximately 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 10 cm thick cushions of polyester urethane foam will sustain a shock force

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



of approximately 22 G. If the cushioning in the packing case is 5 cm thick, then the optimal static load is 0.016 kg cm^{-2} and a force of 45 G would be anticipated (point B, Fig. 26). Because of the dramatic improvement in the performance of the 10 cm thick foam as compared to the 5 cm thick foam, it is highly recommended that foam cushions at least 10 cm thick be used in packing cases built for the transport of panel paintings.

It is not possible to predict the fragility of every panel painting accurately, although the methods described provide a good estimate for reasonably sound objects. Due to cracks and unseen defects, panel paintings will always be more—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 an adequately protective package at the least possible cost. While a small percentage of the items will be damaged, the expense incurred due to loss will be less than the cost of more complex and expensive packing cases. 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. To provide optimal performance, the foam cushions should be at least 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 (Hackney 1987). Relatively thick polyethylene films that are well sealed with packaging tape usually work effectively. The quality of commercial polyethylene film materials varies considerably, however: the film is often made from recycled materials, and a low-quality film might result from the addition of grease, oil, chemical additives, and powders during the manufacturing process. Better moisture-barrier materials are available, but in ordinary transport situations, they provide few advantages over polyethylene sheeting, provided it is of high quality. It would be advantageous, however, to use the better materials when paintings are stored for many weeks in an environment having extremely high or low RH, or one having high concentrations of atmospheric pollutants.

Conservators and packers are often concerned that wrapping paintings in a moisture barrier causes condensation. Condensation problems can occur in packing cases containing large volumes of air relative to the mass and surface area of the hygroscopic materials 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 noninsulated packing case. The most likely cause of condensation is unpacking and unwrapping a cold painting in a warm room (those who wear eyeglasses have experienced similar 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 in which the packing cases will be stored. Most packing cases contain hygroscopic materials, and if they are stored in environments having an unusually high or low RH, they acclimate 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 may be created 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 surrounding the painting reduces the potential of damage from an inappropriate environment.

To improve the microclimate inside packing cases, buffering materials such as silica gel can be added. Additional buffering materials slow the variation of moisture content 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 has become improperly conditioned during the period when the packing cases were in storage. Therefore, if silica gel is used, it is essential that it be checked for proper conditioning each time it is packed.

Silica gel can also be used in a microclimate display case in which the painting remains during exhibition. A properly constructed display case provides a stable microclimate environment for a panel painting and is particularly useful when a painting is accustomed to an environment that the borrowing institution cannot achieve. A panel acclimated to 65% RH, for example, could be placed in a microclimate display case while on loan to a borrowing institution that can only maintain 35% RH during winter. It must be kept in mind, however, that mold growth can develop inside microclimate display cases acclimated to a high RH.

Hand Carrying Panel Paintings

Because of concerns about their fragility, panel paintings are often hand carried by courier during transit. In certain situations, there are advantages to hand carrying works of art. The work remains in the possession of the courier at all times—a situation not possible if works are sent as cargo on an aircraft. The painting will be subjected to smaller temperature variations 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 lightweight but sturdy 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. The case might be placed in an aircraft coat closet if necessary, but it must be secured so that no movement can occur.

Another risk with hand carrying works of art is theft. Carried materials of high value are a potential target for well-informed thieves. Although this is an extremely rare problem, it is a concern that nevertheless must be considered. While couriers may feel more secure because they are never separated from their packing cases, this proximity doesn't necessarily 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 proved very success-

ful. These cases come in various sizes and shapes, the smaller ones fitting conveniently under aircraft seats. The procedure for packing a painting in these cases is straightforward. The National Gallery of Art in Washington, D.C., often follows these steps: First, either the framed panel painting is wrapped directly in polyethylene and sealed with waterproof tape, or it is placed in an inner case that is wrapped in polyethylene. Unframed panels are always fitted into an inner case to prevent anything from touching the surface of the painting. The metal photography case is then filled with polyester urethane foam. A cavity is cut into the foam with a minimum of 2.54 cm of foam remaining on all sides. In this cavity, the wrapped painting or inner case is placed. In this procedure the polyester urethane foam functions as both 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 packed properly. However, there are circumstances when some paintings are at greater risk than others. Therefore, all panels should be carefully examined and an assessment should be made of RH- and temperature-related stresses that may develop from improper framing techniques or from restraint imposed by cradles or battens. Existing cracks in the design layers usually act as expansion joints, but cracks in panels can prove to be 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, Table 2 shows the risks of transporting a restrained, tangentially cut, white oak panel that has been equilibrated to 70% RH or higher.

Tables 3 and 4 show that it is potentially hazardous to ship a panel painting that has been equilibrated to 70% RH or higher and that has a gesso ground or paint directly applied to the wood—particularly if the wooden support is tangentially cut and not restrained.

To maintain stable moisture contents, paintings should be wrapped in moisture-barrier materials, provided they are not already conditioned to an unusually damp environment. Because condensation can occur when paintings acclimated to very high RH are transported in extremely cold weather, such transport could encourage mold growth.

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 |

Table 5 Approximate glass-transition temperatures for selected paints

| Material | Glass-transition temperature, T_g (°C) |
|---------------|--|
| Oil paint | –10 |
| Alkyd paint | –5 |
| Acrylic paint | +5 |

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

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 40–50 G.

For panel paintings, topple accidents can cause more severe damage than edge drops. The edges of panel paintings should be supported

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

| Panel width (cm) | Panel thickness (cm) | Topple G at failure: White oak | Topple G at failure: Pine |
|---------------------|-------------------------|-----------------------------------|------------------------------|
| 127 | 1.25 | 29 | 19 |
| 127 | 1.90 | 44 | 28 |
| 127 | 2.53 | 59 | 37 |
| 102 | 1.25 | 46 | 29 |
| 102 | 1.90 | 69 | 44 |
| 102 | 2.53 | 92 | 58 |
| 76 | 1.90 | 82 | 52 |
| 76 | 1.90 | 122 | 77 |
| 76 | 2.53 | 163 | 103 |

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 uncracked panels of various dimensions and woods. This table assumes that there is no auxiliary support, such as battens or cradles attached to the panels, and that 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.

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

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

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The Structural Conservation of Panel Paintings

Proceedings of a symposium at the
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Edited by Kathleen Dardes and Andrea Rothe



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Front cover: Alessandro Allori, *The Abduction of Proserpine*, 1570. Detail. Oil on panel, 228.5 × 348 cm. The J. Paul Getty Museum (73.PB.73), Los Angeles.

Back cover and page 305: Girolamo di Benvenuto, *Nativity*, ca. 1500, reverse. Tempera on panel, 204 × 161 cm. The J. Paul Getty Museum (54.PB.10), Los Angeles. The panel bears witness to the history of its conservation: This light, modern cradle was installed in 1987, after the removal of heavy, traditional crossbars (see page 187), traces of which are still evident. Strips of aged poplar, inserted to repair cracks caused by earlier restorations, can also be seen.

Page 1: Transverse surfaces of chestnut (*Castanea* sp.) (left) and poplar (*Populus* sp.) (right), showing pore structures.

Page 109: Illustration showing sawyers producing veneers; from J. A. Roubo, *L'art du menuisier* (Paris: Académie Royale des Sciences, 1769).

Page 187: Girolamo di Benvenuto, *Nativity*, reverse. A cumbersome, traditional cradle, installed around 1900 and removed in 1987, is shown.

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