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FORMULATION AND INDUSTRIAL APPLICATION OF SYNTHETIC RESIN AND SPECIAL ADHESIVES USED IN THE JOINERY AND FURNITURE INDUSTRIES AND OTHER SPECIALISED WOODEN PRODUCTS 1/

by

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Summary

Commercially significant adhesives types are discussed first, outlining the advantages and limitations of each. Ways of adjusting the performance of each are also described, so that formulations can be prepared for specific processes. In this part of the paper, the authors restrict themselves to information which can be applied in woodworking plants; formulating some types of adhesive, e.g. PVAC and rubber-based, requiring the use of hazardous chemicals and/or specialised mixing and compounding machinery which makes such processes impracticable, except in adhesives manufacturers' plants. The principal differences between commercial formulations, within each chemical group, are discussed, since this knowledge can help the user to select the right proprietary product for his purpose.

Part two of the paper lists the factors in a series of applications, which determine adhesive selection. Seldom is there a 'perfect' adhesive for any job; often several are equally suitable, and the process of determining the choice, or compromise, is described.

CONTENTS

I INTRODUCTION

The adhesives applications contained in this paper have not been widely treated in published work. This is probably because, compared with plywood and particle board manufacture, the volume of adhesives used is small, and a much greater variety of types is needed. Conversely, papers on specific glue types deal more with the chemical principles of formulation, than with the practical effect of the processes described.

It is hoped that as much as possible of the information presented here can be applied in wood-working plants. Thus the information given in each section varies in quantity according to how readily it may be used in practice. For example, formaldehyde based resins may be converted into adhesives for a wide variety of jobs by the user himself; but the more complex 'hot-melts', PVAC and rubber-based glues often contain expensive and hazardous chemicals in highly critical amounts. These products also have to be compounded in special equipment, fitted with temperature control and extraction facilities. It is unlikely that a single user could justify investing in such equipment, or employing a specialist to operate it. Preparing glues which are water-based, needing only simple mixing, not containing flammable or highly toxic substances, and requiring only reasonable care in proportioning, is within the capabilities of most furniture and joinery plant staff.

All adhesives manufacturers provide a wide range of products, even within one chemical type. It is not always easy for the user to distinguish between them, or to decide which grade is best suited to his needs. These extensive product ranges are mainly the result of market requirements; it might even be possible to reach a situation where each customer has his own grade! If the user is prepared to take one or two basic materials, he can - subject to the limitations described in the previous paragraph - produce most of the finished glues he requires.

The details of formulating within each chemical group of adhesives are given below; but where modification by the user is not practicable, and a formulated material must be purchased, another approach has been used. In these cases, the practical difference is in the performance of individual grades and this is described so that the user can see which general type of glue is needed. Having narrowed the possible choices, he can give an explicit set of requirements to his supplier, who can then make a suitable recommendation. Today, much research is devoted to developing industrial adhesives which do not rely on petroleum-derived chemicals, and materials of vegetable origin have yielded encouraging results. Although starches and soya protein have been known as adhesives for tens and thousands of years respectively, they are also edible. The use of any edible material in an industrial process must be condemmed; indeed, it is already prohibited in many countries. The poly-phenols present in the bark of mimosa (Acacia sp.); quebracho (Schinopsisp) and Douglas fir (Pseudotsuga Menziesii) are capable of reacting with formaldehyde to produce resins upon which adhesives may be based. These and lignin-containing adhesives are described extensively b other contributors to this symposium, but it is the authors' view that these are not yet advanced enough to be used in the operations discussed here; principally because they require large amounts of heat energy to cure them. Hot-curing glues require costly apparatus, and it can be technically difficult to apply heat to small joints, surrounded by a large mass of material. Glues based on tannins which cure between 10°C and 40°C are not yet a reality. Hot-curing tannin glues may be suitable for surfacing sheet materials (veneering); but even here cure-times are often too long and temperatures too high to off-set the cost of importing a conventional glue.

II ADHESIVES

2.1 Naturally occuring

The traditional natural adhesives are based on proteins of either animal or vegetable origin. These are first extracted from the raw materials and are then modified so that they may be made into aqueous dispersions. These dispersions have excellent adhesion properties, but the joints made with them are not as durable as joints made with synthetic adhesives; particularly, in hot humid climates.

As the raw materials to produce these proteins may be incorporated in food, either for farm animals or humans, there is increasing economic, as well as moral, pressure to reduce their use in adhesives manufacture. This factor is now, probably, more important in the decline in the use of protein-based adhesives than the superior technical performance of synthetic materials.

2.1.1 Animal Glues

These are made from gelatine, derived from skins and bones, which are by-products of the meat-processing industry. These gelatines are dispersed in water before use, by heating. The resultant dispersion contains between 30 and 50 % solid material and must be maintained at a temperature of about 60°C to keep it liquid. These dispersions may also be modified so that they are liquid at room temperature, but such products are not commonly used as wood adhesives in the processes considered here.

When applied to wood, the water from the dispersion is rapidly absorbed and, at the same time, the adhesive gells due to the decrease in temperature. This process is analogous in some ways to the setting of hot-melt products, and early hot-melt machines often used gelatine-based adhesives. These were replaced by synthetic materials because of the latter's superior strength, heat resistance and speed of set.

Animal glues are the traditional glue for furniture and cabinet making. Their rapid setting and simple application making them ideal for the small workshop. Considerable skill is needed to use them for bonding large areas (i.e. veneering) but the equipment required to prepare and apply them is extremely cheap.

Under dry temperate conditions, the durability of joints made with animal glues is excellent, although at very low humidities they become brittle. Since the process is reversible, films swell and soften at high humidities and are then readily attacked by micro-organisms; immersion in water will produce complete bond failure in a few hours.

There is little that the user of animal glues can do to alter their basic properties, or to extend and cheapen the adhesive prior to application.

2.1.2 Casein

Casein is also a protein, derived from milk. By treatment with alkali, usually calcium hydroxide, it may be modified and subsequently dried to form a free-flowing powder. This powder can be dispersed in water at approximately 33 % concentration to form an adhesive. The dispersion remains liquid for several hours at room temperature, and after it has become pasty may be redispersed in freshly mixed material; wastage is thus kept to a minimum. When applied to wood the adhesive dries, but the process is less readily reversed than with animal glues; like these, however, casein can be attacked by micro-organisms when softened by heat and humidity. Formulated casein adhesives usually contain a fungicide to inhibit this effect, but the long-term durability of these treatments cannot be permanently relied upon.

The strength of joints made with casein adhesives is excellent. This is borne out by the fact that they were the standard adhesives for assembling structural aircraft components from the earliest days until the middle 1940s, when they were replaced by the more durable synthetic adhesives. Casein adhesives are also used for the manufacture of large building elements, where their long assembly times are a distinct advantage. However, the alkaline characteristic of the adhesive is a disadvantage for high quality joinery and cabinet making as it can often cause unsightly stains in the joint area. Casein may also be used for veneering applications, subject to this limitation, and setting may be accelerated slightly by using heat to dry moisture out of the joint. Unlike animal glue, the dried film of casein adhesive cannot be re-softened by heating.

Hot-setting adhesives may be made for plywood manufacture by blending casein with solubilised albumen, extracted from dried blood. Such adhesives are well known in plywood manufacture but are not used in the applications dealt with in this paper.

As with animal glues, the equipment used to apply caseins is simple and cheap.

2.1.3 Glues of Vegetable Origin

Aqueous dispersions of soya protein have good adhesive properties and have, in the past, been used for plywood manufacture. They are unsuitable for furniture and joinery processes and must be set by heat. The high food value of soya makes the use of these products particularly liable to the restrictions described above.

Many wood extractives, particularly those from bark, contain poly-phenolic compounds which may be reacted with formaldehyde to form materials analogous to the synthetic phenolic adhesives.

Much research is concentrated on this subject because of the obvious advantages of obtaining adhesives with phenolic characteristics without the need for petroleum-derived raw materials. In general, these materials must be cured by temperatures in excess of 100°C, although South African workers claim to have developed adhesives capable of setting as low as 60°C. With specialised-equipment, such adhesives might eventually become suitable for the manufacture of glued laminated components but at present they cannot be considered for assembly glueing, veneering applications, and door manufacture. All such adhesives are dark in colour, resembling phenolic and resorcinol adhesives.

2.2. Synthetic: Thermosetting Types

Thermosetting resins are changed irreversibly, by heat and/or chemical reaction, to form hard, infusible, solids. They form characteristic, cross-linked, macromolecules responsible for their principal properties and distinguishing them from thermoplastics.

2.2.1 Formaldehyde based

Formaldehyde is capable of reacting with a large number of substances to produce thermosetting resins. For wood gluing the most important of these resins are urea formaldehyde (UF); phenol formaldehyde (PF); melamine formaldehyde (MF and resorcinol formaldehyde (RF). Co-condensates of these are also used, chiefly phenol-resorcinol formaldehyde (P-RF) and melamine-urea formaldehyde (M-UF). Although the term resin applies to the reaction product itself, which may be either a liquid or a solid, it is also applied to their dispersions in water, or water-alcohol mixtures. The reactions which produce these resins are controlled during manufacture by altering the temperature and acidity (pH) of the reaction mixture. After a product with the desired characteristics has been obtained the mixture is cooled and, in some cases, the pH adjusted to give the maximum stability; even so, the reaction continues in the aqueous resin and this limits the period over which the material is usable (shelf-life). Shelf-life may be prolonged by removing water from these products and converting them to a free flowing powder; usually by spray-drying. The user must re-disperse the powder in water. Resins which are to be kept for a long period, or transported over a considerable distance, particularly in hot climates, are normally supplied as spray dried powders. Although the resins may be converted to solids (cured) by heat alone, this process is usually speeded up by the addition of a substance known as a hardener. Many formaldehyde-based resins may be combined with hardeners which enable them to be cured at room temperature. Although this statement is true for all those resins used as wood adhesives, the chemical mechanisms used differ widely within the group.

Formaldehyde-based resins adhere well to wood, and may also be used to bond non-wood materials e.g. decorative plastics laminates, paper, asbestos-cement and some types of rigid foam to wood.

Complete adhesive formulations comprise:

- A formaldehyde-based resin
- A hardener (sometimes referred to as a catalyst or accelerator)
- Fillers or extenders
- And (sometimes) additional water
- (wetting agent - optional)

In the following sections the principles of producing these formulations are discussed for each resin type. An understanding of these principles will enable the user to formulate mixtures to suit the various gluing processes he may wish to use and, in many cases, to produce his own hardeners. This facility makes formaldehyde-based resins ideal for use in factories where a number of different processes are being carried out; a single resin may often be adapted to a wide variety of operations by the user himself, this avoiding the necessity to hold several different types of adhesive in stock. The differences between the four main types of formaldehyde-based resins are:

- Durability of the cured product
- Cost
- Colour
- The amount of energy required to cure them, i.e. their ability to cure at room-temperature.

Durability of adhesives based on the different types of resins is widely documented. They may be ranked thus:

PF and RF ↓	Decreasing durability.
MF ↓	
MF-UF ↓	
UF	

It is difficult to give accurate information on the cost of adhesive as this varies widely with market fluctuations, the source of the resin and the amount of fillers etc., in the final mixture. Ascending price order, however, is likely to be:

UF ↓	Increasing cost.
PF ↓	
MF ↓	
RF	

At the time of writing an approximate ratio of costs is as follows, based on prices of products available in Europe

UF	=	1
PF	=	2.6
MF	=	4.4
RF	=	13.0

When considering the above information it should be appreciated that the concentration at which the resins are supplied (solids content) varies considerably and that the amount of filler which may be added to the product before use also effects the price; the above, are therefore, calculated on a 100 % solids basis.

The individual resin types are considered in more detail below. The principles of formulating adhesives are discussed but actual formulations are given in Chapter II, 3.0 Applications.

Urea Formaldehyde

Adhesives based on these resins are suitable for both hot and cold curing applications. They give strong bonds at room temperature, even when heavily filled with flour, or inorganic filler. The resins, when cured, are virtually colourless and the film is hard and brittle. Cured films exceeding 0.1 mm thickness tend to break down over a period of time causing loss of joint strength. This is not a limitation in applications such as veneering and door making; but in assembly gluing, unless the joints are close-fitting, modified glues should be used. UF's may be modified in a number of ways to prevent this defect and such materials are described as 'gap-filling'.

Hardeners for UF resins are either acids or salts of acids which react with the free-formaldehyde in the resin causing the pH of the mixed adhesive to fall. The simplest hardeners are dilute acids such as phosphoric, sulphuric, oxalic or formic; the last produces cured films which do not craze.

If added to the resin, the life of the mixture (pot-life) would be extremely short, so acids are normally applied to one surface of the joint and resin to the other.

Where separate application of resin and hardener is not practicable, or where heat is available to accelerate cure, mixed hardeners are used. These normally contain ammonium salts such as chloride, sulphate, phosphate and, if a long pot life is required a 'retarder'; e.g. urea, hexamethylenetetramine or ammonium hydroxide. The salts and retarders may either be combined as solutions or, with the exception of ammonium hydroxide, dispersed in an inert filler and added to the resin as a powder. Formulation of hardeners can be carried out by empirical experiment, until the desired pot-life and curing time are attained. It is important to remember that a particular combination of hardener and retarder will only give the desired performance with a particular resin; the degree of condensation, ratio of formaldehyde to urea and solids content of the resin will affect performance with a given hardener. For this reason commercially prepared hardeners should not be used with resins other than those for which they were formulated, and for which specific working instructions are available. Figs. 1 - 3 illustrate some of these effects. Adhesives based on UF resins can be very cheap if fillers are added, and one of their main advantages is that they are capable of being heavily adulterated without reducing bond strength; although water resistance and durability under damp conditions may be affected.

When selecting fillers for use with UF resins it is important that they do not react with formaldehyde or contain substances which are alkaline. Gypsum and kaolin (china-clay) are suitable providing they do not contain even traces of calcium carbonate, which are often present as impurities. Carbonates, or other basic substances, inhibit the curing of the resin by limiting the fall in pH brought about by the hardener. Organic fillers such as wood and shell flours are suitable, but softwood flours can be acidic and can reduce the pot-life of the mixed adhesive. Cereal flours - pea and bean flours, and starches are excellent, though subject to the reservations concerning the use of edible materials, already stressed. Flours derived from some types of inedible seed, such as tamarind and gram have been used as substitutes for cereals. It is usually necessary to test non-cereal fillers as they can alter the setting time and pot-life of the glue mix by reacting with the free formaldehyde present.

The rheological effects of fillers are of vital importance, as is the amount of water required to correct the glue mix viscosity. Tests should be made to establish that the final mixture is viscous and free flowing; fillers which produce 'short', lumpy mixes are unsuitable as are fillers of coarse particle size.

UF resins should not be used for adhesives required to withstand weathering for periods of years. In use, they are tolerant of a fairly wide range (7 - 20 %)[1] of wood moisture contents.

Phenol Formaldehyde

PF resins using very strong organic acid catalysts can be used for wood bonding at room temperature. Although such resins have been shown to have excellent weather resistance, the hazards and limitations of handling them mean that they are seldom used today. Most PF wood glues are limited, therefore, to hot pressing applications; especially in the manufacture of plywood, and they are little used in the applications dealt with in this paper.

Resorcinol Formaldehyde

Most so-called resorcinol formaldehyde adhesives are, in fact, co-condensates of resorcinol and phenol with formaldehyde. The resins are prepared with less than equi-molar amounts of formaldehyde and are thus novolacs. These are supplied in aqueous or aqueous-alcohol medium, of approximately neutral pH, and have long shelf-lives.

Hardeners for these resins comprise solid formaldehyde (usually para formaldehyde) or a formaldehyde doning substance, and fillers. Some types use liquid formaldehyde donors as an alternative.

RF resins give bonds of the highest durability and are universally recognised as suitable in the most exacting environments, particularly for structural uses.

Speed of set may be controlled, to a limited extent, by varying the pH of the mixed adhesive but extremely careful control is required and such a process is generally outside the scope of the glue user.

Mixed adhesives usually contain some filler, since the basic resin solutions have a low viscosity. Heavy extension, however, is undesirable as the principal property of these glues is their high durability, which would be reduced by extension, even with inert substances.

As the adhesives set in the neutral to alkaline range they may be used for bonding alkaline materials, e.g. asbestos-cement, to itself or to wood. This is used to advantage in constructing many types of building panels. The sensitivity of these adhesives to pH can also be a disadvantage, however, when bonding timber treated with preservative or fire-retarding chemicals.

RF and R-PF adhesives can tolerate a wider range of wood moisture contents than UF's and successful results have been reported with timber up to 26 % moisture content [1]; this is of practical use in the manufacture of building components often made from air-dried timber.

Melamine Formaldehyde

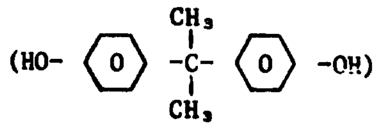
Melamine formaldehyde resins are in some ways analogous to UF's but have greater resistance to boiling water and are more durable when exposed to weather. They must, usually, be cured at elevated temperatures.

There is less agreement about the durability of MF resins on M-U-F materials than about the durability of resorcinols. Some National Standards consider them fully suitable for exterior applications.

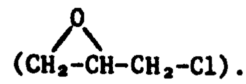
Melamine-urea adhesives are also used and these may be prepared in a variety of ways. The simplest form is to combine melamine with UF resin in amounts between 10 and 20 % based on UF solids. Such mixtures are used for manufacture of certain types of plywood with limited exterior durability and must be cured at temperatures exceeding 100°C. Resins with a greater degree of weather resistance can be obtained by either blending MF and UF resins or co-condensing melamine and urea with formaldehyde. It is generally accepted that such materials must contain at least 50 % by weight of melamine resin, ir its molar equivalent, to obtain a reasonable degree of durability. Such materials are classified as suitable for exterior use in a number of United States specifications and documents based on them.

2.2.2 Epoxy Resin Adhesives

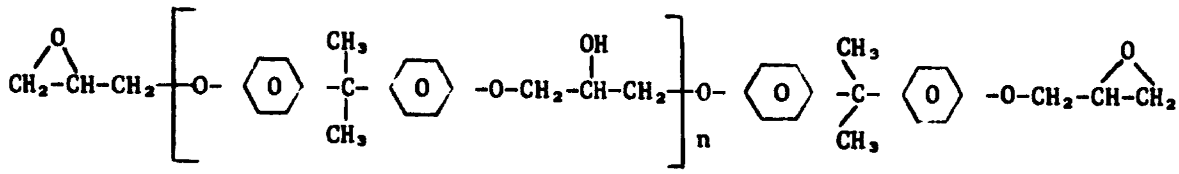
Epoxy resins contain the epoxide group (-C-C-) with bridging O in the uncured state and can be manufactured from a range of substances. The most important types of epoxy resin are those based on the reaction between bisphenol A



and epichlorohydrin



They are polyglycidyl ethers of bisphenol A and their molecular structure may be represented as shown below:



where n = 0 to about 12.

Like the other thermosets, epoxy resins are used with hardeners which in this case react with the resin by polyaddition to form cross-linked polymers. Many substances capable of reacting with the epoxide group can be used as hardeners but the most important in adhesive applications are polyamines and polyamino amides. Formulated adhesives may also contain fillers, thickening agents, diluents, plasticisers and accelerators.

Unlike the formaldehyde-based resins which polymerise by condensation, no water or other molecule is evolved during cure and hence shrinkage is negligible. Epoxy resins are therefore truly gap-filling and are capable of bonding very uneven surfaces providing that a sufficient spread is applied. They are the strongest type of adhesive available and will bond almost any kind of material. Since 100 % solids formulations can be used and no volatiles are evolved non-porous materials like metals, glass, rigid and laminated plastics may be successfully bonded together. As adhesives, these are the most favourable properties of epoxy resins, which are however subject to a number of disadvantages:

- high cost
- relatively slow curing (or short usahle life)
- mixing and application equipment has to be cleaned with organic solvents

Although epoxy resin adhesives will very successfully bond most types of wood and wood based products, in view of the above limitations and because other cheaper adhesives do the job as well or better they are little used for this purpose. However for certain applications involving bonding metal, glass and certain plastics to wood products epoxy resins are chosen either because they have superior adhesion to the adherends in question or are more durable than possible alternatives.

The difficulty of cleaning down after using epoxy resins has recently been largely overcome by the development of water-thinnable types. The authors have found these to be highly satisfactory wood adhesives which can be washed down with water, rather like emulsion adhesives. Although still more expensive than most other adhesives, cost is reduced by dilution with water and this type of epoxy resin could in the future be used for structural and other specialised applications.

2.3 Thermoplastic Adhesives

A thermoplastic is a material which may be reversibly softened by heat without undergoing any chemical change. Thermoplastic adhesives are characterised by consisting predominantly of linear polymer chains. It is this feature of structure which accounts for their basic physical properties and the major differences compared with thermosetting resins. These may be stated essentially as follows. Thermoplastic adhesives have lower water, weather and heat resistance and are susceptible to creep (non-recoverable deformation under applied stress). For this reason thermoplastic adhesives are not recommended for structural applications, which may be defined as joints which can be subjected to continuous stress.

The most important types of thermoplastic adhesives are those based on vinyl polymers. These are formed by polymerisation of substances containing the vinyl group ($CH_2 = CHX$, where X may be a halogen or another group such as hydroxyl or acetate).

2.3.1 Vinyl Resin Adhesives

Vinyl resins are widely used as wood adhesives in the form of dispersions in water ('emulsions') or as solids. They set solely by physical processes in contrast with thermosetting resins which harden essentially by chemical reactions.

When applied as 'emulsions,' the continuous phase (water) is removed from the glue line by evaporation and absorption into one or both adherends. The resin particles (disperse phase) then coalesce to form a continuous film which holds the joint together. Therefore, as with the thermosetting resins, except the epoxide type, covered in section 2.2.2, at least one of the surfaces to be bonded must be porous.

Solid thermoplastic adhesives are applied in the molten state and set rapidly by cooling. They are known as hot-melt adhesives and this technique is generally the fastest practicable method of making joints. Since they set only by cooling and do not rely on loss of water, hot-melt adhesives are capable of bonding two non-porous adherends and this is a very useful facet of their properties.

Polyvinyl Acetate PVAC Adhesives

These are used as general purpose wood adhesives and for bonding wood based panel products, paper and decorative laminates. They are based on aqueous homopolymer 'emulsions' of vinyl acetate (VA), varying in solids content from approximately 40 to 60 %. The process of emulsion polymerisation of vinyl acetate monomer enables a range of polymers to be produced varying widely in molecular weight and other respects. Properties of the liquid adhesive and film forming characteristics are further modified by compounding with additives. Emulsifying agents (surfactants), with which the emulsion was formed, and protective colloids which stabilise it are also present. External plasticisers such as phthalate esters or organic phosphates and sometimes solvents such as higher alcohols are added to promote coalescence and good film integration. The minimum film-forming temperature, which is an indication of the minimum temperature at which a satisfactory glue line can be formed, may be adjusted by altering the plasticiser content and type. Formulations with a high plasticiser content and low minimum film-forming temperature generally have lower heat resistance. Coversely, formulations with higher heat resistance may have a higher minimum film-forming temperature and therefore be unsuitable for use at low ambient temperatures. Viscosity may be increased, for example to reduce penetration into a porous substrate, by the addition of thickening agents, such as polyvinyl alcohol (PVOH) and various cellulose derivatives. Inorganic fillers such as chalk and china clay may also be added to increase viscosity, but they are also used to extend and cheapen the formulation. It can be appreciated therefore that the formulation of a PVAC adhesive is a complex matter and may involve a compromise between opposing parameters. It is generally best left to a specialised adhesive manufacturer who has the necessary experience and expertise. Conventional PVAC adhesives are therefore usually supplied as one-component liquids ready for use in a specific application.

A number of common factors govern the performance of PVAC adhesives irrespective of formulation or application. As previously mentioned PVAC 'emulsions' set essentially by loss of water and the main external factors influencing this, and hence rate of setting, are summarised below:

- Temperature	(Increase favours faster setting)
- Humidity	(Decrease favours faster setting)
- Porosity of adherends	(Increase favours faster setting)
- Moisture content of adherends	(Decrease favours faster setting)

Loss of water by evaporation and absorption ensues immediately after application of the adhesive, initiating the setting process. Assembly times (open assembly + closed assembly) are therefore limited and must not be exceeded or precure may result, causing a defective joint. It is difficult to quantify setting and assembly times since they depend upon the combination of the above parameters. The principal method of extending the assembly time is by increasing the glue spread which may be facilitated by a higher viscosity formulation.

Catalysed PVAC Adhesives

The main advantage of PVAC adhesives is their simplicity of use (generally no mixing is required) and quick setting characteristics under cold and warm pressing conditions. However, at press temperatures above 60-70^{o}C, with conventional one-component formulations, the glue line is too soft (due to its thermoplastic nature) to permit release of pressure. This deficiency has largely been overcome with the introduction in recent years of 'catalysed PVAC adhesives'. These consist of a reactive 'emulsion' capable of limited crosslinking in the presence of a suitable catalyst (usually an aqueous solution of either an acidic metal salt or a transition metal salt). The crosslinking action increases the heat resistance enabling higher press temperatures to be used. Resistance to water and particularly boiling water (the heat of boiling produces a greater degree of crosslinking than occurs in normal curing cycles) is also greatly improved. Similar catalysed formulations are also available for cold pressing and whilst overcoming some of the deficiencies of PVAC adhesives with respect to water and heat resistance, the susceptibility to creep remains and they are therefore still unsuitable for structural applications.

Vinyl Acetate (VA) Copolymer Adhesives

These are based on 'emulsions' of vinyl acetate copolymerised with another suitable unsaturated monomer such as an acrylic ester, a maleic ester or ethylene. They are used principally for bonding PVC (and other thermoplastics) foils, for which materials homopolymer 'emulsions' have poor specific adhesion and inadequate resistance to plasticiser migration. For this application, ethylene is preferred and such copolymers are commonly known as EVA 'emulsions'. These have high resistance to plasticiser migration and good specific adhesion not only to PVC but also many other surfaces which are difficult to wet and bond with other adhesives. Ethylene also acts as an internal plasticiser, producing an inherently flexible polymer, by relieving the resistance to rotation due to stearic hindrance caused by the bulky acetate groups repeated along the chain. However, to promote good film formation and to maintain satisfactory adhesion at low ambient temperatures, an external plasticiser and/or plasticising solvent are usually included in the finished product.

2.3.2 Hot-Melt Adhesives

As previously mentioned, this type of adhesive is applied in the molten state at high temperatures (generally within the range 100-200^{o}C), and sets by cooling. The main outlet for hot-melts in the woodworking industry is edge-banding, but some are used for assembly gluing. The formulations used in these applications are usually based on ethylene vinyl acetate (EVA) copolymers, blended with tack resins, plasticisers, fillers and various other property modifiers in 100 % solids compositions. Hot-melt adhesives based on polyamides and polyesters are also available and whilst these have some very interesting properties, in particular good high temperature resistance, they are at present not used in the woodworking industry to any significant extent.

Setting purely by cooling enables hot-melts to achieve a very fast rate of bond formation and this is one of their main advantages. Another is their ability to adhere to almost any type of substrate. These properties are used to good effect in edge-banding and assembly gluing. Being thermoplastics, hot-melts have some of the drawbacks of conventional PVAC adhesives, only to a greater extent due to the rather superficial adhesion obtained. This is due to the method of application, as relatively high viscosity liquids which set rapidly on closing the joint have limited scope for good wetting and penetration, which are essential for high quality adhesion. This also severely restricts assembly time, compared with most other types of adhesive. Lengthening assembly time is usually achieved at the expense of heat resistance, which is obviously strictly limited with this type of adhesive. Their heat resistance is also difficult to quantify since hot-melts are rather amorphous in structure and soften gradually over a wide range of temperatures.Fig.4. They are also subject to creep and the actual heat resistance in any particular situation will depend upon the duration of exposure to the elevated temperature and the stress applied.

In addition to being applied as hot liquids at the time of bonding, hot-melts may also be coated or extruded onto edgings and veneers, allowed to cool, and then reactivated by heating during the secondary bonding process. The processes are fundamentally similar though the latter technique probably enables better wetting and adhesion to be obtained as the open assembly time is eliminated.

2.4 Rubber-Based Adhesives

Elastomers, or rubbers as they are more commonly called, are another class of synthetic polymer, different from thermoplastic and thermosetting resins, and widely used as adhesives for wood and wood-based products. Many rubbers have adhesive properties, and in particular exhibit good 'tack'. This has been defined (Wake 'Adhesion and Adhesives', Vol. 1) as "that property of an adhesive whereby momentary contact with the substrate is followed immediately by a resistance to any attempted separation. It may be crudely demonstrated by lightly touching the adhesive with a finger and then assessing subjectively the existence or otherwise of a force restraining removal of the finger".

Because of their high tack, solutions of rubber can be used as contact adhesives (sometimes described as 'two way stick' adhesives.) As the description implies, a joint may be formed by coating both surfaces with adhesive and then bringing them into contact - only momentary pressure being necessary. This can be a convenient and quick bonding technique, especially for low volume production. In addition to having good adhesion to a wide variety of adherends, another characteristic of contact adhesives, in common with epoxy resins and hot-melts from the commercially used woodworking adhesives, is their ability to bond non-porous surfaces.

Prior to the development of synthetic rubbers, natural rubber (NR) was the only elastomer available for the manufacture of contact adhesives, and whilst large volumes of NR have been used for this purpose, it has several adverse properties, which may be summarised as follows:

- solutions tend to be viscous even at low solids contents
- films have poor resistance to oils and weather
- films have rather low cohesive strength

In order to improve performance, NR has largely been superseded in contact adhesives by synthetic rubbers. Some nitrile rubber, which is a copolymer of butadiene ($H_2C=CH-CH=CH_2$) and acrylonitrile ($CH_2=CHCN$) is used but the vast majority of contact adhesives employed in the woodworking industries are based on Neoprene, which is polymerised chloroprene ($H_2C=CCl-CH=CH_2$).

Neoprene adhesives have better resistance to oils, weather and heat than those based on NR and greater cohesive strength than all other elastomers on account of their unique ability among rubbers to crystallise during film formation.

Contact adhesives consist of Neoprene dissolved in a solvent blend, usually an aromatic hydrocarbon such as toluene and a ketone such as methyl ethyl ketone; though chlorinated hydrocarbons such as carbon tetrachloride may also be used. In order to ensure suitable tack, viscosity, and adequate ageing, other ingredients are also present.

These include:

- Acid receptors, such as zinc and magnesium oxides
- Antioxidants
- Fillers, such as china clay and chalk
- Resins, such as butyl and terpene phenolics to obtain longer tack retention, improved adhesion and cohesive strength.

The finished product is therefore a complicated formulation and like 'emulsion' and hot melt adhesives, Neoprenes are usually supplied ready for use. They are applied by hand or spray (cold or hot) to both adherends which must then be left for a finite period (usually 2 - 5 minutes) to allow for solvent evaporation. The two surfaces are then brought together and preferably passed through a nip roller (roller press) capable of applying pressures up to about 3.5 kg/cm^2. The bonded panels may then be worked and machined immediately.

Spraying has the following advantages over hand application:

- Faster application and drying
- More economical
- Less risk of solvent entrapment due to more uniform application of adhesive resulting in better adhesion.

In the hot spray technique, the adhesive is heated (to about 60-75^{o}C) in a simple circulatory heater until it is ejected from the gun. Originally this was the only method of obtaining a fast drying Neoprene but now solvent blends are available to give similar rates of evaporation for cold spraying. The latter has the advantage of simpler and less expensive equipment while the former technique possibly facilitates finer atomization and hence better coverage.

The main advantages of contact adhesives compared with other types is their good adhesion to a wide variety of substrates (some of which will be mentioned in Chapter II) and their ability to bond non-porous surfaces to each other. They also allow small workshops without presses to achieve fairly fast production rates with a minimum capital outlay.

Their principal limitations may be listed as follows:

- Poor heat, water and weather resistance compared with thermosetting resins
- Subject to creep and hence not suitable for structural applications
- High cost
- For higher volume mass production, e.g. veneering, not as efficient or as fast as flow-line cold or hot-pressing lines
- The solvents used are both highly flammable and present toxic hazards

In view of the last point and the increasing attention given to environmental, health and safety aspects of industrial processes, much work has recently been carried out on the use of Neoprene (and other polymer) latices as contact adhesives. Formulations have been developed which have satisfactory bond strength, but compared with solvent based Neoprenes, latex adhesives dry more slowly and have a shorter bonding range. Hence they have not yet been widely adopted in the woodworking and related industries.

CHAPTER 2

3.0 APPLICATIONS

3.1 Selection of adhesives in relation to end-use

General

So far the composition and characteristics of adhesives have been considered in isolation; these will now be related to specific applications.

Considering only the performance of adhesives, they may be classified according to the following groups of characteristics:

- The performance of the adhesive in relation to bond-strength, heat, moisture, and permanently applied stress
- The conditions required to achieve maximum performance from a given type; bonding pressure, temperature and wood moisture content
- The types of materials to which they will adhere

Table I sets out these properties against each of the adhesive types discussed in Chapter I. It is appreciated that such a summary omits important exceptions, and also that special formulations within a given type may extend the range normally associated with a particular adhesive; the use of auxilliary products such as primers may also enable adhesives to perform well in applications for which they are not usually employed.

The decision-making process used to select an adhesive is represented diagramatically in Figure 5. In a simple case the diagram may be followed step-by-step and the answers obtained at each stage checked against Table I. Often, however, the 'perfect' adhesive cannot be employed because of modifying factors such as lack of suitable equipment or economic considerations; also more than one system may be suitable for a given application but another modifying factor (such as the use of preservative treated timber, high moisture content wood or low shop temperatures) may narrow the choice or even dictate an 'unconventional' selection. The diagram shows how such modifying factors influence the stages of selection.

Developing the process represented by Figure 5. a check list may be drawn up which will suit most adhesives applications. Such a list is given in Table II and its use explained by the three cases shown. Case A represents the production of flush doors. Critical points are indicated by ticks, and it will be seen that a relatively slow rate of production is required; although both hot and cold pressing are available. Reference to Table I indicates that a number of materials could be used and the final choice will probably depend on glue cost and ease of handling. A UF glue with extender see Section 3.2.1. or a 'simple' PVAC glue could be used. The former would require mixing with a hardener and have a limited usable life; the latter would not be subject to these limitations but would be considerably more expensive. PVAC is also slow to harden at the centre of doors, because moisture cannot readily diffuse from this area.

Case B refers to cement-asbestos faced cladding panels with frames made from preservative treated timber. The type of preservative used will probably be the deciding factor here, also the panels must be suitable for exterior exposure. Reference to Section 3.5.1. will show that R-PF adhesives perform well with many of these preservatives and Table I shows they are fully weather resistant and will adhere to asbestos cement. In this case, therefore, only a single choice is available.

Case C is exterior grade plywood panels faced with high pressure decorative laminate, for use as kitchen work-tops. Both hot pressing and spraying equipment are available, but a production rate of only a few seconds per panel is needed. Table I suggests that a sprayed Neoprene adhesive would be suitable but that resorcinol or UF adhesives could also be used. (Although Neoprenes form a bond in only a few seconds, 2-5 minutes drying time are needed before bonding. Shop lay-out must, therefore, allow for this). Even with very high temperatures, the thermosetting resins would have to be pressed for more than 1 minute (to allow heat penetration through the laminate) and the effect of heat on the laminate could cause distortion. Neoprene is thus the final choice, although excessive wetting may eventually cause bond failure.

The last example has been deliberately developed to show the difficulty of picking an 'ideal' adhesive and, in cases where all requirements cannot be met, it will be necessary to compromise on some factor, e.g. rate of production, adhesive cost, to obtain the desired performance.

Economics may also be a determinant in choosing an adhesive. This subject is difficult to consider in detail, since the price per tonne of glue varies widely, especially if imported. Availability may often overide the selection of the 'best' glue by technical attributes alone. The cost of the bonding process is, of course, influenced by rate, the equipment available and/or the investment required to create the appropriate bonding conditions.

3.2 Joinery

3.2.1 Flush Doors

Flush doors, consisting of a wood frame, light weight cellular paper core and hardboard or plywood faces were introduced only about 30 years ago and are now manufactured on a very large scale. They contain no traditional joints or mechanical fastenings but are stressed skin structures relying entirely on the glue lines between the faces and the frame and core for strength and integrity. The performance of the adhesive as in many other glued structures is therefore of fundamental importance to the whole concept.

Flush doors have gained their great popularity for several reasons, one of the most important being that they can be mass produced economically on an assembly line basis. The assembled components can be hot pressed in multidaylight or flow-line presses or cold cured. UF adhesives are almost universally preferred for gluing flush doors by both processes on account of their:

- excellent adhesion to the materials in question
- high strength
- good heat and water resistance
- low cost, which may be reduced even further by the addition of fillers and extenders without unduly impairing the above properties.

China clay is the most efficient filler for UF resins in flush door manufacture though cereal, shell and wood flours may also be used.

Typical Flush Door Formulations (all parts by weight)

Liquid UF Resin	100	100	100	100
Hardener	10-20	10-20	10-20	10-20
China Clay	50-70	-	-	-
Wheat Flour	-	40-50	-	-
Olive Stone Shell Flour	-	-	30-50	-
Wood Flour	-	-	-	5-10
Water	20-35	40-50	15-25	20-30

For hot pressing a hardener giving a usable life of 5-10 hours is normally used. The traditional cold curing process, which is still the most economical for high volume production, consists of pressing packs of assembled doors between caul boards which are then clamped together so that the pressure is retained when the press is opened. The clamped packs are then moved out of the press and stored at room temperature until the glue has cured. Depending on the turn round required this usually takes from 4-24 hours and hardeners with the corresponding pot-lives are used.

In recent years the need to make better use of available factory space has caused a few of the larger manufacturers to seek an alternative method of cold curing flush doors. Instead of one, several presses are used per production line. The doors are glued and the presses progressively filled. When all the presses are full (which may take from say 30-60 minutes depending on the number of presses and rate of assembly) the first may be unloaded and the cycle repeated. In order to achieve short pressing times of this order reactive formulations with a pot life of 15-45 mins are required. Whilst there is no difficulty in formulating UF systems with this performance, automatic metering and mixing machinery and specialised feeding and application equipment are required to handle them.

The vast majority of flush doors are used in the interior of buildings but when they are required for exterior purposes they may be bonded with melamine, resorcinol or phenolic adhesives for increased weather resistance. Hot pressing must be used for melamine and phenolic resins.

3.2.2 Panelled Doors

Unlike flush doors, panelled doors have been made for hundreds of years and are still preferred for the majority of exterior situations. They consist of a substantial wood frame into which are fixed panels usually made of hardboard, plywood or glass. The horizontal frame members - top, bottom and (where used) middle rails - are joined to the stiles with dowel joints. This type of joint should be sufficiently tight fitting so that after the initial clamping together of the assembled components no further external pressure is necessary while the glue sets. In view of this, the rate of setting is not usually an important factor in the selection of adhesives for this application.

UF adhesives are still quite widely used for panelled doors and from the point of view of all-round performance they are the most satisfactory. For less well fitting joints gap filling formulations should be used. PVAC adhesives are also widely used, particularly in conjunction with automatic application equipment, for which their long pot life is well suited. Also the cleaning down time is reduced. For exterior doors, catalysed PVAC emulsions should be used to provide improved weather resistance. Although technically well suited to this application, resorcinol resins are little used on account of their dark colour and the difficulty of removing any squeeze-out.

3.2.3 Fire-check and other Specialised Doors

British Standards define two types of fire-check door[2], which resist the passage of fire for at least 30 and 60 minutes respectively. The first type may be constructed with a solid core of materials, such as plasterboard, cork, flaxboard or laminated wood strips and plywood skins. This type of door is made by a very similar technique to cellular core flush doors, although they are almost exclusively hot pressed, which is probably more efficient for the volume involved. Thermosetting resin adhesives have a definite technical advantage for this application on account of their high heat resistance. UF adhesives with similar formulations to those quoted for flush doors are used but generally with less filler and water.

This is because there is a greater tendency for solid cores to show through the faces and this can be exacerbated by the swelling action of excess water in the glue line.

The 1 hour type of fire-check door also has a solid core and plywood faces but in addition this has linings of asbestos sheeting (or equivalent material). Asbestos boards are alkaline and hence UF resins are not suitable, unless the surface of the asbestos is neutralised with a primer, since UF resins cure under acidic conditions. Because priming introduces another process, which has to be carefully carried out to achieve good results, these doors are usually made by gluing the asbestos linings with a resorcinol resin. For cold pressing R-PF resins are used but for hot pressing P-RF resins may be used. Filled, powder hardeners, (or a suitable separate filler such as chalk), are normally recommended to reduce excessive penetration into the asbestos. High press temperature must be avoided because of the risk of distortion with a construction of this type, hence PF resins are not suitable.

Other doors with solid cores are also made for aesthetic, sound proofing or security reasons but provided construction is from wood-based materials, they may be treated as ½ hour fire-check types for gluing purposes.

3.2.4 Stairs

The various components of stairs were traditionally bonded with animal glue which was particularly advantageous for the blocks which reinforce and join the 'risers' to the 'treads'. With animal glue these could be simply rubbed in. Nowadays these blocks are usually screwed and glued with PVAC adhesive, which is also used for dowel and other joints in the fabrication of stairs.

3.2.5 Windows

Windows consist of two principal components - the frames and the openings-sashes on casements. The majority of windows are still made from wood which is formed into frames and sashes with comb joints. These are glued with a variety of adhesives including:

- One component PVAC
- Catalysed PVAC
- Separate application UF] both close contact and
- Mixed application UF] gap-filling types
- MUF
- Resorcinol

There seem to be few standardsfor the gluing of windows and it is left to the preference of the individual manufacturer and customer or specifying authority. Some manufacturers even use different adhesives for the frames and sashes. This is not quite so absurd as it first seems since the sashes are really more critical than the frames, which once installed would not be structurally affected by subsequent joint failure (most window joints are also pinned with metal dowels).

With the introduction of pressure operated automatic gluing machines PVAC is more widely used, because these adhesives are better suited to this type of equipment (cf. automatic dowelling machines). However, because of the high degree of exposure of windows, particularly in multi-storey buildings, some specifiers insist on the use of resorcinol resin adhesives.

3.3 Furniture

3.3.1 Veneer Joining

Today, edge-to-edge joining of veneers by gluing, is less common in furniture manufacture. Furniture veneers are normally less than 1 mm thick and splicing by gluing is technical difficult, and requires expensive, specialised machines.

The best methods of edge-to-edge joining of decorative veneers involve either taping, or 'stitching.

For 'taping' gummed paper can be used both for joining 'leaves' of veneer and repairing splits; tapes are applied by static power-driven machines, or where a small volume of work only is required, hand-held applicators can be used. The tapes should be selected with care, the thin tapes intended for this purpose may be laid on the surface to be glued so that no subsequent sanding is necessary.

'Stitching' produces an even less conspicuous joint. The process involves applying a glass filament (coated with a thermoplastic) in a zig-zag fashion across the joint. The filament is then rolled with a heated roller, and a bond is formed instantaneously as the thermoplastic coating cools. These joints too may be laid face down. Both power driven static equipment and hand-held versions are available for applying these threads.

If required, a number of adhesives can be used for edge-to-edge gluing of veneer; the choice depends mainly on the equipment available to apply the adhesive. Traditionally, a hot solution of animal glue may be brushed onto the edges of veneers whilst they are under pressure in the trimmer or guillotine, and a 'hardener' of aqueous formaldehyde is applied by the splicer. The glue is first softened by the heat in the splicing machine, but the tanning action of the formaldehyde hardens it so that a firm joint has been made before the veneers emerge from the heated zone.

Such machines may be adapted to the use of synthetic glues, either by pre-applying unmixed glue and replacing the formalin with a liquid hardener, such as dilute phosphoric acid, or by using a pre-mixed adhesive applied in the trimmer.

With UF glues there is a tendency for the part-cured adhesive to stick to the metal parts of the splicer. This can be overcome by the incorporation of a lubricant such as engine oil, palm oil, tall-oil, steric acid or its derivatives.

Typical formulations are:

1. - for mixed application

Liquid UF resin 65 % solids	100	parts by weight
Light engine oil	3-7	parts by weight (optimum determined by experiment)
Liquid hardener	10	parts by weight (the hardener for pre-applied systems should have a pot life of about 20 hrs at 25°C)

2. - for separate application

Liquid UF resin 65 % solids	100	parts by weight
Light engine oil	3-7	parts by weight (as above)
Separately applied hardener:		
Phosphoric acid 85 % H_2PO_4 w/w	15	parts by weight
Water	85	parts by weight

When pre-applied techniques are used the adhesive should have a long pot life to allow for stacking the veneers some time before they are joined, which allows water to evaporate and gives more reliable bonding. Surprisingly, the veneers may be joined effectively after they have been standing for almost double the pot life. A fast mixed application hardener may have the disadvantage of causing the resin to cure before the edges of the veneers are completely butted together.

Commercial formulations frequently combine powdered UF resin, catalyst and lubricant in a single product, which need only be mixed with water before use. Powder hardeners formulated for this application usually include hardening chemicals, lubricant and filler.

PVAC glues have also been used for edge-joining, usually by pre-applying and re-softening under heat using special splicers. For this process formulated products would be purchased ready for use. A disadvantage of these materials is that they are smeared over the veneer face and can interfere with subsequent lacquering processes, since the thermoplastic product cannot readily be removed by sanding.

3.3.2 Panel Surfacing (Veneering)

Wood Veneers

Wood veneers may be bonded to panel materials (particle board, blockboard, plywood, fibreboard etc.) in a variety of ways; the choice of adhesive is usually determined by the equipment available, rather than by the technical performance required.

Veneering with animal glue is a highly skilled craft which has been well understood for centuries. Disadvantages are that specially trained craftsmen are needed, production rate is limited and the subsequent bond is vulnerable to both high humidity and excessively dry conditions.

Veneering at room temperature is normally carried out by pressing panels in large batches in a cold press. PVAC adhesives are suitable, though expensive, but a quick turn-round is ensured as pressing times of 15-30 minutes can be obtained. When selecting a PVAC adhesive for this purpose it should be remembered that the adhesive must not dry out during the period required to build up a stack of panels and this will limit the speed of set available; both assembly and setting times are greatly influenced by spread rate.

UF glues, either filled or unfilled may also be used for cold pressing.

(a)	Liquid UF Resin 65 % solids	100	parts by weight (or equivalent amount of re-constituted powder)
	Flour Extender	10-20	parts by weight
	Water	10-25	parts by weight (depending on initial resin viscosity and working viscosity required)

Hardener giving working life of 1-2 hours at shop temperature say 10 parts by weight.

(b)	Liquid UF Resin 65 % solids	100	parts by weight
	Filler (wood or shell flour)	0-10	parts by weight (to adjust viscosity if needed)
	Hardener	10	parts by weight (as above)

It should be noted that the inclusion of large amounts of filler and water, although reducing glue cost, also prolong setting time.

Similar formulations may be used for veneering in multi-daylight presses between 60 and 95°C, the choice of hardener depending on the pot life and pressing time required.

When pressing above 100^{o}C, using flow-feed presses, to attain very high production rates, choice of filler and hardener become more critical. The chief factor determining setting time at temperatures in the 115-140^{o}C range is the amount of moisture to be dissipated from the glue line. This should be kept to a minimum by:

(a) Using a low viscosity low water content glue mix
(b) A low glue spread

Glue spread is a matter of careful control by the operators and the use of modern, well maintained, doctor-roll spreaders. Glue formulations are preferably based on resins with a low viscosity in relation to solids content. Large amounts of filler and water should be avoided and either a liquid resin/liquid hardener applied at very low spreads (100 : 110 g/m^2); or a filled, low water content mixture as below:

UF resin 65 % solids content	100 parts by weight (or equivalent re-constituted powder)
Shell flour	10 parts by weight
Kaolin	40 parts by weight
Water	5-10 parts by weight (to adjust viscosity)

Hardener to give working life of 8-15 hrs at shop temperature, say 15 parts by weight.

Phenolic and resorcinol resins are generally difficult to use for veneering because of their dark colour, with consequent risk of staining the surface. Cross linking PVAC glues are also suitable and may show some advantages in speed of set versus usable life in the temperature range 75-85^{o}C, especially where thick veneers are being used. They may also be used in other temperature ranges but experience suggests they do not show significant performance advantages above 100°C, and are substantially more expensive than UF glues. Occasionally, panels are required to withstand surface spread of flame or other fire tests. In these cases, especially where the veneer is bonded to a flame retardant substrate a glue with good heat resistance is required. Here melamine, or melamine-UF glues should be used.

Decorative Plastics Laminates

All the techniques used for wood veneering may be adapted for high pressure plastics laminates. Animal, UF and PVAC glues all adhere well to conventional PF-paper backed material, providing that it is well sanded. Polyester laminates may require special adhesives, such as copolymer PVAC or epoxy. Contact adhesives are suitable for most types. Since laminates are normally thicker than wood veneers high production rates require either high press temperatures or the use of very fast glues. Catalysed PVAC types show some advantages here as it is also prudent to maintain a low press temperature (75-85°C) to avoid undue distortion of the laminated panel.

Paper 'Veneers' and Foils

The high cost of wood veneer has stimulated the development of a variety of substitutes. These are normally printed papers impregnated or coated with resins, which may either subsequently be lacquered or form a decorative finish in their own right. These veneers are best bonded with hot pressing methods using low viscosity adhesives. Catalysed PVAC is suitable and unfilled UF formulations of the type given above may also be used. Care should be taken that the glue mix contains no granular material as this will disfigure the panel surface, or may puncture the foil. If hardeners are added in powder form 30-45 minutes should be allowed between mixing and application to ensure that all crystalline products are in solution.

Plastics Foils

Thermoplastics foils (PVC containing varying amounts of plasticiser) are extensively used as finishes for particleboard. VA-copolymer adhesives have become widely accepted for this application; normally applied by composite machines which unroll, sometimes warm, and apply the foil. The bond is formed by nip-rolling and the panels then require some 24 hours to develop full bond strength before further processing.

Formulation of these copolymer adhesives is highly specialised, and they must normally be purchased from an adhesives formulator. Some proving trials may be necessary to ensure that adhesive and foil are compatible and these should be repeated if either adhesive supplier or grade of foil are changed.

Whilst VA-copolymers give excellent bonds at room temperature, they may fail, or allow creep, at elevated temperatures (e.g. in kitchen furniture). Epoxy formulations are widely used for these applications and, being non-aqueous, they do not swell the board surface as dispersion adhesives do. Proving trials are always required, to assess the compatibility of adhesive and PVC. Polyurethanes have also been used to a limited extent.

Unplasticised PVC sheeting may be bonded with synthetic latices, but these are not normally suitable for thin plasticised foils. Any adhesives containing solvent are likely to result in shrinkage and foil damage over a period of time.

3.3.3 Panel Edging

The edges of furniture panels may be finished with a variety of materials which can be bonded in several different ways. The simplest method of gluing edgings is with a cold setting adhesive and the use of cramps or an elementary jig to apply pressure. The choice of adhesive would depend first upon the material in question and secondly the required setting time - usually as fast as possible for this application. Wood, paper and decorative laminates can be glued by this method with a UF, PVAC or contact adhesive, whereas PVC or other thermoplastics would require a VA-copolymer formulation. Although the rate of production possible with this type of technique is rather low it is convenient for small joinery and shopfitting works.

For higher volume production more complex machinery and techniques are available. With a simple jig the output can be greatly increased by the use of conductive metal strips which can be raised to a fairly high temperature when connected to a low voltage source of electricity. This method is known as low voltage (LV) or strip heating and is particularly effective for thin materials such as wood veneers or decorative laminates which allow heat to pass quickly through to the glue line. Warm or hot setting UF formulations and catalysed PVAC adhesives are most appropriate and setting times can be as short as 30 seconds under favourable conditions. Thermoplastics edging materials cannot be used as they may be softened or damaged by the heat source. The LV heating principle is also used in continuous edge banding machines in which the panels are conveyed between endless heated metal belts. The output of such machines is greater than the simpler static models.

For thicker materials, such as solid wood lippings, used to edge flush doors and some furniture panels, radio frequency (RF) heating is often employed; since strip heating would be uneconomical because of the time required for heat penetration. This electrical method of accelerating the setting of aqueous adhesives (aminoplastic and PVAC types), depends on the glue line absorbing energy, and becoming hot, when placed in an RF field. The principle relies on the difference in electrical properties between the glue and the adherends.

Where adhesive has a higher loss factor (is more lossy) it is a better conductor than wood or wood based products (providing that their moisture content is not excessive). If the moisture content is greater than 15 % the wood competes significantly for the available RF energy and setting times are prolonged. For optimum performance the loss factor of the adhesive can be increased by using special grades of hardener which are formulated to contain extra electrolyte[3]. Alternatively, a standard cold or warm setting hardener can be used and a few per cent of suitable electrolyte added to the mixed adhesive. Common salt (sodium chloride) is recommended for this purpose and normally 2 % is sufficient. Some PVAC adhesives, particularly the catalysed type (which have a higher loss factor due to the presence of the catalyst) are also suitable for RF heating. However, if a one-component formulation is used, pressure must not be released when the glue line is above the softening point of the polymer (generally 60-70°C). With non-catalysed 'emulsions' it is often good practice to switch off the power half way through the pressing cycle to enable the glue line to cool sufficiently before release of pressure.

Since, to attain a rapid degree of polymerisation, glue-line temperatures must exceed 100°C, it is necessary to provide sufficient pressure to prevent the components of the adhesive boiling, thus producing a defective joint. (Boiling point of liquids is elevated by increased pressure).

Three types of electrode arrangement are distinguished in RF applications, but for edging only glue line and stray field heating are used. Lipping is well suited to glue line heating which is the most efficient and fastest form of RF. Setting times, which can be as short as 5 seconds, depend primarily on the following factors:

- Available RF power
- Reactivity and loss factor of adhesive
- Depth of joint, i.e. distance between electrodes
- Moisture content of adherends

PVC and impregnated paper edgings are most efficiently bonded in continuous edge banding machines with hot-melts. Edgings in strip form such as wood veneers and decorative laminates or even solid wood lippings can also be bonded with hot-melt machines but the full potential of the technique is only realised with materials which can be supplied in reel form.

3.3.4 Cabinet Assembly

Glued joints between flat surfaces - mitre, butt, etc.

With the exception of contact adhesives, all the glues listed in Chapter I may be used to form simple butt joints between the edges of solid timber or particleboard; because of its interior construction, blockboard cannot normally be edge glued. Mitre or 'T' joints cannot be satisfactorily made with solid timber because one end-grain surface is involved. Such joints will be inherently weak regardless of adhesive type. Particleboard, on the other hand, can be joined either by mitring or by bonding edge grain to face in the form of a 'T'; such joints are common at the corners of cabinets.

Final selection of glue for these operations will depend mainly on the performance required and the speed of production. PVAC glues give excellent results on mitring or butt-jointing for particleboard, providing a grade is selected which has a high viscosity, to eliminate absorption into the board edge. This selection is best made by experiment since the texture of particleboards varies widely. UF's may be similarly used, and again control of viscosity is necessary. It is not possible to give typical formulations because the initial viscosity of resins varies greatly; however, the most effective way of increasing viscosity of UF's is to add softwood or shell flours. In small workshops, where high outputs are not required it is convenient to use separately applied hardeners with UF's, this avoids the necessity for mixing glue and possible waste of unused materials.

Hot-melts, applied through special guns which heat preformed pellets of adhesive and extrude them through a nozzel, can be used for the corner joints of cabinets. Very rapid (less than 1 minute) clamping must be used with such adhesives, to form the joint before the adhesive begins to set.

It is difficult to apply heat to butt joints of corner joints because of the depth of the glue-line involved. Radio frequency heating (included in carcase clamps) has been successfully used however. 'Simple' or catalysed PVAC's are suitable; as are UF's, either with separately applied or mixed application hardeners. The PVAC glues should be of a type stated by the manufacturer to be formulated for use with Radio Frequency heating; not all 'simple' PVAC glues are suitable as they are not sufficiently lossy (see 3.3.3). UF glues should usually contain filler such as softwood flour (up to about 10 % on glue solids) and/or wheat flour or maize starch in similar amounts, to prevent undue penetration into porous materials. Lossiness of UF's is also important (3.3.3). The use of separately applied hardeners with UF's in conjunction with RF heating is not normally successful, since the hardener tends to dilute the adhesive and may give rise to ionisation near the electrodes with consequent electrical breakdown (arcing). If separate application hardeners are used they should contain non-volatile acids such as dilute phosphotic or sulphuric. A 15 % aqueous solution of ammonium chloride would also be suitable.

Dowelling, Tennon and Mortice Joints

Dowelling, and the forming of tennon and mortice joints may be considered as similar types of gluing processes.

Animal glue has been used successfully on chair frames in both types of joint for centuries; although subject to decay under tropical conditions and eventual embrittlement in dry climates.

'Simple' or catalysed PVAC glues are suitable, particularly used on automatic machines which inject glue into dowel holes or tennonsfrom a pressure vessel. The use of a reactive adhesive such as a UF would present difficulties, owing to their limited pot life.

Any glue used for dowelling should be formulated not to shrink or craze in the joint[4]. PVAC types should be a fairly high solids content (55 % or more), 10-20 % of the total solids being of an inert filler such as whiting or gypsum. UF glues should, ideally, be of the gap-filling type; although with modern drilling or morticing techniques and well made dowels and tennons, the glue film can be very thin giving extremely strong, durable joints with close contact formulations. Separately applied hardeners (such as 15 % aqueous ammonium chloride or 10-15 % aqueous orthophosphoric acid solution) can be used with un-catalysed UF resin. The hardener should be applied to the dowel or tennon by dipping and shaking off the excess; dowels may be treated in batches by immersing them using a net or basket of acid resistant material. Most of the water from either of these hardeners can be allowed to evaporate before gluing without impairing their effectiveness. It should be remembered however that this technique can cause components to swell and render assembly difficult.

Other methods

The 'vee jointing' technique of cabinet assembly[5] can use PVAC, or hot-melts, as described under mitring, above.

A novel method of joining corners of drawers and cabinets is to machine a dumb-bell shaped hole across the joint, and inject a strong molten plastic into this when the components are positioned. As the plastic solidifies, a permanent key is obtained between the parts.

3.4 Special Gluing Processes and Components

3.4.1 Freight Container Floors

Laminated panels for freight container floors are an important industrial wood product. The panels comprise a number of rectangular pieces of wood from 30-40 mm wide and deep, built up to a width of approx. 300 mm. The glued joints have to withstand arduous climatic conditions and cyclic wetting and drying; performance is therefore assessed against specifications comparable to those for exterior adhesives in other applications.

R-PF or M-UF adhesives are suitable and curing is normally accomplished by RF or in specially designed hot presses. Resorcinol glues are not normally lossy enough for rapid use under RF heating and the inclusion of sodium chloride (see Section 3.3.3) should be adopted. The use of high density tropical hardwoods in this application can give some gluing problems but these are normally surmountable by selecting appropriate assembly conditions, spread rates and moisture contents.

3.4.2 Composite Panels

Composite panels comprising frames, skins and cores of dissimilar materials are used in a wide variety of applications.

Examples are:

- Interior and exterior building elements
- Vehicle body panels, including parts for caravans (mobile homes or trailers)
- Demountable partitions

In many cases the skins and/or cores of these panels are made of non-wood materials; some of the most common bonding problems are described below.

Foam Cores

Plastics foams such as expanded polystyrene (XPS), polyurethane (PUR), and phenolic (PF) foams, can be bonded to wood with many conventional wood adhesives. XPS will not normally withstand glue line temperatures above 65-70°C and the adhesive chosen should therefore cure under these conditione. Most foams can be satisfactorily bonded without true adhesion, the adhesive flows into the intersices of the foam structure and locks the material in place. Where foams have large cells or an undulating surface, gap filling adhesives are required. It should be remembered that water will not readily diffuee through plastics foams so that the material to which they are bondsd must be absorbent when using water-based adhesives (see 3.2.1). Where both adherends are non-absorbent, epoxies or specially formulated rubber-based adhesives can be used. Rubber based adhesives should not contain solvents which attack the foam. Phenolic foams can be bonded to wood-based materials with UF glues which contain no hardener, the foams being sufficiently acid to effect the cure of these systems.

Metal to Wood Bonding

Where a high degree of strength, or special heat or moisture resistant properties are required, specialised advice should be sought; the following general principles however can be adapted to most needs.

Cold bonding is preferable, since the expansion of metal can result in distortion if hot pressing techniques are used. Suitably formulated sprayed Neoprenes give good bonds with high peel strength but may not survive repeated wetting and drying cycles. Specialised phenolics, used with or without primers, are well established in this field but require hot curing. Primers based on dispersions of casein in natural, or synthetic latices, can be used with either UF or RF glues; and for less exacting applications or where thin metal foils are to be bonded, can be applied as adhesives in their own right. Epoxy resins are highly suitable because of their excellent adhesion and lack of volatile constituents (see 2.2.2). For mass production, however, their curing times are rather slow and bond quality is often of a higher order than required.

Surface preparation is all important in metal bonding and degreasing and abrasion are normally minimum requirements; acid etching may also be needed with some adhesives.

Asbestos Cement to Wood

The basic principles of this process have been outlined in 3.2.1. Choice of adhesive would depend on the environment of the final panel and for some purposes PVAC formulations are suitable. Asbestos-cement is alkaline and therefore PVACs resistant to saponification should be chosen. Some suppliers recommend VA copolymers for this reason. It should also be remembered that 'emulsion' adhesives are relatively low solids and may not fill gaps between poorly dimensioned or undulating surfaces. Sprayed Neoprene may be used, providing that the adherends are carefully dimensioned, and the environment of the completed panel is consistant with the performance of these glues.

3.4.3 Bonding Plastics-modified Wood

Wood modified by the injection, and subsequent curing, of polymeric materials with or without compression and densification, has sometimes to be bonded to itself or to natural wood. Compressed impregnated laminates made using phenolic resins can be bonded to wood, providing the surfaces are thoroughly abraded and conventional thermosetting wood adhesives used. If the material is to be bonded to itself contact adhesives or epoxies will be required as there is no possibility for volatiles to escape from the joint.

Wood treated with styrene-acrylate, or other acrylic polymers, cured by ionising radiation is difficult to bond even when abraded. The best choice for this is probably an epoxy formulation.

3.4.4 Bonding Preservative Treated Wood[*]

Joints made with thermosetting resins and catalysed PVAC adhesives are resistant to moisture. These adhesives are, therefore, ideally suited for gluing timber structures for use where high moisture contents are liable to develop. Timber used in these situations may be treated with a wood preservative. Special care is required when gluing treated timber to attain satisfactory bond strength.

Preservative treatment may be carried out either before or after gluing. In order to obtain optimum adhesion it is preferable for treatment to be carried out after gluing but practical limitations often preclude this.

Treatment after Gluing

In this case the main requirement is that the adhesive should be allowed enough curing time to withstand the effects of the preservative process. The curing time required will depend upon the particular adhesive used and the conditions, particularly temperature and moisture content. Fully cured resorcinol and phenolic resins are not affected by even the most severe treatments, such as vacuum-pressure impregnation with heated solutions. This type of treatment, which is equivalent to prolonged immersion in warm water, may have a detrimental effect on the bond strength of some PVAC and UF adhesives. Components which are to be treated in this way should therefore be glued with resorcinol or phenolic resins.

Treatment before Gluing

In situations where this is unavoidable, suitable pretreatment of the wood prior to gluing may be necessary to obtain satisfactory adhesion. All preservative treatments interfere to some extent with the gluing properties of wood and the bond strength actually developed depends upon the degree to which the surfaces of the treated wood can be restored to normal.

Preservative Types and Procedures

There are three main types of wood preservative:

- Creosotes
- Water-borne preservatives
- Organic solvent based preservatives

Creosotes

These are tar oils and on account of their oily nature, creosotes interfere with the wetting of the timber by the adhesive. However, if preservative loading is not too high and sufficient drying time has been allowed (no signs of bleeding) satisfactory results can be obtained with resorcinol resins. The surfaces should be clean and free from deposits and it is advisable to plane or sand the faces prior to gluing.

Water-borne Preservatives

These are aqueous solutions of inorganic salts which may, but usually do not, contain water repellant substances. They are usually applied by vacuum-pressure impregnation, because aqueous solutions do not readily penetrate wood simply by immersion. Overall salt loading is low but high localised loadings may occur especially in sapwood. Salt deposits may be left on or near the surface, and apart from this, the moisture content of the timber may be high after treatment. High moisture contents are detrimental to gluing, particularly with PVAC adhesives, and may cause severe stresses to be set up due to subsequent drying and shrinkage of the glued structures.

After this type of preservative treatment, therefore, the timber should be kiln-dried to within the anticipated equilibrium moisture content range of the finished product. The surfaces to be bonded should be planed although care should be taken to ensure that after planing the surfaces still mate well enough to give a close fitting joint. Gluing should be carried out as shortly after planing as practicable but in any event within 24 hours.

Organic Solvent Based Preservatives

This type of preservative consists of fungicides, insecticides dissolved in organic solvents, and may also contain water repellant additives. The solvents used in these formulations penetrate wood more readily than water and hence unlike aqueous based types are suitable for application by dipping, spraying or brushing. However, double vacuum or vacuum-pressure methods may also be used for applying organic solvent preservatives to timber which is used in situations where a greater degree of protection is required.

The main advantage offered by organic solvent preservatives is that they have little effect on the physical properties of wood. Being a dry process, there is no increase in moisture content and no subsequent swelling, shrinkage or distortion of the timber. Surface deposits are unlikely as preservative loadings are usually very low.

Work has shown{1}{6} that treatment with any of the chemicals commonly used in organic solvent preservatives does not interfere significantly with the gluing properties of pinus sylvestris. However, the presence of water repellant additives certainly may do so. For gluing wood treated with water repellant preservatives it has been found that the most suitable adhesives are those which contain organic solvents (ethyl alcohol and ethyl cellosolve giving best results). Such a solvent may be added (at the rate of ½-1½ % based on resin solids) to an unmodified UF resin but a partially etherified UF resin (in which the solvent is reacted with the resin during manufacture) is preferred. Certain resorcinol resins which also contain solvent from the manufacturing process give equally good results.

Care should be taken to ensure that all the solvent has evaporated from the treated wood before use (normally one to three days is sufficient). It is also advisable to plane or sand the surfaces within 24 hours of gluing.

3.4.5 Boat Building

Although wood was the traditional material for boat building, adhesives were not extensively used in their construction until the introduction of the synthetic formaldehyde-based resins during the 1930s and 1940s. Not only did these resins have the performance required for use in conventional wood joints under marine conditions, but their greatly improved strength and durability enabled a new method of construction to be developed - the cold moulded hull. This consists of bonding layers of suitable veneer over a wooden frame to form the exterior skin of the hull. Usually three layers are used and cross-banded for extra strength and stability (i.e. the grain direction of the centre layer is at right angles to the first and third). Alternatively, plywood itself can be used.

In addition to cold moulding, the other main applications for wood adhesives in boat building are:

- laminated keels and other main-frame components
- frame assembly
- edge gluing planking for decks, etc.
- interior joinery and cabinet work

Interior fittings may be glued with normal assembly glues and catalysed PVAC and UF adhesives are the most widely used for this purpose (see Joinery 3.2, Furniture 3.3 and Cabinet Assembly 3.3.4).

All other structural applications must be carried out with either a resorcinol resin or a gap-filling UF adhesive approved for marine applications. It is doubtful whether UF resins would have been approved for boat building if a large number of early vessels of glued construction which had been built with UF were not found to be perfectly satisfactory. Indeed, there are some small boats built over 30 years ago with laminated keels and moulded hulls which are still afloat and seaworthy today. In view of their satisfactory record in service over many years, therefore, some gap-filling UF formulations are still used at the present time, for light craft, although normally resorcinol resin adhesives would now be recommended.

Two difficulties commonly encountered in boat building are due to extreme weather conditions. When laminating or moulding is carried out in hot, dry conditions, the assembly time is critical and a formulation should be selected accordingly. The liquid hardeners developed for use with resorcinol resins have significantly longer assembly times than the corresponding powder hardeners and are particularly useful where this factor is important. The other difficulty is associated with cold weather. Since boat building, particularly of larger vessels, may of necessity involve some gluing with little protection from the elements, these conditions require an adhesive which will cure satisfactorily at low temperatures. Such formulations are available but rate of cure is not the only factor involved. Viscosity and wetting are also affected and gluing below 5°C is not generally recommended.

4.0 Compatibility of Thermosetting and Thermoplastic Adhesives

Where more than one type of adhesive is used in a component care must be taken to ensure that the processing conditions required for one adhesive are not detrimental to the other. For example, if panels are to be lipped or edged before veneering in a hot press a thermoplastic adhesive (PVAC or hot-melt) should not be used because of the risk of softening the glueline and thus weakening the joint during the pressing operation. Although the use of a low platen temperature (less than about 70°C), or a short pressing cycle at a high temperature (e.g. 30 sec. at 120°C) may not be detrimental under ideal conditions, if the initial bond is unsound or subject to stress (as in the case of curved lippings) bond failure is always a possibility.

An example of chemical incompatibility can occur if phenolic bonded plywood or blockboard is sanded so as to expose areas of glueline before veneering with an acid setting adhesive. The high alkali content of the exposed phenolic glueline can neutralise or severely retard setting of a UF resin causing adhesion failure. A similar effect can be observed when repairing casein glued joints with a UF adhesive. In both cases the problem can usually be overcome by treating the effected area with a suitable acidic primer to neutralise the surface before application of the UF adhesive.

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Notes for Table I:

A. Long experience and short term tests correlated & widely accepted. Newer types, which are claimed as suitable by some workers or accepted in certain National Standard are marked [1].

B. Continuous exposure to humidities above 80 %.

C. Load-bearing structural use, or resistant to stress induced by differential movement.

D. It is possible to use some grades of these glues to form bonds below 10°C, but usually undesirable, as wetting or ultimate strengths are impared.

E. The figure given refers to wood at 5-30°C, unless otherwise stated. When bonding at temperatures above 100°C, the generation of steam is a more important determinant than adhesive type in limiting moisture content.

1. Cannot be unreservedly recommended.

2. Formulations setting at 60°C claimed.

3. Special formulations required to meet these conditions.

4. Use of crosslinking PVAC under full exterior conditions not fully proved.

5. Figure refers to hot-pressing types. See E.

Table I: Summary of the Principal Properties and Application Requirements of the Adhesives described in Part I.

Adhesive Type. Those marked (H) require a hardener or catalyst to be added before use.		Glue-line Resistant to: Full out-door exposure (A)	Humid Interior conditions (B)	Occasional Wetting	Permanent Stress (C)	Normal Interior	Conditions required to form bond. Brief Pressure < 1 minute.	Sustained Pressure	Application Temp. (D) °C	Can be used with RF heating	Optimum wood moisture content range (%)	Ability to bond to non-wood materials. Metals.	Thermoplastics foils.	Asbestos-cement.	Rigid Decorative laminates.
Natural	- Animal					√	√	√	Applied @ 60		7-15	·		√	√
	- Casein			√	√	√		√	10-30		7-15			√	√
	- Tannin (H)	√[2]	√	√	√	√		√	[2] 100-130		7-14				
Thermoplastics:	PVAC - 'simple'			√		√		√	10-30	[3]√	7-14			√[3]	√[3]
	PVAC - Co-polymers			√		√	√	√	10-30		7-14		√	√[3]	√
	PVAC - Cross linking (H)	[4]	√	√		√		√	10-120	√	7-14			√	√
Rubbers:				√		√	√		10-30		7-14	√[3]	√[3]	√	√
Thermosetting:	Urea-formaldehyde (H)		√	√	√	√		√	10-120+	√	7-22			Sc	√
	Phenol-formaldehyde (H)	√	√	√	√	√		√	[3] 110-150		4-10[3]	Sc		Sc	
	Melamine-formaldehyde (H)	√[1]	√	√	√	√		√	60-140	[3]√	7-12				√
	Resorcinol-formaldehyde (H)	√	√	√	√	√		√	10-30	√	7-26	Sc		√	√
	Epoxy (H)	√	√	√	√	√		√	10-30		5-15	√	√	√	√

Key:
√ = Suitable.
No mark = Unsuitable.
Sc = Suitable if Special Conditions are provided - e.g. Primers, special surface preparation etc.

Table II. Check List of Factors to be considered when choosing an adhesive for three typical examples.

	CASE		
	A	B	C
Adherends:			
- Wood only (includes wood-based sheet materials)	+		
- Wood to non-wood		+	+
Joint Performance:			
- Full exterior exposure		+	
- Humid indoor conditions			
- Occasional wet-dry cycles			+
- Permanent stress			
- Non Critical	+		
Equipment available - or required:			
- Clamps	+	+	
- Can hot cure	+	+	+
- Radio Frequency			
- Special (e.g. for hot-melt or Spray application)			+
Speed of production:			
- Bond to be formed in seconds			+
- Bond to be formed in minutes		+	
- Bond to be formed in hours	+		
Special Conditions:			
- Wood moisture content			
- High density wood			
- Non wood material heat sensitive			
- Wood has been treated with a preservative		+	

Case A Interior Flush Door production

Case B Asbestos-cement faced cladding panels on preservative treated wooden framing

Case C Kitchen work-tops comprising high-pressure decorative laminate bonded to exterior plywood core.

Fig. 1 Effect of changing F : U ratio on reactivity with a hardener comprising 2.0 % NH_4Cl and 4.0 % Urea on wt of liquid resin.
Resin 'A' F . U = 1.8 : 1 Resin 'B' = 1.35 : 1

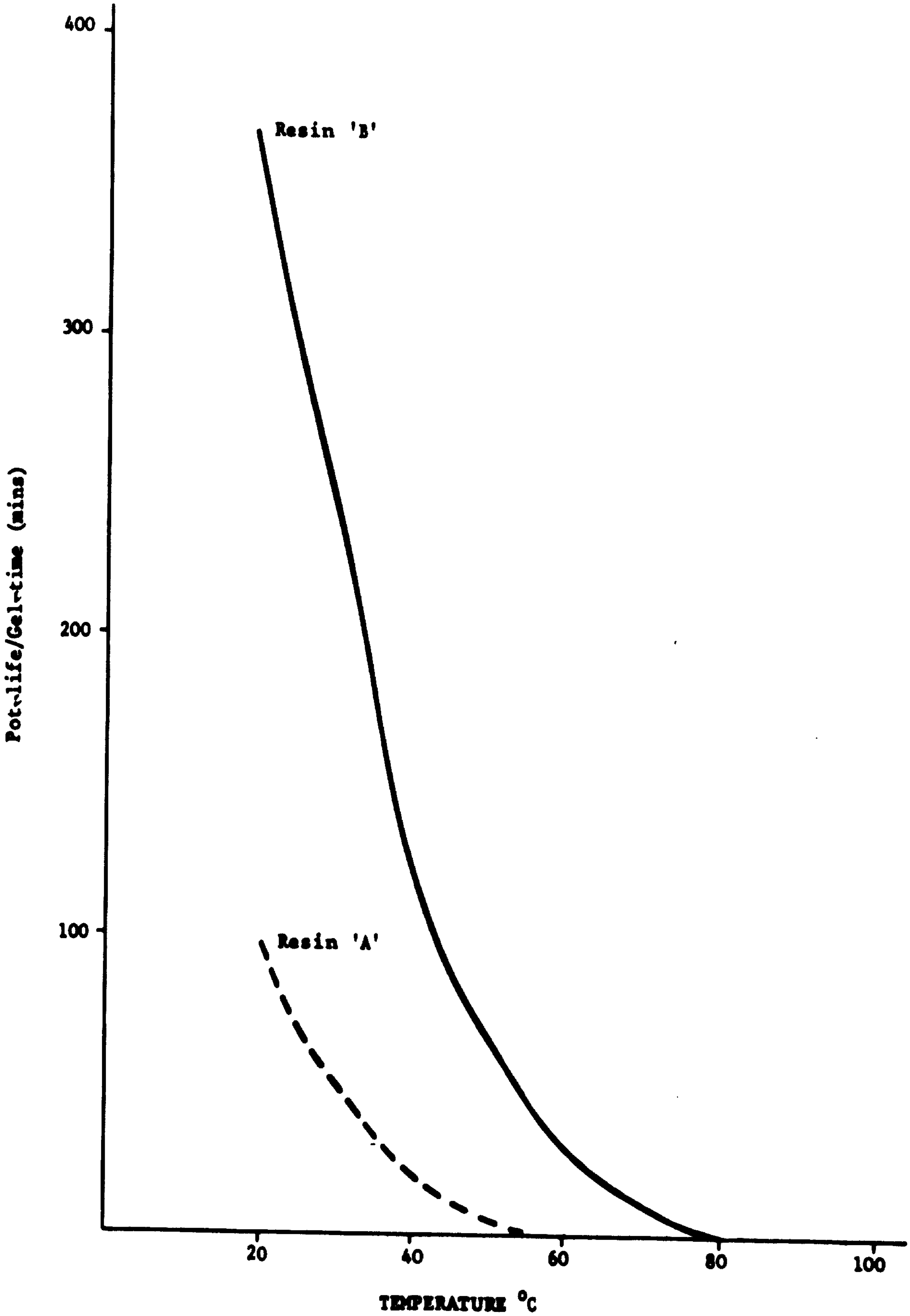


Fig. 2 Effect on Pot-life at 20°C of adding Urea to Ammonium Chloride, using resin 'A' of Fig. 1.

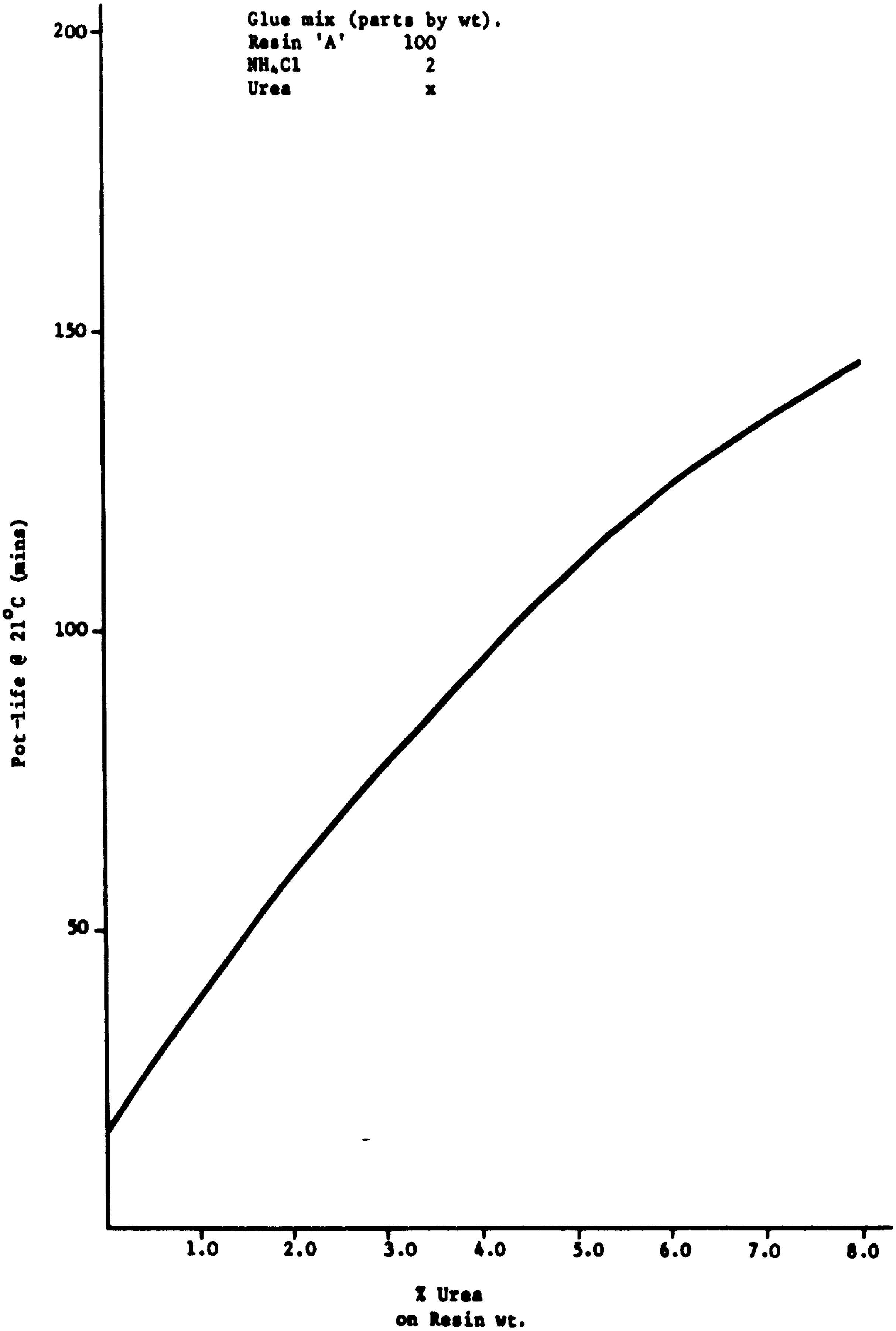


Fig. 3 Effect of Hexamethylene tetramine on Pot-life of an ammonium chloride-urea hardener using resin'A'.

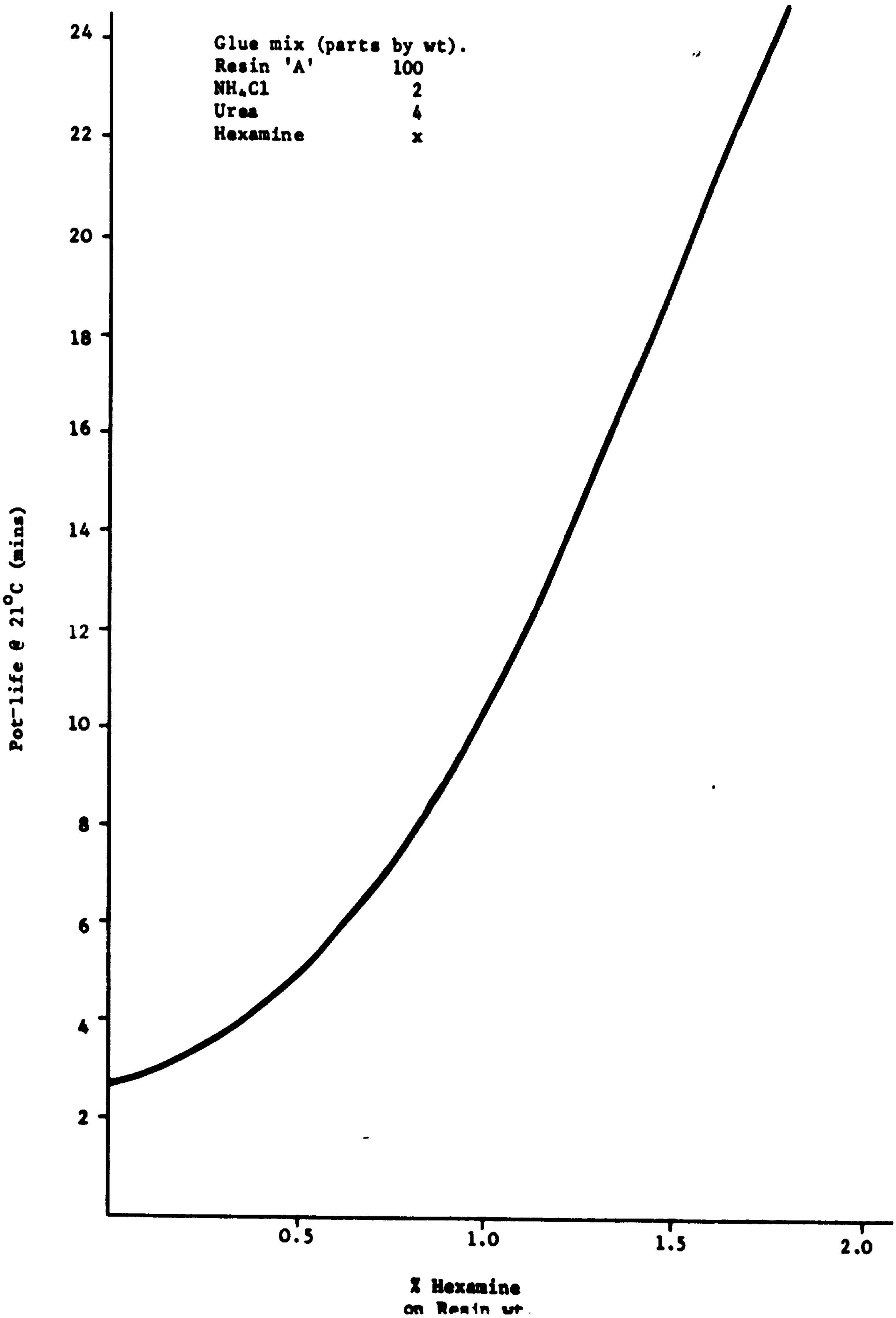


Fig. 4

Typical viscosity - temperature curve for a hot-melt wood adhesive.

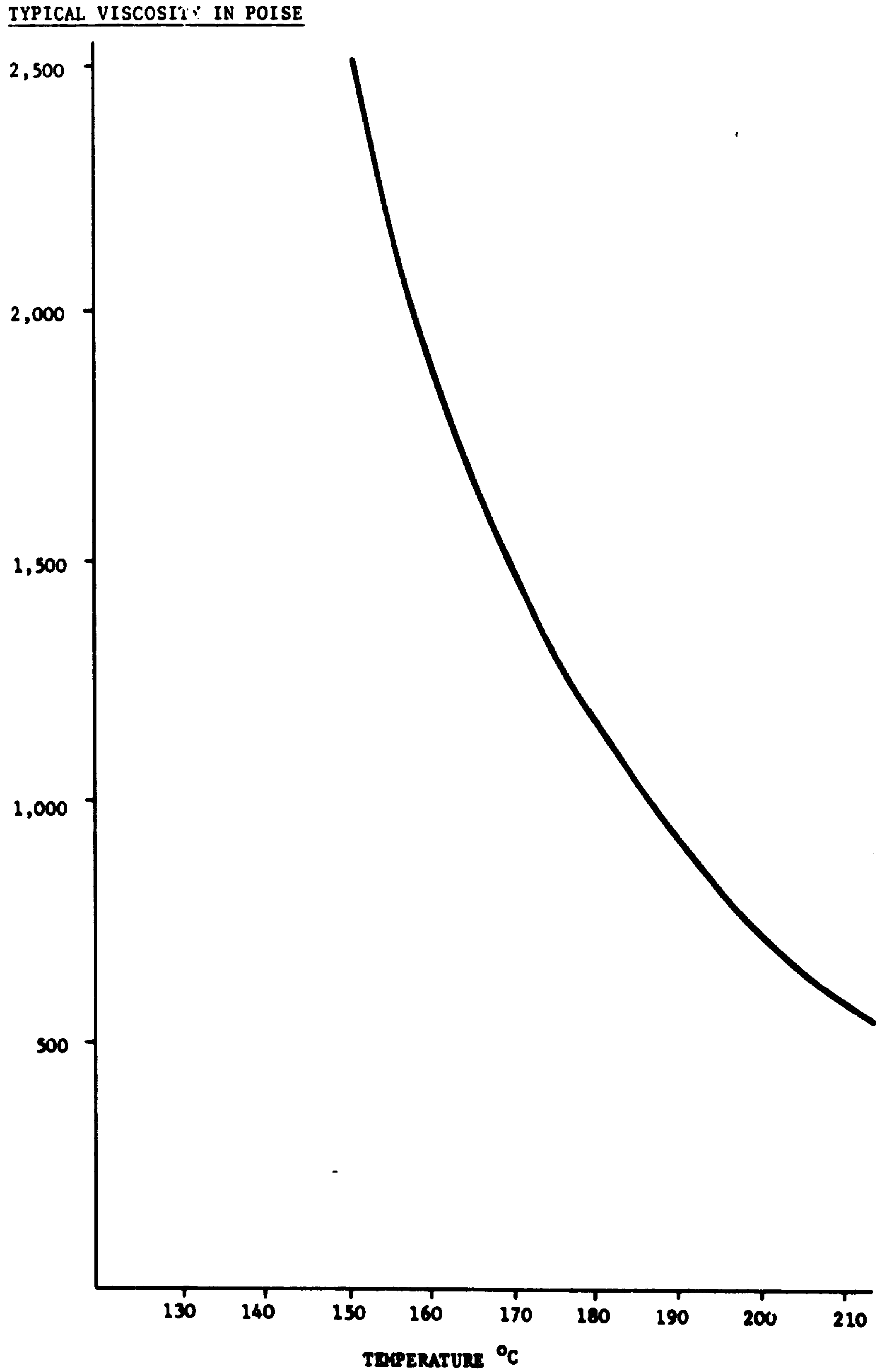
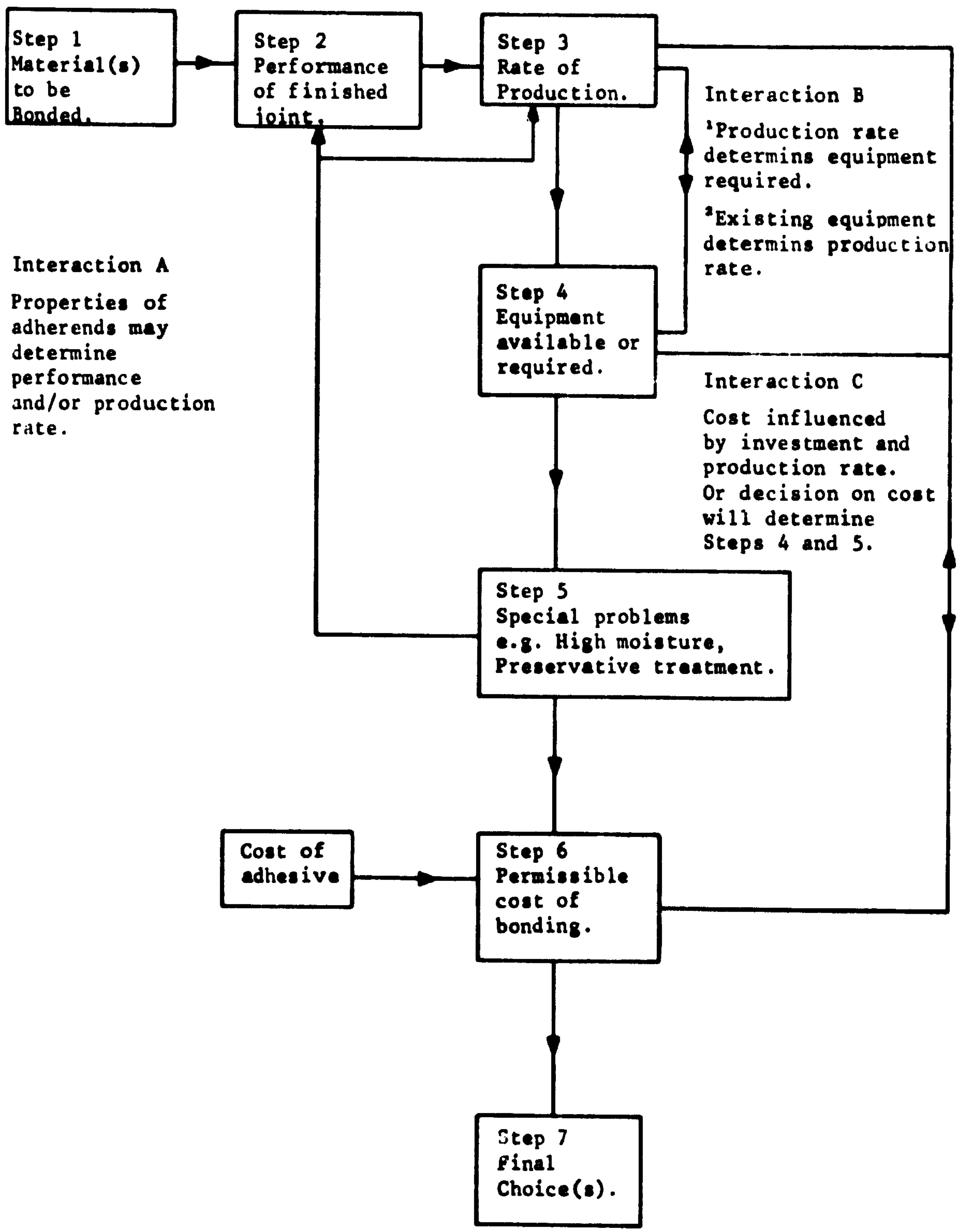


Fig: 5

Diagramatic representation of the process used to select an adhesive.



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