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# ***ADHESIVES FOR PALLETS***

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## ***ABSTRACT***

Reviews 20 years of research by Forest Products Laboratory, including both laboratory and actual service evaluations of adhesive-assembled pallets. Currently no adhesive system possesses all of the necessary characteristics, but evidence indicates the technology appears to be available to work towards meeting the requirements. The severity of the rough-handling environment may be a factor to consider in deciding whether or not to use adhesive-assembled pallets.

# ADHESIVES FOR PALLETS'

By

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## INTRODUCTION

Although adhesives are many centuries old, they are generally not associated with pallets. Artifacts found in ancient Egypt substantiate that an adhesive substance of natural origin was used about 3,000 years ago to bond wood veneers to a wood substrate.<sup>3</sup> More recent history has made furniture, laminated beams and arches, and plywood popular areas for adhesive applications. One of the first uses for adhesives in containers was probably the "Style 6 Box."

The "Style 6 Box" was a popular wood box with sides and ends glued with an animal adhesive in a locked-corner and dovetail arrangement. The use of this container in the market gradually declined because of factors such as the cost of producing and machining the joints, and the overextension or "watering'down" of the adhesive, resulting in poor bonds.

As the "Style 6 Box" lost popularity, so did the use of adhesives in wood containers and other wood packaging applications. Although experience with the "Style 6 Box" indicated that the economics of glued construction were not suitable for wood packaging applications, it was reasoned that new techniques and new adhesives systems would provide more economical assembly practices for pallets. A more efficient joint might provide better utilization of lumber by reducing splitting at the fasteners and by accepting sound knots in the fastening area. Further, an adequate glued joint might require less wood than that required for a nailed joint.

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<sup>1</sup>*Presented at First World Pallet Congress held in Luzern, Switzerland, October 2-5, 1972, organized under the auspices of the National Wooden Pallet and Container Association of the United States and cosponsored by the European Federation of Manufacturers of wooden Pallets and Containers, and the national pallet and container associations in Belgium, Canada, France, Japan, Netherlands, Switzerland, United Kingdom, and West Germany.*

<sup>2</sup>*Maintained at Madison, Wis., in cooperation with the University of Wisconsin.*

<sup>3</sup>*Skeist, Irving. Handbook of Adhesives. Reinhold Publishing Corp. 1962.*

A review of woodworking adhesives can be found in the appendix.

## **EARLY WORK**

### Exploratory Studies

About 20 years ago the Forest Products Laboratory made some exploratory evaluations of wood pallets commercially assembled with glue-nail joints as well as with nails alone. The adhesive was a conventional rigid wood glue in use at that time. The nails provided pressure while the adhesive cured.

To determine the holding ability of the joints, a load was applied to a deckboard while restraining the rest of the pallet so that the deckboard was pulled from the stringers. For the nailed pallets, the average maximum load to withdraw the deckboard was about 3,800 pounds with half of the nails pulling from the stringers while the heads of the other nails pulled through the deckboard. With the pallet that had a glued and nailed joint, a maximum load was reached rather quickly at about 2,400 pounds where failure occurred at the glue bond. The nails, however, apparently began to pick up the load which gradually increased to a maximum of approximately 3,900 pounds. Again failure was by a combination of nailheads pulling through the deckboard, and nail shanks withdrawing. The glue bonds appeared to be of poor quality because they exhibited only about 20 percent wood failure.

Subsequent comer-to-corner diagonal compression tests showed that the pallet with the glue-nail joints was more rigid than the pallet with nails only. The glue-nail joint pallet sustained a maximum load of 2,200 pounds at a deflection of 0.41 inch while the nail joint pallet sustained a somewhat lower load of 1,900 pounds at a considerably greater deflection of 6 inches.

No definite conclusions can be drawn from these early exploratory tests. It appears, however, that the use of those conventional wood glues (thin glue lines and rigid joints) with nails, only serves to increase the resistance of the pallet to distortion. It is conceivable that increased resistance to distortion might cause early failure of a pallet during rough handling by reducing the ability of a pallet to absorb sudden, severe impact shocks. Thus it appeared that different adhesives or gluing techniques or both would be necessary before glue would be acceptable in either pallet or container assemblies.

### A Definition of Goals

In the spring of 1958, a conference was held at the Forest Products Laboratory to discuss the use of adhesives in wood pallet and container construction. The meeting was attended by representatives of the adhesive industry as well as men from the pallet industry and other areas of the packaging field. Dr. J. A. Hall, then Director of the Laboratory, described one idealistic solution to the group: "All we are looking for is an adhesive that is easy to work, has good shelf life, is capable of sticking together a couple of pieces of rough, green wood quickly so that the joint is stronger than the wood itself. And, all of this at a price that people can pay."

Laboratory scientists at the meeting reported that experimental work with a deformable glue line, achieved by bonding a rubber isolator between two pieces of wood simulating box or pallet construction, showed promise of improved resistance to joint destruction as compared to joints made with typical, thin glue line, resorcinol-resin glue.

Although the meeting did not produce a solution, it was generally agreed that adhesives in pallet assembly would not be used under conditions conducive to optimum conventional

wood gluing. Among the conditions the adhesives would have to contend with were (1) sawn surfaces of varying degrees of roughness, (2) varying moisture content of the wood, perhaps as high as or higher than the fiber-saturation point, (3) a range of wood species, from dense hardwoods to low-density softwoods, and (4) grain orientation of adjacent pieces at right angles.

### Selecting Adhesives

Others were also interested in the possibilities of using adhesives in pallets and containers. About this same time, the Stanford Research Institute was doing some related work involving fastening methods for wood boxes for fruit and vegetable products. Discussions revealed that nails, staples, and straps were satisfactory while adhesives for these applications were generally objectionable. The broad, general objections were that the then-available cold-setting adhesives required too long a clamping time while the fast-curing adhesives required elaborate and expensive equipment.

For the next 5 to 6 years, FPL continued its interest in the use of adhesives for pallet and container assembly. During this period two facts became evident. (1) Static tests of simulated joints are not suitable for predicting rough-handling performance of wood pallets or boxes and thus should not be considered as a sole means to screen adhesives or fastener systems. (2) Hard brittle glues such as polyvinyl emulsion or resorcinol-resins are not suitable for wood pallet or container assembly because these types of adhesives result in too rigid a joint. In these rigid joints, shock at impact causes extremely rapid buildup of stresses that become excessively high at the area adjacent to the glue line, and failure results.

Nailed pallet and box joints are not so rigid and become more limber when subjected to rough handling. This relative movement between parts during rough handling dissipates some of the shock energy and reduces the rapid buildup of high local stresses.

Thus, it appeared that to produce a wood pallet or box, assembled with an adhesive, and capable of withstanding some degree of rough handling, requires a joint capable of providing some relative movement between parts--ajoint that would tend to cushion and absorb the shocks resulting from rough handling. Further, it is evident that some method of test other than static loading is necessary to evaluate simulated pallet and box joint performance for the purpose of screening adhesives, mastics, and joint systems as regards their ability to resist rough-handling environments,

### Joint Evaluations

Three impact tests were devised to provide dynamic spread, shear, and tension forces on test joints. Although screening of adhesive systems by these tests was compared with performance of containers assembled with the systems, the information and knowledge is of use in considering adhesives for pallets. The results of this early work<sup>4</sup> provided the following general conclusions:

(1) The use of static evaluation methods to screen adhesive and mastic systems is not adequate for indicating rough-handling performance characteristics of containers assembled with such systems. Conversely, the use of dynamic loading techniques shows promise as a reasonably reliable means of screening systems for consideration in container assembly operations. In general, the performance of the system in the screening evaluations should be equal to or better than the performance of the control fasteners.

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<sup>4</sup>Kurtenacker, R. S. *Adhesives for Assembly of Lightweight Wood Containers.* USDA Forest Serv. Res. Note FPL-054. Forest Prod. Lab., Madison, Wis. 1964.

(2) Although a certain degree of resilience is necessary, the tendency of some mastic and adhesive systems to creep is detrimental in container applications and should be held to a minimum.

(3) In container applications, it is not necessary to demand that the system develop wood failure. It is the performance of the joint or assembly system that is important, not the type of failure. If the joint performs satisfactorily and failure occurs within the adhesive system, it is a better joint than one that has a low level of performance but develops failure in the wood.

While these factors were being studied, other work<sup>5</sup> was being reported involving flexible adhesives or deformable glue lines in lumber-to-plywood joints at different grain angles. This work indicated that lumber density is an important factor in joints such as those in pallets. This is mainly because the magnitude of internal stresses introduced in joints by dimensional movement of the wood members from moisture content changes are more severe for dense woods than for less-dense woods. Further, in such joints where conditions of specific gravity and wood quality permitted direct comparison of a rigid glue and a somewhat deformable adhesive, the benefits of the latter as a strain-absorbing medium were illustrated.

## **RECENT LABORATORY PALLET TESTS**

### Adhesive Evaluation

In order to obtain some preliminary information about the various systems,<sup>6</sup> pallet corners were subjected to either a static compressive force applied at the apex (fig. 1) at a rate of 0.3 inch per minute by a universal testing machine, or an impact compressive force generated by a 45-pound hammer falling from successively increasing heights at increments of 1 inch. Although earlier work indicated that static loading was not too realistic, it was included to give some idea of creep characteristics of the systems.

To simulate the severe actual pallet assembly conditions, the specimens were generally assembled green and then allowed to approach 12 percent equilibrium moisture content. Four different synthetic elastomeric adhesives, A, B, C, and D, were evaluated with different species.

All of these adhesives exhibited good adhesion to wood, some degree of resiliency, and gap-filling characteristics. Adhesive A was easy to apply and use, but had a rather long cure time. Adhesive B was a two-part material that required accurate mixing and had a limited pot life. Adhesive C was a neoprene structural adhesive and D was a conventional construction adhesive conforming to American Plywood Association Specifications AFG-01 for field-gluing plywood to wood framing.

Adhesives C and D contained solvents which evaporated during curing and caused voids and honeycombing of the adhesive. The use of small, thin shims to maintain uniform

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<sup>5</sup>Krueger, G. P., and Blomquist, R. F. *Performance of a Rigid and a Flexible Adhesive in Lumber Joints Subjected to Moisture Content Changes.* USDA Forest Serv. Res. Note FPL-076. Forest Prod. Lab., Madison, Wis. 1964.

<sup>6</sup>Kurtenacker, R. S. *Appalachian Hardwoods for Pallets: Effect of Fabrication Variables and Lumber Characteristics on Performance.* USDA Forest Serv. Res. Pap. FPL 112. Forest Prod. Lab., Madison, Wis. 1969.

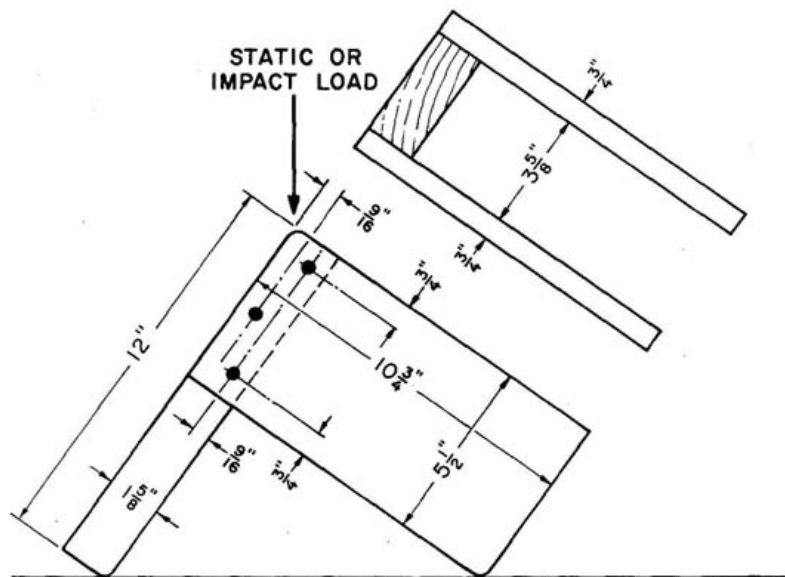


Figure 1.--Pallet corner used to evaluate fastening methods.

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thickness of pallet joint glue line caused some restraint to the movement of the deck-boards which exaggerated the honeycombing effect, This undoubtedly reduced the adhesives' performance.

Typical results for adhesives A and B are given in table 1. The level of performance of adhesives C and D did not warrant further consideration for pallet use and thus the data are not reported in the table.

### Discussion

Adhesive B used with dry wood gave good performance in the static tests and was the best all-around performing system in the impact tests. The material was identified as a mercaptan-terminated butadiene acrylonitrile copolymer. Because it was two-component, and rather difficult to handle, further evaluation was not made.

The performance of adhesive A was erratic and did not appear to be significantly influenced by joint thickness. It was, however, essentially a 100 percent reactive liquid system, without solvents, and designed so that the conversion from liquid to solid in bond formation occurred with no evolution of side products or solvents and with little volume change. Its performance with dry wood was equal to its performance with green wood. Some of the erratic performance could no doubt be attributed to the fact that using glues to make pallets created new handling and assembly techniques that were different from those for conventional fasteners such as nails.

### Pallet Evaluation

Full-size, three-stringer, 40- by 48-inch, two-way entry, double-faced, nonreversible, flush stringer pallets assembled with 1/32-inch glue line of adhesive A were compared to nailed control pallets by three different procedures. The revolving drum test provided a measure of the ability of a pallet to resist rough-handling impact as simulated by falls in the 14-foot revolving drum; the cornerwise-drop test compared the resistance to damage when the pallet is dropped while carrying a uniformly distributed 1,000-pound load; and the free-fall-on-cornerdrop test of empty pallets indicated their resistance to dynamic racking stresses in the plane of the pallet deck.

### Discussion

The pallets assembled with the adhesive performed in the revolving drum almost as well as those assembled with conventional pallet nails. It was observed in this test that species or density influenced the failure associated with the adhesive-assembled pallets. Pallets assembled from hickory exhibited a large percentage of cohesive failure (failure within the thickness of the glue line). This left the parts intact so that the pallet could be repaired either with more adhesive or by predrilling for nails. Pallets assembled from low-density yellow-poplar had a considerable amount of wood failure. Often large pieces of the deckboard or stringer were split or torn away. Damage to the pallet parts was such that reassembly with glues or metallic fasteners would have been difficult and uneconomical.

All pallets were serviceable after the loaded cornerwise drop test. There was no marked difference in appearance or performance attributable to fastening method.

The pallets assembled with the synthetic elastomeric adhesive A outperformed the pallets assembled with nails when subjected to the free-fall-on-cornerdrop test (table 2). The adhesive-assembled pallets deformed momentarily at impact but returned to their original squareness due to resilient nature of the assembly.

Table 1.--Performance of 10 pallet corner specimens

Fastening Methods	Static compression						Impact--drop height of 45-pound weight to failure					
	Yellow-poplar <sup>1</sup>			Hickory <sup>2</sup>								
	Lb.	In.	Lb.	In.	Lb.	In.	Yellow-poplar <sup>1</sup>	Hickory <sup>2</sup>				
							Deflection at maximum load	Deflection at maximum load				
							Range: Average <sup>3</sup>	Range: Average <sup>3</sup>				
							Maximum load	Maximum load				
							Deflection at maximum load	Deflection at maximum load				
							Range: Average <sup>3</sup>	Range: Average <sup>3</sup>				
							Impact--drop height of 45-pound weight to failure	Impact--drop height of 45-pound weight to failure				
Three 2-1/2- by 0.120-inch-helicelly threaded pallet nails	1,220	1.4	1,380	+0.2	1,380	1.2	+0.6	15	+3	15	+1	
1/32-inch-thick synthetic elastomeric adhesive A	920	+1,100	790	+0.1	790	+310	.5	+0.2	15	+11	24	+10
1/16-inch-thick synthetic elastomeric adhesive A	1,110	+500	1,310	+0.2	1,310	+210	.6	+0.2	21	+9	24	+7
3/32-inch-thick synthetic elastomeric adhesive A	880	+520	830	+0.1	830	+320	.7	+0.1	23	+18	24	+8
1/16-inch-thick synthetic elastomeric adhesive A <sup>4</sup>	360	+270	830	+0.2	830	+230	.3	+0.1	13	+4	18	+10
1/16-inch-thick synthetic elastomeric adhesive B <sup>4</sup>	1,070	+150	1,230	+0.2	1,230	+330	.6	+0.2	32	+5	34	+4

<sup>1</sup>Moisture content ranged between 7 and 13 pct. Species average specific gravity 0.40.

<sup>2</sup>Moisture content ranged between 8 and 24 pct. Species average specific gravity 0.64.

<sup>3</sup>Average of 10 specimens.

<sup>4</sup>Wood was dried before assembly. All others assembled with green wood and allowed to air dry.

Table 2.--Results for three-stringer, two-way entry pallets subjected to  
the free-fall-on-corneredrop test<sup>1</sup>

Species	2-1/2- by 0.120-inch helically threaded pallet nail		1/32-inch-thick synthetic elastomeric adhesive A	
	Weight	Racking	Weight	Racking
	Lb.	Pct. <sup>2</sup>	Lb.	Pct. <sup>2</sup>
Yellow-poplar	46	3.3	50	0
Hickory	71	5.8	77	0

<sup>1</sup>Figures are averages of 3 nailed, and 3 glued pallets of each species.  
Each pallet was given 6 falls on same corner from height of 40 in.

<sup>2</sup>Based on average original diagonal measurement.

## Conclusions

These studies indicate that there is no apparent difference in performance within the limits of glue line thickness investigated-- $1/32$ ,  $1/16$ , and  $3/32$  inch. Economics would naturally dictate use of the minimum joint thickness. The synthetic elastomeric adhesive B exhibited capabilities in the tests of pallet corners that warrant further consideration for pallet applications, but moisture content of the wood was more critical with this material than with the other systems used in the study. The synthetic elastomeric adhesive A may be expected to give reasonably satisfactory performance regardless of whether the wood is green or dry at time of assembly.

The density influenced the type of failure that occurred in the adhesives A and B systems. With high-density species, a cohesive failure appears characteristic while with a low-density species there is a considerable amount of wood failure.

This work also revealed two drawbacks to the use of the synthetic elastomeric adhesive A. Although the material was easy to handle and it cured tack-free in 24 hours, it required an excessively long total cure time of approximately 7 days. Future improvements may be able to overcome this. Also in using the material, care had to be exercised to prevent excessive squeezeout. If this occurred, the joint was not sufficiently resilient and it behaved similar to earlier container joints assembled with rigid adhesives with thin glue lines. This could possibly be corrected by changing the viscosity through polymer modification.

## ***IN-SERVICE TESTS***

During the recent laboratory studies of pallets, two opportunities arose to place some experimental adhesive-assembled pallets in actual use. One of these involved a brewery and the other a cement block and brick plant.

### Brewery Pallets

Arrangements were made with the brewery and the manufacturer of the synthetic elastomeric adhesive A to supply the necessary materials for over 200 pallets. These pallets (fig. 2), with aspen deckboards and oak stringer boards and posts, were fabricated from green material according to the brewery's pallet specification. They measured 37 by 32 inches and weighed 45 to 50 pounds. Half of the pallets were assembled with the specified number and size of helically threaded pallet nails while the other half were assembled only with the synthetic elastomeric adhesive A using a joint thickness of about  $1/16$  inch.

One hundred pallets of each assembly method were turned over to the brewery and placed in their transportation system. The pallets were in service for slightly more than 2 years before being lost in the nationwide distribution system because of an oversight. During this time, periodic inspections were made. At the end of the 2 years there was no record of any test pallet, either nailed or glued, having to be repaired or removed from service. All of the pallets examined appeared to be serviceable even though they did show signs of wear. Brewery officials and shipping department personnel noted that the adhesive-assembled pallets remained square and thus did not create problems in the automatic pallet loading equipment.

Extra pallets of each assembly method were subjected to laboratory evaluation. One nailed pallet and one adhesive-assembled pallet were subjected to the revolving drum test to ascertain their overall resistance to miscellaneous shocks and handling hazards. In each instance, the test was stopped after 2,000 falls. Both pallets were still serviceable with little noticeable difference in their appearance.

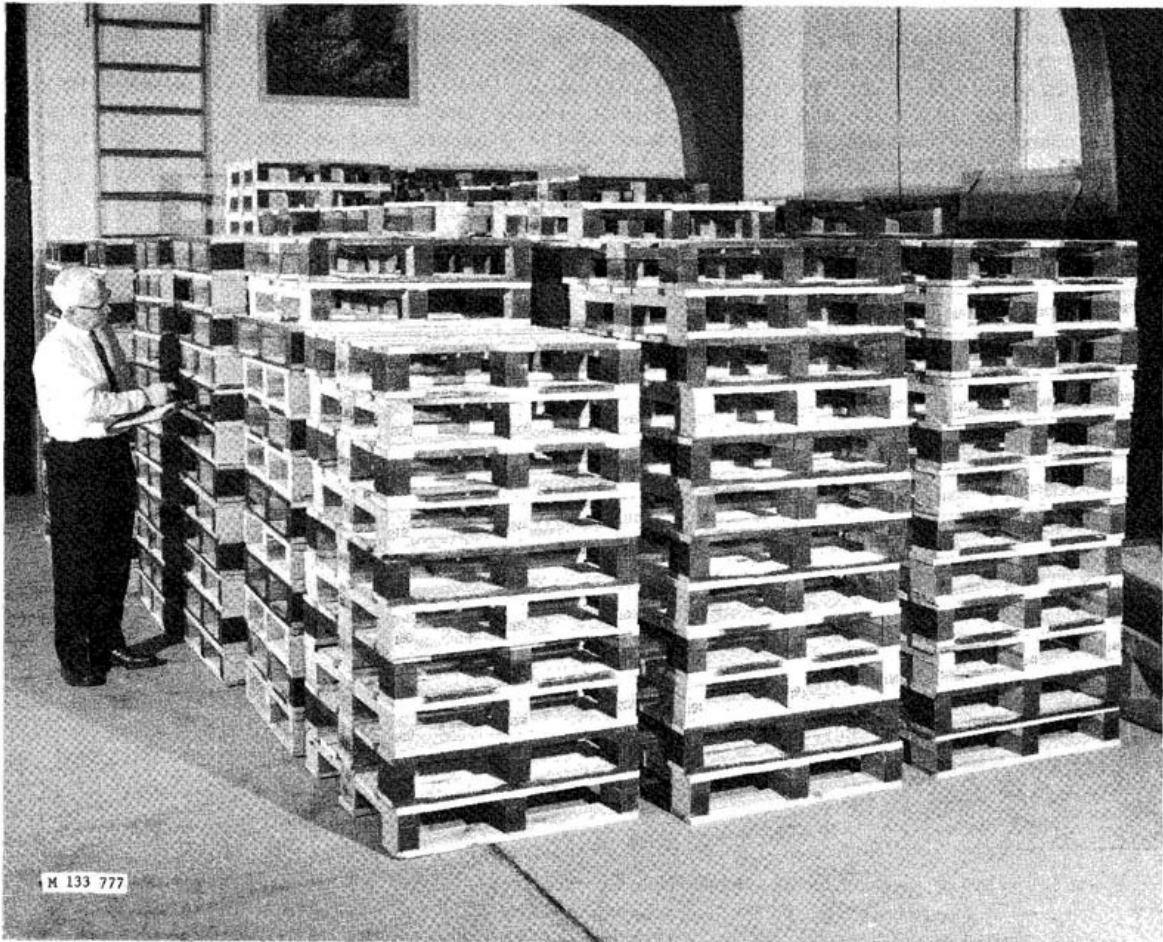


Figure 2.--Brewery pallets being inspected prior to shipment.

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Both nailed and adhesive-assembled pallets were subjected to repeated falls on the same corner from a height of 40 inches. Following an equal number of drops, the average change in diagonal measurement of the pallet's decks was computed. For those pallets assembled with adhesive A there was no serious damage and no apparent permanent or residual distortion. For the nailed pallets there was some slight splitting at the nails in the deckboards but all pallets were considered serviceable. These pallets had an average diagonal distortion of 3.8 percent.

Some untested pallets were stored outdoors at Madison, Wis., for a year after which they were subjected to the revolving-drum test and the repeated free-fall-on-cornertest. The number of pallets available for these evaluations was limited, so the results are not conclusive but are merely indications. The indicated rough-handling performance in the revolving drum of both nailed and adhesive-assembled pallets after storage was somewhat lower than at assembly. There was no indicated reduction in the ability of the pallets to resist diagonal distortion in the plane of the deck when repeatedly dropped on the same corner. As when they were initially assembled, the pallets with the synthetic elastomeric adhesive exhibited no permanent or residual distortion. Those assembled with nails had an average distortion of 3.7 percent which is similar to their initial performance.

#### Brick Plant Pallets

The pallets placed in service at the cement block and brick company were 40 by 48 inches, two-way entry, nonreversible, wing-type pallets (fig. 3). These pallets utilized experimental deckboards which were produced in a matter of minutes by combining three separate known woodworking operations. The concept conceived by Laboratory scientists called for the logs to be knife-cut rather than sawed into laminae; these laminae in turn would be rapidly press dried and then glue-laminated into the finished deckboard with a phenol-resorcinol-type wood-laminating adhesive.—<sup>7</sup> The latent heat in the wood from the press-drying operation provided the means to cure the adhesive. Such an approach is not feasible by present commercial techniques, but Laboratory research on the various phases might hopefully permit putting together a system with high potential.

Advantages of this process, which is another use of adhesives in pallets, were the speed of processing and the high yield from low-grade material. Laboratory evaluations of full-size nailed or staple-assembled pallets indicated that the process produces deckboards for reusable pallets with a high level of performance. Also, it appears that the influence of defects in the laminated deckboards is not as great as in solid deckboards because the defects, such as knots and knotholes, generally do not extend completely through the finished deckboard. It was noted that the use of mechanical fasteners (nails or staples) with the laminated deckboards produced less splitting than with similar solid oak deckboards.

The pallets placed in service at the cement block company were assembled with either synthetic elastomeric adhesive A about 1/32 inch thick, pneumatically driven staples, or hand-driven nails. In addition to these laminated deckboard pallets, there were similar nailed control pallets with conventional sawn oak nominal 1-inch-thick deckboards.

At the end of 1 year's outdoor service, the cement block company officials had no complaints on the performance of the pallets regardless of how they were assembled. Visual inspection of about 40 percent of the test pallets revealed that the glue-laminated

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<sup>7</sup>Hann, R. A., Jokerst, R. W., Kurtenacker, R. S., Peters, C. C., and Tschernitz, J. L. *Rapid Production of Pallet Deckboards from Low-Grade Logs.* USDA Forest Serv. Res. Pap. FPL 154. Forest Prod. Lab., Madison, Wis. 1971.

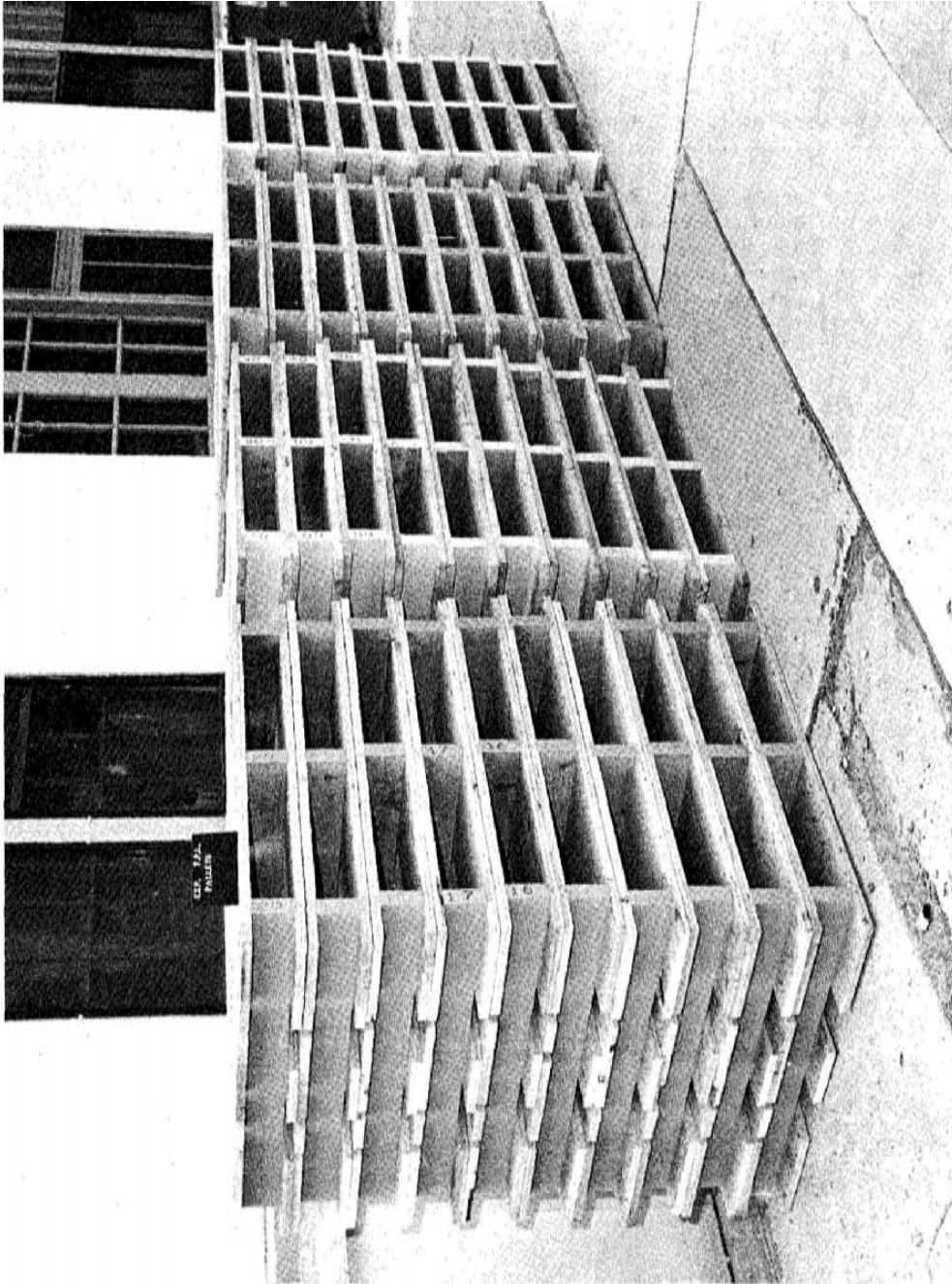


Figure 3.--Experimental pallets prior to being placed in service in a cement block and brick yard.

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deckboards had performed as well as the sawn deckboards. The adhesive-assembled pallets, however, appeared to be in more need of repair than did either the control pallets or the laminated deckboard pallets assembled with either nails or staples.

One of the adhesive-assembled pallets had lost all of its top deck and was no longer serviceable. The remaining adhesive-assembled pallets were serviceable but each had two or three failed glue bonds in the assembly joints. These appeared to be cohesive failure and could have been repaired by the addition of a few nails. Part of the cohesive failures appeared to result from some warp and twist that developed in the laminated deckboards during service. Deformation tended to be greater than for the solid oak deckboards possibly because most laminated boards were at least twice as wide as the solid boards. The resulting stresses set up in the glue bond apparently exceeded the capability of the synthetic elastomeric adhesive A to resist them. The general appearance of all the pallets indicated that they had been exposed to a severe rough-handling environment.

During the in-service tests, a steel firm expressed interest in obtaining wood pallets assembled with glue to eliminate scratching of highly polished metal sheets by the metal fasteners in their pallets. Another firm indicated a desire for 20,000 glued pallets in order to eliminate scratching of ceramic tile floors.

A joint specification of the National Wooden Pallet and Container Association and the American Plywood Association entitled "Specifications for Softwood Plywood Pallets," issued in March 1972, contains an appendix dealing with glued pallets. This appendix and the research of the American Plywood Association with glued-plywood pallets substantiates the Laboratory and in-service tests of the synthetic elastomer sealant.

## **CONCLUSIONS**

From the work reported it appears that adhesives may be used in pallets either as an assembly medium or in fabricating pallet components.

The use of currently available adhesives for pallet assembly may be considered when a moderate handling environment exists and when damage could result due to protruding nailheads caused by subsequent shrinkage of pallet parts. Wood pallets properly assembled with a suitable synthetic elastomeric adhesive tend to resist developing residual or permanent racking in the plane of the pallet deck. Although there were no complaints by those who used adhesive-assembled pallets, it appears that presently formulated adhesive compounds may not be entirely suitable for extremely severe rough-handling environments. Experience indicates that continued future advancements should provide improvement.

An adhesive to be used in wood pallet assembly should possess some specific characteristics. It should (a) be easy to handle and simple to use, (b) possess gap-filling characteristics, (c) be suitable for use with sawn surfaces of wet or dry lumber, (d) possess a certain permanent degree of resiliency with minimum creep, and (e) have a short cure time and long pot life.

At the present time, there does not appear to be a commercially available adhesive system that possesses all of the desirable characteristics for use in pallet assembly, but technology appears to be available in the United States to work towards meeting these requirements. There also appears to be sufficient interest in the adhesive assembly of pallets to promote further work towards improving both the adhesive materials and assembly techniques.

## APPENDIX A

### A REVIEW OF WOODWORKING ADHESIVES<sup>8</sup>

Wood adhesives have generally been developed to provide thin, rigid glue lines that do not readily accommodate stresses introduced by dimensional changes in wood members when they vary in moisture content, or when external stresses are applied. For example, in making plywood with thin veneers typically assembled at 90° grain angles, dimensional stability of the plywood is achieved because the individual plies are restrained in movement by the glue line. To avoid such stresses, heavy glue-laminated timbers are usually fabricated with wood members parallel.

For normal wood bonding, surfaces are planed smooth, prior to gluing, to avoid torn wood fibers on the surface. Because adhesion is a surface phenomenon, it is usually futile to bond fibers separated from the mass of the wood. For all these reasons, then, the conventional nailed wood pallet of high-density green wood with rough-sawn surfaces offers a real challenge to adhesive bonding, and will probably require a different adhesive system than is commonly used in gluing.

Conventional wood adhesives can be classified on the basis of their chemical origin. The older adhesives were based on naturally occurring materials such as proteins from animal hides, casein from milk, blood from slaughterhouses, and from soybeans. These protein glues are typically used in room-temperature curing, although most blood glues have been used in hot-press operations. These glues, plus the starch glues from potatoes, wheat, and similar sources, provide good dry strength but lack resistance to moisture, molds, fungi, and other biological agents, particularly under wet, warm service conditions. In addition, these natural proteins and starches are quite variable in quality and must be blended for better uniformity in different glue mixtures.

The advent of the synthetic resins, commonly used in the plastics industry, began in the late 1930's and offered new adhesive systems that could be synthesized from simple compounds by the chemical industry, under good quality control.

Some of these resin adhesives are durable under severe conditions including extended periods of outdoor weathering, water-immersion, high temperatures, and are resistant to biological deterioration. The resin adhesives include various thermosetting resins based on urea-formaldehyde, phenol-formaldehyde, resorcinol-formaldehyde, and melamine-formaldehyde polymers, and various combinations of these. Another series of thermoplastic resins include the familiar polyvinyl acetate emulsions, and various copolymers of acetate and vinyl monomers. While these thermoplastic emulsions are convenient to use, and have found wide application in furniture assembly, they are generally subject to softening in heat and moisture, and tend to creep under such conditions.

More recently, adhesive systems have been developed for uses other than wood bonding. Epoxy resin adhesives are now well known, and offer a wide range of properties and use characteristics, depending on specific formulations. Polyurethane resins, for example, are available in both rigid and flexible formulas. These have had considerable application as sealants or caulking compounds for building operations, and a few of these systems have potential as good wood adhesives. Some polyurethane sealants have attractive combinations of good adhesion, deformability in joints, and freedom from volume change on

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<sup>8</sup>Prepared by Dr. Richard F. Blomquist, USDA Forest Serv., Southeastern Forest Exp. Sta., Forest. Sci. Lab., Athens, Ga.

hardening; they contain no volatile solvents, and are essentially 100 percent chemically reactive liquid systems.

Mastic construction adhesives are a relatively new development. These adhesives were originally intended for on-site bonding of wood and similar materials in wood-frame building construction. They are typically formulated from various elastomers, such as natural rubber, neoprene, or Buna-S rubbers, dispersed in organic solvents as a thick mastic that can be extruded as a bead. They provide some of the potential for gap-filling in thick and variable-thickness glue lines that our conventional wood adhesives cannot offer. These rubber-base systems have been quite widely used recently in the United States for bonding plywood subfloors to wood joists in home construction, where some bonding pressure is provided by nails, usually spaced farther apart than when only nailing is used.

Such mastic construction adhesives, which develop strength primarily from loss of solvent, provide lower ultimate mechanical strength in joints than do the conventional wood adhesives, and take several weeks to develop full strength because of the slow loss of solvent to the wood. Because they are based on elastomers, they do continue to retain some deformability in the joints, although some of these adhesives become quite brittle due to oxidation and other effects.

As a group, there is quite a large variability in performance among the various commercial mastic adhesives now. Because of the great potential for these thick adhesives in building construction, these are being studied extensively by various laboratories,