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STRUCTURAL ADHESIVES

the theory and practice of gluing with synthetic resins

This work I have not adorned or amplified with rounded periods, swelling and high-flown language, or any of those extrinsic attractions and allurements wherewith many authors are wont to set off and grace their writings; since it is my desire that it should either pass wholly unhonoured, or that the truth of its matter and the importance of its subject should alone recommend it.

Niccolo Machiavelli—*The Prince.*

STRUCTURAL ADHESIVES

the theory and practice of gluing
with synthetic resins

2022

LECTURES GIVEN IN CAMBRIDGE AT THE SUMMER SCHOOL
"THE TECHNOLOGY OF SYNTHETIC RESIN ADHESIVES"
HELD BY AERO RESEARCH LIMITED, DUXFORD, CAMBRIDGE
FROM SEPTEMBER 23RD TO THE 29TH, 1951.



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The wings and pressurised fuselage of the "Comet" Airliner make extensive use of metal to metal adhesive bonding.
(By courtesy of the de Havilland Aircraft Co. Ltd.)

PREFACE

EARLY this year, when enrolments for our Summer School first began to reach us, we decided that the lectures ought to be published as soon as possible for at least three good reasons.

Firstly, we could not hope to accommodate more than about half the number of applicants for enrolment. Secondly the publication of lectures avoids much tedium in note-taking and is helpful to overseas visitors who are confronted with difficulties of language. Nearly one third of our members came from eleven European countries.

Thirdly, it seemed to us that the lectures were of sufficient interest to be assembled in a permanent form and made available to a wider public. We believe that no school of the kind has been held before in this country, and the great interest already shown has suggested a ready acceptance for the book of the lectures. *Structural Adhesives* covers all aspects of the subject that could be brought within the scope of a week's talks and we hope that it may take its place, as a work of practical value, in the larger domain of literature on synthetic resin adhesives.

N. A. de BRUYNE

December, 1951

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COURSES I and II

INTRODUCTORY LECTURES

SOME BASIC IDEAS

N. A. de Bruyne

INTRODUCTION

In this first lecture I want to talk about some basic ideas in adhesion and their practical significance. To some of you what I will have to say will be elementary but I hope nevertheless not dull.

Matter consists of atoms and or molecules held together by interatomic or intermolecular forces. These forces are responsible for the cohesion of matter and we believe that they are also responsible for the adhesion of one solid to another. Although all these forces are of an electrical kind it is convenient to class them as

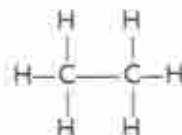
- (1) primary forces
- and (2) secondary forces.

PRIMARY FORCES

Primary forces are those forces responsible for the formation and existence of definite chemical compounds. Primary forces are distinguished from secondary forces (which we will discuss later) by their strength and by their property of saturation. Thus when atoms are held together by primary forces the atoms behave just as though each had one (or sometimes two, three or four) hooks, and once each hook is linked up no further combination is possible. Thus one atom of chlorine combines with one atom of sodium to form one molecule of sodium chloride and never 2 or 2½ or 3.4 chlorine atoms with one atom of sodium. The number of hooks on the atom is called its valency. Sodium and chlorine are univalent, each has one hook and never more or less; only one sodium atom can link with one chlorine atom. So in brief primary forces obey the laws of valency.

PRIMARY FORCES BETWEEN CARBON ATOMS

Of all the elements carbon is the one of greatest significance to us because it forms the backbone of the materials—wood, rubber, plastics, adhesives—in which we are interested. Carbon has four hooks. It is quadrivalent and for our purposes we can think of a carbon atom as a sphere 10⁻⁸ cm. in diameter with four arms sticking out of it, each arm representing one of the valencies or directed primary forces. If you put a hydrogen atom (univalent) on the end of each stick you have methane which the chemist writes CH₄. A more complicated molecule is formed by linking two carbon atoms together and putting hydrogen atoms on the remaining hooks. This is ethane, C₂H₆.



It is even possible to get two direct inter-carbon bonds, as in ethylene



This is an unsaturated compound. Such a double bond is a source of weakness not of strength. The arms have to be severely strained and are longing to fly apart. Such unsaturated compounds are therefore very reactive and are ready to link up to form saturated or less unsaturated compounds. It is by the bursting of double bonds and the formation of long chains of molecules that plastics are formed.

Thus ethylene produces polyethylene (polythene)



Polyethylene is formed by the process of polymerisation of monomers (the ethylene molecules) and is a typical example of a long chain compound.

As the length of the chain increases its properties change. The melting point rises, crystallinity gives way to amorphous behaviour.

MONOMERS AND POLYMERS

The development of knowledge of wood, rubber and plastics began with the realisation that they all consist of such long chainlike molecules made by the repeated linking by primary forces of small molecules called monomers, just as a railway train may be made up by the coupling together of coaches; though, as in a railway train, the first and last units generally differ from the others.

If these chain molecules are rigid and more or less parallel to one another and subject to lateral attractions then we have an anisotropic material such as wood with good strength in one direction but liable to cleave apart at right angles to the chains. If the chains are rigid but in a muddle and tied together at odd places we get an amorphous isotropic material like "Bakelite". If the chains are flexible, are in a muddle, are not tied together or subject to strong side attractions, then we have a collection of sleepy gas molecules which behaves like a drugged gas—this is rubber.

SECONDARY FORCES

The monomeric groups are built up into polymeric molecules by strong primary chemical bonds. But the forces between one polymeric molecule and another are secondary forces of a kind far less definite than that of the primary links, and though much weaker they are often in a sense more important than the primary forces, since it is the weakest links which decide the strength of the chain. When rupture takes place failure occurs through disruption

of the secondary forces; and the existence of matter in a liquid or solid form is only made possible because of these secondary forces.

In a liquid these secondary forces make themselves apparent by producing what is called "surface tension". The molecules at the surface are subject to an inward attraction, exerted by the molecules inside the liquid, which is not counterbalanced by any outward attraction. The surface behaves as though it were under tension. For this reason the liquid will gather into drops unless it rests on a solid which attracts the molecules of the liquid more strongly than they do each other. If the attraction of the molecules of the solid is great enough to do this then the liquid is said to "wet" the solid.

Roughly speaking secondary forces between atoms and molecules are of two distinct kinds called "polar forces" and "non-polar forces". These forces are electrical, although the atoms or molecules are themselves electrically neutral. Thus a molecule can be electrically neutral, considered as a whole, although there may be a concentration of positive electricity at one end and a corresponding concentration of negative electricity at the other end of the molecule. Such a molecule is said to have a permanent "dipole moment" and it is the electrical equivalent of a permanent magnet with a north pole at one end and a south pole at the other. A polar molecule has an asymmetrical structure; benzene, for instance, with its symmetrical ring structure, is not a polar molecule. Polar solutions are characterized by high dielectric constant and a big power factor at frequencies at which the dipoles can resonate in tune with an applied alternating electric field.

But even if a molecule has no permanent dipole it can exert attractive forces either by inducing dipole moments on neighbouring molecules or because (like an alternating current supply) though electrically neutral over a finite period of time it is the seat of rapid periodic changes in density of charge which can interact to produce attractive forces on neighbouring molecular systems. The attraction between conductors carrying alternating currents provides an analogy. Non-polar materials have low dielectric constants and a low power factor.

The existence of two kinds of secondary forces becomes apparent when one reviews the rules of

solution. The chemist has long recognised that like mixes with like, and that there are two main groups of "like" solutions. One group (the polar group) contains such liquids as water, alcohol, glycerine. The other group (the non-polar group) contains such liquids as benzene and paraffin. Polar liquids mix with polar liquids and non-polar liquids with non-polar liquids, but polar and non-polar liquids will not mix together. Oil and water will not mix, though it is possible to disperse oil in water in the form of minute droplets to produce the "soluble oil" used in machining operations.

Both polar and non-polar molecules are held together by attractive forces but because the polar forces are usually much stronger than the non-polar forces, the two kinds of molecule will not mix. If we add non-polar molecules to a polar liquid the attraction between the polar molecules is sufficient to squeeze out the non-polar molecules. The difference between the behaviour of materials in which the molecules are held together by polar forces and those in which the forces are non-polar is illustrated by the simple experiment shown in Fig. 1. Two tubes of glass and polythene respectively are filled with water and toluene. The water (polar) will not mix with the toluene (non-polar) and the

two liquids separate into two immiscible layers. At the interface between the liquids the shape of the meniscus shows that the polythene (non-polar) is preferentially wetted by the toluene while the glass (polar) prefers the water. (See Fig. 1).

Experiments of this kind, but more refined, made by Dr. Frank Moser (1950) of the Pittsburgh Plate Glass Co. have shown how contact angles studied can be used for correlating the "polarity" of a surface with its adhesion behaviour.

Here is a classification of materials into polar and non-polar categories :—

Polar	Non-polar
Cellulose (wood, cotton, paper)	Rubber
PF and UF resins before setting takes place	Polystyrene
Anything with OH groups	Polyethylene
Water	"Teflon"
Alcohol	Benzene
Metal Oxides	Mineral oils

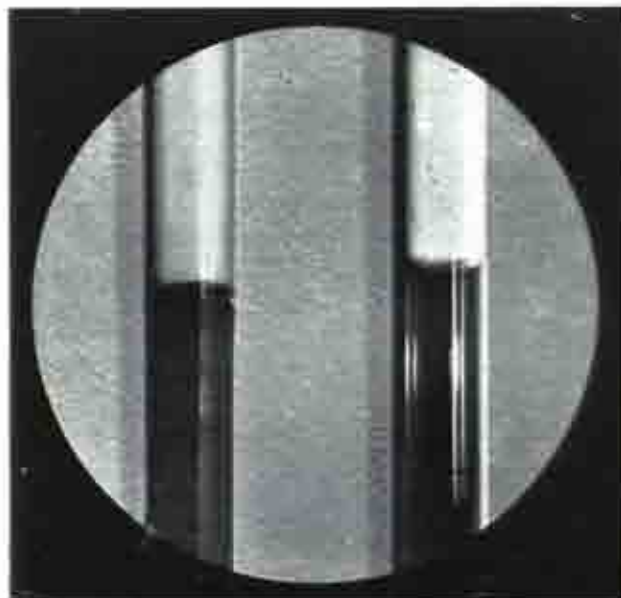


Fig. 1. The interface between water (dark coloured) and toluene in (left) a tube of polythene and (right) a tube of glass.

THE TWO BASIC RULES OF ADHESION

If you want to stick a material make sure that you use an adhesive that "wets" the surface, in other words has a similar polarity. That is the first rule of adhesion. It does not guarantee a good joint because while it is a necessary condition it is not a sufficient one. We must take account also of the stress in the joint.

The second rule is that on solidification the adhesive must not develop a residual stress sufficient to disrupt the bond, nor should the adhesive be much more rigid than the adherends otherwise an external load will give rise to premature failure because of the concentration of stress that will occur.

These are the basic necessities for good adhesion. To make good joints one has of course to take care of a host of other things. These are dealt with by D. A. Hubbard in his lecture beginning on page 27 of this book.

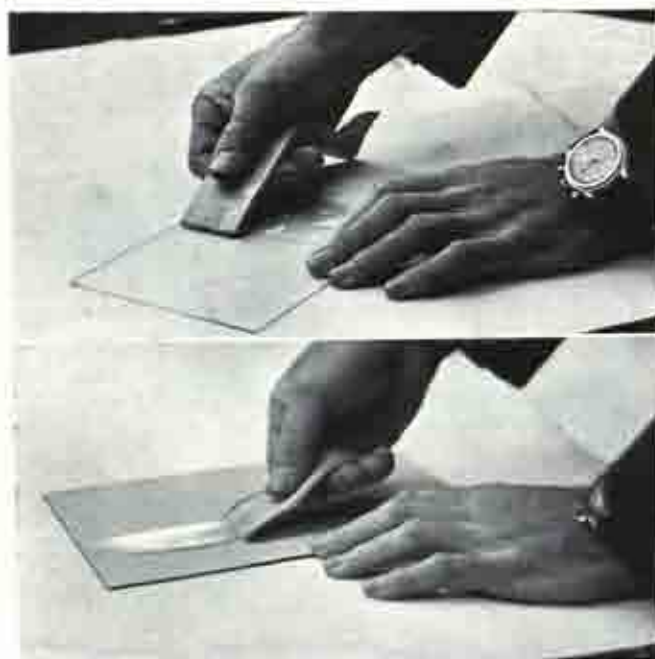


Fig. 2. The gummed paper tape shows little adhesion to a wax surface (upper picture) but sticks well to glass.

APPLICATIONS OF THE TWO BASIC RULES

A simple experiment can be made to illustrate the importance of wetting (Fig. 2). A glass plate is coated on one side with paraffin wax; the other side is rubbed clean in running water. A moistened gum tape is now applied and a strip pressed on to each side of the plate. In a few minutes after it has had time to dry an attempt is made to pull the tape off. The tape sticks to the clean glass but not to the paraffin surface. Water and hydrophilic materials like gum spread out easily in a continuous film over a clean glass surface but gather up into drops on a wax surface; according to Thomas Young's equation (admittedly only an approximation), wetting takes place when the interfacial forces between adhesive and adherend equal or exceed the cohesive forces of the adhesive. Correspondingly the formation of drops signifies that the interfacial forces are smaller than the cohesive forces. Thus if good adhesion is the direct result of strong interfacial molecular forces we should expect it to be associated with wetting and, conversely, poor adhesion with drop formation.

Probably, however, the connection between strong interfacial molecular forces and strong adhesion is

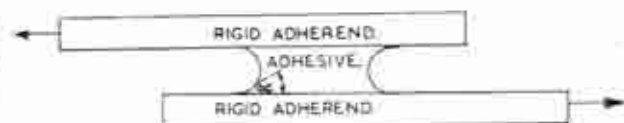


Fig. 3. A lap joint under tensile stress. The glue layer is greatly exaggerated to show the critical angle.

less direct than this argument suggests. Strong interfacial forces cause wetting and give a continuous film; less strong interfacial forces cause drop formation and result in a discontinuous adhesive layer with considerable stress concentration under an external load at the rim of each solidified drop. The decisive effect of the angle made by a solidified adhesive is demonstrated in some beautiful photoelastic work done by Dr. C. Mylonas at Aero Research Ltd. Among other types of joint he investigated the kind shown in Fig. 3. He used adherends which were rigid in comparison with the adhesive. If the angle is less than about 50° there is no appreciable stress concentration (as one would expect from the flexible nature of the adhesive) and the position of maximum stress is in the glue on the meniscus away from the corners. As the angle is increased the magnitude of the stress concentration increases and its position moves to the corners; rupture can



Fig. 4. Stress patterns in a layer of glue between rigid adherends.

therefore be expected to occur at the adhesive-adherend interface at a low load. Fig. 4 shows one of his photographs (see also page 21 of this book).

Resins soluble in water, such as urea formaldehyde resins, also wet glass but unfortunately they do not make good adhesives for glass because among other things they disobey the second rule.

If you want to stick rubber, which is a non-polar material, to wood, the best course is to alter the polarity of the rubber which can easily be done by a few minutes immersion in sulphuric acid. You will then find that the rubber is wetted by water and by, say, urea formaldehyde resins and can be strongly glued. Polystyrene can be treated with fuming sulphuric acid, and polyethylene can be halogenated (B.P. 653029) to enable them to be glued with polar adhesives.

How are metals to be glued? In everyday life it is almost impossible to get a clean metal surface and in effect a "clean" metal surface is nearly always an oxide surface. Any material that will wet a metal surface and at the same time is strong enough or flexible enough to be unaffected by residual stresses will do. In the "Redux" process we use a polyvinyl formal resin as the adhesive but because of its high melting point it never becomes sufficiently liquid to run and wet the metal surface. To obtain wetting we first coat the metal with a phenol formaldehyde resin in which the polyvinyl formal will dissolve as soon as the melting point of the P.F. resin is attained. The following is a description of a simple experiment carried out to demonstrate the principle.

Two moulded Formvar cylinders each 0.3 in. high by $\frac{1}{8}$ in. diam., were stood side by side on a sheet of aluminium, part of which had been previously coated with PF resin; one cylinder (A) was stood on the coated surface and the other (B) on the bare aluminium surface. A clean sheet of aluminium was then placed on top of the cylinders and the whole assembly pressed at 150°C. for 8 min. at a pressure on the Formvar cylinders of about 550 psi. The press was then cooled and the top sheet of aluminium lifted off. The cylinders were found to have been flattened to disks of 1.3-1.4 in. diam.

Disk (A) adhered fairly tenaciously to the sheet whereas (B) was easily picked off. Each disk was then sectioned along a diameter and photographed



Fig. 5. On the left is shown, in section disk A (on aluminium coated with a phenolic resin) and on the right disk B (on an untreated aluminium surface).

at a small magnification. The resulting photographs, Fig. 5, show that the PF considerably reduces the contact angle. These contact angles are not, of course, comparable with those of a liquid under equilibrium conditions; the effect of the pressure applied will be to increase the contact angle considerably. Nevertheless, the photographs show beyond dispute that the PF produces wetting which otherwise could not take place in a finite time.

It is quite possible to make certain metals adhere together by their own surface forces if we take care to obviate high residual stresses. This we can do by using a soft metal such as soft aluminium or indium. Lead should also be suitable but it oxidises so very rapidly that it is difficult to get it to stick. However, aluminium can be joined to itself at room temperature by (1) removing the original surface by scratch brushing, (2) bringing the new surfaces thus made into intimate contact by squeezing them together.

SPECIFIC AND MECHANICAL ADHESION

In all that I have said above I have ascribed the existence of adhesion to intermolecular forces. It is also possible that the adhesion can be assisted by mechanical interlocking with the asperities present even on a smooth surface and in a porous material such as wood: such mechanical adhesion may make a significant contribution to the strength of a joint. However, the fact that roughening a surface, as for example by sandblasting, often leads to an increase in joint strength is not a decisive argument in favour of the importance of mechanical interlocking because the area of the surface can easily be increased twenty times by such a process.

POROUS AND NON-POROUS ADHERENDS

Apart from the possibility of providing mechanical interlocking the existence of porosity in one or both adherends can be of decisive significance in obtaining a sound joint.

Porosity is beneficial in that it allows solvents to escape. It is impossible to make a good joint between non-porous solids with a urea formaldehyde aqueous solution: "Vulcanised fibre" sheet, for instance, has a smooth non-porous surface which makes the escape of water very difficult. If this smooth skin is removed, however, excellent joints will be obtained with an aqueous UF resin. To make good joints between impermeable adherends one must use adhesives that do not give off volatiles.

On the other hand porosity can be detrimental if it allows the glue to run out of the joint. This "rheological" aspect of gluing is dealt with in other papers in this book.

CONCLUSION

Adherends can conveniently be classified as polar or non-polar, porous or impermeable and the type of adhesive must be chosen to suit the conditions. Use polar adhesives for polar adherends. If possible, convert the surfaces of non-polar adherends to a polar state: alternatively, use a non-polar solvent. If both adherends are impermeable avoid an adhesive containing volatiles, or which splits off volatiles, on setting.

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CELLULOSE AND WOOD

N. A. de Bruyne

POLAR AND NON-POLAR ADHERENDS

TABLE I

In the preceding lecture it was shown that the physical behaviour of an organic material such as wood or rubber is governed by (1) the *nature* of the forces (primary or secondary; polar or non-polar) holding the molecules together and (2) by the *magnitude* of the secondary forces. Whenever the secondary forces are weak the kinetic energy (or energy of thermal agitation) of the molecules begins to make itself felt and the material takes on a rubbery character.

A physicist sees a solid as an assembly of stationary ping-pong balls vibrating with a small amplitude about fixed positions. A gas on the other hand consists of molecules with such weak attractions that they are rushing about colliding with one another: the kinetic energy preponderates over the potential energy. (Demonstration).

Polar forces are so strong that solid polar materials are always rigid unless they are swollen by a suitable liquid when they become softened. Materials which exert a swelling action and are themselves involatile (or nearly so) are called plasticisers. Polar materials, when heavily plasticised, have a rubbery character though they lack tensile strength. Materials in which non-polar forces predominate always become rubbery or elastomeric within a certain temperature range, which may or may not fall within room temperature. Rubber itself is rubbery at room temperature but is a brittle solid at the temperature of liquid air. (Demonstration)

It is extremely interesting to compare the properties of cellulose (a polar material) with rubber (a non-polar material) as in Table I:—

Cellulose	Rubber
Held together with strong polar forces.	Held together by dispersion forces.
Rigid	Highly distensible (strain 500%)
Swollen, dissolved or cemented by polar liquids.	Swollen, dissolved or cemented by non-polar liquids.
Unaffected by non-polar liquids.	Unaffected by polar liquids.
The molecules constitute a system having high potential energy like a compressed spring.	The molecules have high kinetic energy like a gas.
Little change in entropy on swelling.	Big change in entropy on swelling.

CELLULOSE

Cellulose is Nature's strong material. It is the main constituent of cotton, flax, rayon, wood, paper. Its strength is shown in Table II.

The cellulose molecule is a polymer. We cannot build it up from its monomer but we can break it down or depolymerise it. Horses and cows are able

TABLE II

	"Breaking length" = Tensile strength/S.G. (km)
Flax fibre	96
Aluminium alloy (30 tons/in. ²)	17
Stainless steel (80 tons/in. ²)	16
Spruce (4.5 tons/in. ²)	14

to break down the cellulose in grass into sugars before digesting it. Wood can be turned into sugars by treatment with HCl (Bergius' process). The cellulose polymer is, in fact, built up of what are practically molecules of β Glucose (Barley Sugar). Why then is cellulose so strong under tension when sugar is so weak? The answer lies in the length of the chains. The strength of cellulose is due to the multiplying effect of polymerisation.

Each β glucose unit is twisted about its axis through 180° , the combination of two such units makes up what is called a cellobiose unit which has the structure shown in Fig. 1. The cellulose polymer is a long, straight chain made up from these cellobiose units, and each chain probably contains about 70 such units.

Fig. 2 shows a model of part of a cellulose molecule. Such models can be made quite easily and cheaply, as Dr. L. Hartshorn, (1938) of the National Physical Laboratory has shown from the standard "ball feet" made by Messrs. Hobbies, Ltd. The important features to grasp are:—

- (1) That the molecule is much longer than it is wide.
- (2) That it is straight.
- (3) That all the big "branches" end in OH groups.

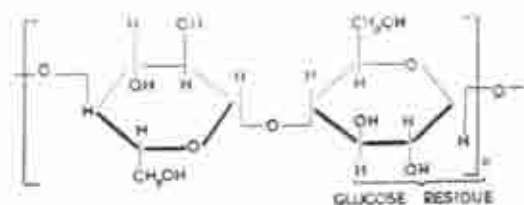


Fig. 1. Cellobiose, the unit of cellulose, consisting of two glucose residues.

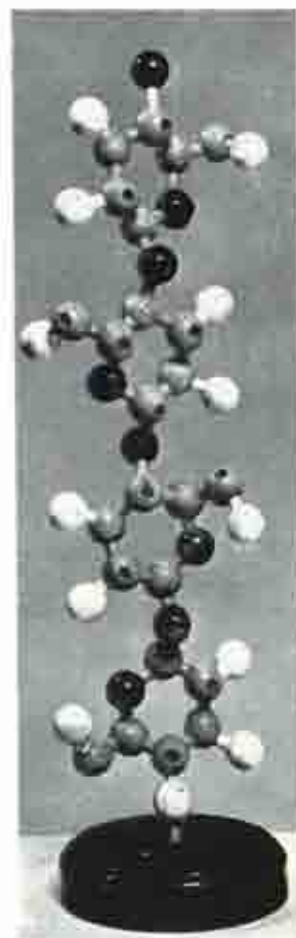
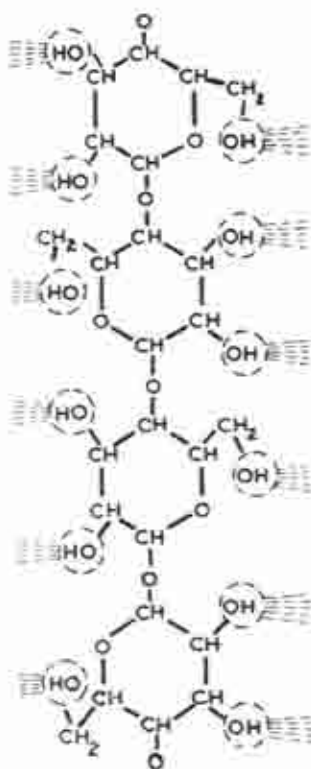


Fig. 2. Part of the cellulose chain shown conventionally on the left (the dotted rays represent the secondary forces) and in model form on the right (the OH groups show white in the photograph).

Micellar Structure of Cellulose

The cellulose polymers are hunched together into bigger units called micelles. Just how many polymers there are in a micelle and just how they are arranged is not known. X-ray diffraction studies suggest that the micelles can be thought of as bricks containing 50 or 60 polymeric molecules (see Fig. 3) and that these bricks are interleaved to produce a structure like a brick wall. The bonds between these bricks are supposed to be due to secondary forces. Such a picture gives a ready explanation, of why, for example, wood (a material chiefly made of cellulose) swells far more across than along its grain. The water creeps all round the bricks or micelles but since there are many more gaps

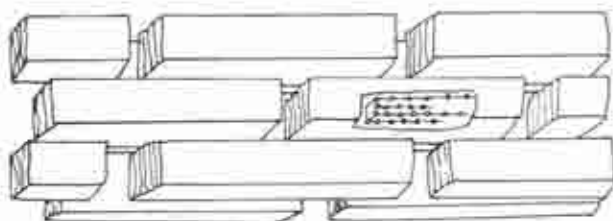


Fig. 3. The "brick-wall" picture of cellulose. Each brick represents a micelle. One has been sectioned to show the molecules of which it is composed.

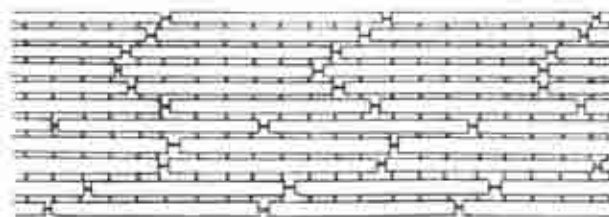


Fig. 4. Cellulose swollen (upper picture) and with water molecules between the micelles (lower picture). The lateral expansion is greater than the longitudinal expansion because of the shape of the micelles. (W.F. Astbury [1933]).



Fig. 5. A model of the micellar structure that is less crude than the brick-wall one. The chain molecules form an irregular network bunched together in certain localized regions and are shown dotted. These localized regions correspond to the micelles detected by X-ray diffraction studies.

in an inch across the grain than along it, the amount of swelling per inch must be greater across than along the grain. This process of swelling can be visualized by the drawing shown in Fig. 4.

But the brick-wall picture of the micellar structure of the cellulose is an over-simplification. It is probably better to suppose that the cellulose chains extend from one micelle into the next and that a micelle is in fact a region in a net-like structure where there is a local concentration of parallel chains.

Fig. 5 shows a net-like structure in which there are gaps at irregular intervals so that the molecular chains are correspondingly bunched together. It is probably these regions that produce X-ray diffraction patterns.

Cellular Structure of Cellulose

The micellar structure is too small to be detected by a microscope of even the highest resolving power. Micelles are only about six-millionths of a millimetre wide. The micelles are themselves grouped into microfibrils which are about one ten-thousandth of a millimetre wide. These microfibrils form the fibrils that are arranged in layers to form the walls of single woodfibres (which are hollow tubular structures closely packed together so that their external perimeters are often of approximately hexagonal shape); these microfibrils are the cells that can be seen under the microscope. But as S. H. Clarke (1938) says: "In all probability neither micelles, microfibrils, nor fibrils are distinct units and their apparent independence is illusory and is due to peculiarities in arrangement that affect certain types of observation. It seems probable that the spaces between the cellulose units, such as might contain water, non-cellulosic wall constituents, or protoplasm at certain stages in the life of the cell, are of a continuously graded size, and may be regarded as the successive ramification of a single system."

WOOD AS EXPANDED CELLULOSE

The form of cellulose with which engineers are most familiar is wood which is expanded cellulose impregnated with a resinous material called lignin. It is possible to dissolve out the lignin, leaving a

continuous cellulose structure as described by K. Freudenberg (1933). As engineers we are not interested in the botanical structure of wood, and for most purposes it is sufficient to regard the different species as being made of the same fundamental material expanded to different extents. Thus the specific gravity of solid wood substance is about 1.56 (or 97.4 lb/cu.ft) and this figure varies very little among different types of wood. The apparent specific gravities of different types, of course, vary considerably. If "a" is the fraction of the total volume occupied by solid wood substance, then

$$a = \gamma / 1.56$$

where γ is the apparent specific gravity of the particular sample. Conversely, the fraction of the total volume occupied by air is

$$(1 - \gamma / 1.56) \text{ or } (1 - 0.64\gamma)$$

The above relations are represented graphically in Fig. 6. It will be seen that in balsa, which has an apparent specific gravity of 0.10, the pores fill 94 per cent of the total volume; whereas in "Lignostone" (a compressed wood), which has a specific gravity of 1.32, the pore volume is only 15 per cent. Fig. 7 shows cross sections of balsa and of lignum vitae illustrating the difference in the amount of expansion of the wood substance found in nature.

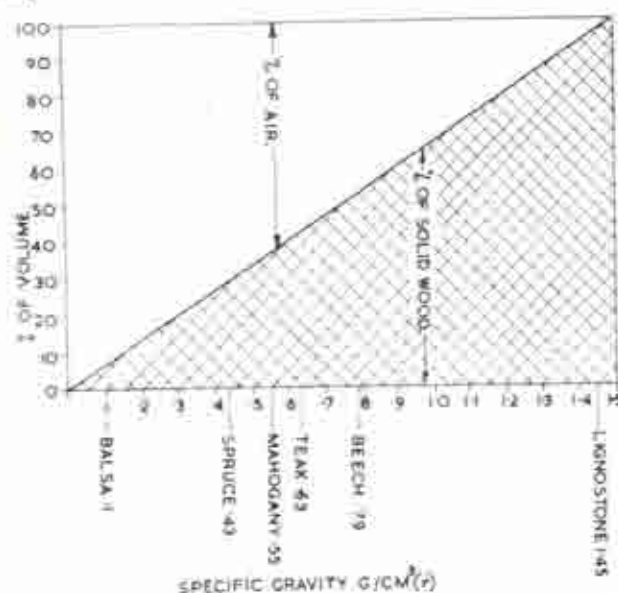


Fig. 6. Relation between porosity and apparent specific gravity of a wood (adapted from F. Kollman [1936]).

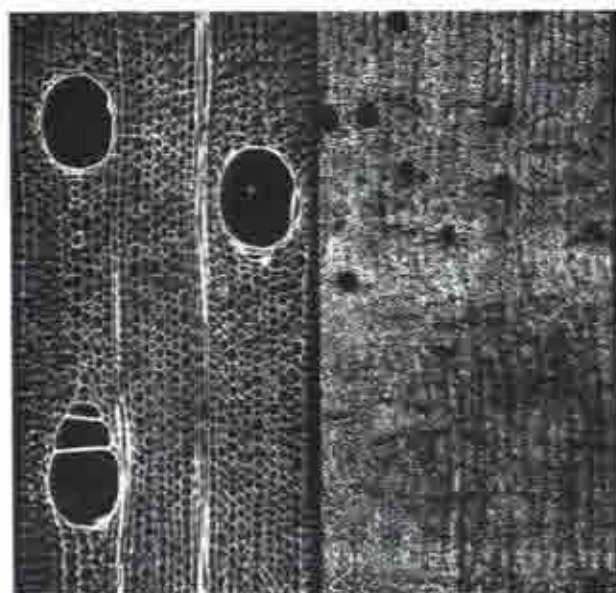


Fig. 7. The apparent density of balsa (left) is less than one-tenth of that of lignum vitae (right) but it is essentially of the same material—though considerably expanded.

RELATION OF DENSITY OF WOOD TO STRENGTH

This concept of all woods being just one basic material "blown out" to different extents in different species is a very useful one in surveying the physical properties of wood. But this topic has been enlarged upon elsewhere (A.R.L. Bulletin No. 37 [1916]) and for the present purpose Fig. 8 will serve to demonstrate the principle. It shows the relation between the shear strength of a glued joint and the density.

The Swelling of Wood

One of the unpleasant characteristics of wood is its power of swelling and shrinking according to its water content. These changes in shape are caused by penetration of the water between the micelles not by the absorption of water in the microscopic cells. Actually in swollen wood the ratio of pore volume to total volume is smaller than in dry wood. Swelling, in fact, is chiefly caused by "bound" water; that is to say, by water absorbed on the surfaces of the micelles; X-ray diffraction photos show that the water does not penetrate *into* the micelles. Of course, in thoroughly water-logged wood there is

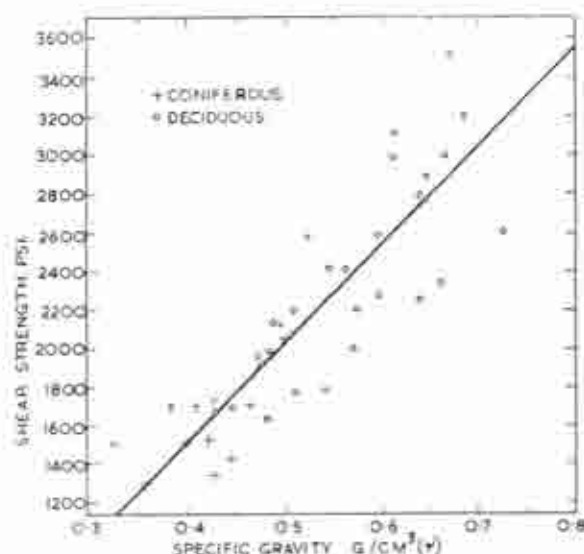


Fig. 8. Relation between "block shear" strength of glued joints and oven-dry specific gravity of wood.

also "free" water present in the microscopic cells, but roughly speaking such "free" water is not responsible for swelling or shrinking.

Bearing in mind that from an engineering point of view, the different species of wood represent only different degrees of expansion of the same solid material, it is possible to represent the behaviour of all woods on a single diagram of the kind shown in Fig. 9. It will be seen that the final percentage increase in volume, produced when dry wood takes up water, is directly proportional to the specific gravity of the dry wood; the greater the porosity the smaller is the percentage change in volume. This is in accordance with the fact that swelling is an intermolecular and not a cellular process. The more wood substance there is in a cubic inch of a wood, the greater will be the number of intermolecular spaces. Heavy woods and compressed woods are, therefore, more subject to changes in dimensions than lighter woods.

That water should cause swelling of wood is quite in accord with what is to be expected from the fact that the cellulose molecule is studded all over with OH groups (see Fig. 3). It will be remembered that in my lecture *Some Basic Ideas* a distinction was drawn between polar and non-polar molecules, and it was stated that polar liquids will dissolve easily in other liquids. Now the OH group is extremely polar so that it is not at all surprising the cellulose

has such an affinity for water molecules, which of course, are only OH groups attached to hydrogen atoms. The swelling of wood is, in fact, a process of restrained solution. The micelles try to separate out and try to go into solution, but do not quite succeed in getting free from their own intermolecular attractions. By using solutions of certain salts instead of water, however, it is possible to cleave them right apart and get a solution of cellulose micelles. If the micelles are re-precipitated, they link up once more to give "regenerated cellulose" often called "rayon" or "Art Silk".

If instead of immersing wood in water we use other liquids then we find that the maximum swelling increases with the square root of the dielectric constant of the liquid; for further details see "Nature" Vol. 142.

Some such relation might be expected if the micelles are indeed held together by electrical forces: the strength of an electric field is weakened by the presence of a dielectric, so that the separation of the micelles should increase. Of all common substances, water has the highest dielectric constant and, is, in

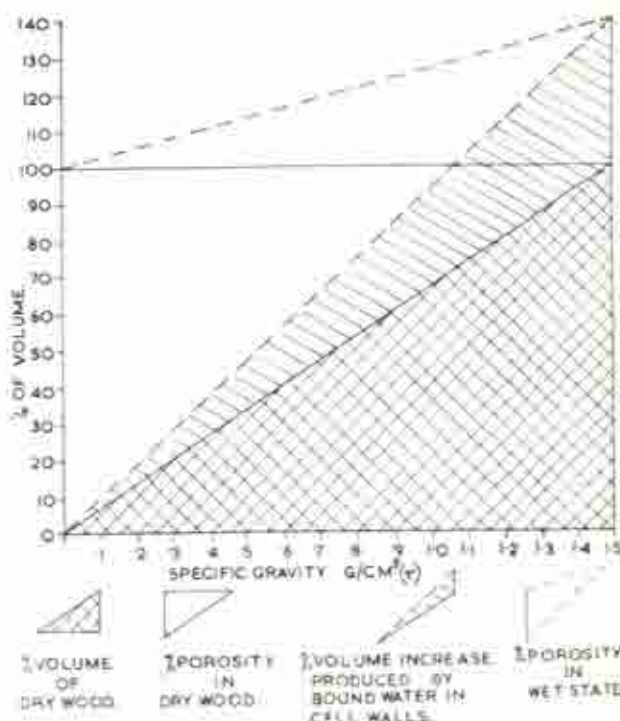


Fig. 9. Relation of swelling to specific gravity (adapted from R. Treubenberg [1939]).

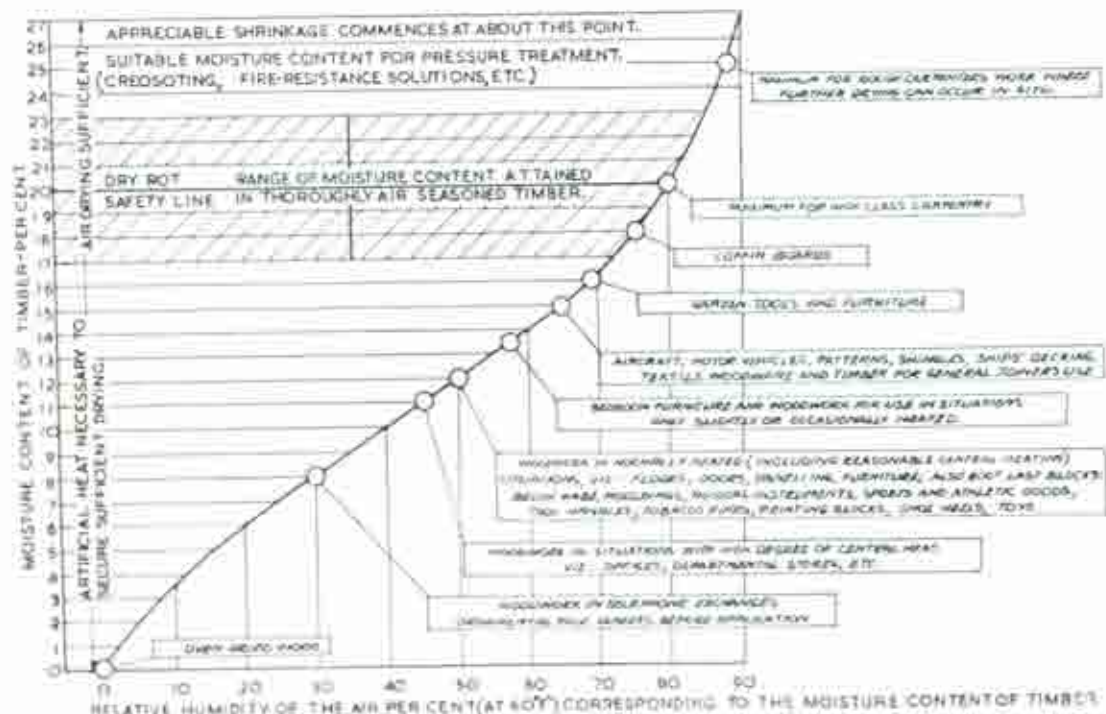


Fig. 10. Chart showing suitable moisture content of timber for various purposes (by permission of the Comptroller of H.M. Stationery Office).

fact, the most effective swelling agent. We shall see later that rubber (a non-polar substance) is swollen most effectively by just those liquids which are the least effective swelling agents for wool, another instance of the distinction between polar and non-polar substances.

The considerable change in dimensions caused by variations in humidity makes it necessary to dry wood to the particular moisture content suited to the relative air humidity in which it will be subsequently used, before the wood is finally shaped and fixed in position. Fig. 10, due to the Forest Products Research Laboratories of Princess Rishborough, shows how the moisture content of wood varies with the relative humidity of the air when equilibrium has been attained. It should be noted that it is the relative and not the absolute air humidity that is the determining factor. The chart also indicates the correct moisture content which the wood should have for various jobs.

In plywood we reduce movement in the plane of the sheet by gluing veneers with grains crossing (usually but not invariably at 90°). But in doing so

we increase the movement at right angles to the plane of the sheet.

CONCLUSION

The properties of wood of any species can be made intelligible by regarding it as an expanded material composed largely of cellulose. The behaviour of cellulose is what would be expected from its structure and the forces holding it together.

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RUBBER AND PLASTICS

N. A. de Bruyne

INTRODUCTION

YESTERDAY we discussed wood as being one of the most important materials with which glue technologists are concerned. Today I will make a brief survey of rubber and plastics from a physical rather than a chemical point of view.

RUBBER

Rubber is a non-polar material. It is swollen, dissolved, or cemented by non-polar liquids like benzene or toluene but it is unaffected by water.

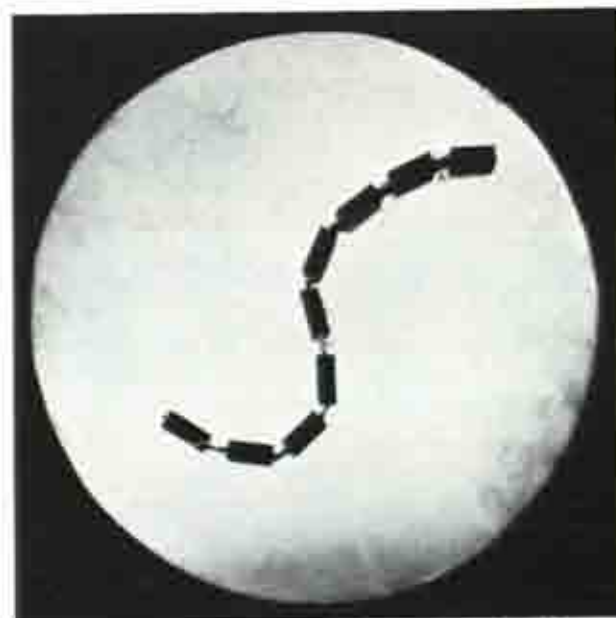
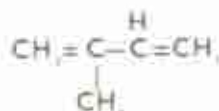


Fig. 1. This model consists of small wood blocks joined by tape. The centre block is fixed to a vibrating plate. When the ends of the "snake" are pulled out straight and then left it always takes up an irregular shape again - in other words it contracts after an extension.

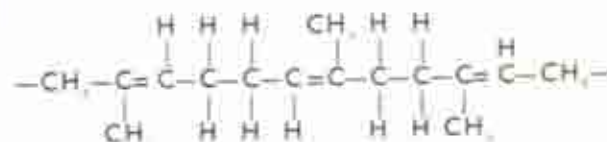
The non-polar intermolecular forces are generally so weak, however, that the behaviour of the rubber polymeric molecule is governed not so much by these forces as by the energy of thermal agitation. In fact as Joule (1859) pointed out in "the elastic force of rubber is owing to the motion of its constituent particles"—in other words rubber is a kind of gas.

There is not time to follow through the close similarity between the behaviour of rubber and that of a gas and I must confine myself to saying that rubber appears to behave like a collection of large lazy gas molecules thoroughly entangled and unable to rush about freely. A collection of coiled up and contracted rubber molecules corresponds to a state of greater probability and therefore greater entropy than an assembly of linear chains; an extension of rubber, just like compression of a gas, will be resisted by a force of a kinetic origin. Fig 1 shows a simple model designed to demonstrate the behaviour of the rubber molecule.

The monomer of the rubber molecular chain is isoprene.



These monomeric units are linked up to form molecules about $10,000 \times 10^{-7}$ in length as follows :-



If we cool rubber its energy of thermal agitation becomes small and it reverts to a brittle solid. Thus a piece of rubber tube immersed in liquid air can be smashed with a hammer (demonstration).

If we stretch rubber sufficiently it acquires a new strength because the chain molecules become orientated. The rubber molecules can also be cross-linked with a considerable gain in rigidity by sulphur atoms; this process is called "vulcanisation".

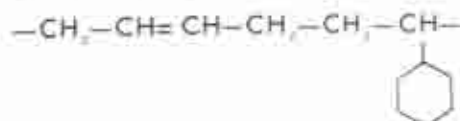
Other Elastomers

Natural rubber is one example of an elastic polymer, a name conveniently contracted to "elastomer". Balata and guttapercha are examples of other natural elastomers but in addition there are many synthetic elastomers of which the synthetic "rubbers" have a special significance as they are capable of vulcanisation. But rubber-like behaviour is shown at some temperature, high or low, by a large number of other substances not capable of vulcanisation and this is not surprising if we remember that the rubbery state corresponds to a condition where the energy of thermal agitation exceeds that due to intermolecular forces. Thus a material such as "Polystyrene" which is brittle at room temperature becomes rubbery if the temperature is raised to 80°C. Alternatively, if we "plasticise" a material, i.e. swell the material with a non-volatile solvent, we can obtain rubber-like behaviour at lower temperatures. Plasticised polyvinyl chloride (P.V.C.) is such a material.

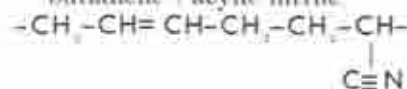
Synthetic Rubbers

There are only four synthetic rubbers of commercial significance at the present time:—

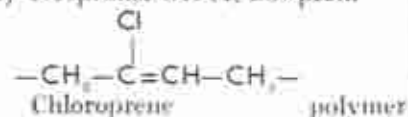
- | | |
|---|-------------|
| (1) Buna S., GR-S Hycar OS,
Ameripol F., Chemigum S.,
Nabun, Butaprene S. | } For tyres |
| butadiene + styrene | |



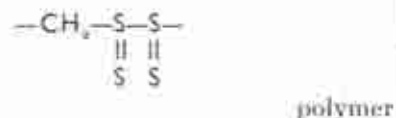
- (2) Perbunan, GR-A, Hycar,
butadiene + acrylonitrile



- (3) Neoprene, GR-M, Sowpren.



- (4) Thiokol, Perduron



Resistant to
oil because of
polar character
of
C≡N and Cl
side groups.

Specialised
uses.

There are signs that polyester products (such as Paracron) may be useful synthetic rubbers.

PLASTICS: THERMOPLASTIC AND THERMOSETTING

It is convenient to distinguish between thermosetting and thermoplastic plastics. Both types possess the characteristic feature of a plastic, that of being about to pass through a plastic fluid or mouldable state to a solid state. But in thermosetting plastics the change is irreversible while in thermoplastic plastics the process can be repeated as often as desired.

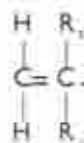
The thermosetting property is due to the formation of cross linkings between the polymeric molecules so that they are joined together into a solid infusible three-dimensional network. This is the same process as in the vulcanisation of rubber.

In the thermoplastics there are no rigid cross linkages though there may be strong attractive forces. However, on heating the energy of thermal agitation is sufficient to overcome the attractive forces, and softening takes place. There is no definite melting point because the molecules are of different sizes.

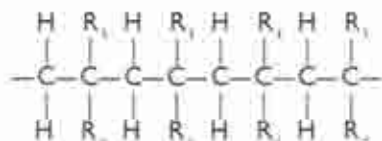
Thermoplastic Materials

Vinyl polymers sometimes known as "Ethenoid" plastics are the most important class of synthetic

thermoplastics. They are all derived from monomers of the type



R and R stand for any group we may choose to put on. The double bond is as usual eager to burst asunder and form long chains of the following forms:—



Thus if R₁ is a benzene ring and R₂ a hydrogen atom we have polystyrene. If R₁ is a CH₃ group and R₂ a COOCH₃ group we have "Plexiglas" or "Perspex".

If all the hydrogen atoms in polyethylene are replaced by fluorine atoms we obtain "Teflon", a remarkable material in which the large fluorine atoms screen off the carbon atoms.

TABLE 1. The Vinyl family of Plastics.

$\begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ -\text{C} - \text{C}- \\ \quad \\ \text{H} \quad \text{H} \end{array}$ <p>Polyethylene</p>	$\begin{array}{c} \text{OH} \quad \text{OH} \\ \quad \\ -\text{C} - \text{C}- \\ \quad \\ \text{H} \quad \text{H} \end{array}$ <p>Polyvinylalcohol</p>
$\begin{array}{c} \text{CH}_3 \quad \text{CH}_3 \\ \quad \\ -\text{C} - \text{C}- \\ \quad \\ \text{CH}_3 \quad \text{CH}_3 \end{array}$ <p>Viscose, Opanol Polyisobutylene</p>	$\begin{array}{c} \text{Cl} \quad \text{Cl} \\ \quad \\ -\text{C} - \text{C}- \\ \quad \\ \text{H} \quad \text{H} \end{array}$ <p>Polyvinylchloride</p>
$\begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ -\text{C} - \text{C}- \\ \quad \\ \text{C}_6\text{H}_5 \quad \text{C}_6\text{H}_5 \end{array}$ <p>Polystyrene</p>	$\begin{array}{c} \text{CH}_3 \quad \text{CH}_3 \\ \quad \\ -\text{C} - \text{C}- \\ \quad \\ \text{CH}_2\text{COOCH}_3 \quad \text{CH}_2\text{COOCH}_3 \end{array}$ <p>Plexiglass, Perspex</p>
$\begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ -\text{C} - \text{C}- \\ \quad \\ \text{C}_6\text{H}_5 \quad \text{C}_6\text{H}_5 \end{array}$ <p>Polystyrene</p>	$\begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ -\text{C} - \text{C}- \\ \quad \\ \text{CH}_3 \quad \text{CH}_3 \end{array}$ <p>Acetate Acetate Polyvinylacetate</p>
Non Polar. Not water soluble. Good insulators. Cannot be glued with hydrophil adhesives.	Polar, swollen or dissolved by water, and compatible with polar adhesives.

Physical Characteristics of Vinyl Plastics

The vinyl group joined together without R branches forms the material butadiene (CH^s=CH—CH=CH^s), which is a synthetic rubberlike material that has already been mentioned in the section on rubber. Roughly speaking, the vinyl polymers always retain this underlying hydrocarbon nature even if we attach strongly polar R groups to the chains. It will be remembered that the swelling of rubber is a process accompanied by an increase in entropy, while the swelling of cellulose is purely a change in potential energy, and that the properties of rubber in many other respects suggest the existence of a preponderating amount of kinetic energy in the molecules in comparison with the preponderating amount of potential energy stored up in mutual attraction between the cellulose chains. In the vinyl polymers the energy of thermal agitation is also large; sufficiently so as to give flexible or rubber-like materials in the absence of polar R groups, and sufficient to confer thermoplasticity on polymers with polar R groups.

There are no strong secondary forces, as there are in cellulose, between the chain molecules. Though it is possible to cross-link these chain molecules (as it is possible to vulcanise rubber), the cross-link (as with rubber) is of a non-polar character, such as paradi-vinyl benzene. When cross-linked, the vinyl materials lose their thermoplastic character and ability to swell in organic liquids. As we shall see later, one of the most potent cross-linking agents for polar molecules is formaldehyde, but if formaldehyde is allowed to react with polyvinyl alcohol we obtain resins (known as Formvars) which though of high softening point remain soluble in such liquids as chloroform, suggesting that the formaldehyde has only joined up OH groups on the same chain, without producing any linking between different chains.

The vinyl elastomers cannot be vulcanised as rubber can and lack the tensile strength of natural or reinforced synthetic rubbers; they show considerable permanent set under load and usually require plasticisers.

Polyisobutylene, polyethylene and P.V.C. and its co-polymers are examples of vinyl elastomers.

The vinyl non-polar polymers are specially suited for electrical work. Polystyrene and poly-

ethylene have outstandingly low power factors and water absorption.

It is interesting to compare polyethylene with isoprene where the methyl groups keep the chains just far apart enough to give the freedom of motion essential for rubber-like elasticity.

Thermosetting Plastics

The thermosetting plastics differ from the thermoplastic materials in that on heating or under the influence of catalysts (hardeners) cross linking takes place so that the whole structure becomes rigid and does not soften again.

The main thermosetting plastics are phenol formaldehyde, resorcinol formaldehyde, urea formaldehyde and melamine formaldehyde, all of which are condensation products.

Their chemistry is still obscure and need not detain us here. Whereas the vinyl polymers are produced by opening of double bonds and linking up of monomers the thermosetting products mentioned above are made from molecules which join together by a process of "condensation" rather than of simple chain formation and the linking up is accompanied by a splitting off of some of the constituents of the parent molecules.

Other Plastics

Other types of adhesives and plastics are discussed in Mr. Rayner's lecture "An outline of the chemistry of some synthetic adhesives", beginning on page 41 of this book, and need not therefore be described here.

SIZES OF POLYMERS

The figures quoted in Table II give an idea of the size of some polymers.

TABLE II*

Substance	Molecular weight	Degree of polymerisation
Cellulose (wood)	300,000—500,000	2,000—3,000
Rubber	75,000—100,000	500—600
Polystyrene	60,000—500,000	1,200—6,000
Nylon	16,000—32,000	150—300

STRENGTH OF PRIMARY AND SECONDARY BONDS

We have spoken of primary forces and of secondary forces and Table III gives some numerical values of great interest.

TABLE III*

Primary bonds			Secondary bonds		
Bond	Distance in Å	Energy equivalent in kcal/mole	Group	Distance between adjacent molecules in Å	Coheision in kcal/mole
C—H	—	92	—CH ₃	3—4	1.78
C—C (aliphatic)	1.55	71	—CH ₂	3—4	0.99
C—C (aromatic)	1.45	96	—OH	3—4	7.25
C=C	1.20	125	—CO	3—4	4.27
C=O	1.10	203			

Note that the primary bonds are much stronger than the secondary bonds. Nevertheless in a polymer the number of secondary bonds *per molecule* will be a good many multiples of the secondary forces from a single group. That is why adhesives are polymers; small molecules would not have sufficient adhesive force. Note the high bond energy of the hydroxyl group.

CONCLUSION

The physical behaviour of any particular elastomer or plastic is a necessary consequence of its structure.

* These figures are given by H. F. Mark.

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THE STRENGTH OF GLUED JOINTS

N. A. de Bruyne

SOME FACTS

IF with a given glue and given adherends we make up a series of lap joints in which (1) using adherends of constant thickness we vary the overlap, and (2) using a constant overlap we vary the thickness of the adherends, we shall find on pulling these joints to destruction that:—

- (i) The breaking load is not proportional to the overlap.
- (ii) The breaking load increases with thickness of the adherends.
- (iii) The breaking load is always proportional to the width of the joint.

Alternatively if we make up a series of butt joints with a given glue and given adherends in the form of, say, rods, and we vary the diameter of the rod, we shall find that the failing tensile load is not proportional to the area of the joint. Moreover, the strength of the joint will increase as the thickness of the glue layer is reduced.

The extent to which these apparently anomalous effects are observed will depend on the relative extensibilities of adhesive and adherends. If the adherend is much more rigid than the adhesive they are not so evident but in normal adhesive-adherend combinations they are very much in evidence.

In saying that the failing load does not increase in proportion to the overlap we are also saying that the apparent failing stress (which is the failing load divided by the glued area) is not a constant. In fact the apparent failing stress decreases with increasing overlap.

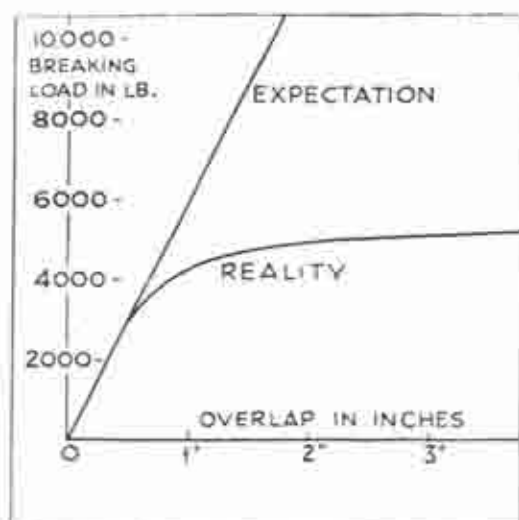


Fig. 1. *Breaking load of a lap-joint.*

Results of tests we made many years ago on "Resin" joints between mild steel pieces 1 in. wide and $\frac{1}{8}$ in. thick are summarized in Fig. 1. Instead of following the straight line labelled "Expectation" the failing load in reality is proportional to the overlap only for values up to about $\frac{1}{2}$ in. For longer overlaps it tends to a constant value.

ADVANTAGES OF BEVELLED OR SCARFED JOINTS

The differential straining can be much reduced and the failing load increased by beveling off the adherends so that the longitudinal stress in them remains approximately constant. The beneficial effect of this is shown in Fig. 2. A more practical construction is the familiar scarf joint.

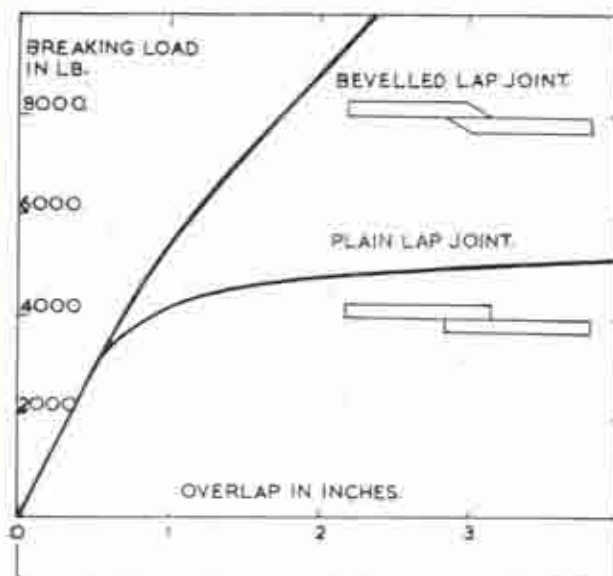


Fig. 2. The beneficial effect on strength of beveling off the adherends.

EXPLANATION OF RESULTS

The anomalous results described are due to non-uniformity of stress. In the lap joint there is a concentration of stress at each end of the joint caused partly by differential straining and partly by tearing forces.

The bending or "tearing" or "peeling" forces manifest themselves clearly when a lap joint is tested in a tensile testing machine because it is subjected at its ends to couples due to eccentric loading even when the plane of the applied load is initially in the plane of the joint (Fig. 3).

The concentration of stress due to differential straining is perhaps less obvious and to make clear what is meant let us make nine equidistant arrow

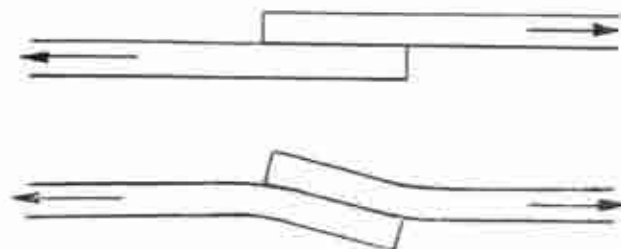


Fig. 3. "Peeling" forces in a lap-joint due to differential loading.

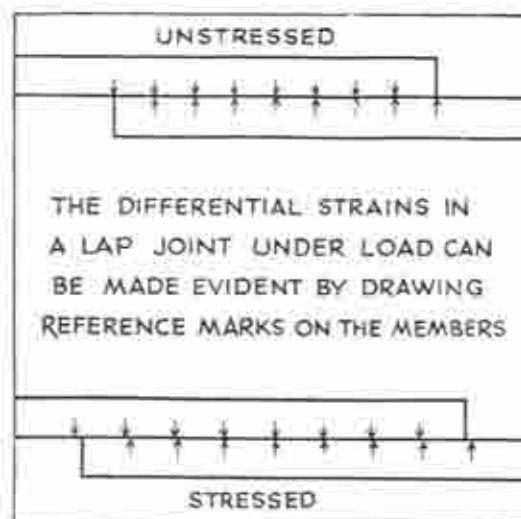


Fig. 4. Concentrations of stress due to differential loading.

marks on the edge of a lap joint (Fig. 4). Assuming that Hooke's law holds good, and that the bending effects are disregarded, then when we load the joint the arrows will move as shown in the lower half of the picture. The end of each member lags behind the adjacent member, whereas in the middle there is no relative motion.

The adhesive layer in between the two members has to look after these differences in strain and in so doing transmits the shearing forces from one member to the other. This is shown in Fig. 5 where the

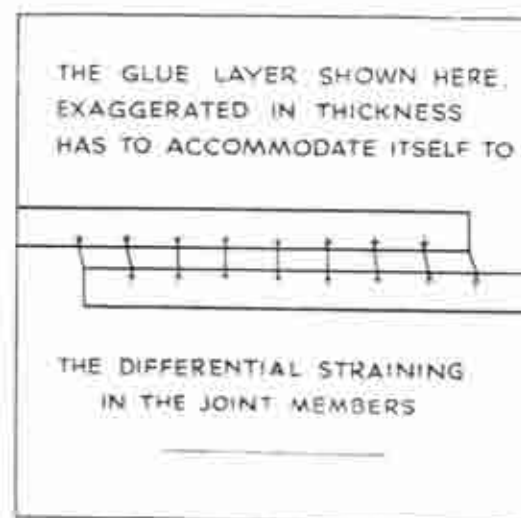


Fig. 5. The transmission of shearing forces from one member to the other through the glue.

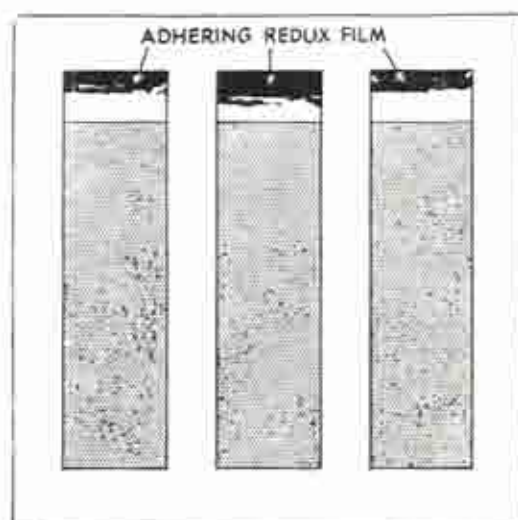


Fig. 6. Broken "Redux" lap-joints, showing how the film of adhesive has come away at the more highly stressed part of the interface.

thickness of the glue layer has been exaggerated for clearness. At the centre line there is little relative motion or differential straining and therefore little load transfer between the adhesive and the members of the joint.

It can be shown that in a single lap joint under a gradually increasing load, the glue transfers load almost entirely at the ends, so that the strength of the joint is naturally not much altered by varying the overlap.

Due to tearing forces and to differential strains the greatest stress in the glue is at the interface between the glue and the member where the joint begins. Fig. 6 shows some typical fractured "Redux" joints between 10G duralumin and it will be seen that the film of adhesive has come away in each specimen at the more highly stressed half of the interface.

The more ductile the adherend the greater will be the differential straining and with a sufficient overlap the maximum breaking load of a metal to metal joint rises with the yield point of the metal as shown in Table I.

THE JOINT FACTOR

We have seen that the apparent failing stress of a lap joint is not a constant and therefore it is meaningless to state (though it is still frequently done) that

TABLE I

Adherends 1 in. wide, 20 SWG thick, $\frac{1}{2}$ -in. overlap

Adherend	Apparent failing stress (psi)	Yield point of adherend (tons/in. ²)
Al. half hard	1100	5.8
"Alclad" DTD 300	3600	15
DTD 546	4000	21
DTD 687	5000	26

such and such a glue gives a breaking strength of so many psi or kg/cm².

In order to compute the strength of a lap joint it is convenient to have a graph of apparent failing stress against the square-root-of-thickness divided by the overlap. This quantity is called the joint factor because, for a given type and thickness of adhesive and for a given adherend, it is the quantity determining the degree of stress concentration.

Fig. 7 (A.R.L. Bulletin No. 8 [1943]) shows two such curves for beech in inch and in millimetre units. Some examples showing how, with the aid of Fig. 7, it is possible to estimate the strengths of various joints, are given overleaf.

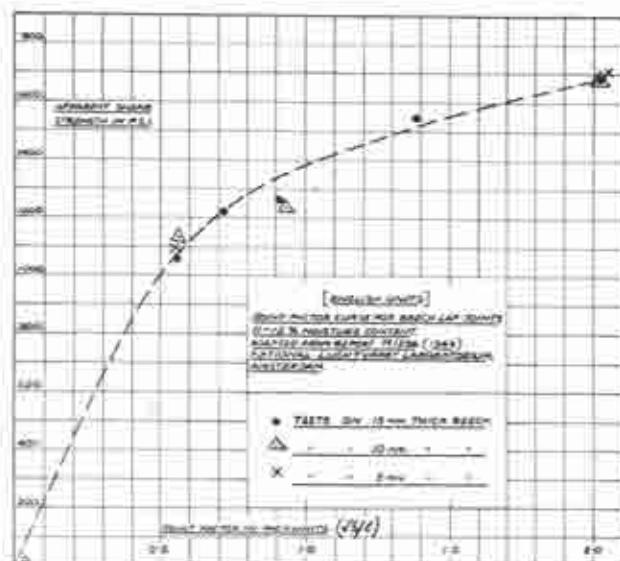
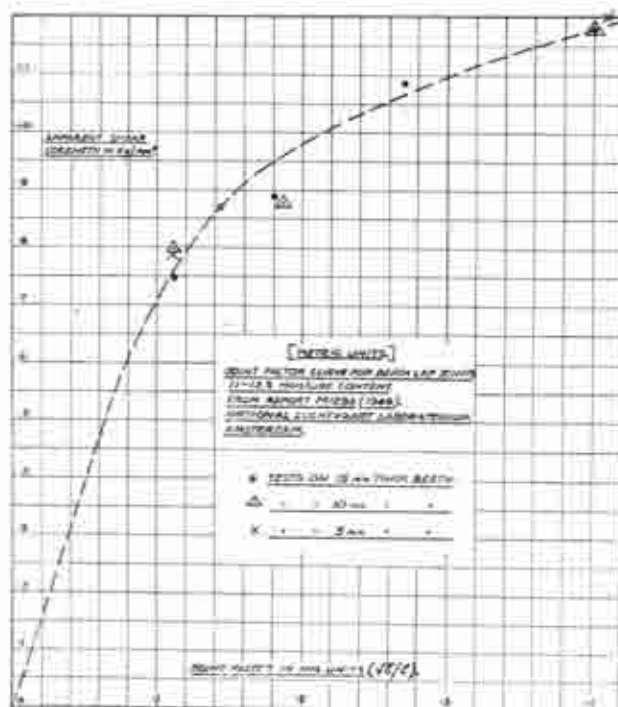


Fig. 7. Joint factor curve for birch in inch units (above) and (right) in millimeter units.



(a) What is the strength of a joint with $\frac{1}{2}$ in. overlap between two pieces of birch each $\frac{1}{8}$ in. thick by 1 in. wide? The square root of $\frac{1}{8}$ is .25; the joint factor is therefore .25 divided by $\frac{1}{2}$, i.e. .5. The chart shows that at a joint factor of .5 the mean failing stress is 1000 psi. The failing load equals the mean failing stress multiplied by the glued area and is therefore 500 pounds.

(b) What is the strength of a joint 1 in. overlap and 1 in. width between pieces of birch each of .707 in. thickness? The joint factor is .841 and the mean failing stress is therefore 1300 psi. The failing load on a square inch of glued area will be 1300 pounds.

(c) What is the strength of a joint of 0.8 in. overlap between two pieces of spruce $\frac{1}{2}$ in. thick by $\frac{1}{4}$ in. wide? The joint factor is 2.0; the mean failing stress (per unit width) is seen from the chart to be 1080 psi. The failing load will be 2020 pounds.

(d) What is the strength of a joint of $\frac{1}{2}$ in. overlap between two pieces of birch 1.5 in. wide by $\frac{1}{8}$ in. thick? The joint factor is 1.5; the mean failing stress is therefore 1520 psi and the failing load will be 1160 pounds.

Fig. 8 shows a similar type of graph for metal to metal joints made with "Redux" (A.B.I. Bulletin No. 8 [1943])

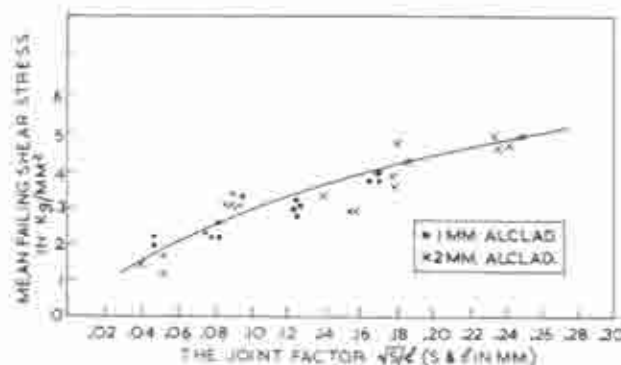
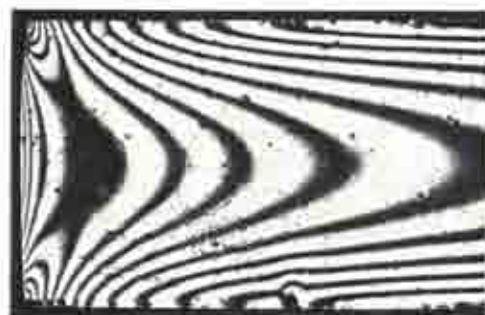


Fig. 8. Curve for determining the shear strength of metal-to-metal joints made with "Redux".



(a)



(b)

Fig. 9. (a) Stress patterns in a layer of glue between two rigid bars subject to shearing load. (The right hand adherend is pushed upwards, the other downwards).

(b) The glue is here subjected to a normal force due to compressive or tensile stress applied to the adherends as in a butt joint.

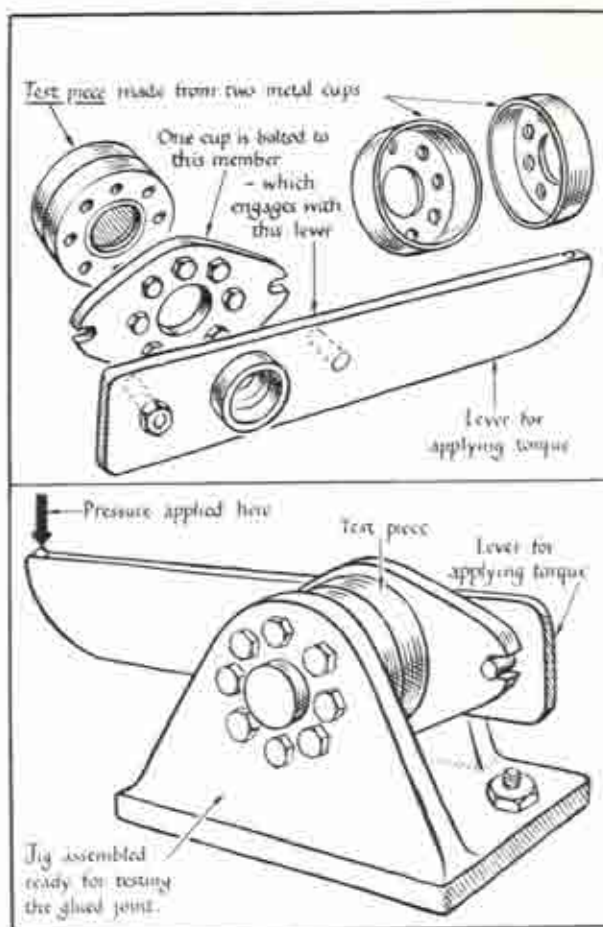


Fig. 10. Apparatus for applying a substantially uniform shear stress.

PHOTOELASTIC EXAMINATION OF GLUED JOINTS

Dr. Mylonas working in the laboratories of Aero Research Ltd. has investigated the stress distribution in glued joints under conditions in which the adhesive is very flexible compared with the adherends. We should expect a uniform shear stress under these conditions but this is only true in the middle of the joint.

The first photo shows stress patterns in a layer of Araldite stuck between two rigid bars subjected to shearing load, such that the right hand bar is pushed upward and the left hand downward. The edges of these solid bars produced the black margins in the photographs. In Fig. 9 (a) the boundary of the adhesive is semi-circular and the photograph shows that the irregular stress distribution occurs only near

this boundary (i.e. near the edge of the overlap), whereas further in towards the centre the stress is uniform. On the semi-circular boundary the stress is zero in the middle; on the right half it is tensile and on the left half it is compressive with maximum at about 45° , but the stress is of course always tangential to the boundary.

Fig. 9 (b) shows a layer of Araldite stuck between rigid adherends subjected to a normal force (tension or compression) corresponding to a butt joint. Along the free boundary the stress is least in the middle and rises to very high values at the corners from which failure under load will eventually be propagated.

APPROXIMATING A UNIFORM SHEAR STRESS

Having seen how non-uniform is the stress in a lap joint and a butt joint (the two commonest types used in glue testing!) one is naturally led to ask whether it is possible to devise any test which gives a substantially uniform and calculable stress. Provided the strain is small a fairly uniform shear stress can be imposed by twisting two similar rings glued one on top of the other. If "Redux" is tested between steel rings shear strengths of about

8000 psi are obtained. Fig. 10 shows a device due to the Division of Mechanical Engineering of the National Research Council (Canada) for applying a substantially pure shear stress.

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SOME TESTS ON SYNTHETIC RESIN ADHESIVES

N. A. de Bruyne

STRENGTH TESTS

THE glue maker tests representative glued joints both as a routine control tests of the quality of his production and also to assess the performance of new products. The glue user makes tests of specimens taken from his product (e.g. plywood). The specifications of main interest to the glue maker are therefore those that seek to test the glue, while the user's main interest is in tests on his finished product. In England, British Standards 1203 and 1204 (obtainable from the British Standards Institute, 24/28 Victoria Street, S.W.1.) cover the testing of synthetic resins for both plywood and assembly work while the testing of plywood (including the strength of the bond) is covered by B.S. 1455.

In the U.S.A., AN-G-8 and JAN-A-397 cover cold setting synthetic adhesives for wood, while MIL-A-5534 covers hot setting synthetic adhesives (obtainable from Air Technical Service Command, Wright Field, Dayton, Ohio, U.S.A.).

For metal-to-metal adhesives we have DTD775 in England and MIL-A-5090 (Superseding G-36) in U.S.A.

The testing of glues to B.S. 1203 and 1204 is fully described in A.R.L. Bulletin No. 28 and I will not repeat the details given in that bulletin except to summarise the requirements below.

B.S. 1203

This requires a mean failing load of at least 250 lb. on six dry beech lap joints. In testing for wet strength four different classes of performance are recognised as follows:—

Type	Temperature of Water	Time of Immersion	Min. Failing Load
A 15	15°C (59°F)	16-24 hours	250 pounds
A 70	70°C (158°F)	3 ..	200 ..
A 100	100°C (212°F)	3 ..	100 ..
AN 100	100°C (212°F)	6 ..	200 ..

B.S. 1204

B.S. 1204 calls for a mean failing load of at least 600 lb. on six dry pressure joints of the type shown in Fig. 1 and of 450 lb. on dry gap joints of the type shown in Fig. 2. Joints aged for 12 months at 25°C must also fulfil these requirements for dry strength. In testing for wet strength consideration is given to six different types of adhesive. Three are described as "B" type adhesives and are tested (and used) in both gap filling and pressure, or close contact joints. The other three are described as "C" type adhesives and are only tested (and used) where sufficient pressure can be applied to bring the surfaces into close contact. The requirements for these six types are as follows:—

Type of Adhesive	Temperature of Water	Time of Immersion	Min. Mean Failing Load	
			Gap Joints	Pressure Joints
B 15 & C 15	15°C (59°F)	16-24 hours	400 pounds	450 pounds
B 70 & C 70	70°C (158°F)	3 ..	225 ..	325 ..
B 100 & C 100	100°C (212°F)	3 ..	225 ..	325 ..

Both B.S. 1203 and B.S. 1204 describe mycological tests for resistance to attack by fungus and both draw attention to the undesirability of strongly acid exudations from the glue line.

METHOD OF PREPARING PRESSURE TEST PIECES

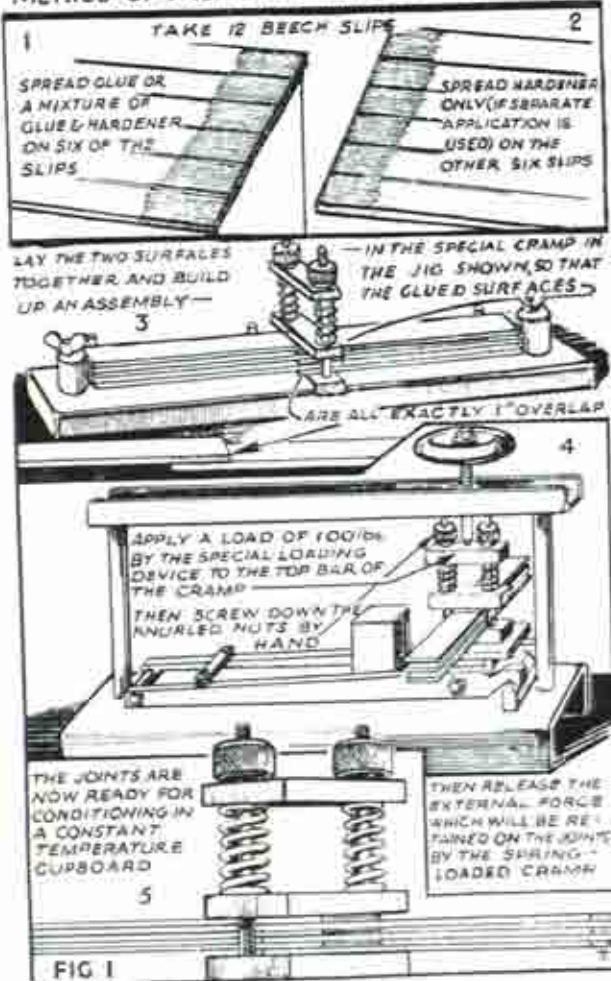


Fig. 1. The preparation of lap joints (separate application method).

I would like to emphasise that both B.S. 1203 and 1204 are intended to be tests of the glue: for this purpose the wood used is beech.

The most usual form of test piece for strength tests is the lap joint pulled in tension. A great many other types of test piece are used or have been suggested and for details of these I will refer you to Chapter 9 of "Adhesion and Adhesives". They can be classified as follows:

(1) Shear Tests:

- Lap joints under tensile load
- Lap joints under compressive load

Scarfed joints
Shear by bending
Shear by torsion

- (2) Tensile Tests :
Axial tension
Eccentric tension (cleavage test)
Peeling test
- (3) Miscellaneous Tests :
Punching tests
Chisel tests
Impact tests

The great majority of tests are static tests but, of course, fatigue tests are also of value, particularly in assessing the reliability of metal-to-metal joints.

While tests to destruction of glued joints have a certain value, particularly where the joint has previously been subjected to treatment (such as

METHOD OF PREPARING GAP TEST PIECES WITH SEPARATE APPLICATION OF GLUE AND HARDENER

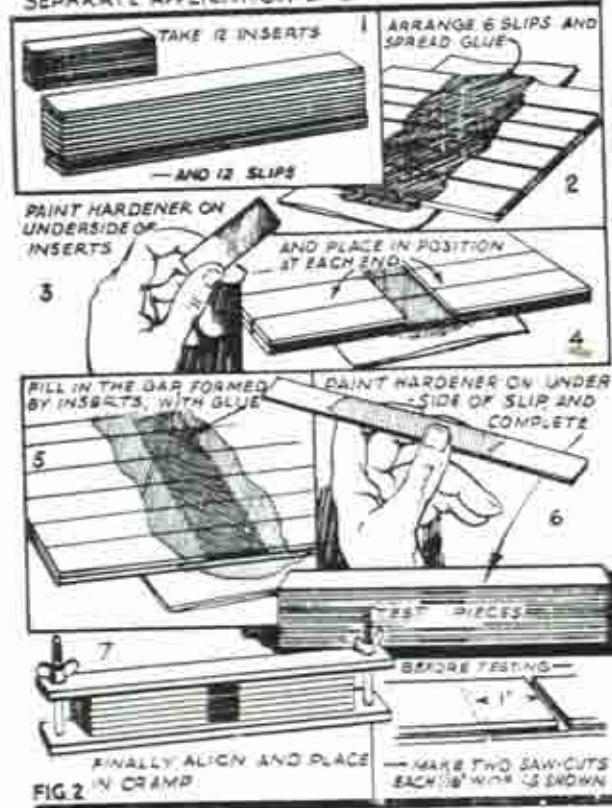


Fig. 2. The preparation of gap joints (separate application method).

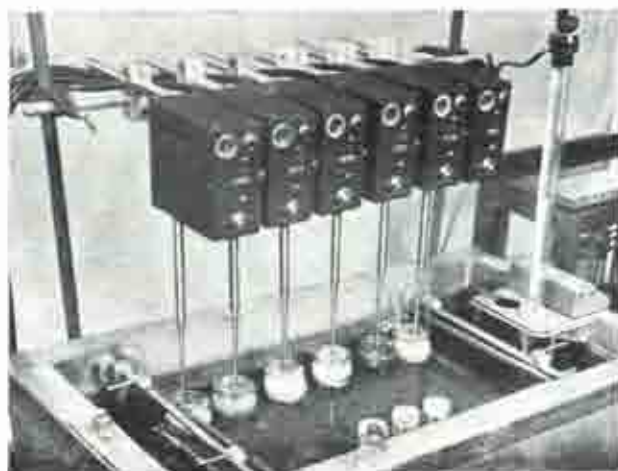


Fig. 3. The gelation timer consists essentially of a plunger slowly oscillated in the liquid glue. When gelation takes place the motion is arrested and the electric clock incorporated in the timer is stopped.

immersion in boiling water) likely to weaken the glue, it must be admitted that on the whole they are not a very good test of glue quality because they necessarily introduce so many variables extraneous to the glue and as my colleague, Mr. R. F. G. Lea, has pointed out, we ought to be developing means of isolating and testing glue films.

SOME OTHER TESTS

Pot life

If the pot life is short it is not particularly troublesome to make a simple test of a sample of the mixed

glue and hardener contained in a small paper cup kept at constant temperature in a water bath. The pot life is the time at which the mixture goes "rubbery" as indicated by repeatedly pulling out a glass rod. If however the pot life is long we find it saves trouble to use a gelation timer of the kind shown in Fig. 3.

Setting time

The setting time is the time taken at a specified temperature for a glued joint to reach its optimum strength. For most purposes, however one is interested in the time taken for a joint to reach a strength at which it is possible to do further work (shaping or planing) on it: this is about half the setting time. It is of some interest to note that the

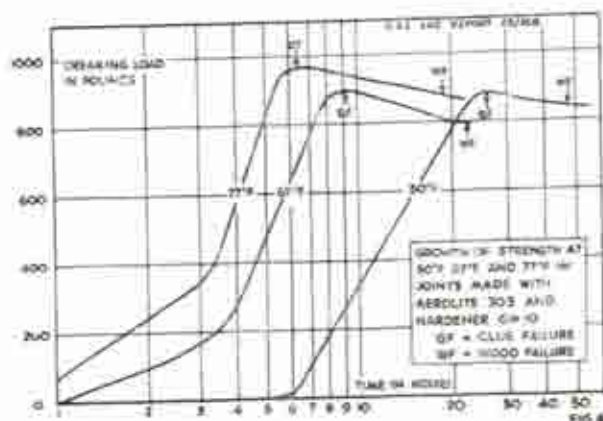


Fig. 4. Curves showing the changes in strength of joints as time elapses after assembly.

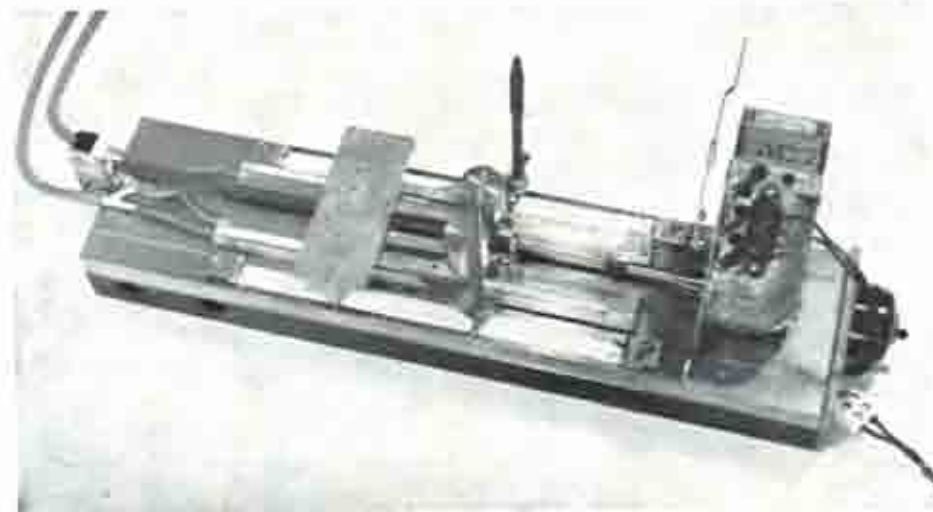


Fig. 5. After gelation the glue continues to gain strength and the time taken at any given temperature for the glue to set hard is measured by this instrument in which a weighted steel needle is driven at constant speed through a trough of glue at a constant temperature. When set the hardness of the glue is sufficient to lift the steel needle and also a ball pen forms a strip of paper. The length of the ink track of the paper gives the setting time.

strength of a joint does not asymptotically approach a limiting value as time passes, but as shown in Fig. 4, passes through a maximum value after which there is a slight decline to a stationary value. This maximum value corresponds to the point at which the glue still has enough pliability to distribute the stress fairly evenly over the glued area.

Till recently we have determined setting time of assembly glues by making up a number of joints and breaking them successively after known intervals of time. Hot setting glues are tested by using two ply samples of thin veneer supplemented by inspection of the behaviour of the glue on a hot plate. Recently, however, we have devised the setting indicator shown in Fig. 5 and this has been useful particularly in giving objective comparisons of the setting time of different hardeners. A weighted gramophone needle is dragged at constant velocity through the mixed glue and hardener contained in a narrow and shallow trough maintained at a constant temperature. The pressure on the needle is such that it is only lifted when the glue has acquired considerable strength; the time at which the needle lifts is shown by the trace made by a ball point pen on a paper strip.

There is sometimes confusion about the concept of "basic setting time". "Basic setting time" is not the actual setting time of the glue at a given temperature but a hypothetical setting time chosen to fit the rule which states that setting time of a joint is equal to a basic setting time plus one minute for each millimetre from press platen to the most remote glue line.

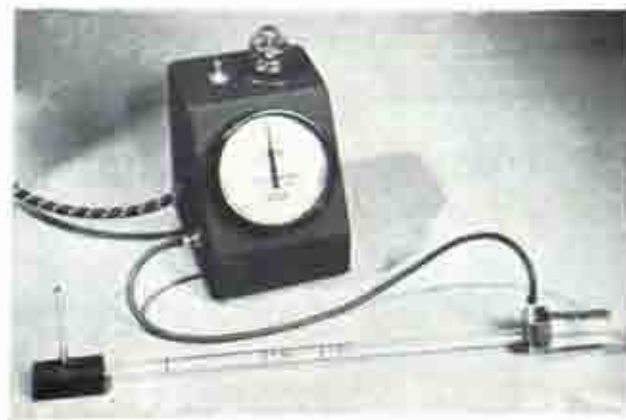


Fig. 6. This is an absolute viscometer of the isflux type devised to measure the viscosity of small samples of thick, opaque, volatile liquids.

Viscosity

Adhesives are rather viscous materials and often opaque. Their viscosity changes rapidly with temperature and they are inclined to skin. Measurements of viscosity are therefore somewhat troublesome. Instruments of the "Brookfield" type are useful though expensive. We ourselves use the instrument shown in Fig. 6 which has been fully described in Bulletin No. 91.

Solids content

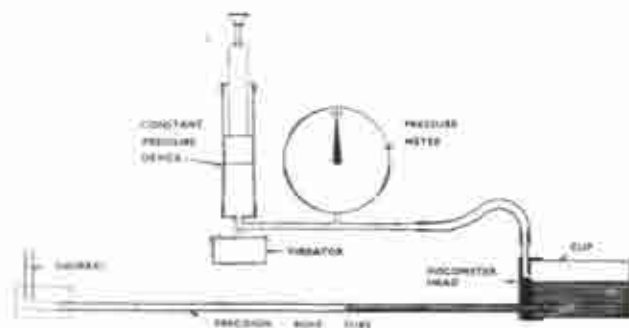
It is impossible to obtain an absolute value of solids content by evaporation of a liquid synthetic adhesive. The result will depend greatly on the temperature and conditions of evaporation. The British Plastics Federation in publication No. 21 (1947) gives three temperatures (100°, 120° and 135°C) at which heating can be carried out.

Expected Shelf Life

The life of liquid synthetic adhesives is limited and it is important to be able to anticipate what shelf life may be expected of a batch at room temperature. For this purpose a sample (without hardener) is heated at 80°C until gelation takes place; it is possible from experience to correlate the life at 80°C with the life to be expected at 15°C.

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AN INTRODUCTION TO THE PROPERTIES OF SYNTHETIC RESIN ADHESIVES

D. A. Hubbard

INTRODUCTION

IN this lecture are reviewed some of the more practical aspects of adhesion, the properties of adhesives used commercially, the manner in which they are used, and how the right adhesive is selected for a particular job.

The lecture is confined to what may be called "structural" adhesives, i.e. adhesives which are initially in a liquid state but subsequently solidify or "set". There are also of course permanently tacky adhesives; these never solidify, and while they have great value for certain tasks they are of no use for "structural" purposes.

METHODS OF SETTING

There are many ways (by no means mutually exclusive) in which we may classify adhesives; in practice one of the most useful is to group them according to their methods of setting. As will be seen later, most of the common adhesives will then fall readily into four main groups and many of their other properties can quickly be established once this first main classification has been made.

Methods of setting can be classified as follows:—

(a) *Setting by Loss of Solvent*

A great many of the common glues such as sodium silicate, starch, dextrin, cellulose esters, vinyl esters and so on set by losing their solvents. In this group the actual adhesive material is itself a solid and is made into a solution of syrupy glue by the addition

of water or occasionally of other solvents. This liquid syrup is applied to the joint which is then closed. The solvent begins to leave the glue line at the edges and by diffusion into the porous structure of the adherend. When all the solvent has left the film of glue in the joint maximum strength is reached and the glue film itself has become a dry solid.

The main point of interest is that the process is purely a physical one and is completely reversible. The addition of water or the appropriate solvent to the finished joint will re-dissolve the glue and allow the members to separate.

It should be noted that the speed of setting of such adhesives is governed by a number of variables over which the user may have no control. For instance when water, the most common solvent, is used the humidity and temperature of the surrounding air, the porosity and moisture content of the members being joined, and even the general dimensions of the joint itself and the method of applying pressure will all play a large part in determining the speed of setting.

Adhesives whose setting processes are completely reversible are unsuitable for use where a bond of great permanence is required and conditions of service are severe.

(b) *Setting by Cooling from the Molten State*

Gelatin and bitumen belong to this group of adhesives. Both of these liquefy when heated sufficiently and are applied to the surfaces to be joined when molten. The joint then cools until at

room temperature the adhesive forms a hard solid film and the bond attains its maximum strength. If gelatin is the adhesive the mixture will contain water as a solvent to reduce viscosity and to lower the temperature at which melting takes place; thus gelatin glues set by a double process: by cooling and by losing added water.

This process of melting and subsequent setting is again completely reversible and such adhesives are not suited for extreme conditions of service.

(c) Setting by Permanent Chemical Change

The important point concerning most of the adhesives which set mainly by chemical change is that the process is permanent and irreversible. Such adhesives will thus give permanent bonds of high strength under the most severe conditions of service.

In reality the groups are not of course quite as clearly defined as the brief outline above suggests. There are adhesives, for example, which set mainly by a reversible physical change accompanied by minor permanent chemical changes and there are some which set mainly by a permanent chemical change accompanied by a slight, reversible, physical change. Thus the properties of such adhesives are spread over the whole range from the extreme of reversible physical change to that of irreversible chemical change.

Chemical change in adhesives may be brought about in two main ways:—

(i) By the addition of a "hardener", i.e. a chemical compound which promotes chemical change in the syrupy liquid adhesive itself. This process goes on readily at ordinary room temperature, but is speeded up if the temperature of the adhesive is raised. The amount and strength of the hardener added govern the speed of setting (at constant temperature). If a weak hardener only is used, the setting process at room temperature may be so slow that heat must always be applied as an additional accelerator. Such adhesives are labelled "hot-setting only".

(ii) By simple heating only. Melamine formaldehyde and phenol formaldehyde resin adhesives harden irreversibly on being heated. They may be applied to the joint as liquids or as solids in the form of film glues. If film glues are used the first result of heating is to cause the glue to melt and flow;

continued heating brings about the chemical change in the adhesive which leads to solidification.

Table I gives the grouping of all the adhesives under consideration according to the manner in which solidification is brought about.

TABLE I
CLASSIFICATION OF ADHESIVES
ACCORDING TO METHODS OF SETTING

Group	Nature of change	Type of glue
1	(a) Entirely physical and reversible (cooling, loss of dextrin, bitumen, gelatin, solvents, etc.)	Sodium silicate, starch, cellulose esters, vinyl esters.
	(b) Some chemical. Noticeably reversible.	Casein, soya bean, blood albumen.
2	(a) Mainly chemical—some slight physical. Slightly reversible.	Urea formaldehyde (UF).
	(b) Almost entirely chemical. Irreversible.	Melamine formaldehyde (MF), resorcinol formaldehyde (RF), phenol formaldehyde (PF), Ethoxyline resins, PF acetal resins.

MATERIALS TO BE JOINED

Having considered solely the setting properties of all these adhesives, we now come to the general properties which must be surveyed before one can choose the right adhesive for a particular duty.

The next most important property required is that of specific affinity for the adherend. As Dr. de Bruyne has explained in the first lecture in this book, *Some Basic Ideas*, one must use a polar adhesive for joining polar materials and a non-polar adhesive for joining non-polar materials, unless by some means or other the surface of the non-polar material can be treated to bring it into a polar condition. In Table II the adhesives are classified according to the materials they are used to join together. It will also be noticed that those adhesives depending partially or entirely on loss of solvent for solidification can only be used for joining porous materials.

TABLE II

ADHESIVES CLASSIFIED ACCORDING TO THE MATERIALS THEY ARE USED TO JOIN

Paper	Wood	Textiles	Wood-metal	rubber-metal	Other non-porous adhesives, e.g. metal-metal, glass, earthen-ware, etc.
Sodium Silicate	Gelatin	Vinyl esters	Casein/lutec	RF	Vinyl esters (Glass)
Bitumen	Casein	MF	Ethoxy-line resins	PF acetal	Ethoxy-line resins
Starch/dextrin	Soya bean		PF acetal	Ethoxy-line resins	P.F. acetal
Dextrin + UF	Blood albumen				
Gelatin	Starch/UF				
Casein	UF				
Cellulose esters	MF				
Vinyl esters	RF				
	PF				

WATER RESISTANCE

Having selected a group of adhesives which are known to have a specific affinity for the materials to be joined, it is then necessary to assess the severity of the conditions of service the joint is expected to survive. Where conditions of service are likely to be extremely severe, it is clear that the adhesive must possess a high degree of inherent water resistance and from Table I, in which the adhesives are classified according to their methods of setting, it is quickly established that those which set entirely or almost entirely by reversible physical change are unsuitable.

Adhesives classified as Group 2 (a) or 2 (b) should therefore be considered; it is then necessary to determine the precise degree of water resistance required. Some of the adhesives in Groups 2 (a) and 2 (b) possess indefinite resistance to immersion in water at room temperature, some of them have good resistance to boiling water and others again are resistant indefinitely to boiling water.

Clearly high water resistance is required for all exterior work: for boat building, for aircraft manufacture, and for the manufacture of plywood and other containers holding damp substances or liquids, such as food-stuffs, beer, etc. For normal work of this character an adhesive resistant to cold or warm water is sufficient.

It is even more necessary for dry joints, which may encounter high or variable humidities, to possess a high degree of water resistance, for the most severe conditions of exposure are those which couple a high humidity with a high ambient temperature—conditions such as are met with in the tropics. For this type of work resistance to warm water or even to boiling water is an absolute necessity.

It is unlikely, of course, that a glued wooden article will ever be immersed in boiling water for any considerable period of time, but conditions frequently arise, for example inside wooden aircraft wings in the tropics, where the temperature may be as high as 80-90°C and the humidity approaching 100%. For work of this character an adhesive possessing indefinite resistance to boiling water must be used.

When wooden joints are subjected to high and low humidities alternately, severe strain is imposed on the adhesive bond: under these conditions again, irrespective of the ambient temperature, it is good practice to use an adhesive possessing indefinite

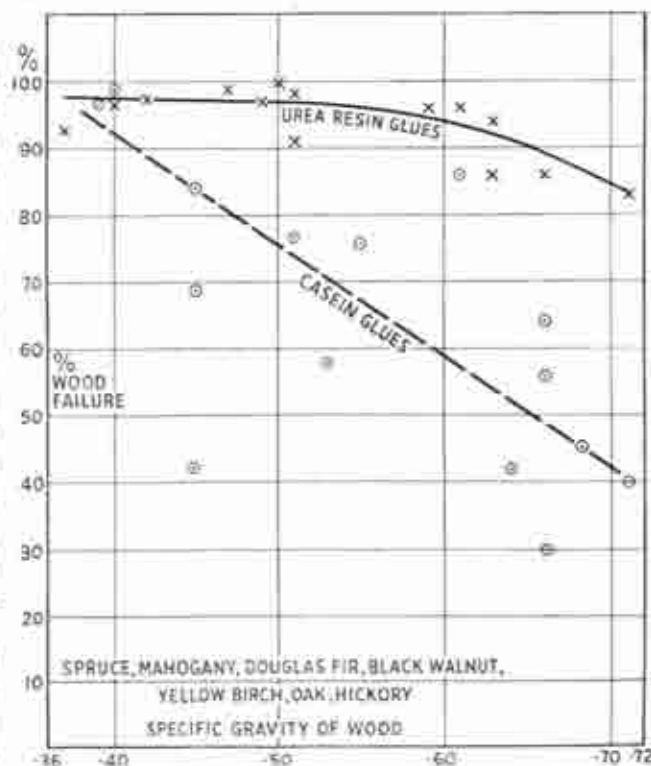


Fig. 1. Readings obtained from many hundreds of dry shear tests are shown above. As the density of the wood increases the urea resin glues show a marked superiority over the casein glues.

resistance to boiling water. Table III classifies under 5 headings the adhesives we have been discussing according to their resistance to water at various temperatures.

TABLE III
WATER RESISTANCE OF GLUES

Not resistant to water	Resistant to cold water, 20°C.	Resistant to warm water, 70°C.	Good resistance to boiling water, 100°C.	Indefinite resistance to boiling water
Sodium silicate Starch/dextrin	Bitumen Cellulose esters	UF	UF+MF UF+RF	MF RF
Gelatin Casein	Vinyl esters		Ethoxylated resins	PF
Soya bean Blood albumen	UF+starch		PF+urea	

It will be seen that, as we mentioned earlier, adhesives in groups I (a) and I (b) generally are listed as not resistant to water. Casein, soya bean and blood albumen do possess some slight resistance to water, but not nearly sufficient to reach a higher classification. Bitumen and the cellulose esters and vinyl esters all possess reasonable resistance to cold water.

Urea formaldehyde when extended with considerable additions of starch or rye flour remains resistant to cold water; alone it is completely resistant to water at all temperatures up to 70°C.

Under the heading *Good Resistance to Boiling Water*, it will be noticed that UF appears again when in combination with MF or with RF. Small additions of these fortifying resins improve the water-resistant properties of UF markedly, so as to bring the combined resin into this higher category. Unmodified MF, RF and PF are, of course, all resistant indefinitely to boiling water.

Another point of interest is that increase in water resistance means an increase in the cost of the adhesive, so only the minimum permissible degree of water resistance should be aimed at where the cost of the finished article is the prime consideration. It will be seen that in the case of UF resin, the water resistant properties and incidentally its cost can be considerably modified over a wide range. If little or no water resistance is required, it is common practice to add large quantities of starch or rye flour to the UF resin. If moderate water resistance is required,

the UF is used in its unmodified form. If high water resistance is required and a higher cost is permissible, the UF can be up-graded with small additions of melamine formaldehyde or resorcinol formaldehyde. These additions are commonly carried out in the works where the goods utilising the glue are produced. Plain urea formaldehyde is purchased from the glue manufacturer and the modifying agents added by the buyer according to the production on hand.

RESISTANCE TO MYCOLOGICAL ATTACK

If glued joints are intended to survive in a humid atmosphere or in a situation where they may be alternately wetted and dried, it is necessary to take note of the actual chemical nature of the adhesive to be used. A good many of the early adhesives were produced from proteins and carbo-hydrates, both of which chemical groups are foodstuffs and therefore provide a good breeding ground for moulds and bacteria; thus the glue will eventually be destroyed.

Requirements for the successful growth of most of the lower forms of life are the presence of moisture, the presence of suitable food-stuffs, and lastly a moderate ambient temperature. In many situations all these conditions are fulfilled, so that if really permanent joints are required, it is essential not to use a foodstuff as the adhesive, but instead either an inorganic binder or a synthetic resin. Neither of these materials is suitable for supporting the growth of bacteria, and in fact some of the synthetic resins, particularly those containing traces of free formaldehyde, are even toxic to low forms of life. It will be remembered that formaldehyde finds a wide use as a disinfectant.

TABLE IV
CLASSIFICATION ACCORDING TO CHEMICAL NATURE

Proteins	Carbo-hydrates	Inorganic chemicals	Synthetic resins
Attacked by bacteria		Not attacked by bacteria	
Gelatin Casein Soya bean Blood albumen	Starch/dextrin Cellulose	Sodium silicate Bitumen	Vinyl esters UF MF RF PF Ethoxylated resins PF urea

In certain cases the adhesives with a protein and carbo-hydrate base are protected against bacterial attack by the addition of sterilising agents, but most of these agents are not really permanent, so that the protection given is not lasting.

RESISTANCE TO DRY HEAT

A small number of adhesives are not suitable for permanent bonding in conditions where the average temperature is likely to be high. These are of course the adhesives included in the list of those setting by reversible physical change, and in particular, joints made with bitumen or gelatin will soften and separate if exposed to a high temperature.

GAP-FILLING PROPERTIES

Synthetic glues were used for the first time for the manufacture of aircraft in the early part of the recent war, and a very serious problem arose soon after their introduction. Urea formaldehyde resins were chosen for the work, on account of their high properties of water resistance, but there are very many gluing operations in the building of an aeroplane where it is impossible to apply sufficient pressure to the joint during setting to bring the surfaces into intimate contact. In many places it was found necessary to make joints with glue lines having a thickness of 25/1000 to 50/1000 of an inch and it was soon discovered that such joints if made with an unmodified UF adhesive fell to pieces after a few months; the reason was that the shrinkage stresses set up during the setting of the resin were so great that the thick resin layer disintegrated into innumerable tiny fragments, much in the same way as a badly annealed piece of glass may shatter for no apparent reason.

It was thus found necessary to "anneal" the UF resin during setting, so as to prevent the building up of locked up stresses in the glue mass; this was achieved by the use of special hardening agents. (Prevention of cracking or crazing can also be carried out to a lesser extent by the incorporation of wood flour or starch into the adhesive mixture.)

Such modified adhesives are called gap-filling adhesives, because they will give strong permanent joints between members which may be spaced some distance apart. It is clear that the use of a gap-filling

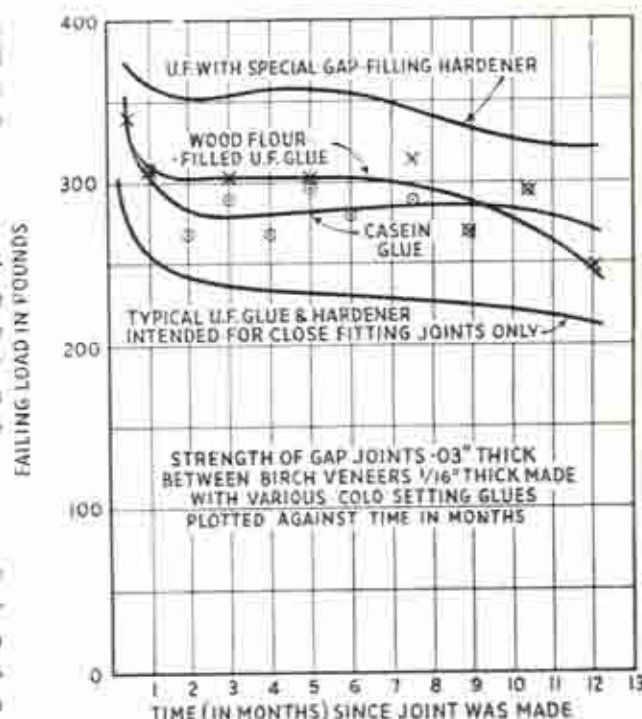


Fig. 2. The relationship between the age and strength of a joint. These results are based on work carried out by Mr. R. A. G. Knight of the Forest Products Research Laboratories at Princes Risborough.

adhesive is of the utmost importance if it is difficult or impossible to apply adequate pressure to a joint during manufacture.

Non gap-filling adhesives will provide good joints providing the thickness of the glue film does not exceed 10/1000 of an inch. If the glue film for any reason is likely to be thicker than this in the finished joint, a gap-filling adhesive must be used.

Gap-filling adhesives are often required where the presence of gaps of the lack of adequate pressure is not at first sight obvious; a good example of this is in the manufacture of laminated bends. Very considerable pressures are often required to force the straight laminae into the curved male and female moulds, but these moulds are rarely so accurately machined that the pressure is distributed uniformly over the entire surface of the bend. Usually most of the pressure is applied at the centre or ends of the bend, and little or none in the intervening sections. With variable pressure of this sort a gap-filling adhesive must be used.

The list, headed "Table V", gives the names of

TABLE V

GAP-FILLING ADHESIVES

Casein
Modified urea formaldehyde
Resorcinol formaldehyde
Cold-setting phenol formaldehyde
Certain ethoxyline resins

all the gap-filling adhesives. It will be seen that they are few in number.

AGEING CHARACTERISTICS

A small number of the adhesives we are considering do not give joints of great permanence, even when these joints are maintained at normal room temperatures in a dry climate; and this can perhaps be attributed to the gradual falling off in real chemical affinity between the adhesive and the adherend.

Sodium silicate and starch/dextrin adhesives by themselves suffer from this defect, and it is for this reason that they are classified only as adhesives for paper, where the strength requirements are, of course, low. Blood albumen glue has been extensively used for the manufacture of plywood. As mentioned earlier, it possesses some slight degree of water resistance, and initially it provides an extremely high strength bond. After several months' ageing, however, the dry strength of the bond falls off considerably, so that plywood glued with blood albumen is of interest only as a short term material and should not be used for permanent work.

It should perhaps also be mentioned that blood albumen is often used as an extender for PF glues for the manufacture of plywood. The strength and permanence of the PF resin more than counterbalances the tendency to fall off in strength characteristic of the blood albumen, so that a plywood glued with this combined adhesive is a high grade product.

Gap joints glued with unmodified UF resin, as previously mentioned, are also not permanent, disintegration taking place after a few months.

DEGREE OF FLEXIBILITY

If joints are to be made between very elastic materials, the choice of adhesives is quite limited. Gelatin glues are of course extremely flexible, and they can be made even more so by the incorporation of glycerin into the mix. Such glycerin/gelatin adhesives are often used for the manufacture of moulded cork products made with cork granules and designed for use as oil-sealing gaskets and so on.

The cellulose and vinyl esters also possess a high degree of flexibility.

A noticeable degree of flexibility in the adhesive bond is required when dissimilar metals having different co-efficients of expansion are glued together or where metal is to be glued to wood.

For the gluing of metal to wood, in, for example, the manufacture of metal-faced plywood, large quantities of casein glue have been used in glue mixes specially modified to give increased flexibility by the incorporation of rubber-latex emulsion. In recent years, however, a number of very special synthetic resins have been developed, both for metal to wood and for metal to metal bonding. These are the ethoxyline resins and PF acetal resins; in both these resins the foremost problem which has had to be considered when they were produced was that of imparting sufficient flexibility to the hardened glue film to accommodate the violent stresses set up between the dissimilar metals or between the metal and the wood. Dr. de Bruyne has already discussed the problems involved in ensuring that the adhesive material wets the metal surfaces adequately. It also has to be remembered, of course, that the greater the degree of flexibility in the adhesive, the lower will be the ultimate joint strength, so that the production of the metal bonding adhesives has involved striking a very delicate balance between two opposing needs.

COLOUR AND STAIN

Most adhesives produce colourless glue lines and a barely visible joint. A few adhesives, however, are highly coloured, notably the resorcinol resins, the phenol resins, blood albumen and bitumen, so that if a colourless glue line is required, these adhesives cannot be used.

A more important point is that some of the adhesives discussed are strongly alkaline in character,



Fig. 3. A new type of furniture made possible by the development of synthetic resins which will bond metal to wood. Walnut veneers are bonded by the 'Relax' process to thin sheet aluminium.

and although they may themselves be colourless, they can develop a strong colour under certain conditions when, for example, they come into contact with woods containing a high proportion of tannin. This leads to patches of stain which in furniture manufacture can give endless trouble, particularly in the later stages of manufacture when the article of furniture is to be stained or polished. Alkaline or alkali-containing adhesives are sodium silicate, some of the dextrins, casein, soya bean, some blood albumen glues, and phenol formaldehyde. Any of

these glues if used, for example, on oak, would produce purple or black patches of stain.

RESIDUAL TASTE OR SMELL

Certain adhesives give off volatile products during application, and also during setting, and in some cases these volatiles may be objectionable. An example of this has occurred in the manufacture of plywood beer barrels and other food containers. UF resins are not particularly suitable for this

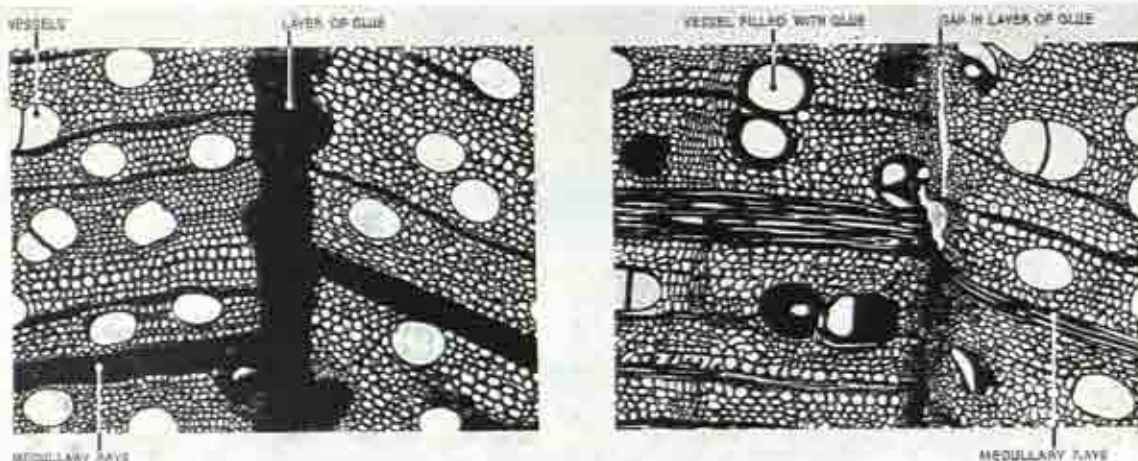


Fig. 4. The application of too heavy a pressure during bonding is the most common gluing fault.

purpose, because during and after setting they give off traces of free formaldehyde, which has a pronounced taste and smell even in minute quantities, and such a material is not to be tolerated in a foodstuff. Other examples are the cellulose and vinyl esters, which give off volatile inflammable solvents during setting (here their use may be attended by a high fire hazard) and the PF resins which give off traces of free phenol during setting which has a strong taste and smell even in tiny quantities.

METHOD OF USE

With some adhesives high bonding pressures are necessary while others, as mentioned earlier, will only set or harden at high temperatures; in using these adhesives there is therefore a possibility that the adherends may suffer damage; for example, PF film glues require bonding pressures of more than 200 lb per sq. in., and such pressures will crush a large number of soft woods.

Again, the PF resins are cured or set at temperatures in the region of 140°C., which temperatures, if used in bonding wood, will cause severe drying and shrinkage of the wood; also high pressure steam blisters may be produced. Special precautions have to be taken to deal with this situation. Plywood made with phenolic resins is commonly conditioned after manufacture by being immersed in water, sponged or otherwise damped to raise its moisture content back to a normal figure, and so reduce the

brittleness produced by the excessive removal of moisture.

The ethoxyline resins used for metal binding require high temperatures of the order of 200°C for prolonged periods, but do not need excessively high pressures, whilst the PF airtal resins require relatively high pressures as well as a bonding temperature of 110°C.

Melamine formaldehyde resin sets most successfully when heated to between 80-100°C and is thus not particularly suitable for constructional work outside the hot press for plywood. Mixed with UF resins, however, melamine resins will give adhesives setting at much lower temperatures and especially suitable for the manufacture of the curved plywood bonded in rubber-bag moulding presses.

EASE OF HANDLING

It is necessary here to say a word or two about some of the newer synthetic resins. The fire hazard in connection with cellulose and vinyl esters has already been mentioned; in the case of the urea resins, the melamine resins and the phenolic resins, some care must be taken by the operator in handling. It should always be borne in mind that the majority of these resins stick as well to human skin as they do to wood, so they should never be allowed to harden on the skin, as this would rapidly lead to sore places giving rise perhaps to all sorts of secondary infections. As mentioned earlier, urea resins contain traces of free formaldehyde, and this can give rise to dermatitis, particularly in persons with sensitive skin.

PF resins contain traces of free phenol, and phenol is a solvent for skin tissue.

The important point to remember, therefore, is that all these resins should be handled with care, and if possible the hands should always be protected with gloves. If this is out of the question and contamination of the skin is unavoidable, the next best remedy is frequent washing. Work people who repeatedly clean their hands free from traces of resin with soap and water very rarely get dermatitis. Melamine resins are extremely difficult to wash off as they are practically insoluble in water but they can be removed by first cleaning the hands with soft sawdust. UF resins used in hot presses for plywood manufacture often give off large quantities of hot formaldehyde gas which is irritating to the eyes. It is therefore always good practice to install a fume hood over every hot press on work of this sort.

TRACES OF OTHER ADHESIVES

In repair work and also when building up sub-assemblies into a complete structure it is important to note which kind of adhesive has been used previously on the surfaces to be joined as traces of the old glue may remain to interfere with the reaction by which the resin sets. It would, for example, be useless to apply a UF resin which requires to be made acid by a hardener before it will set, where considerable casein glue remained; the very high degree of alkalinity of the casein might neutralise the whole of the acidity of the UF resin and setting would very likely be unduly prolonged or even prevented altogether.

COST

In all the foregoing remarks little has been said on the subject of the actual cost of the adhesive but an attempt has been made to show how to select the right adhesive for a particular application strictly on the basis of its technical qualifications for the work in hand. In some cases, however, cost may be the overriding consideration, and it is perhaps interesting, in this context, to recall the groupings in Table III.

Generally speaking the cost of the adhesive rises as the degree of water resistance increases, although there are some exceptions, notably the cellulose and vinyl esters and ethoxylated resins. It should always be borne in mind, however, that it is futile to try to assess the cost of the gluing operation purely by finding the cost per pound or per kilogram of the adhesive. A great many other variables must be given the most serious consideration. The spreading capacity in terms of pounds per 100 square feet of glue line can vary enormously, and an adhesive costing very little per pound may have only a low spread and thus may prove to be much more costly in use than another adhesive which has a higher cost per pound but a far greater coverage.

Another point which is often overlooked, particularly in plywood manufacture, is the value of the uniformity in the results obtained. The cheap adhesive will generally give more variable results and this may lead to the production of large quantities of plywood which are subsequently rejected. To arrive at a proper assessment of the relative merits of the cheaper adhesive as compared with a more expensive one, the cost of such faulty work should be taken into consideration.

A third point is that for some special applications, for example, metal bonding, there is only one adhesive to use so that there is no question of discussing relative costs.

It is often instructive to estimate the total cost of a manufactured article and then to determine the cost of the adhesive alone used in it: the cost of the adhesive will usually be found to be a surprisingly insignificant fraction of the total overall cost.

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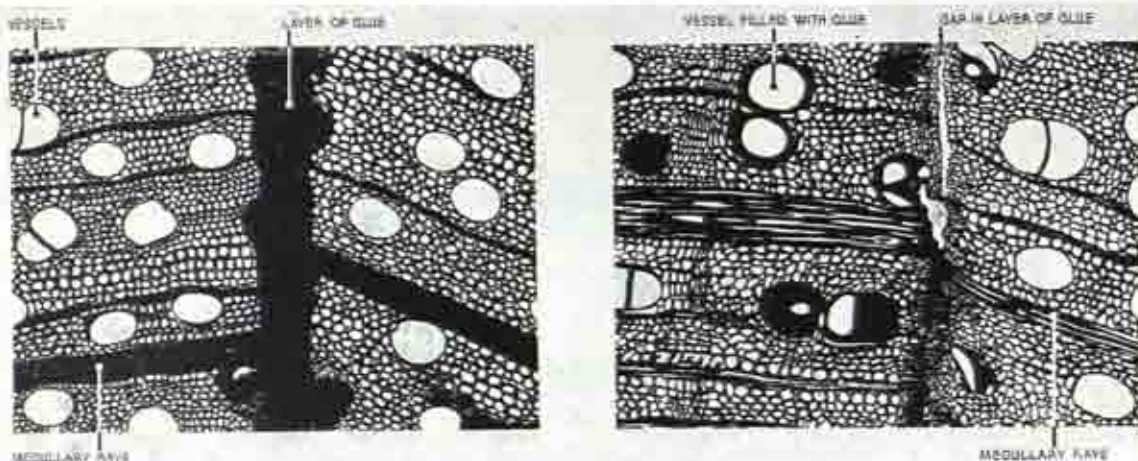


Fig. A. The application of too heavy a pressure during bonding is the most common gluing fault.

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AN OUTLINE OF THE CHEMISTRY OF SOME SYNTHETIC RESIN ADHESIVES

C. A. A. Rayner

INTRODUCTION

AN important application of the group of substances known as synthetic resins is their use as adhesives, so a study of the chemistry of synthetic adhesives is in effect a study of the chemistry of synthetic resins.

By synthetic resin is meant a resinous substance prepared by chemical reaction from simpler compounds. None, so far as is known, has a counterpart in nature.

Many synthetic resins can be produced in forms suitable for use as adhesives. An adhesive may consist entirely of one particular resin or it may be a mixture of several different resins. In this talk I shall confine myself to those synthetic resins of which I have had first-hand experience.

I shall begin by defining some of the terms which are used in this field so that we may have them clear in our minds. Some of these expressions are used rather loosely in discussing the chemical and technological aspects of adhesives; some could only be explained thoroughly by occupying the whole time allocated to this talk—so I must ask the forbearance of you who are well-informed if my definitions are not comprehensive.

There is a significant difference between substances which are easy to distil or crystallise and those with which these processes are difficult or impossible. The former are made up of molecules containing few

atoms; the molecules of the latter contain a large number. The essential requirement of a chemical reaction capable of producing a resinous material is the ability to form large molecules. This requires a certain reactivity of the component substances—the molecules must contain a minimum number of reactive chemical groups. And this brings us to the first definition.

FUNCTIONALITY

Probably the most fundamental conception in the chemistry of synthetic resins is that of functionality. Whether or not molecular growth is possible depends on the number of functional groups in the molecules of the starting materials.

A functional group in a molecule is a group which is reactive under the conditions of the experiment. For example, acetic acid (i) reacts with methyl alcohol (ii) to produce methyl acetate (iii).



Here the functional groups are hydroxyl ($-\text{OH}$), of which methyl alcohol has one, and carboxyl ($-\text{COOH}$), of which acetic acid has one. The product, methyl acetate (iii) possesses none of these functional groups and consequently ceases to react.

Now consider the reaction between acetic acid and an alcohol with two functional groups, say ethylene glycol (iv), a dihydric alcohol.



The first reaction leads to the glycol monoacetate (v) which, as you can see, still contains one functional hydroxyl group. It can, therefore, react with another molecule of acetic acid to give glycol diacetate (vi) and here the reaction ceases.

Similarly, the reaction between oxalic acid (vii) (with two functional groups) and methyl alcohol (with one) will stop when it reaches the stage of dimethyl oxalate (viii).



However, if we take oxalic acid and ethylene glycol (iv), the first product of the reaction (ix) contains two functional groups, —COOH and —OH, and can react at each end of the molecule with alcohol or acid respectively.

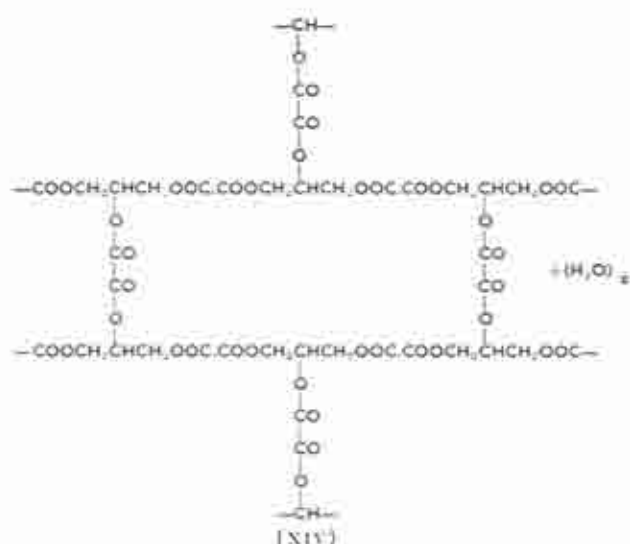
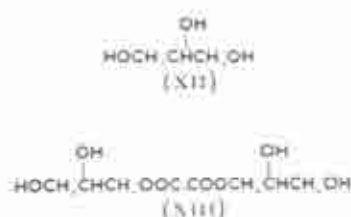


The products (x) and (xi) still possess two functional groups, either COOH as in (x) or OH as in (xi) and can therefore continue to react indefinitely.



The final result will be a linear molecule; such a substance will be fusible.

When a trifunctional starting material is used, for example, glycerol (xii) with oxalic acid, the intermediate product (xiii) has four functional hydroxyl groups and as a result can grow in more than two directions. The final product (xiv) is therefore tri-dimensional and substantially infusible.



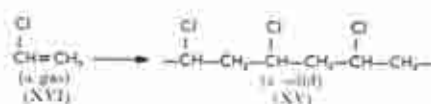
In order to obtain a synthetic resin the molecules of the starting materials must each contain a minimum of two functional groups. With two each a fusible resin is formed whereas when one or both molecules have more than two functional groups an infusible resin may be formed.

It is possible to distinguish four different ways in which complex resin-molecules can be built up from simple starting materials, a general process which may be termed poly-integration. Three of these ways involve processes of direct addition without the elimination of any by-products and can be, therefore, broadly described as polymerisation reactions. The fourth type results in the elimination of by-products, for example water, and is properly called poly-condensation. Their relationship can be seen in the table below.



TRUE POLYMERISATION

True polymerisation is a process of combination of like molecules which is purely additive and therefore does not result in the evolution of any by-products; an example is the formation of polymeric vinyl chloride (XV) from vinyl chloride (XVI) (1)(3).



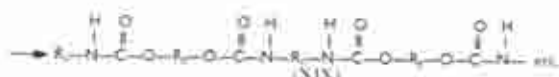
Just as readily as some will polymerise, so will they de-polymerise and revert to the monomeric form. A higher temperature than the materials normally encounter will often effect such a reversion. From this we may deduce that the degree of instability, normally associated with the double-bond, is to some extent dependent on temperature.

CO-POLYMERISATION

Certain substances capable of independent polymerisation to form resinous substances are also able to polymerise together. This process of co-polymerisation is extremely important; it often results in products with properties which are superior to those of mixtures of the individual polymers. An important example is the co-polymerisation of vinyl chloride and vinyl acetate.

POLY-METATHESIS

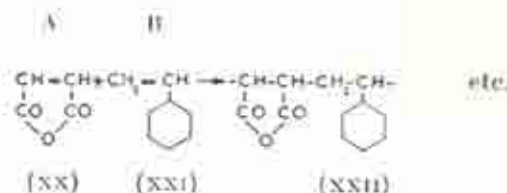
The third type of addition polymerisation I shall term poly-metathesis. This type of molecular growth is exemplified by the resins known as the polyurethanes (p. 48). To prepare these a di- (or poly-) isocyanate (XVII) is reacted with a di- (or poly-) hydric alcohol (XVIII).



This reaction resembles poly-condensation in that the two different molecules link up alternately to form long chains; it differs, however, from true

condensation in that no by-products are formed. Also, it resembles polymerisation in that the process is additive, but it differs in that the separate starting materials will not polymerise independently.

A somewhat similar reaction, which is really a hybrid of poly-metathesis and co-polymerisation is that between maleic anhydride (XX) and styrene (XXI), to yield a resinous product (XXII). This reaction is sometimes referred to as a hetero-polymerisation.



Under the conditions of the reaction styrene alone can polymerise *per se*, so the structure might not consist of alternating molecules but might, for example, be of the form ARABBARBARA.

POLY-CONDENSATION

In certain chemical reactions between two or more organic molecules, water or a similar simple substance of low molecular weight is split off; this is a condensation reaction and Equation A is an example. Where this results in the formation of a macromolecular structure it is called poly-condensation.

Poly-condensation may produce two-dimensional structures as in the fusible Alkyds and the polyamides (Nylon), or three-dimensional, as in fully cured phenolic and urea resins.

All of these processes involving molecular growth may be induced by heat, light, pressure or by catalysis—frequently by two or more.

CURING OR SETTING

In the preparation of synthetic adhesives the reaction is frequently stopped at an intermediate stage. This is clearly necessary in the case of the infusible resins; such reactions are completed during the process of gluing and the chemical change imparts certain physical properties.

Some adhesives are applied as solutions and lose solvents during gluing; some are applied in

the form of an emulsion and thus lose the equivalent of a solvent; others are applied in the form of a dry film.

These are the chief examples of setting or curing; usually it means the conversion of the resin from the liquid to the solid state.

THERMOSETTING

A thermosetting resin is one which hardens under the influence of heat as the result of an irreversible chemical change; thereafter the resin usually remains substantially infusible.

THERMOPLASTIC

A thermoplastic substance is one which, within limits, softens on heating and hardens on cooling without deleterious effect on the material. Usually, the limits are set by the temperature at which there is either incipient decomposition or the onset of a reversible chemical reaction, e.g. de-polymerisation.

The dividing line between thermosetting and thermoplastic is fairly sharp, but there are some borderline cases, for example certain resins may need heat to set them but nevertheless soften when heated to higher temperatures, so they are heat-hardenable but not infusible. These, however, are not usually softened by heat to a sufficient extent to render them capable of being moulded or used as adhesives by merely applying heat.

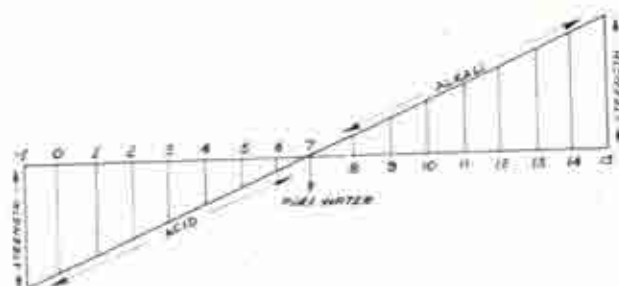
CATALYST

This is the name given to something which influences the rate of a chemical reaction. It may accelerate or retard a reaction; but the word is generally used to mean an accelerator. Not very much is understood about the mechanism of catalysis and the word catalyst is used rather loosely in connection with synthetic resin adhesives; for example, as a hardener or curing agent.

pH VALUE

In a few words, it is possible only to say what pH value indicates. Substances which dissolve in water may be acid, alkaline or neutral; briefly, pH value

is a numerical assessment of the degree of this acidity or alkalinity as indicated by electrical measurements.



The pH scale ranges from about 1 (e.g. a strong solution of nitric acid) to a pH of about 15 (e.g. a strong solution of sodium hydroxide), tapering off from each extreme towards neutrality in the middle.

COLLOIDAL SOLUTION

There is no really adequate definition of a colloidal solution. Salt dissolves in water to form a true solution; the dissolved particles of salt are of extremely small size. If, however, the particle size of a substance is large, a colloidal solution is formed; it is a state which is determined by the particle size of the substance which is dispersed in the "solvent"; it lies between true solution and physical suspension. For example, a dispersion of clay in water may be colloidal or it may be a suspension, depending on the particle size.

There is a crude method of distinguishing colloids from true solutions and suspensions: a true solution will pass through parchment paper, a colloid will not; a colloidal solution will pass through filter paper, a physical suspension will not. Colloids can frequently be recognised by an increasing viscosity with increasing concentration instead of the precipitation which occurs when crystalline substances reach their limit of solubility.

The particle size of many synthetic resins is relatively large, so they form colloidal solutions. All the useful adhesives are colloids, indeed the word comes from the Greek "kolla" meaning glue. A mobile colloidal solution is called a "sol"; an elastic or rigid one a "gel".

EMULSION

An emulsion is a liquid/liquid system of immiscible substances. By vigorous agitation, water and paraffin can be made to "mix" because one of the liquids, called the dispersed phase, is broken up into droplets and distributed throughout the other, called the continuous phase. Such an emulsion is not stable, separation into two layers taking place rapidly on standing. If, however, an emulsifying agent is added, having the ability to reduce the interfacial surface tension, and provided the droplets are sufficiently small, there is no tendency for them to coalesce. Either the water or the paraffin may be made the dispersed phase, according to the nature of the molecule of the emulsifying agent.

PLASTICISER

A plasticiser is usually an organic liquid with a low vapour pressure: certain solids, however, can have a plasticising effect.

The addition of a plasticiser is a somewhat inferior way of providing properties which cannot be induced by better means; its incorporation is an admission of inherent deficiencies. Plasticisers, however, do impart valuable properties such as softness and ductility: the softness may often be undesirable but it is not usually possible to obtain extensibility without it. Sometimes, plasticisers are not permanently retained by the resin and that is one of the objections to their use.

The co-polymerisation of vinyl chloride with vinyl acetate has the effect of plasticising the poly-vinyl chloride which, if of high molecular weight, is hard and horny. The effect of this type of co-polymerisation is known as "internal plasticisation".

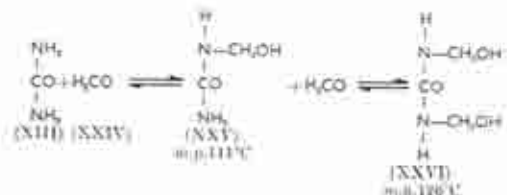
WE will now proceed to consider the individual resins. Where no unanimity of opinion exists as to the chemical structures to be assigned to the poly-meric forms of the resins, the structures have been omitted; and this in general applies to the fully-hardened products of poly-condensation reactions.

UREA-FORMALDEHYDE GLUES

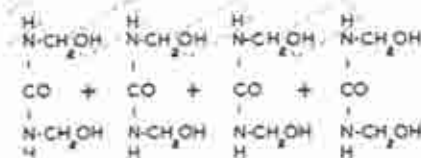
The urea-formaldehyde resins are rapidly becoming the most widely used wood-glues in all industrial countries. The starting materials, urea and formaldehyde, are prepared synthetically: urea, a colourless crystalline solid, from ammonia and carbon dioxide; and formaldehyde, a gas, from methyl alcohol. Formaldehyde is generally used in the form of an aqueous solution, but sometimes in the solid polymeric form.

Urea (XXIII) and formaldehyde (XXIV) react together under various conditions^(a) to give products which may be either crystalline or amorphous, forming either true or colloidal solutions. It is the latter which are of the greater interest as adhesives.

Under neutral or weakly alkaline conditions the initial reaction-products are principally the methylol ureas, (XXV) and (XXVI), the reaction being reversible.



In the presence of dilute acid the methylol ureas combine together with the elimination of water, another example of a condensation reaction.



The reaction of urea with formaldehyde has been investigated by a number of workers, and different structures have been suggested for the resulting poly-condensate. It has been concluded, however, that no uniform molecular arrangement can be assigned to it, and it is quite certain that the structure varies with the reaction conditions, for example the pH, temperature, etc.

The best UF glues are obtained by heating one molecular proportion of urea with about two

proportions of formaldehyde under weakly acid conditions. Using an aqueous solution of formaldehyde a mobile liquid is produced, which is then concentrated to a viscous syrup by evaporation of some of the water present. If the evaporation is carried further a substantially anhydrous resin is obtained, which is supplied to users as a powder.

During the reaction between urea and formaldehyde the molecular growth is indicated by a progressive increase in the viscosity of the reaction-mixture and solidification results if the reaction is not arrested; this may be done by cooling the product and raising the pH to 7-8; the resin solution then has sufficient stability for it to remain usable over a period of time known as its storage-life or shelf-life. The shelf-life may be a period of days or months; it can be made as long as a year or two but there are technical reasons which make this undesirable in a liquid UF glue having a high solids-content. Powder resins, however, are inherently more stable and may have a shelf-life of more than a year.

The water-tolerance of UF glues may vary from almost zero to infinity and in general it may be said that it increases with increase in temperature.

At the time of application of the glue the molecular growth is once more set in motion by the addition of an acid—the catalyst, accelerator or hardener. Under these acid conditions the glue proceeds to its final solid state.

Like some other infusible resins, UF glues are extremely sensitive to pH conditions, particularly below about pH 6. This necessitates rigid control during manufacture in order to produce a consistent material; but this sensitivity is very valuable in that individual requirements can be met by the supply of a range of hardeners, some of which do not require the aid of heat to cure the resin.

Some discrimination in the choice of acids is desirable, but the broad effect is that the speed of setting is a function of the pH—the lower the pH, the quicker the setting.

It is frequently advantageous to use as hardeners, instead of acids, substances which split off an acid when mixed with the glue, for example the ammonium salts. These combine with the free and loosely bound formaldehyde to liberate the equivalent acid: for example, ammonium chloride liberates

hydrochloric acid, together with the formation of water and hexamethylene tetramine (XXVIII).



This liberation of acid can be observed by adding an ammonium salt to a glue containing an indicator. With the average UF resin there is an immediate drop in pH owing to combination of the salt with free formaldehyde. This is then followed by a gradual (further fall in pH as the loosely-bound formaldehyde reacts with the salt. In general, hardeners made of ammonium salts of strong acids give the best ratio of pot-life to setting-time.

In the use of ammonium salt hardeners, a basic minimum amount (depending on the properties of the glue) is required to effect a satisfactory cure. This may result in a pot-life which is inconveniently short, because the pH is lowered too rapidly or too much; to prevent this it is necessary to add a retarding substance and ammonia or hexamethylene tetramine are commonly used.

Depending on the composition of the hardener, the amount added to the resin may have a marked influence on its pot-life and setting-time.

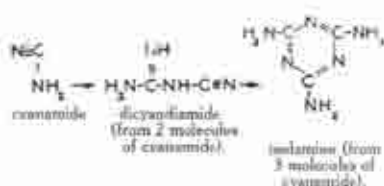
Within certain limits, the pot-life, with an ammonium salt hardener alone, is inversely proportional to the amount added. The addition of an acid hardener may produce a similar effect up to the point when dilution becomes excessive.

The properties of a cured urea-formaldehyde glue include insolubility in all the common organic solvents. It has excellent resistance to acids and alkalis and although it is attacked by certain strong ones in high concentration, it may be said that any substance which attacks the glue would certainly attack timber also. The heat-resistance of urea-formaldehyde glues is not as high as that of some other infusible resins; it is, however, greater than that of cellulose. Modern UF glues have extremely good resistance to water up to about 80°C; thereafter the resistance falls sharply and at 100°C an unfortified glue has little or no strength in a wood joint.

UF glues are frequently fortified with either melamine or resorcinol in order to impart resistance to boiling water. There is experimental evidence that co-condensation takes place in these reactions.

MELAMINE-FORMALDEHYDE GLUES

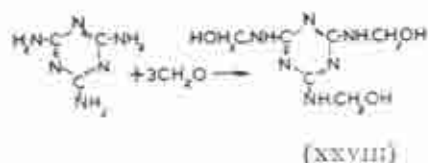
Another example of polymerisation is the preparation of melamine from cyanamide:



There is evidence that melamine may also exist in the form of a secondary amine with 6NH groups.

Although melamine may be produced from cyanamide via the fertiliser calcium cyanamide, it is, nevertheless, an expensive raw material; this is largely due to high conversion costs. Commercially it is made by heating cyanamide or dicyandiamide under high pressure in the presence of liquid ammonia. It can be made similarly in the presence of certain other inert gases. Also a process has been patented for its production from urea under extremely high pressure; even in this reaction it is quite conceivable that the melamine is produced via cyanamide and dicyandiamide.

Melamine reacts with formaldehyde to form a resin under similar conditions to those employed for making a urea-formaldehyde glue⁽⁹⁾. Here again, various authors have proposed different structures for the poly-condensate. As in the case of urea, the formation of a methylol compound (XXVIII) is probably the first stage in the reaction:



As with the UF glues the methylol melamines react with fresh melamine, eliminating water and producing a highly cross-linked structure.

A typical melamine formaldehyde glue employs a molecular ratio of 1 : 3. The MF resins are rather less sensitive to pH than the UF resins, but more sensitive to high temperature; they can therefore be more easily cured by heat without the addition of acid hardeners.

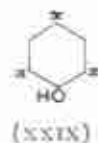
Normally, the melamine glues are physically unstable in aqueous solutions, hence it is usual for them to be supplied in powder form.

They differ from the UF glues in two main respects: the first is that they do not make satisfactory cold-setting adhesives—they are best used at a temperature above about 60°C and in consequence are chiefly used in hot-press gluing. The second is that they are completely resistant to the effect of boiling water, being equal to the phenolic glues. Undue emphasis is frequently given to this property. There is, however, a belief—supported by a little evidence—that boiling water resistance is a measure of durability when the glue is used on externally exposed plywood; certainly the case is by no means proved.

MF resins have a greater heat resistance than the UF resins, but this is a property of more importance in their use as plastic mouldings than in the gluing of wood. In both chemical and physical properties they are superior to the UF resins; their dry adhesive strength is, however, no better.

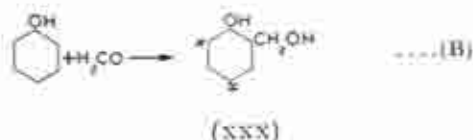
PHENOL-FORMALDEHYDE GLUES

In the group of compounds known as the *phenols*, phenol itself (XXIX) or carbotic acid, is both the simplest and the most important. In its reaction with formaldehyde^(10, 11), phenol is trifunctional and is reactive at all the positions marked x.

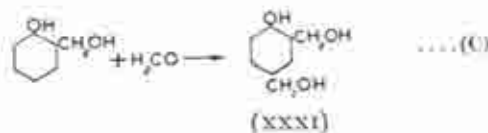


The reaction of phenol with formaldehyde can result in the formation of two distinct kinds of resin, both of which are initially fusible and soluble in a number of organic solvents. They differ in that one (a Novolak) may be permanently fusible, while the other (a Resol) is heat-hardenable to an infusible state (a Resite).

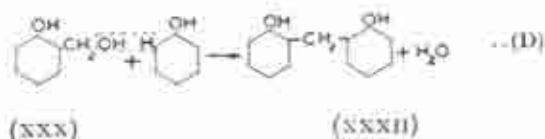
The first reaction between phenol and formaldehyde is the formation of a monomethylol phenol, for example saligenin (XXX), which under appropriate conditions can be isolated.



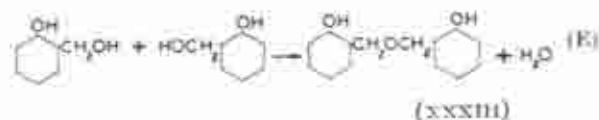
Saligenin still has two reactive positions (α) and can react with more formaldehyde to yield a dimethylol phenol (XXXI) or even a trimethylol phenol, although neither has been isolated from the reaction.



Subsequent reactions may be of two types. First, a methylol phenol (XXX) can react with free phenol, eliminating water and forming a dihydroxydiphenylmethane (XXXII):



Secondly, two molecules of methylol phenol can react to form an ether-linked compound (XXXIII), with the elimination of water:

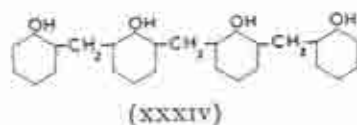


Now the extent to which the above reactions, B, C, D and E are favoured depends upon the reaction conditions, viz. pH, temperature and ratio of reactants.

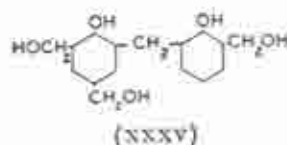
Effect of pH

Under acid conditions the formation of methylol-compounds (reactions B and C) is rather slow while the conversion of methylol-compounds to diphenyl methanes (reaction D) and dibenzyl ethers (reaction E) is fast. This means that methylol-compounds never accumulate in the reaction mixture and the resulting resin is largely of the form (XXXIII) and

(XXXIV), although the linkages are not necessarily *ortho* to the hydroxyl groups. This type of resin is permanently fusible and is called a Novolak.



Under alkaline conditions the formation of methylol-compounds (reactions B and C) is rapid, but their dehydration to diphenyl methanes (D) is comparatively slow. Thus, mono-, di- and trimethylol-compounds tend to accumulate in the reaction-mixture with only an occasional methylene bridge present in the molecules. The resin is of the form (XXXV). This is a thermoplastic resin called a Resol and is capable of being hardened to form an infusible resin, a Resite.



Temperature

Increase in temperature has the general effect of accelerating all of these reactions. However, it will be seen that the Novolak (XXXIV) does not contain reactive methylol-groups and consequently is not chemically changed by heat, whereas the Resol (XXXV) can react either with other Resol molecules or with free phenol to eliminate water and yield a highly cross-linked, infusible resin, the Resite.

Ratio of Reactants

From a consideration of the formulae for a Novolak and for a Resol it will be seen that the Resol contains a higher ratio of formaldehyde systems, (i.e. methylol-groups and methylene-bridges) to phenol systems than does the Novolak. Accordingly the formation of a Resol is favoured by the presence of an excess of formaldehyde, while an excess of phenol tends to produce a Novolak. There is still considerable doubt about the structure of the fully hardened resin.

The choice of aldehyde has some effect upon the type of resin produced; acetaldehyde tends to form Novolaks more than formaldehyde.

A Novolak can be converted to a Resol by the addition of more formaldehyde, and a Resol to a Novolak by addition of more phenol.

For use as hot-setting adhesives the PF resins are usually made under weakly alkaline conditions and the resulting resin formation may cause a separation into two layers—an aqueous layer at the top and the water insoluble resin at the bottom. In more strongly alkaline solutions, however, the resin is "water soluble"—it is really alkali-soluble. The separated resin layer referred to is soluble in certain organic solvents such as alcohol and acetone; it may, in some cases, be soluble in certain acids.

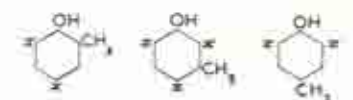
A solution of appropriate viscosity is used as a liquid glue or it may be used in the form of a dry resin film, using paper as a carrier. As adhesives these resins normally require a temperature in excess of 100°C for curing and alkaline hardeners are generally added. Acid hardeners may be used but a low pH is required to effect satisfactory setting without the use of heat, and therefore criticism is often brought against their use because of the possibility of damage to the wood. But it should not be overlooked that many timbers withstand the action of some strong acids remarkably well, indeed wood is generally less sensitive to acids than alkalis.

Phenol formaldehyde adhesives are completely resistant to boiling water but, unlike the melamine resins, they are of a dark colour.

CRESOL-FORMALDEHYDE RESINS

Resins similar to the phenol-formaldehyde resins can be prepared from the cresols. Cresol is the general name given to the three methylphenols (xxxvi), (xxxvii) and (xxxviii), the difference between them being the relative positions of the hydroxyl and methyl groups in the benzene ring. The methyl group may have the effect of blocking a reactive position in the phenol molecule, thus *ortho*-cresol is difunctional, *meta*-cresol is trifunctional and *para*-cresol is difunctional. This means that *ortho*-cresol and *para*-cresol tend to produce fusible resins (Novolaks), while *meta*-cresol yields an infusible

resin. For this reason *meta*-cresol is generally preferred by makers of phenolic glues. Since, however, it is not very easy to isolate pure *meta*-cresol from the mixture of isomers which are obtained from coal tar the price of the product is higher; as a result, mixed cresols containing a certain minimum proportion of *meta*-cresol are used for the preparation of glues.



(xxxvi) (xxxvii) (xxxviii)
ortho-cresol *meta*-cresol *para*-cresol

The reaction of the cresols with formaldehyde is similar to that of phenol; for example, it is similarly influenced by pH and by the ratio of reactants.

RESORCINOL-FORMALDEHYDE RESINS

Resorcinol (xxxix) is *meta*-dihydroxybenzene and, having two hydroxyl groups, is called a dihydric phenol. It has three reactive positions and resembles *meta*-cresol (xxxvii) except that, having a hydroxyl-group instead of the methyl, it is much more reactive. As a result of this reactivity it will produce with formaldehyde a resin which can be converted into the fusible state without the aid of either a catalyst or heat, but merely by addition of a further quantity of formaldehyde.



(xxxix) (xxxvii)

It was stated that as a rule formaldehyde and ordinary phenol, under identical conditions of temperature and ratio of reactants, can produce resins which may be either thermoplastic or thermosetting, and one can be easily converted to the other if the reaction is interrupted at the right stage. Similarly with resorcinol, it is possible to produce a virtually non-hardenable resin and then add formaldehyde to convert it to a completely infusible material which is resistant to boiling water. This is the method adopted in the use of the cold-setting resorcinol adhesives, hence the hardener used is formaldehyde and as such is in no way a catalyst.

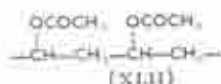
POLYVINYL ACETATE

Polyvinyl acetate is a true thermoplastic resin. As you have already heard from a previous talk there is a chemical arrangement $\text{CH}_2=\text{CH}-$ which is called a vinyl group. Compounds containing this group are used to prepare a number of thermoplastic resins, many of which are used as adhesives. The chemistry of the thermoplastic resins is more clearly understood than that of the thermosetting ones.

The monomeric form of vinyl acetate (XLII) is a liquid with a boiling point of 73°C ; it can be obtained by reacting acetylene (XL) with acetic acid (I) in the presence of a catalyst:



The polymerisation of vinyl acetate may be catalysed by light, but commercially heat and peroxide catalysts are used. As polymerisation proceeds the individual molecules join up and the viscosity progressively increases to the solid state, the softening point depending on the length of the chain. The average molecular weight of the polymer (XLIII) may exceed 20,000; the number of recurring monomer units being in that case more than 200.



In certain textile and adhesive applications it is an advantage to have the resin finely dispersed; this is frequently obtained by emulsion polymerisation, a process which involves emulsification of the liquid monomer and its subsequent polymerisation. The product of emulsion polymerisation may not be a true emulsion, that is, a liquid/liquid system; it can be, and frequently is, a dispersion of small solid particles.

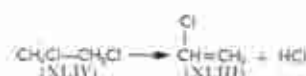
Polyvinyl acetate is the basis of many "adhesive cements"; its availability as a dry film permits solventless gluing; its solution has good "tack" and adhesives are available in a variety of organic solvents, but solvents are expensive to waste and their recovery from adhesives is neither easy nor cheap.

Polyvinyl acetate has good adhesion to many porous and non-porous materials. In most applications it is sufficiently flexible to render the use of plasticisers unnecessary. Although it has fairly good water resistance its water absorption is high.

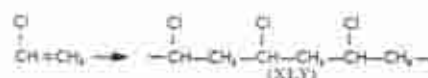
POLYVINYL CHLORIDE

This is a synthetic polymer of which I have had no first-hand experience, but I am introducing it because I mentioned it as an important component in co-polymerisation.

Many of the vinyl monomers can be prepared from different substances. Commercially, vinyl chloride (XLIII) is made from acetylene and hydrochloric acid or by removing hydrogen chloride from ethylene dichloride (XLIV). The former reaction is similar to that in the preparation of the acetate; the latter is shown below:

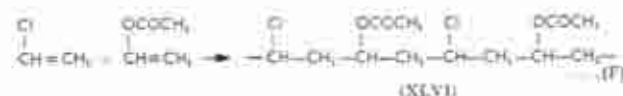


Vinyl chloride is a gas at ordinary temperatures and polymerises rapidly and violently. It is polymerised either as an emulsion or in solution. In both methods it is precipitated as a powder; in the former from water and in the latter from a liquid in which only the monomer is soluble.



The average molecular weight of polyvinyl chloride (XLV) may be as high as 500,000 (over 8000 monomer units) and such a polymer is a hard and somewhat horny material.

Polyvinyl chloride is not used as an adhesive unless co-polymerised (F) with vinyl acetate, as mentioned earlier.



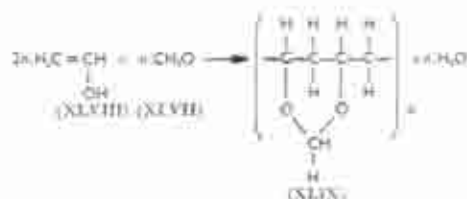
In many applications it is essential to plasticise polyvinyl chloride, but co-polymerisation with the acetate may often make this unnecessary. Co-polymerisation has very great importance in the

vinyl resins; previously it was stated that simple mixtures of polymers frequently fail to produce properties representing the average to be expected, whereas co-polymerisation usually imparts superior ones. Another advantage of co-polymerisation is in the preparation of solutions; polyvinyl chloride is soluble in fewer solvents than polyvinyl acetate, hence in dissolving a mixture, care is necessary in the selection of solvents. The co-polymer, however, is soluble in a wider range of solvents than polyvinyl chloride alone. The co-polymerisation of monomers in emulsion-form is a process of considerable industrial importance.

PVA/PVC co-polymers (XLVI) have fairly good adhesion to wood, paper and textiles. They have considerable use in surface coatings, but that is outside adhesives in the sense in which we are thinking of them. They do not give the best adhesion on air-drying alone, but by application of heat and pressure.

POLYVINYL ALDEHYDE RESINS

These are sometimes known as the Polyvinyl Acetals, although this name is more specifically applied to one particular representative. They are prepared by reacting polyvinyl acetate with an aldehyde, such as formaldehyde, acetaldehyde or butyraldehyde, and they are known respectively as polyvinyl formal (Formvar, XLIX), polyvinyl acetal (Alvar) and polyvinyl butyral (Butvar). The reaction really takes place between the alcohol and the aldehyde, the alcohol being liberated by hydrolysis of the acetate under the acid reaction-conditions. Polyvinyl alcohol is itself an adhesive; it is water soluble but has excellent resistance to oils. Monomeric vinyl alcohol has, so far, not been isolated. The reaction between formaldehyde (XLVII) and vinyl alcohol (XLVIII) is:—



This is another condensation reaction and a similar structure results from reaction with other aldehydes.

The polymeric product of the reaction is precipitated from acid solution by the addition of water, which produces sponge-like particles of low apparent density. Formvar and Butvar are used as adhesives in the form of a dry film, as precipitated particles or in solution. The high molecular weight polymers are tough, horny materials but a rubbery nature can be imparted by the addition of plasticisers.

Formvar is the thermoplastic component used in the metal-metal adhesive "Redux" and the particular polymer used has a molecular weight of about 30,000.

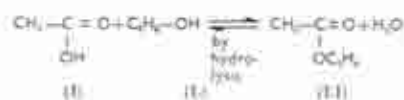
Butvar is widely used in making laminated safety-glass, where one of its foremost advantages is its complete stability to light. Glass is not an easy material to glue. A relatively high proportion of hydroxyl groups is considered by some writers to be one of the requirements of a glass adhesive; this is an apparent contradiction of the idealised structure of polyvinyl acetal shown. It is, however, probable that both hydroxyl and acetate groups are present because complete hydrolysis of polyvinyl acetate is unlikely under the conditions of manufacture.

THE ALKYDS

There is an extremely important class of synthetic resins known as the Alkyds, which, though not used much by themselves, are incorporated as modifiers in a large number of adhesive preparations. By sufficient stretching of the imagination one can see that the word can be coined from "alcohol" and "acid"—alco-id, then Alkyd.

The alkyds are polyesters and there is another type, known as the unsaturated polyesters, which come into a separate chemical sub-division.

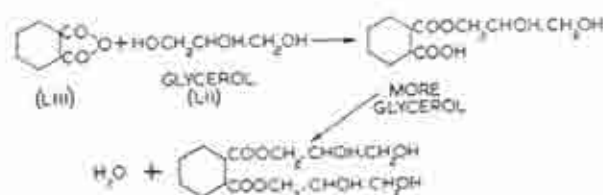
An elementary esterification reaction is that between ethyl alcohol (I) and acetic acid (II):—



Under appropriate conditions this reaction proceeds to the right to form ethyl acetate (II); no polycondensation follows because, as stated earlier, only mono-functional groups are present: one hydroxyl group in the alcohol molecule and one carboxyl-group in the acid. If, however, the

alcohol is polyhydric and the acid polycarboxylic, poly-condensation takes place. The broad properties of the resulting resin depend very largely on the number of functional groups. A dihydric alcohol, e.g. ethylene glycol, reacted with a difunctional acid produces fusible resins and a trihydric alcohol, e.g. glycerol, produces resins which are substantially, but not entirely, infusible; they will soften slightly if heated to a sufficiently high temperature.

One of the original Alkyds is still one of the most important; it is the reaction product of glycerol (I.ii) and phthalic acid, polyglyceryl phthalate; but it is more common to use the anhydride (I.iii) of the acid. Alkyd resins result from poly-condensation reactions; water is split off and it is shown in the following reaction how this probably takes place.



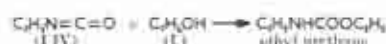
The hydroxyl groups which remain can react with further phthalic anhydride molecules, splitting off more water, and in some such manner proceed to build up into large molecular aggregates; the physical and chemical properties being influenced by the initial molecular ratio.

The largest use of the alkyd resins is in the preparation of surface coatings, which are not, of course, adhesives in the sense we have in mind.

THE POLYURETHANES

These are representative of the form of polymerisation which I referred to as poly-metathesis. With the extremely reactive isocyanate group ($-\text{N}=\text{C}=\text{O}$) as the basis, a new type of resin was being investigated in both England and Germany before 1939. During the war Germany achieved a considerable measure of success⁽¹⁰⁾ and marketed isocyanates under the name of the Diisodurs, and a two-component adhesive under the name of "Polystal".

The history of the reaction dates back a hundred years when it was found that ethyl isocyanate (LIV) reacted with ethyl alcohol (L) to give a product with the generic name of a "urethane", without eliminating any by-products.



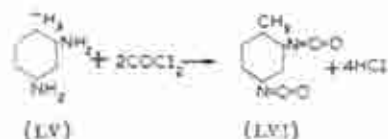
At a later date this reaction was confirmed with aromatic isocyanates. An isocyanate group is particularly reactive towards replaceable hydrogen atoms, it therefore combines readily with OH, COOH and NH_2 groups, but its reaction with the former only will be dealt with here. Polymerisation results from the use of reacting substances which are poly-functional. If R_1 is a radical with two $-\text{N}=\text{C}=\text{O}$ groups and R_2 a radical with two OH groups, linear polymerisation takes place resulting in a thermoplastic resin.



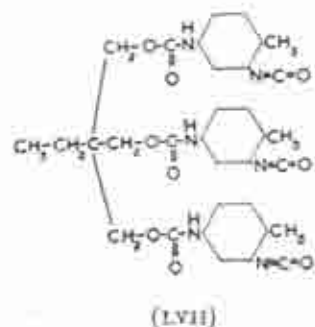
In a similar manner to the Alkyds, if one of the reacting molecules is tri-functional, for example glycerol, then three dimensional polymers are possible and broadly speaking these conform to the same general rule and have melting points or infusibility, and solubility or insolubility, according to the number of reacting groups per molecule.

In Germany a linear polymer was used to make filaments or bristles although it was generally considered to be inferior to Nylon for this purpose. However, the polyurethane which was of particular interest as an adhesive was that obtained by reacting an aromatic di-isocyanate with an Alkyd resin containing free hydroxyl groups. This was the two-component adhesive referred to earlier as Polystal.

The isocyanate component of Polystal is prepared by treating tolylene diamine (iv) with phosgene. A salt of tolylene diamine may also be used and this results in a smoother reaction.



The tolylene 2:4 di-isocyanate (LVI), known as Desmodur T is then partially reacted with a trihydric alcohol in order to render it less unpleasant to handle. The product, known as Desmodur TH, is shown in formula (LVII), but this is an idealized picture as Desmodur TH is resinous.



The other component of Polystal, the alkyd (Desmophen), is prepared by reacting adipic acid with trimethylolpropane using a molecular ratio of 2:3 to ensure having a large number of free hydroxyl-groups. The Alkyd is added to the Desmodur TH at the time of application as an adhesive and the mixture is capable of setting at room temperature to produce strong wood-joints with good gap-filling properties. The adhesion to metal, however, is not outstanding and the hot water resistance inferior to that of MF and PF resins.

A disadvantage with Polystal, is its tendency to produce foamed-up material during setting, and it is interesting to note that a foamed isocyanate resin is now available in America. The reason for this foaming is obscure. The gas evolved contains carbon dioxide and yet the reaction is not a condensation; it is probably due to the instability of the urethane group in the presence of impurities.

Apart from Alkyd resins tolylene di-isocyanate reacts with polyvinyl acetate and Formvar to make an adhesive having some very attractive properties. One particular tri-isocyanate is used as a rubber-metal adhesive and as an agent for improving adhesion of the fibres in rubber tyres.

The application of the polyurethanes as adhesives has made rather slow progress, partly, perhaps, because they are somewhat unpleasant to handle.

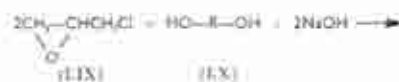
THE ETHOXYLINE RESINS

There is a new class of synthetic resins known as the ethoxyline and Araldite is an example.

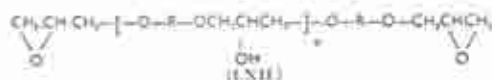
A very reactive chemical system having the structure shown (LVIII) is known as an oxirane ring.



Oxirane compounds, convertible to ethoxyline resins, may be prepared from a variety of starting materials; a typical method of preparation is the reaction between epichlorhydrin (LIX) and a diphenol (LX) under alkaline conditions^{17, 18}.



The initial product (LXI) is difunctional and continues to react so that long-chain molecules (LXII) are produced.



A resin of this type has poor mechanical strength but by the addition of a suitable hardening agent it is converted into a hard, tough material with a high softening point.

The chemistry of the ethoxyline resins is not at present clearly understood; investigation and development is in progress in Switzerland, America and here at Duxford.

Appropriate types of ethoxyline-resins are the most versatile adhesives yet produced: they stick to nearly everything; moreover the strength of the bond is outstandingly high—it is in a completely different class to some of the thermoplastic adhesives we have previously considered.

As a hot-setting glue Araldite sticks to wood, metal, thermosetting plastics, leather and rubber. It has remarkably good adhesion to glass and other

vitreous surfaces such as glazed china; if vulcanised rubber is treated by "cyclising" the surface, Araldite sticks so well that failure always takes place in the rubber. It is resistant to boiling water, acids and alkalis and to many organic solvents.

The cold-setting type sticks to the same things but the strength is somewhat lower; it has good adhesion to concrete.

Considering both hot and cold-setting types, this adhesive is probably the nearest approach to a universal glue.

CONCLUSION

We have now seen something of the chemistry of a few synthetic resins, and although we look upon them as a new class of materials, many of the basic reactions were known a very long time ago—in some cases more than a hundred years. There are many

possible explanations for the apparently slow development; in some cases, there was a complete lack of appreciation of the value of substances which would not crystallise, so resinous materials were often poured down the laboratory sink with disgust.

ACKNOWLEDGMENT

I am grateful to Dr. N. J. L. Megson for his criticism and advice after reading the manuscript of this lecture.

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CHARACTERISTICS OF SYNTHETIC RESINS

and their application as adhesives

G. M. Scales

THE SETTING PROCESS

THE characteristic setting process of the plastic group known as *condensation products* are described in this lecture. Typical of this group is the urea formaldehyde (UF) resin. This resin starts life as a solution of urea formaldehyde and water and undergoes the changes shown opposite.

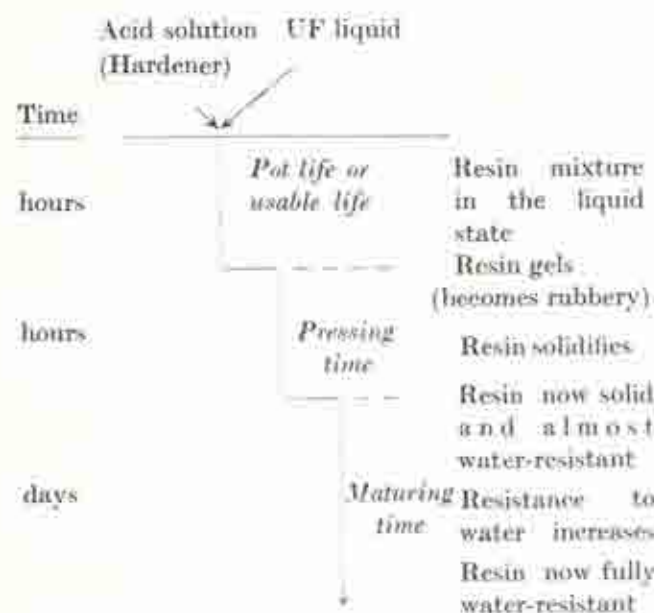
It is important to note that when the glue first becomes solid it is still not completely water-resistant and a considerable amount of time must elapse before it becomes completely solid and insoluble in water (fully water-resistant).

Clearly if such a resin is to be of practical value as a water-resistant adhesive something must be done to speed up this reaction. The method generally adopted is to add a chemical to the resin to make it more acid because, generally speaking, the more acid the resin is made the more quickly it will become solid and completely water-resistant. Chemicals added to the resin to accelerate the rate of setting are usually called hardeners.

The UF resin whose setting process has been illustrated now becomes, when used with a suitable hardener, of practical value as a glue. The following

Time	Urea formaldehyde + water	
Hours	Manufacture	Heated and cooked for a few hours. After which it can be thickened by the evaporation of excess water. The resin content is now about 70%, most of the remainder being water.
months	Storage	The liquid gradually thickens (cooking continues slowly at room temperature) until it reaches a semi-solid (gelled) state.
years		The semi-solid continues (at room temperature) to throw out surplus water and become solid and will in time become completely solid and insoluble in water, i.e. fully water-resistant.

diagram shows the stages of setting after the hardener is added.



The time taken for the resin to set will be controlled by the strength of the hardener chosen as well as by varying the temperature of the mixture (like other chemical reactions the speed of the reaction is increased as the temperature is increased). Therefore stronger solutions of hardener are required for use as cold-setting hardeners and comparatively weak ones as hot-setting hardeners. The following two examples illustrate how the cold-setting and hot-setting processes differ in timing :-

Example I. Resin + cold hardener :

Pot life	20°C (68°F)	1 hour
Pressing time	2 hours
Maturing time	a few days

Example II. Resin + hot hardener :

Pot life	20°C (68°F)	20 hours
Pressing time	95°C (203°F)	4 minutes
Maturing time	95-20°C (203-68°F)	a few days

THE QUANTITY OF HARDENER REQUIRED

For the sake of convenience in workshops the addition of hardener to resin is most often made in a proportion of ten parts (by weight) of hardener to 100 parts of resin for gluing by the mixed-application method. For gluing by the separate-application method the proportion of hardener is often nearer 25% and this is allowed for when the hardener is formulated.

Hardeners act in various ways and so no rule generally applicable can be given by which to predict their behaviour should they be added in greater or smaller quantities than those advised by the manufacturers. Illustrations of such variation are given in the graphs shown in Fig. 8 on page 78 of this book and in Fig. 3 on page 72.

It is well known that certain advantages can be gained from varying, on occasion, the quantity of hardener added but such departure from the instructions laid down is inclined to be dangerous unless the user has particular knowledge of the ingredients in the products being used.

Hardeners can be applied by *separate application* instead of *mixed application*. Very strong hardeners give such a short pot-life that it is often impracticable to mix them with the resin before application to the joint: they are, therefore, applied separately. The quantity of hardener used for separate application is of the order of 50 gm/m² which equals 1 lb/100 ft² and because it is not easy to control the quantity applied, as this will depend very much on the nature of the surface, there is a tendency for the setting speed to vary somewhat. Careful note should be taken from the instructions given with the adhesive as to whether the hardener should be allowed to dry on the surface before bringing it into contact with the glue or whether it should be still wet or damp. As a general rule acid hardeners should be wet and acid-forming hardeners should be dry when brought into contact with the glue. If the manufacturers advise allowing the hardener to dry before contact, and the instruction is not followed, it will probably be found necessary to increase the pressing time. (see the graph shown in Fig. 10 on p. 80 of this book).

THE EFFECT OF HEAT

As mentioned earlier in this lecture, if the temperature of the glue is raised the speed of the reaction is accelerated. This holds good for all phases of life of the glue, for storage, for pot life, for pressing and for maturing times. The converse is also true, of course, and it is not often realised to what extent the life of the resin is increased by lowering the temperature of the store. A resin which will keep for only a few months at 20°C (68°F) may at 0°C (32°F) store for several years. The effect of temperature on the storage life is shown in Fig. 1.

PRACTICAL LIMITATIONS OF APPLIED HEAT

Whilst it has been shown that heat may be used to speed up the setting of a resin glue mixed with a "cold" hardener* the temperature should be raised with discretion. Glue mixes made with cold hardeners lose some of their efficiency when heated to too high temperatures (similarly hot hardeners are relatively inefficient if the applied temperature is not high enough); each hardener has its own range of temperatures within which it operates most efficiently. A very fast hardener used at a high temperature will cause the resin to gel, or become rubbery, very quickly, suggesting that an efficient setting process is in operation; but the trouble is that setting does not continue at the same pace after this gelled state has been reached. Real solidification is achieved only very slowly, and with some resins and hardeners, never takes place at all. Hardeners should be chosen so that the one selected is the best compromise for all conditions. Table I below illustrates the setting times, in minutes, of one resin glue with a variety of hardeners at various temperatures.

TABLE I
(setting times in minutes)

°F	39	77	93	113	131	149	167	185	203	221	239
°C	15	25	33	43	55	65	75	85	95	105	115
Hard. A	Impracticable	—	—	—	—	—	8	5	2	1	1
Hard. B	Impracticable	—	—	—	10	5	4	3	1	—	—
Hard. C	Impracticable	—	11	5	4	3	2	Impracticable	—	—	—
D	60	45	12	8	7	—	—	—	—	—	—
E	120	40	12	8	5	—	—	—	—	—	—

* Strong solutions of hardener are often called cold hardeners as they are intended for use at room temperatures; hot hardeners are weaker solutions for use in hot presses.

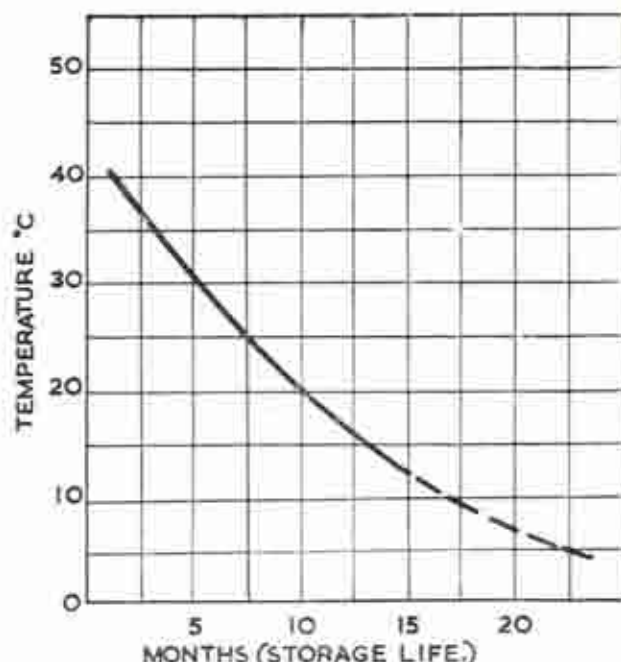


Fig. 1. The effect of temperature on the storage life of a synthetic resin.

SUMMARY

From the foregoing it is clearly an advantage to:—

- (1) Store the resin at a low temperature in order to increase the storage life.
- (2) Keep the glue mixture (with hardener) at as low a temperature as possible (if necessary by water cooling the glue spreader) in order to increase the pot life.
- (3) Raise the temperature of the glue line, when it is required to set the glue, in order to shorten the pressing time.
- (4) Stick the glued article in such a way that the heat from pressing is retained for as long as possible in order to reduce the maturing time and cause the glued joint to gain final strength relatively soon after pressing.

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COURSE I

ADHESIVES IN THE WOODWORKING INDUSTRIES

VENEERING: FLAT AND CURVED WORK

G. M. Scales

COLD VENEERING

General Remarks

VENEERS are sometimes glued in a cold press either to economise in equipment or for some technical reason. Cold-setting resin glues usually having considerably less water in their composition than other cold glues and therefore the tendency of delicate veneers to warp and crack is reduced when they are used. But obviously cold-pressing does not make the most use of the heat-reactive properties of the resin and therefore to achieve a high output it is necessary to use a special technique, such as that of separate application.

Separate Application

It is easiest to apply the resin to the core and the hardener to the veneer. As the hardeners most easily applied are acid-forming liquids which are allowed to dry on the surface of the veneer there is considerable tendency for the veneer to warp unless stacked flat whilst drying. Too much hardener is not likely to assist quick setting and is likely to induce warping.

A convenient spreader for hardener consists of a "saucepan" with holes drilled in the bottom. A pad of felt is attached to either side of this perforated bottom and the whole placed on a felt pad in a tray containing hardener. The "saucepan" is then lifted out of the tray and applied to the surface of the veneer, the weight of the "saucepan" being

sufficient to hold the veneer flat; by this means sufficient hardener is applied without making the veneer wet enough to roll up.

The type of hardener that is most efficient when allowed to dry on the veneer should be used, and not direct acid types which work fastest when wet.

Gluing is best carried out in a heated room in which the assemblies are stored to absorb heat before gluing. If, to reduce pressing times, fast hardeners are used, the closed assembly time should be controlled carefully.

The extenders should be limited and an addition of 15% regarded as a maximum.

As no heat is applied to soften the glue line the glue should not be allowed to dry completely before applying pressure. A viscous glue requires very much higher pressures to enable it to "wet" the surfaces sufficiently.

At room temperature any change in the conditions governing the setting of the glue has much more effect than when hot pressing. If an unusually long cold-pressing time is required it can almost always be attributed to one or more of the following causes:—

- (1) The veneers have a high moisture content and the resulting dilution of the glue is prolonging the setting time.
- (2) Core-board from stock is still cold and is lowering the glue-line temperature.
- (3) The glue is from a new batch and is setting slightly more slowly than usual.

- (4) The glue has been diluted. (Operators often add water in cold weather to make spreading easier.)
- (5) The glue spread is thick. (A thin glue line will set faster than a thick one because the drying power of the wood on either side is limited.)

After the panel has been cold-veneered the edges must be trimmed. This is most quickly done by a coarse file when the panel is veneered on one side only, but when it is veneered on both sides more care must be taken and it may be an advantage to use a tool with a blade long enough to trim only one side at a time.

It is usual to stack 10 or 20 panels on top of each other in the press. Any differences in thickness of the panels may therefore be cancelled out or multiplied several times. Should difficulty be experienced with occasional blisters due to local lack of pressure the panels should be interleaved with rubber sheets about $\frac{1}{8}$ in. (3 mm) thick.

HOT VENEERING

General Remarks

Construction is sometimes unbalanced and this tends to produce warping. Veneering may have been done on one side only, or there may be a more obscure cause, for instance the veneers may have been edge-spliced while under strain.

Glue mixes should contain as little water as is practicable. A thin spread of a relatively thick glue, though not so easy to apply, is more effective than a thicker spread of a diluted glue costing as much per unit of area covered.

Powdered, semi-gap-filling hardeners are convenient to handle and provide a cheap method of compensating for unevenness in the thickness of the coreboard and of combating the effects of badly cut veneers. They also tend to reduce penetration as well as lowering the cost of the glue line. Penetration is not always entirely avoidable and in certain circumstances it may be necessary to add a water stain to the glue-mix to match the colour of finish ultimately required.

The modern tendency is to use powdered hardeners having a pot life of about 10 hours at 21°C (70°F) and short pressing times at temperatures of about 70°C (158°F). Such hardeners provide a setting

time in the region of three minutes at the temperature quoted and besides reducing warping and penetration they also lower the cost of operating and maintaining the press. The relatively high temperature of pressing reduces the time in the press and also, in plywood manufacture, it reduces losses through compression of the wood. The characteristics of such hardeners are shown in Fig. 1.

Bulk Storage

Consumers of large quantities of glue find that deliveries in bulk cost less, save labour and eliminate wastage of glue in "empty" containers returned. Glue remaining in an "empty" 200 kg (40 gall) drum frequently weighs between 0 and 10 kg, representing a direct loss of between 3 and 5%. Thus a factory of moderate size using 150 tons of glue a year can expect, at the minimum, a loss of more than £300's worth of glue a year.

Twin tanks are usually used for bulk storage so that one tank may be drained completely before refilling. A mobile road or rail tanker makes connection with the empty tank and a power-driven, heavy-duty glue pump refills the storage tank in a short time. The glue pump is part of the equipment of the mobile tanker so that the initial cost of the static tank installation is not heavy. Maintenance of the static equipment is negligible provided that it has been installed with care and thought. The glue is drawn from a self-cleaning tap near the glue mixer which need not be situated near the static tanks. Branch pipes can be provided to serve other glue mixers. The saving of labour is therefore considerable.

Mixing Glue

It is advisable to make periodic checks to ensure that the glue manufacturers' directions are being carried out. Whilst the operating tolerance of UF glues (which are the glues most widely used for veneering) is remarkably wide, over-confidence may occasionally lead to a too free interpretation of instructions for mixing. It is a common fault to dilute the glue with water to obtain an easier spread. (See page 81 of this book.)

TESTS WITH U.F. POWDER HARDENER A & B (15% ADDITION)

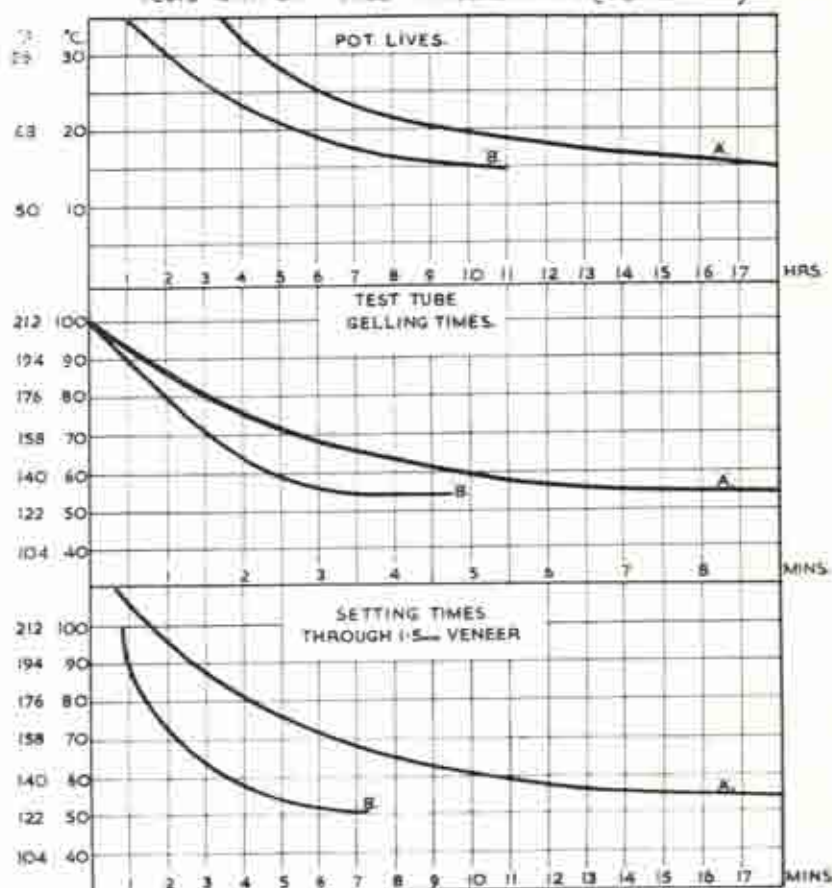


Fig. 1. Characteristics of a U.F. glue used with powder hardeners A and B.

Extenders

Of the many extenders in use those containing starch are probably the best. Penetration and the cost of the glue can be reduced by their use (see pages 89 and 90). They should be mixed carefully so that the formation of lumps is avoided and not used in quantity where the pressure applied is small. Unless very high pressures are applied extended glue lines should not be allowed to dry out before pressing.

Glue spread

The absorbency of wood varies with the species but in general it is surprising how little glue is required on the surface to obtain good adhesion. There are many fallacious ideas and wide differences of opinion current concerning the minimum quantities of glue needed to make effective spreads. For example, we

find that some firms manufacturing 4-in. three-ply from gibbon veneers consider that the minimum factory requirement is 100 gm/m² (2.2 lb/100ft²) at the other extreme, some consider that a spread of not less than 300 gm/m² (6 lb/100 ft²) is necessary.

Whilst most people agree that the thinnest glue spread is the best, there is a temptation to put on a little more than is necessary to be on the safe side.

The general rule is a *thick glue mix and a thin spread*. The following factors must be considered in determining what is the minimum quantity of glue needed.

- (1) The species of the wood.
- (2) The condition of the surface (this is often dependent on the thickness of the veneer).
- (3) The variation in thickness of the veneer (on uneven cores soft rubber rollers permit lower spreads than steel ones).

- (4) The precision of the spreader, the types of rollers used as well as their surfaces.
- (5) The temperature of the glue line immediately after spreading.
- (6) The closed-assembly time.
- (7) The flow and gelling characteristics of the glue under pressing conditions.

Low glue spreads reduce—

- (1) Cost,
- (2) Penetration,
- (3) Tendency to warp,
- (4) Minimum pressing time, and
- (5) Trimming labour.

Closed Assembly

It is frequently an advantage to allow some time between the spreading and pressing operations. This time is called the closed-assembly time and its purpose is to allow the glue line to dry somewhat by losing some moisture to the air and some by diffusion into the veneers.

The closed-assembly time should never exceed the pot life of the glue, which should be measured from the time the glue was mixed with the hardener and not from the time it was spread. There is a clear distinction between a dried and a pre-set glue line. It is easy to get a perfect bond from a completely dried resin glue line providing that it has not gelled. As a simple check the glue line should be moistened: if it is still tacky it has not yet gelled. When spreading glue on to cores still warm from the drier, or assembling on to hot or warm metal cauls, allowance should be made for this test in calculating the maximum permissible closed-assembly time. The correct technique is to cool all veneers and cauls to room temperature before using them. Glue lines containing extenders should not be allowed to dry out.

Loading

It is essential to load a hot press quickly and apply full pressure at once, otherwise pre-curing is likely to occur on some of the panels.

The maximum loading time varies for each glue but as a general rule it will be very roughly 0.75 of the minimum pressing time required under the same

conditions. The loading time is the time from the moment of loading the first panel into the press to the time when full pressure is applied.

Loading times can be reduced by pre-loading on to a metal caul and placing this in the press either automatically or by hand in a loading jig. This offers a considerable saving in time and labour for repetition work. Loading cauls should be cool.

Loads should be placed directly under one another in a multi-daylight hot press as this reduces platen distortion.

Pressing

Pressures from 2.5 kg/cm² (25.75 psi) are used for veneering; the pressure applied is often dictated by the type of equipment available rather than by the requirements of the glue line. The lower range gives extremely good results with unextended UF glues if applied by fluid pressure (such as that afforded by the rubber-bag moulding press). Metal-platen presses are rarely operated at lower than 3.5 kg/cm² (50 psi) as it is often advisable to compress the high spots slightly to ensure that some pressure is available at the low spots. High pressures are rarely employed unless there is evidence of considerable variation in thickness. Pressure should not be varied during the pressing cycle.

High pressures are inclined to induce penetration and glue-starved joints. (For further remarks on pressing practice the reader is referred to page 72 of this book).

Temperatures

The operating temperature should be as low as is convenient after consideration has been given to the other factors mentioned in this lecture. Short pressing times are also desirable as they are less likely to dry the wood and crack or warp the panel. It should be remembered that the lower the temperature the greater the variation in temperature over the platens. On an aluminium-platen hot-water press this variation may be of the following order:—

Operating temperature		Degree of variation in temperature over platens			
(°C)	(°F)	(°C)	(°F)	(°C)	(°F)
95	203	+2	+3.6	-2	-3.6
70	158	+6	+10.8	-6	-10.8

The temperature at the water outlet is quite a reliable guide to the minimum temperature on all platens, and on a press in good condition it is unlikely that even at the corners there will be spots of 3°C (5.4°F) less than this temperature. This temperature does not, however, serve as a reliable guide to the maximum loading times.

As soon as a mass of cool wood is put into the hot press the temperature of the platen drops. This is relatively unimportant in a multi-daylight hot press but increases the pressing times considerably with presses, such as the rubber-bag presses, which have a lower capacity for heat storage. With the latter, considerably reduced pressing times are possible if the mould is of metal or covered with metal.

Measurement of Temperature

The temperature of the platen is conveniently measured by crayons for indicating temperature. A thermo-couple placed in the glue line will enable a pyrometer reading of the actual temperature of the glue line to be taken. (The wires can be cut off in the glue line after the operation is complete). Temperatures for operating rubber-bag presses are best taken by thermo-couple methods. Reliance on thermostat indications of temperature are unsatisfactory as they rarely give accurate readings.

Unloading

This should be done carefully, as any glue, even if of a thermo-setting variety, is relatively weak when first removed from the hot press. Panels should not stick to the platens but should they do so the platens can be treated with some of the special lubricants available for the purpose.

Panels removed from the hot press should be stacked hot and given at least two hours for maturing before undergoing the next operation.

Methods of Producing Curved Plywood

Sawcuts through to the last veneer but one are made at the corner. The wood is then bent and either held in position by the side pieces or by a backing block glued behind the sawcuts (see Fig. 2). Veneered thin plywood can be thinned at the point to be bent (see Fig. 3) and fixed into position in ways

similar to those just described. There are several types of patented machines for producing bends in ways which differ slightly from those outlined; if they are used it is usually because they offer some economic advantage.

Plywood can be cured in the curved position so that when removed from the mould it is permanently shaped. Such shaping is now achieved very economically in a rubber-bag press by using quick-acting hardeners. For example, using a hardener with a pot-life of six hours (see Fig. 1) and a rubber-bag moulding press operating at 70°C (158°F), curved plywood 8mm in total thickness can be shaped and bonded in only four minutes in the press.

The rubber bags are sensitive to heat and the lower the operating temperature the longer they last. It is emphasised that low temperatures mean longer pressing times and more time for the operatives to be idle. The argument often advanced is that the operatives require a certain time for spreading and laying the veneers. Whilst this is true it is also true

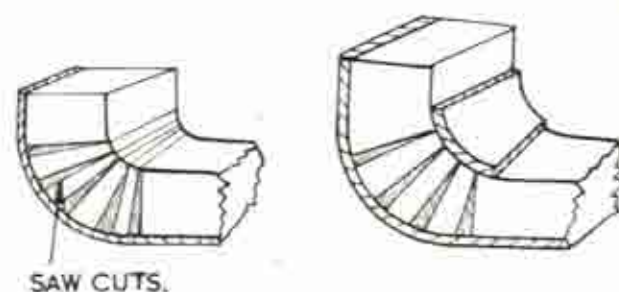


Fig. 2. Method of producing curving plywood by making saw cuts.



Fig. 3. Bending thin plywood.

that reorganisation and modernisation of technique can often reduce these times considerably. I know one furniture factory that in 1946 was pleased with a pressing time of 21 minutes for eight curved panels. Today eight of these panels are being removed from the same press every six minutes. Metal-covered moulds with the metal curving under the jig to convey the heat from the table heater-element are a worthwhile refinement.

Veneers can be stuck to metal (flat) and afterwards rolled or stamped to give the desired shape. It is even possible to achieve a double curvature by this method. The veneer must have very good adhesion to the metal.

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THE TAPELESS EDGE-SPLICING OF VENEERS

G. M. Scales

INTRODUCTION

THE principle of the process of edge-splicing veneers is shown in Fig. 1 where two veneers, to whose edges glue has been applied, are pushed together under a hot iron which causes the glue to set.

The mechanical interpretation of this process is shown in Fig. 2 where the two veneers are passed under a hot bar by a conveyor track. The machine is fitted with a moistening wheel for applying hardener to the glued edges and a series of inclined track wheels perform the task of the hands shown in Fig. 1, and force the edges of the veneers together.

This is basically the form of the modern edge-splicer in general commercial use. Glue is applied to the veneer edges whilst they are still in the trimmer; the glue is then allowed to dry before the veneers are fed into the edge-splicer.

The operator selects a pair of veneers and feeds them under the pilot track wheels which force them together and into the conveyor track which passes them through the machine. After passing the pilot wheels the edges of the veneers are guided past a moistening wheel (which can also be used to apply hardener if required) until they are gripped between the series of inclined wheels and the conveyor track. The traction at this point is sufficient to draw the veneers along under the heated pressure bars (which are a few feet in length).

Until a few years ago the glues used for edge-splicing were mainly gelatine (animal) glues made partially thermosetting by the addition of formalin in the moistening tank. These are still used to a



Figure 1. The principle of tapeless splicing: two veneers are pushed forward and together under an iron which causes the glue applied in the edges to set.

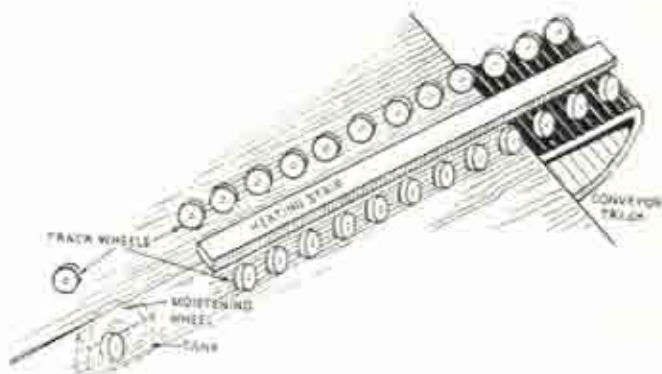


Figure 2. The mechanism of tapeless splicing: the veneers are moved forward under a heating strip while inclined track wheels push the edges together.

considerable extent but are being replaced by synthetic resins where rapid production is required, as the essentially thermo-setting character of the resins can be exploited to give a bonding process which is almost instantaneous.

The requirements for a resin for edge-splicing are as follows:—

- (1) It should be comparatively well reacted (i.e. not under-cooked) and should harden quickly under the action of moderate heat.
- (2) It should be quick drying.
- (3) It must be capable of being spread thinly without undue penetration.
- (4) It should possess good "wetting" characteristics even when dry.
- (5) Its colour should be neutral.

Several combinations of glue and hardener fulfil the requirements listed above and the application of these is considered next.

Some prefer to spread the resin, let it dry and permit the moistening wheel to apply the hardener just before splicing, while others prefer to mix the resin and hardener together before spreading and allowing to dry (the veneers must then be spliced before the expiry of the closed-assembly time).

Occasionally special machines are used to apply a mixture of glue and hardener by means of a moistening wheel just as the veneers enter the splicer.

METHOD 1: SEPARATE APPLICATION

UF resin 100 parts by weight
Liquid lubricator .. 10 parts by weight

This mixture is spread as thinly as possible by brush or machine on to the edges of the veneer which have just been trimmed. The veneers are then removed from the trimmer, spread out slightly and allowed to dry before being passed through the edge-splicer where a fast hardener is applied by the moistening wheel.

Temperature	Minimum drying time	Maximum drying time
21°C (70°F)	1 hour	1 month

Providing that the operating temperature of the splicer is 177°C (350°F) or above it can be fed at very high speeds. The very fast hardener has a charring action on the wood over 204°C (420°F) so this is the upper limit of temperature.

METHOD 2: MIXED APPLICATION (DRY)

UF resin 100 parts by weight
Hardener A 15 parts by weight
Liquid lubricator .. 10 parts by weight

This mixture is spread as thinly as possible either by brush or machine on to the edges of the veneer which have just been trimmed. The veneers are then removed from the trimmer, spread out slightly and allowed to dry.

Temperature	Minimum drying time	Maximum drying time
21°C (70°F)	1 hour	0.75 (pot-life)

The veneers are then passed through the splicer in the usual manner.

This method can be modified to suit spreading machines (trimmers) and production conditions. Although the glue should be dry before splicing it should not have gelled and it is here perhaps worth while repeating some of the remarks made on closed assembly times in the preceding lecture "Veneering flat and curved work".

There is a clear distinction between a dried and a pre-set glue-line. It is easy to get a perfect bond from a completely dried resin glue-line providing that it has not reached the gelled state. To check whether it is dried or pre-set the glue-line should be moistened: if it is still tacky it has not yet reached the gelled state. Manufacturers of plywood who spread glue on to cores still warm from the drier should make an allowance for checking when estimating the maximum permissible drying time. An illustration of how the maximum permissible drying time varies with temperature is given in Fig. 3, and how it varies with the amount of hardener added is shown, by the curve given in Fig. 4. It should be remembered that the greater the hardener addition the slower will be the maximum speeds of feeding obtainable unless the glue mix is permitted to dry out completely before splicing. If the weight of hardener added exceeds 20% of the weight of resin the mix will take some considerable time to dry out. The following glue mix is suitable for automatic spreaders which usually require a glue mix (cold) of a viscosity of about 12 poises.

U.F. resin 100 parts by weight
Hardener A 33 parts by weight
Lubricator 10 parts by weight

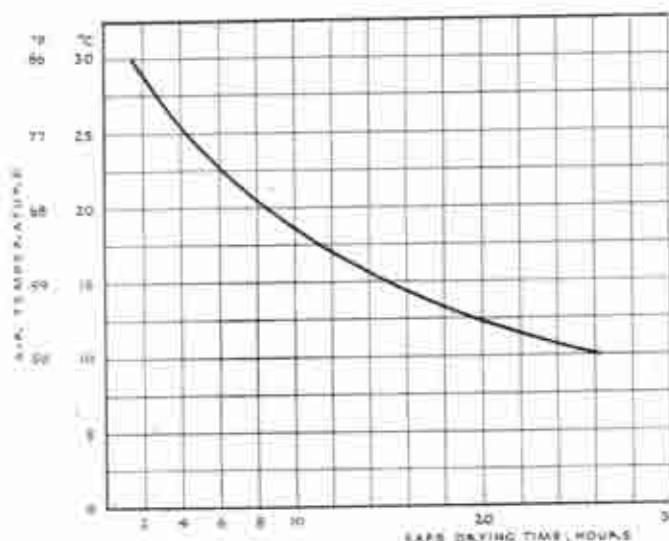


Figure 3. Graph showing variation of safe drying times with change of air temperature. Safe drying times vary considerably from day to day according to changes of temperature.

Temperature	Minimum drying time	Best drying time	Maximum drying time
21°C (70°F)	1 hour	12 hours	7 days

It will be noticed that the maximum drying time has been extended to several days and provided that several hours drying can be given the feed speed remains much the same.

Additions of hardener of up to 50% of the weight of the resin may lengthen the maximum drying time to two weeks but the effect on the feed speed is likely to be noticeable.

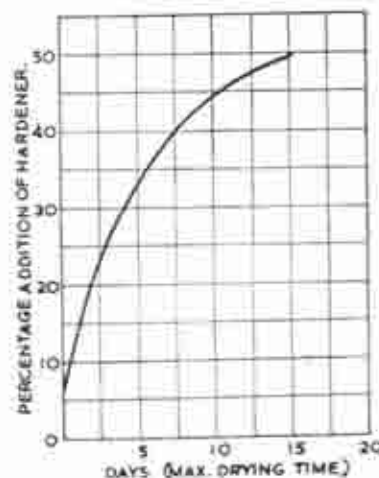


Figure 4. Graph showing how maximum drying time varies with percentage of hardener added.

METHOD 3: MIXED APPLICATION (WET)

Some machines have glue applicators in place of the moistening wheel but whilst these are convenient they are not often used if a factory also possesses an automatic trimmer and spreader. The following glue mixes are advised:—

UF resin	100 parts by weight
Hardener A	15-30 parts by weight (according to the viscosity required)
Lubricator	15 parts by weight (according to the viscosity required)

A very thin glue-spread is essential as the resin is still wet when passing through the machine.

The glue reservoir tends to get warm after the machine has been running for several hours and in order to prevent difficulty with short pot lives a water jacketed reservoir is provided and can be used with advantage.

R.F.-heated machines of this type require non-arcing, quick-setting hardeners.

COMPARISON OF METHODS

Whilst each of these methods has its own advantage, Method 2 is the most logical from the glue specialist's point of view. In this method all the solvents from the glue and hardener are evaporated before the splice is made and so the glue can set with the minimum interference and at the maximum speed. As the glue is expected to set in a few seconds, maximum efficiency is required and it is noticeable at once if this is not being achieved.

There is an unfortunate tendency in each of these methods for the glue to stick on to the pressure bars and cause stoppages. Gelatine glues, being thermoplastic, are less likely to cause stoppages than resin glues. Lubricators should be added to all glues for edge splicing and these do assist to a very great extent but they are only completely successful when the splicer is in good condition and carefully operated.

LUBRICATOR

Liquid lubricators are preferable to the powders as the latter sometimes make spreading difficult and produce white glue lines. The weight of lubricator added will be anything from 5 to 20% of the weight of the glue, but 10% is the usual addition.

Powdered lubricators often have considerable bulk; when materials such as zinc stearate are used a $\frac{1}{2}\%$ addition is sufficient.

If glue, hardener and lubricator are mixed together the lubricator should be stirred in last because the hardener sometimes contains materials which, if they are not first mixed in with the resin, may cause separation between hardener and lubricator.

It should be remembered that lubricators are not adhesives and that the quantities should be kept as small as possible.

CARE OF THE MACHINE

Even when large quantities of lubricator are used glue may stick to the pressure bars and cause stoppages but this is often due to the pressure bars being in poor condition. These should have lightly polished surfaces as any scratch or point of wear is a likely place for glue to stick to. Chromium plated pressure strips should be replaced when worn and operators should not be permitted to scratch away any solid glue with hard tools. For this purpose a stick of solder hammered and filed to a chisel edge is recommended and will be found to be foolproof.

FEED SPEED

Machines with long heater strips give the fastest feed speeds particularly when used with resins and fast hardeners (machines having a heater strip of 1.5 m (60 in.) permit feed speeds about twice as great as those with heater bars of 1 m (42 in.))

The higher the temperature of the machine, the higher the speed at which it can be fed. UF resin glues are not often operated at less than 177°C (350°F), but if the work calls for an especially low temperature an MF resin should be employed which, with a suitable hardener can operate at 100°C (212°F). Most failures with synthetic resins are caused by working at too low temperatures; it is important therefore to discover what the actual operating temperature is and not to go by that indicated by the thermostats.

The thickness of the veneers affects the speed at which they can be fed into the machine; a comparative relationship is given in Fig. 5. This graph is for normal methods of heating and does not apply

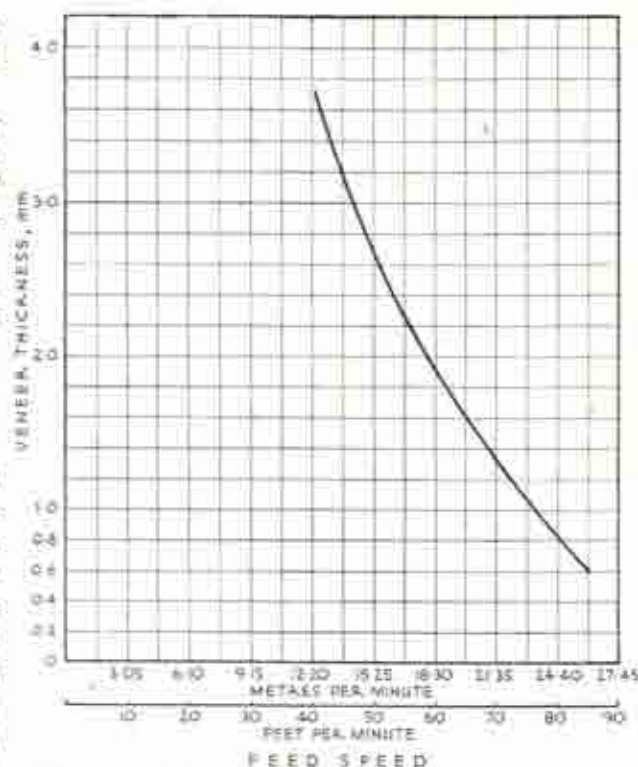


Figure 5. The relationship between feed speed and veneer thickness.

to R.F.-heated machines which are, of course, relatively unaffected by the thickness of the veneers. For example, veneers 6 mm thick can be spliced in an R.F. machine at 26 m/min (85 f.p.m.). Compare this with the figures for conventional heating given in Fig. 5.

GENERAL NOTES

Trimming

Without accurate trimming good edge-splicing is not to be expected. It is important that the veneers should be of the same or nearly the same moisture content at the time of trimming otherwise they are likely to shrink unevenly and cause the spliced sheets of veneer to warp. These sheets may be pressed flat during the next manufacturing stage but nevertheless the residual internal stresses will tend to relieve themselves and cause the fabricated panel to warp as soon as it is free to do so. (See Fig. 15 on page 86 of this book.)

Staining

The remarks on this subject in the lecture "Gluing difficulties and their remedies" (see page 83 of this book) are equally applicable here. Certain hardeners are more active in absorbing iron than others. Those having the least affinity for iron are the least likely to cause stains (and also the least likely to cause corrosion) but they are often made from more expensive materials and, being specialised products, are not in general use.

Veneers, particularly oak, sometimes receive iron contamination from the veneer-cutting knife. Staining will almost certainly result and often takes the form shown in Fig. 13 on page 83. The staining shown forms where the steam condenses just outside the area covered by the pressure/heater bar.

Scorching or Charring

For the highest rate of production the temperature of the heater bar is often above the scorching temperature of the wood. The wood surface will not be burnt unless it attains its charring temperature, which, for oak is relatively low, about 137°C (278°F). The higher the feed speed the less is the likelihood of discolouration by scorching for if the veneer passes quickly through it has little opportunity to become too hot.

Extremely Fragile Veneers

Very thin veneers such as those of 0.3 mm (1/85 in.) thickness are difficult to splice as they are very sensitive to changes of moisture content. To prevent them from kinking badly after splicing, the splicer should be run at as low a temperature as possible. Sometimes it is desired to work the splicer at 100°C (212°F) or below and at this temperature the feed speed is too low to be practicable if a UF resin is used. MF resins are more heat sensitive than UF resins and so the following type of mixture may give successful results under these difficult conditions.

MF powdered resin	100 parts by weight
powdered hardener	5 parts by weight
powdered lubricator	1 part by weight

As these materials are in powder form at least 70 parts by weight of water are required to make a mixture that will spread easily. This MF resin is expensive and its use is justified only when the desired results cannot be obtained by cheaper methods.

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SHORTENING THE SETTING TIME

G. M. Scales

INTRODUCTION

IN the following brief account the various industrial methods of heating glue lines are given. The more important of them are described in greater detail elsewhere in this book.

HOT ROOM

In many temperate climates winter is not sufficiently hard to compel the use of central heating in factories. The ordinary temperature of the workshop in winter is often insufficient to raise the wood above 7°C (45°F), and so it is of considerable advantage to store the wood and carry out gluing in an especially insulated and heated room. It is, of course, the temperature of the glue line that affects the rate of setting but the fact that gluing is carried out in a warm room is not in itself a sufficient guarantee of successful work: the wood should also have been stored in the warmth for some time beforehand. The mass of a cold piece of wood is sufficient to chill the glue very quickly even though it has been applied in a hot room and the result will be disappointing. It should be remembered that cold wood takes some time to acquire room temperature and also that thermometers should be placed at the same levels as the stored wood. Thermometers placed in draughts or above steam pipes give very misleading information.

WARM RUBBER SHEETS

An interesting variation of the hot-caul method makes use of rubber sheets heated to about 60°C (140°F): they can be handled conveniently at this temperature. If the rubber is $\frac{1}{8}$ in. thick and the initial temperature is 60°C the rise and fall in temperature of the glue line is similar to that shown in Fig. 1. As the rubber conserves more heat than the aluminium it permits a longer effective heating cycle even though its initial temperature may be lower. The use of lower temperatures is an advantage as it permits a longer closed-assembly time which means that a greater number of articles can be pressed at once without danger of pre-curing.

Rubber sheeting is extremely useful when veneering on to ply or block-board which is of a slightly

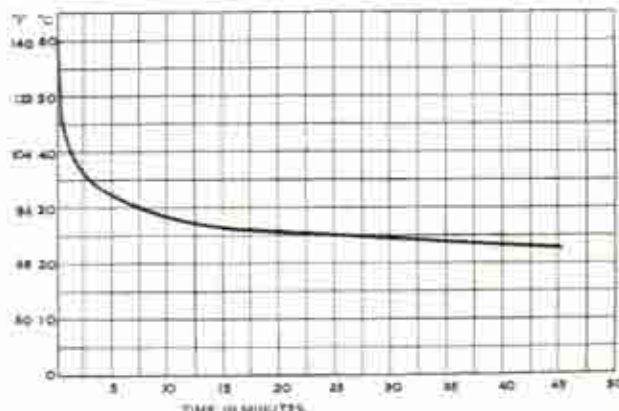
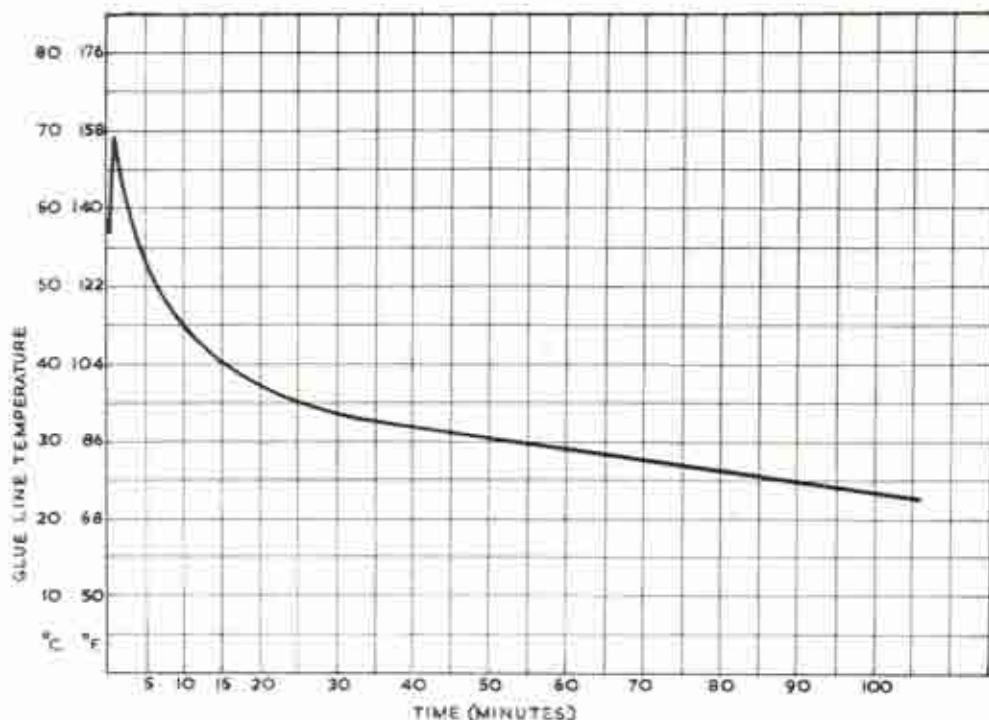


Fig. 1. The effect on glue-line temperature of placing a warm (60°C) rubber sheet ($\frac{1}{8}$ -in. thick) on top of the veneer (0.0 mm. thick).

Fig. 2. The effect on glue-line temperature of placing a hot (95°C) aluminium caul (3 mm. thick) on top of the veneer (0.6 mm. thick)



uneven thickness. The effect of any unevenness is of course amplified when several panels are stacked in the cold press and aluminium cauls do not reduce the effect, but when rubber is used its resiliency takes up small unevennesses and equalises the pressure, thus preventing many blisters.

HOT-WATER TROUGH

Although rarely seen in England a cheap and very effective means of heating for curved work glued in a vacuum press is a hot water trough. The sides of the clamping irons are built up slightly, the corners are sealed and one is provided with a draining plug. The trough thus formed is filled with hot water by means of a hose, converting a cold-bag press into a hot press.

ELECTRIC BLANKET

The industrial type of electrically heated blankets can be used with advantage particularly when the hot water method described in the preceding paragraph is impracticable. A considerable amount of trouble is saved if the heating of the blankets is

thermostatically controlled and care should be taken that the blankets do not overlap each other to produce local over-heating. If these blankets are handled carefully they should have a fairly long life which is an important consideration as they are comparatively expensive.

RESISTANCE-STRIP HEATING

This is a very efficient means of heating which has not yet found as wide application as it should. Current from the mains is passed through a step-down transformer and taken from the output at a low, safe, voltage, (usually in the region of 10 volts). This low-voltage, high-amperage current is then passed through a strip of metal of high resistance which is in contact with, and conveys heat to, the glue line. The strip is thin and flexible and can be used for curved veneering and in making plywood although if the electrodes are of large surface area considerable attention must be paid to the design of the equipment. Heating can be controlled by means of a resistance across the input of the transformer or by several other methods which are described in detail in Mr. Lacey's lecture on strip heating.

WIRE RESISTANCE

An alternative to the strip resistance is a fine wire resistance, buried in the glue line. After the glue has set the input and output wires are cut off flush with the surface and are almost impossible to detect when the assembly is finished. As resistance heating is relatively cheap and easy to install it is especially suitable for use when the production run is not long enough to warrant more elaborate equipment.

HOT WIRE-NET

A method used by the Goldschmidt A.G. of Essen before the war employed a wire net of very fine mesh cut to size and embedded in the glue line, the resistance of the net was high enough for a transformer to be dispensed with though points of contact from the mains to the net were inclined to be dangerous.

A variation of the process was devised by Dr. W. Gallay who used a conducting textile mesh in place of the wire net.

In both these methods the heat is generated exactly where it is required and a glue-line temperature of 100°C (212°F) can be expected within a few minutes. Unfortunately, both these methods have rather limited applications because, with a mains voltage not greater than 230, the net can only be relatively small in size.

ELECTRICALLY-HEATED PLATE OR PLATENS

Sometimes it is convenient to heat a platen or mould electrically, when, for instance, a large number of comparatively small curved articles are to be produced and rubber-bag techniques are impracticable. The heat in the mass of metal in an electrically heated platen reduces the drop in temperature which occurs each time a fresh glued assembly is placed in the jig. The avoidance of a considerable drop in temperature is important in gluing assemblies that require considerable heat penetration, such as thick curved plywood. It is easier to manufacture an electrically heated curved platen than a steam-heated one but, although

thermostatic control can be provided, precise temperature control is not so easy to achieve.

Electrically heated platens are also sometimes advisable for flat work where high temperatures are required as in the scarf-jointing of thin plywood or veneers, where bonding can be achieved in a matter of a few seconds by direct heating at temperatures above 150°C.

HOT CAULS

Hot aluminium sheets about 3 mm or $\frac{1}{8}$ in. thick are often used for accelerating curing when hand presses are used. These aluminium cauls are usually heated over steam pipes, gas jets or in ovens and are interleaved in the pack of components to be glued. Heat is transferred from the aluminium caul to the adjacent wood and thence to the nearest glue lines. The hot cauls cool fairly rapidly as soon as they are brought into contact with the relatively cold wood but even so pressing time may be reduced by as much as 50 to 75%. Fig. 2 shows how the heat is transferred from a 0.3-mm aluminium sheet, initially at 95°C, through a 0.6-mm veneer to a glue line underneath. It is a relatively simple calculation to estimate the pressing time that must be given for the glue to be sufficiently set.

Care must be exercised to ensure that the hot sheets are put into position and under full pressure before the glue has started to cure.

PRE-HEATING

Where it is impossible to use a hot room for storage long setting times can often be avoided by pre-heating components before gluing. This is a useful technique for small assemblies and may enable work to be removed from a jig after a few minutes instead of an hour or two. The gluing in of small blocks to strengthen the corners of a cabinet, is a typical application of this technique. The blocks are kept in a heated oven until they are required for use. Resin glue is applied to the corners of the cabinet and simple quick acting clamps hold the blocks in position until the glue sets hard. This method is useful for products that call for the use of synthetic resins but where conditions of manufacture make the use of more elaborate

equipment undesirable. Either a mixed or a separate application can be employed with this technique. If a fast-acting, separately-applied hardener is applied to the blocks and allowed to dry before brought into contact with the glue, about thirty minutes at room temperature must elapse after clamping before the glue acquires sufficient strength for the jig to be released; but should the blocks be heated in an oven to about 60°C before being brought into contact with the glue, the time in the jig can be reduced to about ten minutes.

STEAM OR WATER-HEATED PLATENS

The means of heating in the familiar hot-press equipment is hot water or steam which is circulated through coils or channels in the platen.

In this country where the temperatures of the platens are usually kept below 120°C (248°F) hot water is circulated through them from a steam-heated water tank. The platens are built up with fabricated steel steam-coils and pressure-bars working inside an aluminium housing. When platens are fabricated with aluminium pressure plates the pressure that can be applied is usually limited to about 100 psi. Besides being rather prone to corrosion the platens can be also distorted easily by bad manipulation of the press. Aluminium platens are, however, considerably cheaper than the steel platens which are used for work at high pressures and temperatures.

Temperature is controlled for both types by a steam-pressure-reducing valve.

INFRA-RED LAMPS

Though not often used for generating heat in glue lines, infra-red lamps give far better heat penetration than convection heating by, for instance, an electric fire of equivalent power. But articles to be glued which are suitable subjects for infra-red heating are comparatively rare; the use of infra-red lamps is most advantageous when the production runs involve the use of a conveyor belt which can be passed through an infra-red tunnel, but, in general, use of infra-red heating equipment is not justifiable economically in the woodworking industry.

RADIO-FREQUENCY (R.F.) HEATING

This is sometimes called high-frequency, electronic or di-electric heating and is perhaps the most popular method of heating the glue line where it is important not to lose too much heat in the material on either side of it. The cost of R.F. generators is comparatively high and considerable experiment is required before jigs can be adjusted to give the best results. Because of its selective heating capabilities, radio-frequency methods are most economically used where there are many glue lines far from the surface.

The technique of R.F. heating is specialised and this course includes a lecture devoted to this subject.

DIFFICULTIES IN GLUING AND THEIR REMEDIES

G. M. Scales

INTRODUCTION

THERE are five main factors which affect the adhesion of a glued joint. These are :—

- (1) Pressure
- (2) Temperature
- (3) Moisture content
- (4) Glue spread
- (5) Surface porosity.

All these factors influence one another so that the total effect of all together must be considered; it is not sufficient to see that each individually lies within the prescribed limits for good adhesion.

The way in which these factors influence each other must be considered when attempting to diagnose the cause of failures. This lecture gives a detailed account of the operation of these factors and of the chief difficulties encountered in gluing.

MOISTURE CONTENT

The moisture content of the wood at the time of gluing has an effect upon the performance of the bond; this effect is much more marked with some glues than with others. In general phenol-formaldehydes (PF) work well only when the moisture content of the wood lies within the range of 6-10%, whereas urea-formaldehydes (UF) give their best performance between 8 and 12%. The UF resins also allow more latitude and work comparatively well between the wider range of 7-15%. Unlike the PF resins it is actually a disadvantage to use UF on wood of too low a moisture content but this is a rare condition and in general UFs are considered

to be the easier to use. From the point of view of operating economy PFs have the disadvantage that they require more exact control and are therefore more expensive to use. The lower moisture content they demand also reduces the output of the veneer drier.

Every make of glue has its own limits of toleration of moisture content, and it is advisable that manufacturers should be approached for information concerning their own particular products. It should be borne in mind that the range of moisture content which can be tolerated varies with the type of timber as well as with the type of glue (birch, for example, allows a wider range than maple).

It is of course necessary to have all the timber at the same moisture content at the time of gluing. Wood gains or loses moisture to adjust itself to the humidity of the atmosphere. If woods of different moisture content are glued together the amount each swells or shrinks before reaching equilibrium will not be equal and internal stresses, concentrating in the glue line, will persist throughout the life of the joint and may well cause its complete breakdown, perhaps long after the joint has been made.

The results of gluing at a high moisture content are often unsatisfactory because it is difficult to exercise a sufficiently close control over the many other factors involved (e.g. the viscosity of the glue, the pressure and the temperature); as the moisture content increases small variations in these assume greater importance.

The higher the moisture content of the timber, the more diluted the glue becomes, and this lowering of

viscosity causes the glue to penetrate more freely into the pores of the wood. A slightly thicker glue may therefore be needed in order to avoid a glue-starved joint.

If the glue, on setting, turns milky it indicates that excessive moisture has caused over-dilution and, consequently, precipitation. This precipitation weakens the glue line because setting takes place under conditions that prevent the complete cross-linking of the molecules (Fig. 1). Figs.

2, 5-7 and 12-15 show other common faults.

If it is necessary to make an emergency joint with wood at a moisture content far above the recommended limit, the following method may be used. Remove the surplus moisture from the surface of the joint and dry the surface as quickly as possible before gluing. A fast hardener should be used, and further acceleration of the glue by heating is an advantage. This is impracticable when veneering and instead the addition of 10% of plaster of paris ($\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$) to the glue mix is advised.

SPREADING THE GLUE

The condition and the design of spreaders must affect considerably the success of the glue spread. To a great extent, the type of groove in the roller controls the quantity of resin laid on the wood and also the tendency to skid. The steel rollers fitted to spreaders of the tray type last longer but are more difficult to adjust to give the low spread obtainable with soft rubber-covered rollers. The use of precision-built spreaders, including doctor-roll spreaders, is likely to lead to a considerable saving of glue.

Resin spreads of the order of 3lb/100 ft² (150 gm/m²) are considered to be comparatively economical in England although many makers of plywood, particularly in Scandinavia, obtain excellent results using far lower spreads. Perhaps this is

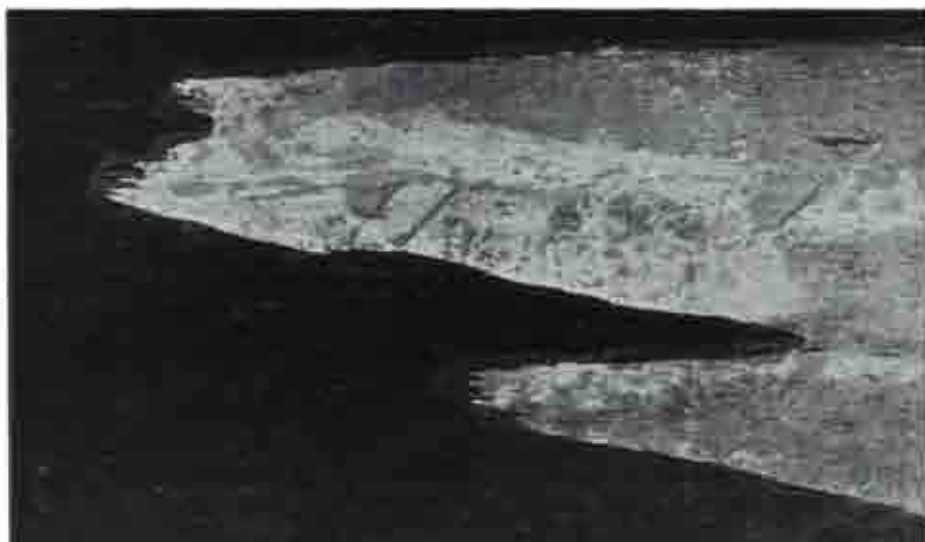


Fig. 1. An example of glue "precipitation" caused by excessive moisture content of the wood. This condition weakens the glue line.

because in England timber is far more costly than resin whereas the position in Scandinavia is exactly the reverse.

An extremely thick glue line is likely to craze if the resin used is not of a permanently gap-filling type. The thinnest glue line capable of giving a continuous glue layer between the surfaces will provide the best adhesion. The quantity of resin required for such a thin glue line depends very much upon the physical characteristics of the wood to be glued; in certain circumstances a resin spread of only 1½lb/100 ft² (75gm/m²) is enough. The even application of such spreads is often difficult. Extremely careful control must always be exercised over the preparation of veneers, the moisture content, the closed assembly time, the temperature and the pressing time. For further remarks on glue spreading the reader is referred to my paper called "Veneering; flat and curved work" in this book (see especially page 57).

PRESSURE

As a general guide the pressures within the following range give satisfactory results:—

	Minimum	Maximum
Softwoods	20 psi	150 psi
Hardwoods	75 psi	250 psi

To obtain satisfactory results outside these ranges requires a considerable understanding of the ways in

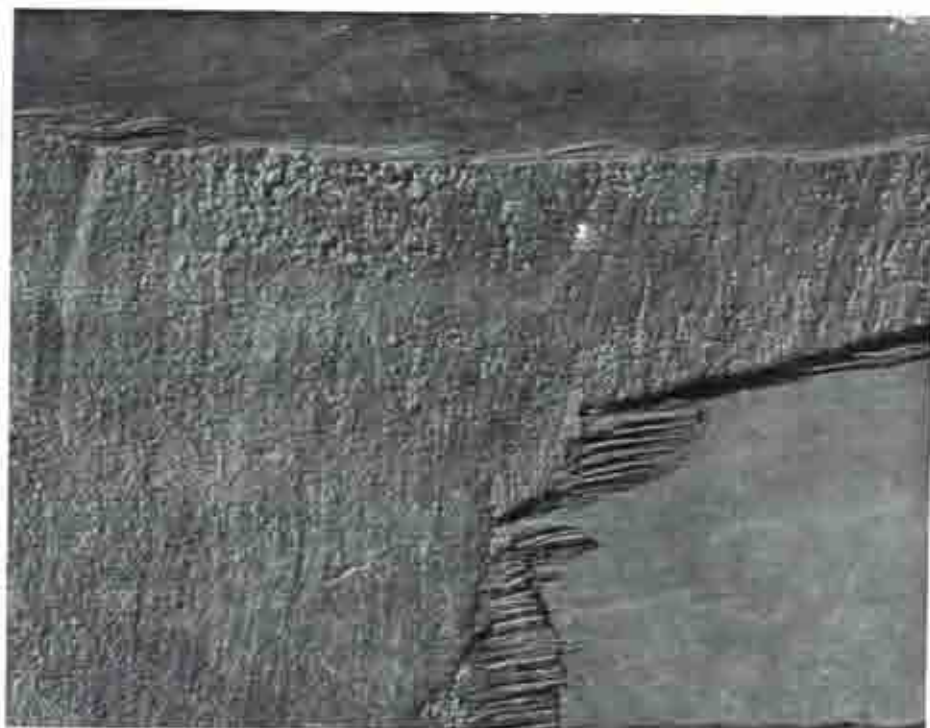


Fig. 2. A crazed glue line caused by insufficient pressure during curing of a non-gap-filling glue.

which pressure can affect the glue line. It is unfortunately a common misconception that the sole reason for applying pressure is to bring the surfaces into close contact. Some of the ways in which pressure can influence the behaviour of a glue line are discussed in the following paragraphs.

Hardwoods generally need and can withstand greater pressures than the more porous softwoods which will, of course, permit much more penetration. A certain amount of penetration is required to "wet" as much as possible of the wood surface and thus increase the area of contact. Excessive penetration can, however, result from the application of too much pressure, and this should be avoided.

Pressure should not be varied during the setting of the glue as any variation may exert a pumping action and cause loss of glue through penetration. The application of pressure by hydraulic or pneumatic means is preferable; if hand-presses are used there is a very natural tendency to apply as much pressure as possible in the hope that this will compensate for any shrinkage which may occur while the glue is setting. The difficulty of judging the

pressure applied by one or more screw-threads contrasts with the ease with which a fairly accurate estimate may be made when using a hydraulic press.

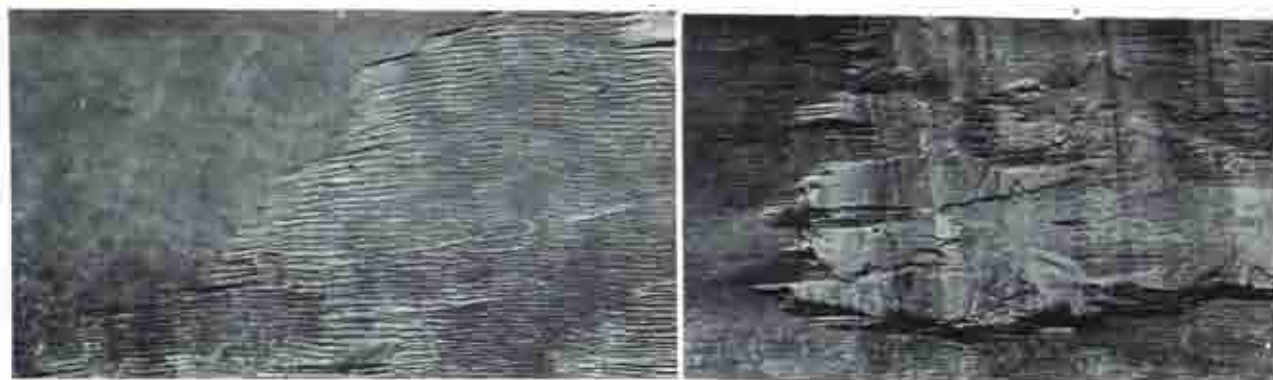
The pressure required also depends upon the viscosity of the glue: thin glues need less pressure than thick ones, and, while considering this aspect of the subject, it is worth bearing in mind that a newly-manufactured glue is likely to be considerably thinner than one approaching its "expiry" date. Temperature also has a great influence upon

the viscosity of the glue so that an increase of the temperature at which the press is operating is accompanied by a slight increase in the glue's capacity to penetrate. Should it be necessary this penetration can be reduced in a number of ways one of which is to lower the pressure.

If the woods to be joined have a high moisture content there is a tendency for the glue to be diluted and the viscosity lowered; a slight reduction of pressure is then required.

The faster-acting hardeners allow less time for penetration before the glue gels. But when they are used, it is impossible for the glue to be already partially cured before full pressure can be applied, although from examination of the resulting failure it may appear that the pressure has been inadequate.

The general principle is: the greater the viscosity the greater the pressure required. The application of the well-known film glues affords a clear illustration of the operation of this principle, for these glues, being in a dry state, have to be subjected to very high pressures indeed before they will flow sufficiently to wet the surfaces. The use of film glues



Figs. 3 and 4. Gelling of starch contributes to the adhesive qualities of a glue mix. Results of hot-pressing (Fig. 3, left) and cold-pressing (Fig. 4, right) are shown. In both cases the same resin and 100 per cent extender were used.

requiring such high pressures often results in a slight loss in the thickness of the board through compression. This loss becomes noticeable when boards of some thickness are required and may account for the greater interest now being shown in the less critical, low-temperature-and-pressure adhesives fortified with melamine formaldehyde; these give thoroughly boil-resistant bonds.

Some, but comparatively few, failures are caused by crazing of the glue line when non gap-filling glues are used. This crazing can be recognized by the crystalline appearance of the glue line, and is only likely to occur when the pressure applied is insufficient to bring the surfaces into close enough contact over their entire area.

Contributory causes of crazing of the glue line may also be (1) the use of thick wavy veneers which only flatten under considerable pressure, (2) a very thick glue spread, and (3) a low temperature for cold-pressing (from this it may be gathered that crazing is more likely to occur when pressing cold than when pressing hot).

PENETRATION

Loss of glue from the glue line can occur either inwards towards the core or outwards through the surface veneer. The effects of inward penetration are difficult to observe without the aid of a microscope, but it is easy to recognize places where the glue has penetrated the outer veneer. On such places, stain-resistant patches, even after sanding, are likely to form; moreover, adhesion of the

cellulose finish may not be good. This faulty adhesion sometimes remains unnoticed for days, or even months, when "blisters" or "fraying" may appear on the cellulose finish. Excessive penetration of glue both inwards and outwards can result in the almost complete disappearance of glue from the glue line, and, in consequence, glue failure.

Penetration can be controlled by paying careful attention to the viscosity of the glue, the spread, the pressing temperature, the pressure, the addition of fillers that promote "gelling" and the assembly time. These factors are discussed in detail in the following paragraphs.

Some synthetic resins formulated for plywood and veneer bonding contain small proportions of filler, the purpose of which is to flow into the wood pores before swelling, and thus reduce the passages of outlet for the resin. Cheap starch-containing fillers can, however, be mixed in by the user and will serve the same purpose, except that additions made after manufacture will need to be greater in order to achieve the same results. This is because any material added after manufacture is unlikely to be so completely "wetted" by the resin.

The addition of a quantity of raw cereal flour to prevent penetration certainly has the advantage both of achieving this result and of lowering cost; nevertheless, the quality of the adhesion will be reduced and the bond may have little water resistance. A thick urea-formaldehyde resin, used correctly, will not require loading with extenders to prevent penetration. A more detailed description

is given in the lecture on extension beginning on page 89 of this book.

The application of normal pressure using heavy glue-spreads often results in glue being squeezed out at the sides of the board or being pressed into and through the pores of the wood. Neither of these conditions is desirable; the glue spreader should be re-adjusted to give the thinnest spread consistent with good adhesion so that penetration is decreased and the wastage of glue, and therefore the cost of production, reduced.

When veneers of high moisture content and open grain are used, careful attention should be paid to the prevention of penetration as the moisture from the wood tends to dilute the resin.

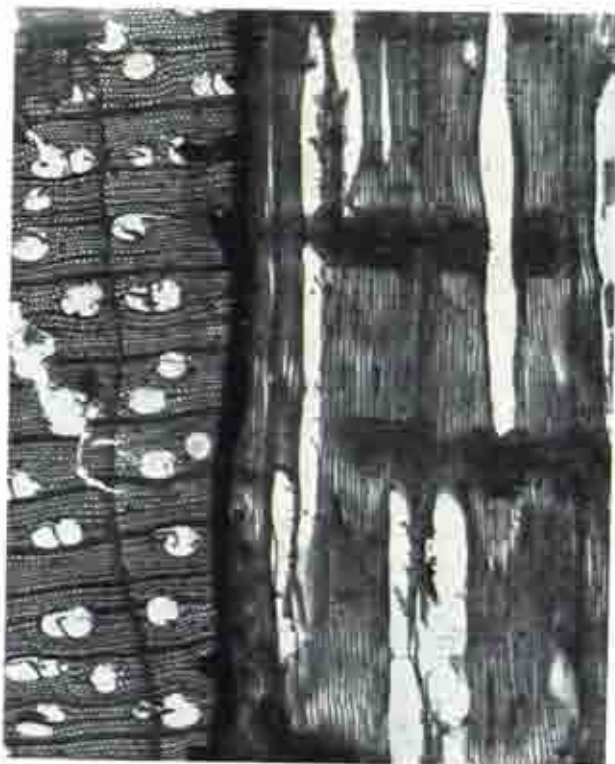
Any increase in the time allowed between spreading the glue and hot pressing will assist the diffusion of moisture from the glue line, though the resin itself

will remain there. This effect can be increased still further by air-drying the glued surface before assembly; this is yet another method of controlling penetration.

Operators using urea-formaldehyde glues for hot press veneering have recently shown a tendency to reduce the operating temperatures of their presses from 200°F (93°C) to between 160°F (71°C) and 170°F (77°C). This reduction diminishes the effect of heat upon the core board and reduces the likelihood of penetration. The same setting speed is maintained by the use of faster setting hardeners.

PRE-CURING

This condition occurs when a resin-glued joint becomes partially cured before full contact between the surfaces is achieved. A complete loss of adhesion can be caused by pre-curing although failure



Micro-photographs of glued joints in section (the glue itself shows as heavy black patches and areas).
Fig. 5. A good joint.



Fig. 6. A glue-starved joint (glue has penetrated into the wood).

Fig. 7. A pre-cured glue-line. This is most likely to occur when hot presses are used, and may result in a complete loss of adhesion.



more often occurs in small areas producing patches or "blisters". These frequently pass unobserved until the work reaches the polishing shop when the application of the cellulose by compressed air is usually sufficient to unseat any potential "blister" and make it apparent on the polished surface. The prevention of any such "blisters" is therefore of considerable importance to economical production. Those caused by pre-curing can be recognised by examination of the glue line beneath the veneer. A shiny surface or one in which there are still air bubbles, or craters from exploded air bubbles, indicates that intimate contact between the surfaces had not been made before the glue line began to set.

Pre-curing is most likely to occur when hot presses are used, and for this reason manufacturers of resin glue often state in their instructions that the loading of the press should be carried out as quickly as possible. This, it must be admitted, is difficult when as many as ten daylighters have to be loaded with small components. Rapid loading is, however, essential for the heat from the platens soon raises the temperature of the veneers on the lower surfaces and causes the speedy setting associated with resin adhesives to begin. Pre-curing will occur if full pressure is not applied before the resin begins to gel; the resulting

"blisters" will form at the points of contact with the hot platen before full pressure has enabled contact to be made over the whole area.

Pre-curing can be prevented in several ways all of which are designed to alter the relationship between the time taken from the beginning of loading to the application of full pressure, and the basic setting time of the glue. One solution is to allow a longer loading time, by using either a slower hardener or a lower press temperature. This method, however, reduces the output of the press and as many operators are committed to an output depending upon a pressing time of five minutes or less, it may not prove entirely satisfactory.

Another solution is to use a jig so that the press can be loaded in about 10 seconds. The number of components does not affect the loading time, and a jig for this purpose has great possibilities, not only as a practical solution to pre-curing troubles, but also as a means of increasing output both of press and operative.

An unloading jig of generally similar design can also be employed. The receiving areas of such a jig should be about $\frac{1}{16}$ in. lower than the platens when fully opened.

Resin glue nearing the end of its pot-life in the spreader will cure more rapidly than a freshly mixed batch and may therefore give pre-curing trouble when results from the fresh mix are perfect. This would suggest that there is little margin for safety, and that a change to methods offering a greater safety factor is desirable.

Resin glues near the end of their storage life become somewhat "fast" (page 78) and can also be the indirect cause of pre-curing.

The greatest freedom from pre-curing is given by hardeners which give a gelling time which is (comparatively) low in relation to pressing time. The efficiency of hardeners varies very much and so does this ratio. It is quite possible for two different types of hardener, used with the same glue, to give a basic setting time of three minutes at 95°C. But the gelling times under the same conditions, (i.e. the maximum loading times) may be quite different; for instance, the gelling time for one may be 45 seconds and for the other 1½ minutes.

THE STORAGE OF RESINS

It is well known that synthetic resins have limited shelf lives and that, even when stored under the most favourable conditions, they will in time become too thick to spread, and will eventually solidify. This process of thickening is slowed down if they are stored at low temperatures and for this reason the glue should always be kept at as low a temperature as possible and never be left uncovered in the sun. Table I shows the effect of storage temperatures upon a typical urea formaldehyde resin.

Caps of containers should be replaced after each time of use to prevent the air from causing the glue

to skin. Any skin so formed should be removed as attempts to stir it in are likely to produce lumps. In order to prevent traces of hardener from entering the glue containers, it is preferable that the glue should be stored well away from the hardeners. The storekeeper should ensure that the resin which has remained longest in stock is issued to the factory first, otherwise there is a danger that older glue may be left unused while fresh batches are being consumed.

STORAGE OF HARDENERS

Although the storage life of most hardeners is indefinitely long, care should be taken to ensure that caps of containers are correctly replaced immediately after use; any evaporation of the contents will alter materially the pot-life and pressing time of the mixes in which the hardeners are used. The storage site should be chosen so that it is protected from the heat of the sun and from freezing. Neither of these conditions affects the hardener itself, but each may be the cause of burst containers or of caps blowing out.

THE MIXING OF GLUES

Resin glues are most often set under carefully controlled conditions that are mildly acidic; any change in these conditions, apart from altering the pot-life and pressing time, may prevent complete setting. Harmful effects can, for instance, result from the use of dirty mixers or of containers which have been washed out with an alkaline cleaner containing caustic soda. Residues of alkaline glues should, for the same reasons, be removed; cleanliness is of the greatest importance.

Resin glues are by no means difficult to use, but mixing requires care if the best results are to be obtained. A glue will, perhaps, give good adhesion if 5, 10 or 15 per cent of hardener is added, although an addition of precisely 10 per cent may be recommended by the makers. All hardeners have their own characteristics when used with the glue for which they have been designed, and what may be true of one hardener will almost certainly not apply to others. The effect upon pot lives and pressing

TABLE I

Storage temperature (°C) (°F)		Storage life (months)
10	50	Over 12
20	68	8
30	86	4½
40	104	1

times of varying the quantities of hardener added is given in Fig. 8. The graphs in this figure relate to one particular glue and hardener ("Aerolite" and FHL60) and offer no guide to the behaviour of any other glue or hardener. They indicate, however, that no simple relationship exists between the quantity of hardener added and the pot-lives and pressing times. The quantities of glue, hardener, extender and water used in production should, therefore, be weighed or measured accurately according to the manufacturers' instructions, and not estimated roughly.

Steel containers used for mixing should be protected by galvanisation, vitreous enamel or paint, and hardeners are best stored in glass or earthenware jars. Vertical glue mixers give very satisfactory results and are generally easily cleaned.

MIXING UNDER TROPICAL CONDITIONS

Liquid resins, made from glue in powder form, can be a source of annoyance to the user unless precautions are taken to prevent the formation of lumps during mixing. Powdered urea formaldehyde resin is usually supplied in drums equipped with lids that are easy to refit and are sealed with rubber rings. The resealing of these drums each time after use is important as the powder is very hygroscopic, and lumps, difficult to re-dissolve, are soon formed. When mixing in the powder by hand, it is preferable to add it to the water gradually whilst stirring, any lumps formed can then be beaten out before more powder is added. Power mixing, however, requires the opposite technique and liquids should be added slowly to the powder whilst the mixer is in operation. For the best results the liquid glue so made should be allowed to stand for several hours before the hardener is added.

NEW AND OLD RESIN

In order to obtain the best adhesion reconstituted glue mixes should be allowed to stand for several hours after mixing. The mixture will then be thicker. As illustrated in my paper "The characteristics of synthetic resins and their application as adhesives" (see page 51 of this book), liquid resins

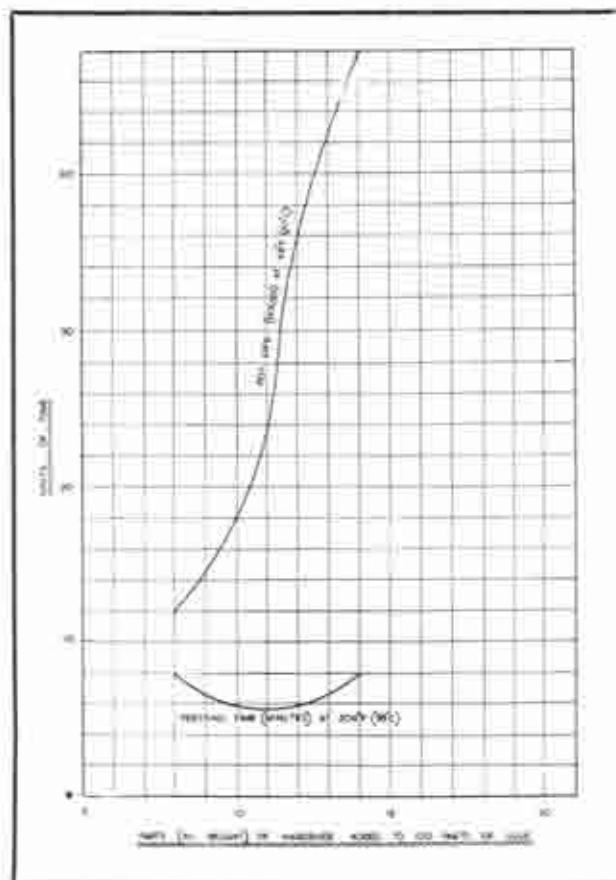


Fig. 8. The effect upon pot lives and pressing times of varying the percentage of one hardener to a particular glue.

thicken with age, and when they become too thick to spread the shelf life is said to have expired. This process of thickening is irreversible and any attempt to thin the resin must result in a drop in the final strength though this may not be apparent. A plywood manufacturer was compelled because of the shortage during the war to reclaim some resin that had just "expired". After considerable difficulty the resin was thinned down and used without any apparent loss in the quality of the adhesion. This is understandable, for the strength of synthetic resin glues is such that the loss of strength would have to be considerable for the resin to become weaker than the wood components of the joint. Such treatment, however, should be confined to emergencies and any thinning of old resins should be limited to dilution by 5% of water or alcohol. This dilution, as well as thinning the resin and increasing the

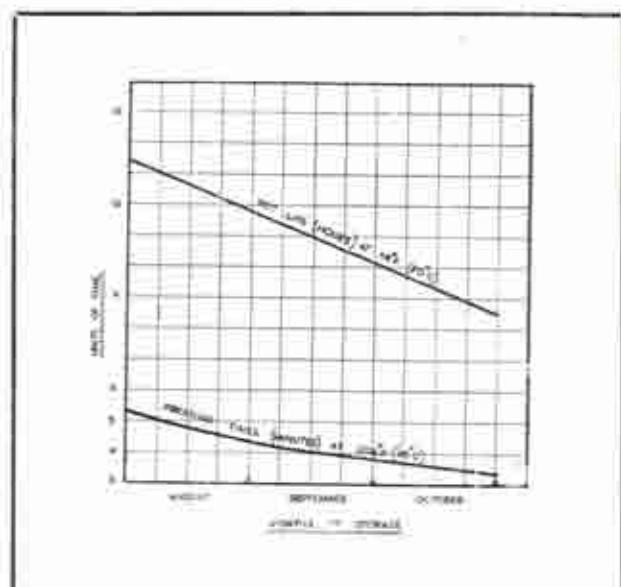


Fig. 9. Change of characteristics in urea-formaldehyde resin during three months' storage.

remaining shelf life, reduces the likelihood of the pot life and pressing times being extremely short as they often are when the glue is approaching the end of its shelf life.

The urea formaldehyde resins have gained widespread popularity as being most economical in spite of their having one of the shortest shelf lives of any of the liquid resins in common use. A date marked on the glue container is the usual method of indicating the estimated end of the shelf life, when stored in normal temperatures (70°F or 21°C). In practice, however, storage temperature varies a good deal, and so the value of this inflexible expiry date is somewhat doubtful. Deliveries of new resin should be adjusted to balance consumption and, in this way, if the older drums are used first, operatives are provided with glue that is always of the same age. However, the achievement of such management is not always possible and, since the extremes of old and new glue provide such wide discrepancies in viscosity, pot lives, and pressing times, it is desirable that all who are responsible for gluing should be suitably instructed. Fig. 9 illustrates this change in characteristics of a glue stored in a cool room from July to October.

ABNORMALLY SHORT POT-LIVES

Unusually short pot lives can cause considerable annoyance particularly when their occurrence coincides, as it frequently does, with a spell of very hot weather. The effect of temperature upon the pot life of a typical UF cold-press glue mixture is shown in Table II, from which it may be gathered that it is well worth while making every endeavour to keep the glue temperature down.

TABLE II

Temperature (°F) (°C)		Pot-life (minutes)
59	15	110
68	20	55
77	25	33
86	30	21

Sunlight falling directly upon the glue mixer or spreader should be prevented by colour washing of roof lights and windows. Ample ventilation should be provided to remove the heat generated by hot presses. Glue mixing should be carried out quickly in hot weather, otherwise the mix will become unnecessarily hot. Frictional heat which is generated in the glue spreader also facilitates evaporation of moisture from the thin glue-spread on the rollers. This evaporation, which is likely to be considerable in hot weather, reduces the pot-life and makes it advisable to dilute the glue slightly by a 3 per cent addition of water or ice cubes while the spreader is working. If, however, it is thought inadvisable for the spreader operators to dilute the glue in this way then the 3 per cent of water can be added in the mixer. Certain types of glue spreader can be adapted so that the trays are water-cooled and this represents a further advantage. As has been already explained, old glue, hardener containers left uncorked and inaccurate additions of hardener can all contribute towards variations of pot life.

SETTING TIMES

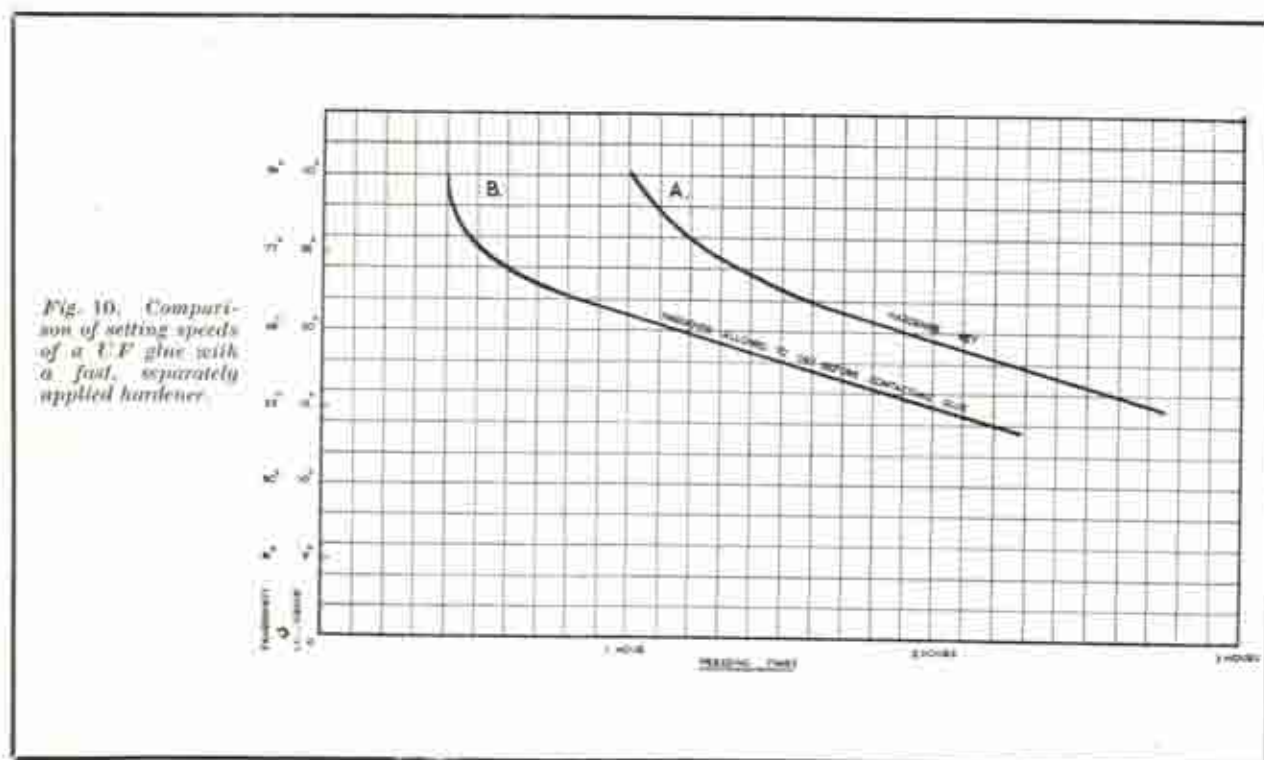
The setting times quoted by glue manufacturers for certain temperatures are the minimum times

needed for the glue to develop sufficient strength for the joint to be handled. Unfortunately, opinions vary concerning the degree of strength required for handling purposes, and consequently some of the published pressing times appear to be more optimistic than others. A strength of 300 psi (21 kg./cm.²) is nevertheless gradually becoming accepted as standard and sufficient for the removal of pressure. This, however, does not signify completion of setting; resins continue to develop strength until, finally, complete water resistance is achieved, which may not be for several days.

Joints that are subject to appreciable strain immediately after pressure is released should be allowed a pressing time of at least double the advertised minimum for unstressed joints. Table III shows how joints develop strength with increasing age.

TABLE III

Pressing time (hours)	Strength	
	(kg/cm ²)	(psi)
1	5	70
2	12.5	175
3	18.7	265
4	28.8	410
5	34.8	495
6	35.9	510
7	36.8	525
8	37.2	530
16	38.9	555
24	42.6	605
48	49.8	708
168	49.9	710



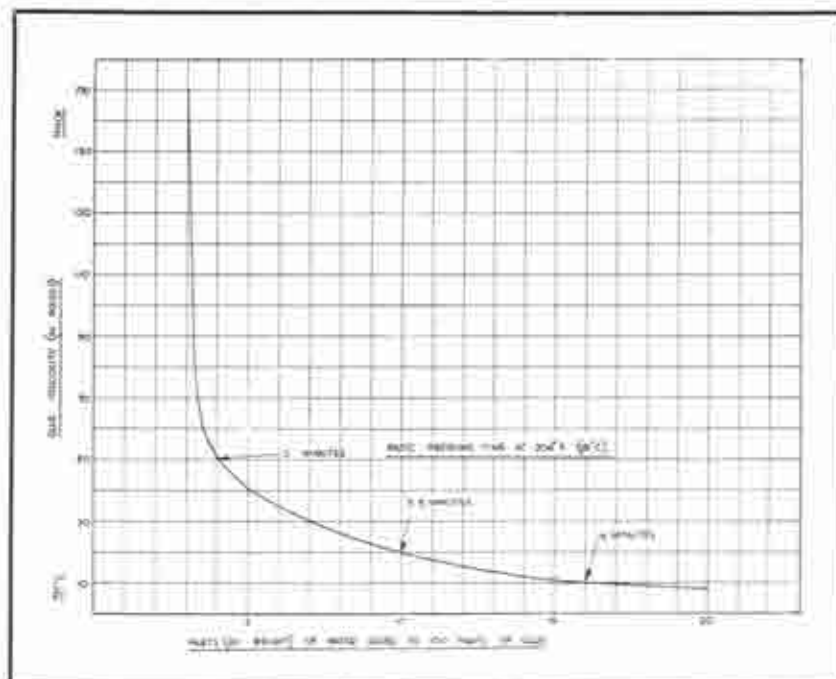


Fig. 11. Lengthening of pressing time caused by high moisture content of wood which cools and dilutes the glue.

ABNORMALLY LONG SETTING TIMES

Longer pressing times are more common when pressing cold than hot, and the information given below refers therefore for the most part, to cold-pressing technique.

The minimum pressing times advised in manufacturers' instructions are based upon glue-line temperatures, and any change in these temperatures has an effect upon the setting speed of the resin. The glue-shop thermometer should be situated about level with the spreader trays and away from open windows, steam pipes and draught. The glue-line temperature in a cold press is not always equal to that of the glue shop, for the wood may not have had time to acquire this temperature. An accurate reading can, however, be obtained from a pyrometer with its thermocouple embedded in the glue line.

The manufacturers' instructions should be followed closely when adding the hardener particularly if it is applied separately. Some hardeners cause the fastest set when allowed to dry and some the reverse. See Fig. 10 for one example.

For hot pressing it is usual to allow one minute for each millimetre of thickness through which the heat must travel to reach the innermost glue line. This, whilst good enough for many purposes, is nevertheless inaccurate. Those wishing to estimate more accurately the penetration of heat into wood are advised to study Aero Research Bulletin No. 2.

THE DILUTION OF GLUE

Resin glues are viscous liquids and some are not too easy to spread. Many users of glue maintain that the addition of water to resins makes them easier to spread, and more economical. This may be so but there is considerable danger, if the glue is diluted, of faulty adhesion and

it should be remembered that it is not always the resins with the highest solids content that can tolerate the heaviest dilution. It is therefore prudent to ask the glue manufacturer's advice before adding water. See the paragraphs on penetration (page 74), short pot lives (page 79) and long pressing times opposite and glue nearing expiry (page 31). Any addition of water above 5% may reduce the safety factor and enable relatively small variations in other conditions to cause disproportionately large effects.

Wood in the normal state contains 10% or more of its weight as water. If the moisture content of the wood is high it tends not only to cool the glue but also to dilute it and this lengthens the pressing time as the water must be thrown out again from the resin during the process of setting (see Fig. 11). The porosity of the wood and its capacity to absorb moisture thus also affect the setting time of the resin; dense woods need a considerably longer pressing time than more porous woods.

The effect of dilution is shown even more emphatically in Fig. 10 which compares the setting speeds of a U.F. glue with a fast hardener separately applied.

(a) assembled wet, and (b) allowed to dry before making contact with the glued surface.

Certain cold hardeners achieve their excellent pot life/clamping time ratio by the inclusion of alcohols. The purpose of these materials is to slow down the hardening action in the "pot", but if the glue-spread is thin their evaporation is more rapid and the hardening action is accelerated. With this type of hardener a certain amount of air-drying is essential if the minimum pressing times advised are to be achieved.

It is well known that whenever the quality of the bond is poor, adhesion can always be improved and the effects of penetration prevented by air-drying the glued surface until they are tacky before assembling. With certain types of glue and hardener this may be vital to success for reasons which are given in the following paragraphs.

WETTING CHARACTERISTICS

Liquid resin glues contain solvents, of which water is the most commonly used, to enable them to be spread. These solvents must escape or be driven off before the resin can achieve a complete cure and, therefore, any solvent still present whilst the glue is curing will retard the process and may even impair the final quality of the adhesion. It is evident that once the glue has been spread the solvent serves no further useful purpose and the sooner it is removed the better. A glue line, however, which is initially completely dry, requires very considerable pressure from steel-plate platens as well as the application of heat before it will flow sufficiently to "wet" the adjacent surface completely; therefore the technical advantages of film glues, as mentioned earlier in this paper, are sometimes offset by the loss in thickness of the timber resulting from the use of high pressure.

One of the best ways of removing the solvents is to dry the glued surface immediately after spreading and before the assembly of the components hinders evaporation. Where hot presses are used the glue line can be almost completely dried and there is no danger that "wetting" will not take place even when only moderate pressures are used. It is

unfortunate that this method is frequently quite impracticable owing to the layout of the factory and the space required for the conveyor rail, for it gives excellent results and combines the advantages of liquid glue with those of film glue.

Sometimes glue spread on one surface fails to "wet" the other surface. Certain resins have better "wetting" properties than others for some require to be spread on both surfaces and to be air dried under careful control. The UF have extremely good wetting properties although they should not be allowed to air-dry completely unless hot pressing is to follow. The use of extenders reduces the wetting qualities of the glue.

The time elapsing between assembling the glued panel and pressing is known as the "closed assembly time" and it should not exceed that advised by the glue manufacturers, otherwise the glue line is liable to be pre-cured. As, however, during the closed assembly time the same process takes place, but to a lesser extent, as during air-drying it is a good practice to allow at least several minutes' closed assembly before pressing. This, besides giving better adhesion, reduces the tendency towards penetration. Closed assembly times are dealt with in the lecture on veneering (see page 58).

SETTING CHARACTERISTICS AT LOW TEMPERATURES

It is well known that the clamping time for resin glues is greatly affected by the temperature of the glue line and that the choice of speed of the hardener should be made to suit the temperature of the glue line.

TABLE IV

Temperature (°F) (°C)		Pressing time (hours)
45	7	20
50	10	12
60	15.6	7
70	21	4
80	27	3



Fig. 12. A badly "iron-contaminated" oak-veneer board. The stains were caused by glue penetrating through the veneer and reaching the iron plate. The use of aluminum caul plates would have prevented this.

The lower the temperature the longer it will take the glue to set and it is to be doubted if some cold-setting glues ever completely harden at less than 10°C (50°F). The setting action of most resorcinol-formaldehyde assembly glues used with powder hardeners, for example, becomes extremely slow even at 15°C (60°F). Extreme cold may arrest the hardening process at any stage but the action will start again as soon as the temperature rises. Table IV illustrates the effect of temperature upon the pressing times of a cold-setting urea-formaldehyde glue.

As no glues give their best performance at low temperatures gluing in cold weather, below 15°C (60°F) is to be avoided whenever possible. When it is necessary to glue at a low temperature a fast hardener should be selected and the materials to be joined should, if possible, be preheated and the joint wrapped in a heater muffle during setting.

STAINING

The use of synthetic resin glues can, under certain conditions, result in staining even though the resins themselves may be colourless. These stains can become apparent immediately after gluing, or after a lapse of several months, depending on the strength of the stain-forming chemicals present in the wood. One of the substances necessary for this stain formation is tannin, which is present in wood in varying amounts; of the woods in more common use ash and oak have the highest tannin content. Everyone has seen the inky discolorations which appear round a nail in a piece of oak that has been left out in the rain, but the cause of these is not widely known. Rainwater contains some (very dilute) acids, and these dissolve a small proportion of iron from the nail to form an acid salt. This salt reacts with the tannin from the wood to form the ink-like dye that stains the wood. Urea formaldehyde glues and hardeners, being mildly acidic, will



Fig. 13. Stains caused through iron contamination in the splice.

have the same effect on an oak veneer if they are contaminated by iron. There are many ways in which this iron contamination can occur; and the following paragraphs describe some of the ways and also the means of overcoming them.

Severe glue penetration may mean that the glue comes into contact with the platen of the press which, if it is an iron one, is likely to cause some dark staining on oak. Prevention of any possible contact between wood (wet with glue) and the iron is easily achieved by using aluminium caul plates, although in certain classes of work sheets of cellophane laid between the outside veneer and the platen are preferable.

The mixing of the glue and hardener should not be carried out in an iron container unless the metal is well protected by vitreous enamel, paint, or galvanised. Even these finishes can be insufficient if they are, in places, worn through or chipped. The same conditions also apply to any measure or funnel through which the hardener may be transferred, for only a small degree of contamination is necessary to promote staining. Trays of glue-spreaders are usually sufficiently protected by a thin layer of paint and old glue and are rarely the cause of trouble, although ribbed steel spreader-rollers that have become somewhat corroded are more likely to cause staining. The remedy is to change the rubber-covered rollers of the glue spreader and, if necessary, to line the trays with plastic, wood, or even a sheet of cellophane.

There is, of course, always the possibility that the tap-water used for washing the spreader and mixer may contain iron. It is, however, easy for a simple test for iron-content to be carried out by the local chemist. It is unlikely that the hardener itself will contain iron, as most resin manufacturers take precautions to prevent such an occurrence and test for iron content before despatching the material. Some sample jars have metal caps protected by wax-covered paper washers and damage to these washers will sometimes permit contamination.

The faster setting hardeners, being stronger, have a greater capacity for dissolving iron and with these, therefore, staining is more likely to occur. The tendency to stain is accentuated by heat and pressure and this is why unprotected spreader-rollers are far

more often the cause of this trouble than are unprotected glue trays.

Hardeners are sometimes coloured as a means of identification but almost all hardeners can be manufactured in a colourless form which is, for most purposes, more convenient.

SPLITTING AND CRACKING OF VENEERS

This trouble can be overcome to a considerable extent by ensuring that each veneer is laid with the grain at an angle, preferably of 90° and certainly of not less than 45° to that of its neighbour, and, if possible, a padding veneer should lie beneath a decorative one. The moisture content of all veneers and core-board should, when liquid resins are used, be equal at the time of gluing. Where a ply core-board is to be veneered the selection of a resin-bonded core-board is an advantage and a hardener should be chosen which will enable the veneering to be carried out at moderate temperatures (170°F or



Fig. 14. A too familiar sight: a split veneer. Moisture content of all veneers and caul board should, for liquid resins, be equal at the time of gluing.

77°C). Urea-formaldehyde glues can be rendered slightly more flexible by the use of 25 to 50% of cereal extender, and this proportion can be increased to 75 to 100% quite safely if a melamine-formaldehyde glue is used.

Certain delicate curl veneers are extremely sensitive to movement of the baseboard and with such delicate veneers some cracking or crazing is always likely to occur. Whilst cracking can sometimes be prevented entirely by the use of a cold-setting resin glue of low moisture content, the use of a thermoplastic glue is, in these circumstances, usually preferable.

BLISTERS

As the boiling temperature of water increases with pressure (see Table V) it follows that the moisture in glued veneers being pressed at, say, 50 lb/in.² and at 230°F (110°C) is not given off as steam until the pressure is released. Should the pressure be released suddenly then all this moisture is quickly converted into steam, and, if it cannot escape through the wood pores, steam pockets that blow up the veneer into blisters are formed. It is therefore advisable, when pressing at temperatures much in excess of 212°F (100°C), to release the pressure slowly, thus reducing the rate of generation of the steam and assisting it to diffuse harmlessly through the wood.

TABLE V

Applied pressure		Boiling temperature	
kg/cm. ²	psi	°C	°F
0	0	100	212
0.703	10	151	289
1.406	20	162	259
3.515	50	182	296
7.03	100	205	337

The minimum permissible rate at which pressure may be released varies with conditions of temperature, pressure, moisture content and the permeability of the veneers, and may range from several seconds to a few minutes.

Another type of blister, although less conspicuous, is more frequently encountered and is often not discovered until the veneered article acquires a polished surface, when any distorted reflections may reveal the presence of small blisters of non-adherent veneer. If the method of veneering rules out the possibility of steam having been the cause, then the possibility that the fault may be due to preening, penetration or lack of wetting should be examined. Certain blister formations can be attributed to uneven distribution of pressure during veneering. This can be caused by a variation in the thickness of the core-board or by the use of distorted platens which results in patches of incomplete contact between veneer and core-board, with consequent lack of adhesion.

Blistering and peeling of patches of the surface finish occurs occasionally; and these troubles have the annoying characteristic of failing to develop until some appreciable time after the surface finish has been applied and passed as satisfactory. This fault is particularly noticeable on panels decorated with delicate veneers cut to show the grain figure, as the movement of such veneers with variation of moisture content often results in large local movements and stress concentrations. These troubles can be reduced to some extent by the use of a cross-banded padding veneer of soft wood between the core board and decorative veneer.

Such delicately figured veneers are, in places, often extremely porous and likely to absorb from the glue line a considerable amount of resin which will partially impregnate the wood as well as penetrate to the surface of the veneers. Sanding the veneer after gluing will remove the resin from the surface but not from the wood pores or the partially impregnated fibres. Since cellulose does not adhere so well to resins as to wood, it will begin to flake off at places where penetration has been severe and also where the movement of the veneer is greatest. The most satisfactory remedy is to control resin penetration when the veneer is glued.

WARP OR TWIST

Although the tendency of plywood to warp is widely known, it is so frequently aggravated by treatment received after the plywood leaves the manufacturer's warehouse that a few remarks on the

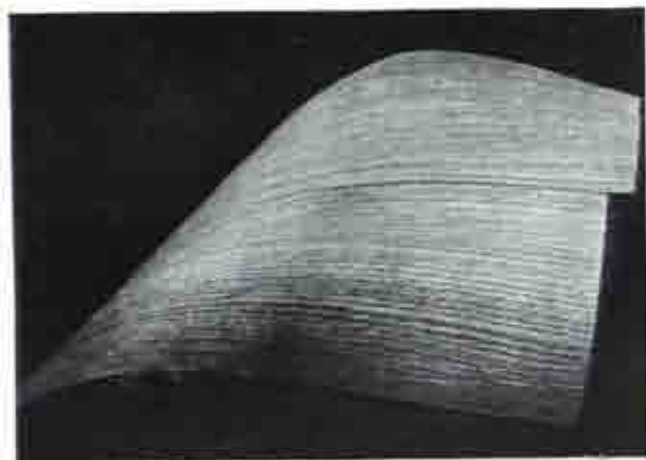


Fig. 15. An edge-to-edge spliced sheet of veneer that has warped as a result of inaccurate trimming.

causes of warping and its prevention may prove useful.

The plywood panel is of balanced construction, generally three or five-ply, which reduces the tendency to warp in any one direction when a change of moisture content causes movement to take place. Subsequent veneering on one side only will upset the balance and greatly increase the possibility of warping. Decorative veneer should therefore be balanced by gluing on simultaneously a backing veneer of, if possible, similar characteristics. As the core-board is passed through the glue-spreader the outer surfaces start to absorb moisture from the glue. Subsequent hot-pressing helps to diffuse this moisture throughout the board and it is not until an even moisture distribution is attained, while the board is still, in some way or another, held flat, that one of the causes of warp is eliminated. The panel should next be conditioned until it reaches a moisture content in equilibrium with that of the surrounding air. A faulty technique in edge splicing can also cause warping. (See the paper called "The tapeless splicing of veneers" in this book, especially page 64.)

FAULTY ADHESION AT THE EDGES OF VENEERS

In factories and storehouses concentrating on high-quality products an air-conditioning plant giving automatic control of temperature and humidity contributes to the consistent quality of the products

as well as to the contentment of the operatives. As soon as the article is assembled and polished it is in a far better state to resist the effects of changing humidity and temperature.

Furniture stored in extremes of damp or where it may be affected by excessive central heating, is, however, liable to warp and open at the joints unless especially manufactured for such conditions.

A rounding of the edges of the core-board can occur during the sanding operation and this will result in the core-board being thinner at the edges than at the centre. This makes it difficult to achieve good adhesion with the veneer over the whole surface, for pressure cannot be applied to the edges and it is frequently as impracticable as it is wasteful to trim away the faulty edges. Improved adhesion, however, can be obtained by using a powdered, semi-gap filling hardener. An increase in gluing pressure of about 50% is also advantageous and, with a glue mix thickened with cereal flour, is not likely to cause undue penetration.

The glue spread need not be heavy but there should be sufficient to squeeze out evenly all round the edges of the board. The use of a very heavy spread in the hope that it will fill the gap between the veneer and the core is to be avoided, for, unless the glue is a true gap-filler, it will craze and lack of adhesion will result although not perhaps for some considerable time after gluing.

TREATED WOODS

Woods treated with preservative, such as creosote, are often difficult to stick. The advice of the glue manufacturers on the choice of glue for any particular preservative is therefore helpful, although, of the resin adhesives in quantity production, resorcinol formaldehyde would appear to have a wider range of compatibility than most others.

The degree of penetration of the preservative may be a deciding factor in the quality of the adhesion obtained. Vigorous sanding or rasping along the grain almost always improves the bond, which may be perfect if it has been possible to sand-off the wood fibres impregnated with preservative. It is also an advantage to arrange the joint so that the surface area to be glued is as large as possible, and that, by the use of gussets, such scarf-joints are avoided.

OILY WOODS

Woods containing a high proportion of oily material incompatible with the glue can be "degreased" with trichlorethylene and washed with methylated spirit before gluing. Another method is to wash the wood surface with a detergent, such as "Teepol" or a similar sodium higher-alkyl sulphate, before gluing.

CASE-HARDENED WOOD THAT CANNOT BE GLUED

Case-hardened describes the condition of certain veneers, particularly of birch, that are sometimes unpredictably hard to stick. The condition is thought to be due to the method of preparation and of cutting the log in making the veneer. It appears to be further aggravated by the application of the heat and pressure required in the manufacture of plywood. A special ink is sometimes used to indicate when this condition is present; the usual remedy for case-hardening is to sand thoroughly along the grain shortly before gluing.

VERY HARD WOODS

Hard woods, which are sometimes required for special purposes, are often difficult to stick, but adhesion can be improved by thoroughly sanding both surfaces, rubbing in a diluted glue, and gluing in the manner recommended for end-grain surfaces (see the next paragraph). The maximum possible time for air-drying, provided the glue is not permitted to skin, should be allowed for the final layer. To compensate for the lack of porosity of the wood, double the usual pressing time should be allowed.

GLUING OF END-GRAIN SURFACES

The gluing of end-grain surfaces should be avoided whenever practicable as the resulting joints often give disappointing results. As, however, it cannot always be avoided a technique is described here for improving the joint strength.

The low strength of a joint between end-grain surfaces may, in part, be attributed to the small surface area that each wood fibre offers to the glue compared with the total surface area of the fibre. Any increase in depth of penetration of the glue will thus increase the strength of the joint, provided that the glue when set is stronger than the wood and that the glue that has penetrated forms an unbroken link with the glue line. This penetration should therefore be achieved by pressure as well as capillary attraction, otherwise the continuity of the glue may be broken. A practical method is as follows: Rub well into the end-grain surfaces glue diluted with about 20% methylated spirit and 10% water, but no hardener. Allow this mixture to dry before gluing in the normal manner with a gap-filling glue. This method often improves the joint strength by over 50%, but, of course, rarely gives wood failure.

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EXTENSION

G. M. Scales

INTRODUCTION

It is often desirable to reduce the glue line cost and in order to do this cheap materials are added to the glue mixture. Many different materials are used for this purpose in various parts of the world, these include flours from cereals, roots and beans, dried blood, wood flour and inorganic substances such as china clay. The choice of extender is often limited by local economic conditions but clearly the best results are most easily obtained by using extenders that themselves possess some adhesive qualities.

STARCH

Extenders containing starch give excellent results when hot-pressed because the starch particles swell and burst at about 70°C (158°F) to form a glutinous mass. This change is irreversible and the adhesive qualities are retained when the starch is cool.

So that advantage may be gained from this gelling of the starch the hot-press should be operated at 70°C (158°F) or above. It will be found possible to obtain excellent results with an extension of 200%* or more using a hot-press though a cold glue-mix extended as much would give poor results. (See Figs. 3 and 4 on page 74 of this book.)

POT-LIVES AND PRESSING TIMES

The addition of extenders increases the viscosity of the glue and it is therefore customary to add water as well to keep the viscosity low enough for the glue to be easily spread. This water dilutes the mixture

* The quantity of extender is expressed as a percentage of the weight of resin in the mix.

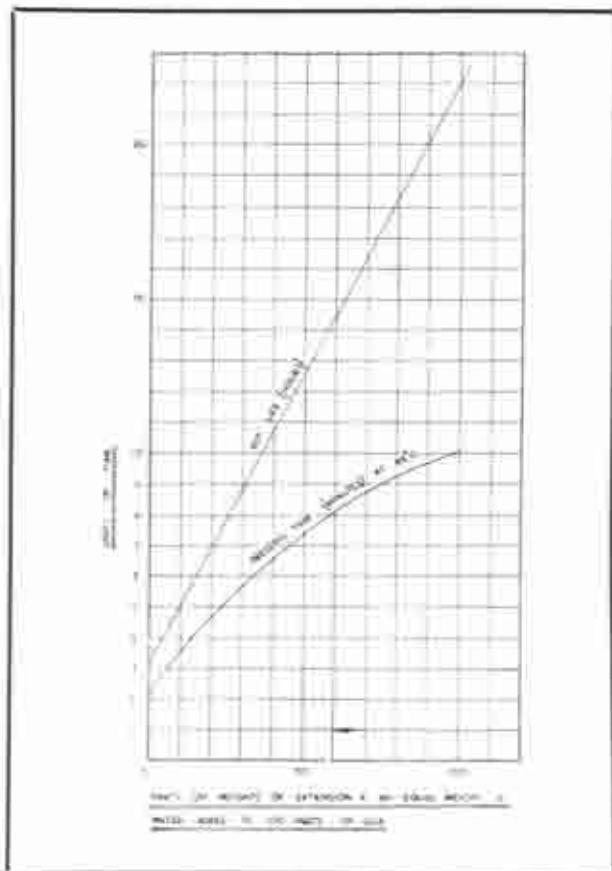


Fig. 1. Graph showing the effect of various rye-flour extensions on the behaviour of a urea-formaldehyde glue.

of resin and hardener and lengthens the pot-life as well as the pressing time, as can be seen in Fig. 1.

As a pot-life of over 24 hours is rarely required it is good practice to use relatively fast hardeners with large extensions; this also reduces the pressing time.

TABLE I

Extension (%) Pot lives (hours) with :—	0	25	50	100
UF Hardener A	9	12	18	—
UF Hardener B	2½	3	8	30
UF Hardener C	¾	1½	4	12

Extension (%) Pressing times (min) at 95°C with :—	0	25	50	100
UF Hardener A	4	6	10	—
UF Hardener B	1	8	6	8
UF Hardener C	1	2	4	8

TABLE II

Extension (%)	Dry strength	Wet strength (BS. 1203 A.70)
0	100	80
25	97	65
50	91	44
100	84	—

GLUE SPREAD

The greater the quantity of extender added, the heavier the glue spread must be to ensure the best results. Similarly pressing times are lengthened by the addition of extender and it is, in fact, possible unless the extender is extremely cheap, for the article produced with a much extended glue line to cost more than if an unextended resin were used.

PRESSURE

A glue extended with starch tends to dry quickly and so an increase in pressure is advisable to ensure that the surface is completely wetted. The length of the maximum closed assembly time is therefore dependent upon the speed of drying as well as upon the pot-life.

OTHER EFFECTS

Extenders, in particular those containing starch tend to reduce penetration by filling the pores of the wood and this may be a sufficient reason for their use. An extension of 15 to 30% is usually required to fulfil this purpose.

SEMI-GAP-FILLING EXTENDERS

Some extenders such as woodflour or china clay act as fillers and make the glue semi-gap-filling. As small unevennesses often occur in core boards a semi-gap-filling glue is an advantage. For this purpose an addition of 5 to 10% of woodflour or china clay is sufficient: if good adhesion is required this quantity should not be exceeded. Such semi-gap-filling glues are unlikely to give good permanent results if the gap to be bridged exceeds 0.25 mm (1/100 in.). The resistance to hot water of such glues is often poor.

FORTIFICATION

G. M. Scales

INTRODUCTION

GOOD quality UF glues have considerable water resistance (see B.S. 1203 A 70) but occasionally a higher water resistance (A100 or AX100) is required. This higher water resistance can be imparted to the UF resin without destroying its characteristics by mixing in with it a small proportion of a glue of very high water resistance. Two examples of these fortifying resin glues are melamine-formaldehyde (MF) and resorcinol-formaldehyde (RF). Both are relatively expensive and so only the smallest addition to the UF which will give the desired result should be made. Broadly speaking both of these resins act in a similar way so for simplicity the action of only one of them (MF) is described in detail.

One thing that must be understood quite clearly for the interpretation of test results to be of any value is the swelling characteristics of the wood used. Some woods swell in water very much more than others and different trees in the same species can vary in this respect; tropical hardwoods are particularly variable. If the wood swells in a glued joint it naturally sets up internal stresses. Boiling a joint accelerates swelling and the more the wood swells, the more likely is the joint to break down. But the boiling test is not by itself a complete test of the glue; glues have been made that are resistant to boiling for several hours but fail completely in a simple cold water test.

REQUIREMENTS FOR DIFFERENT WOODS

For several years it has been the practice in England to make water resistance tests on two species of wood: beech and birch. The beech swells in water about twice as much as birch and subjects the glue line to very severe strain. This can be seen from the graph in Fig. 1 which compares the quantities of MF resin required to be added to a UF resin in order to pass the A100 and AX100 specification for these two kinds of wood.

Fig. 2 shows the difference in the amount of fortification needed for some species of wood and it will be seen that the variation in quantity is considerable. It will be noticed that a plywood specification to AX100 is of doubtful value for some woods of low strength.

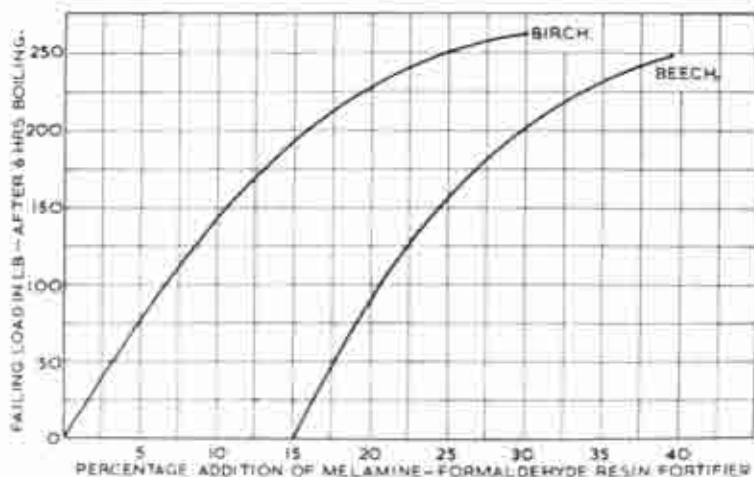
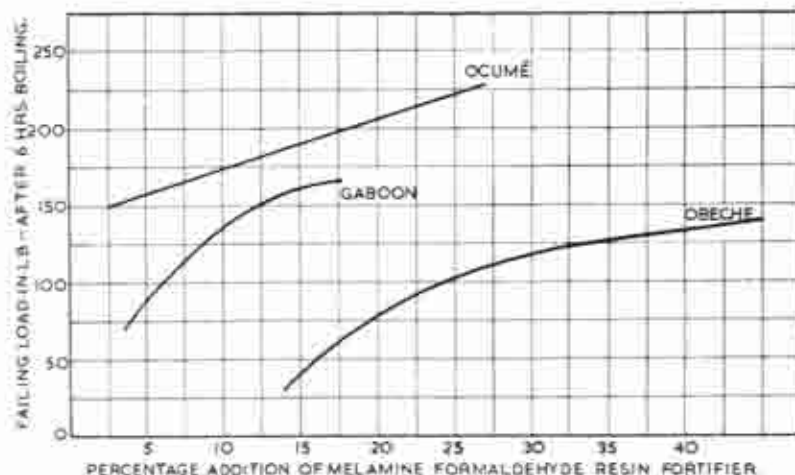


Fig. 1. Effect on joint strength of varying addition of MF fortifier to a UF resin glue-mix.

Fig. 2. Effect on joint strength of varying additions of MF to a UF resin glue mix.



FORTIFIED HARDENERS

Fortification presents no technical difficulty since MF and UF resins mix readily in any proportions but unfortunately it is an expensive process owing to the high cost of MF resins which are difficult to produce. For several years as an alternative process UF resins have been used with hardeners containing free melamine. This free melamine combines with the free formaldehyde in the UF resin to form an MF resin in the mixture during the hot-pressing period. Economically this is advantageous as for equivalent durability the glue mix containing the free melamine is cheaper but the degree of fortification that can be achieved by this method is limited by the quantity of free formaldehyde available in the UF and any excess melamine added will have nothing to combine with and act only as an inert filler. Too great an addition of melamine will therefore reduce the water resistance (see Fig. 3). Much the same effect is obtained by using hardeners containing resorcinol.

PRESSING TIMES AND TEMPERATURES

The resin combination must be fully cured before boiling and the cure should take place in the hot press. (The "end-point" for most resins is reached sometime after solidification.) Should it not be possible to give the full hot-pressing time required, then the panel should be hot stacked and allowed to mature for several days before testing.

Glue mixtures fortified with hardeners containing free melamine require a slightly longer pressing time (or a higher pressing temperature) than do those fortified with MF resin. This is because a certain time is required for the melamine to react with the free formaldehyde.

Sometimes a glued joint satisfies the AX100 standard but fails in the cold water test and this is probably because the panel is only partially cured; it delaminates in the cold water but in boiling water the cure is completed and so good results are obtained.

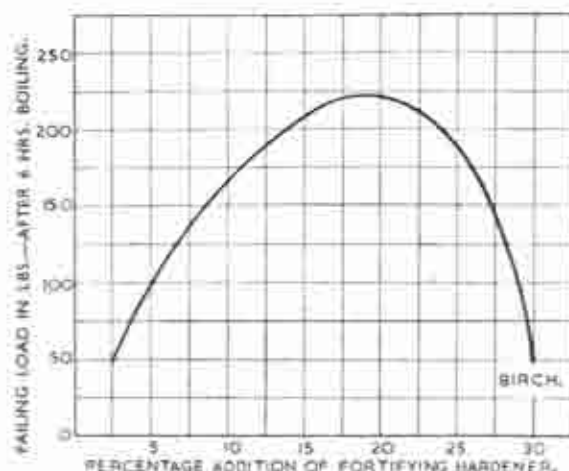


Fig. 3. Effect on joint strength of varying addition of melamine hardener to a UF resin.

EXAMPLE

To give joints proof against boiling with a UF resin on birch (on a commercial scale) the following is a suitable and typical mix :—

	A100	AX100
UF liquid	100 parts by weight	100 parts by weight
Fortifying hardener	12 " " "	20 " " "
Basic pressing time at 95°C (203°F)	5 minutes	6 minutes

Recent developments indicate the possibility of considerably reducing the fortifying addition and also the pressing time, but it should be noted that figures obtained from laboratory tests will not serve as an exact guide to the manufacturer. Fortification additions and pressing times used on production will usually be considerably in excess of the minimum found possible in the laboratory.

PROCESS CONTROL IN PLYWOOD MANUFACTURE

J. G. Ellison

INTRODUCTION

PLYWOOD is made use of in a great many ways in industry and manufacturing technique must vary to suit the special requirements of each particular trade and also be modified by the nature of the wood available. The main factors influencing the process adopted may be listed as:—

- (a) The type of "End Product"
- (b) The species of timber to be used
- (c) The manufacturing plant and labour available
- (d) The adhesives available.

These factors are to a great extent dependent upon geography; probably the most decisive controlling influence will be the character of the region of the world where the plywood is to be manufactured. In the first place this decides what species of timber will be available, and the process and plant must then be developed to suit the characteristics of the species, presuming the wood to have already satisfied the general requirements demanded of a timber suitable for plywood manufacture. The adhesives to be used will be dictated firstly by the type of plywood to be produced (e.g. an "exterior" type will demand a synthetic resin and an "interior" type will probably be manufactured with a soya bean, casein or blood albumen adhesive) and secondly by the place of manufacture. In Sweden, for example, probably casein or urea-formaldehyde will be used whereas in tropical conditions phenol-formaldehyde will be found more suitable if the right type of equipment (e.g. dryers and presses) is available. It will be seen, therefore, that a number of factors must be known before experimental work can be started to determine the manufacturing technique.

In order to confine this lecture to a reasonably narrow path it is necessary to limit the descriptions of processes to those most commonly used—involving peeling by rotary lathes—and to consider the 2 or 3 variants of the rotary lathe system. The operations, in each case, advance by the same basic steps which may be listed as follows:—

1. Sorting and grading of logs
2. Cross-cutting and steaming of logs
3. "Barking" logs and peeling them on rotary lathes
4. Clipping the veneer and sorting the clipped veneer
5. Drying the veneer
6. Grading the veneer
7. Edge-jointing and splicing the veneer
8. Spreading glue and assembling the packs
9. Pressing the packs
10. Trimming the panels
11. Scraping or sanding the panels
12. Testing the batches
13. The final inspection and despatch.

TECHNICAL CONTROL

Technical process control is not entirely a matter of statistical charts. Charts are extremely useful and can offer great assistance in maintaining the standard of the product, but first, before such charts can be used effectively, methods of obtaining accurate information to fill them must be developed. It is obviously no use whatsoever consulting charts prepared from information of doubtful origin or figures which are not truly representative of the material under consideration. Statistical graphs

represent one aspect only of control and this must be recognised. Technical Process Control may be conveniently divided into three major steps, viz :—

- (1) Development of manufacturing technique
 - (i) Laboratory scale tests
 - (ii) Pilot scale factory tests
 - (iii) Process control instructions
- (2) Application of control measures
 - (i) Statistical charts
 - (ii) Technical process control
 - (iii) Testing of products
- (3) Record system and reference data
 - (i) Record charts
 - (ii) Log books

Notice particularly the deliberate distinction I have made by dividing the last five items into two groups: (2) and (3). The data collected during manufacture should be available for two purposes:—

- (a) to establish the maintenance of quality and provide direct records of particular batches of plywood, and
- (b) to provide a basis for future development and improvement of the product.

Development of Manufacturing Technique

In the laboratory stage the purpose of the work will be to decide the tolerances permissible at various process stages and the effects of faults in manufac-

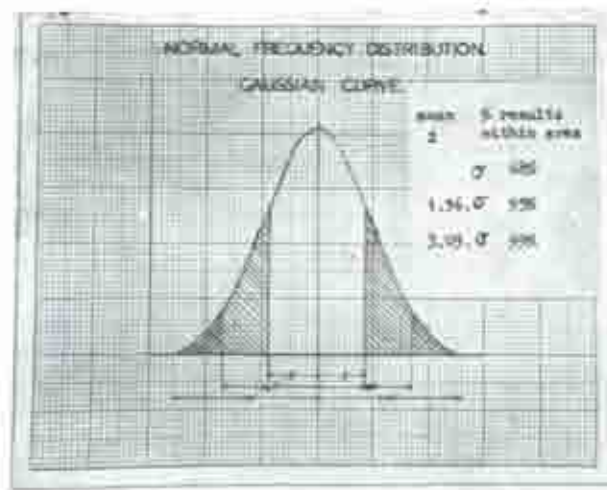


Fig. 1. Example of normal frequency distribution curve.

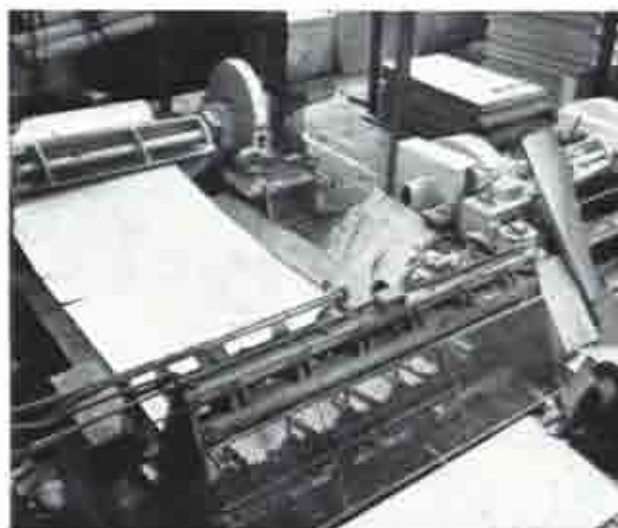


Fig. 2. Rotary peeling lathe and automatic clipper showing veneer being clipped to size, direct from lathe.

ture. The main features to be decided in relation to the adhesive will be:—

- (a) The tolerance of veneer thickness and degree of rough-cutting permissible
- (b) Limits of moisture content of veneers
- (c) Glue spread—the best and most economical
- (d) Pressure, temperature and the time cycle for the press
- (e) Methods of conditioning panels to maintain stability and flatness
- (f) Batch representation for testing purposes

From laboratory work a great deal of information will be amassed upon the types of defects produced by incorrect procedure either individually, or what is more likely, collectively, i.e. the effects added together of a number of slight deviations from the correct procedure.

Small scale production runs on the factory-scale plant will follow to confirm the laboratory findings and establish methods of operating the equipment to meet the requirements of the product. Determining the limits within which the process control must work is a most important stage because a compromise must always be made between the needs of the product and the abilities of the equipment available.

The relation between the temperature of the platen of the press and the moisture of the veneer, the glue spread, the standing time before pressing, etc., are all calculable from the laboratory work and in good process control these items are balanced against one another. The equipment for veneer drying must be analysed and accurate and detailed information made available on the performance of the machine (in terms of quality and output) under optimum operating conditions.

At this stage it will be possible to draw up a Basic Process Control Instruction. The object of this is to lay down what has been established by laboratory-scale tests and the factory-scale run. The Instruction should be written partly as a specification and partly as an instruction on machine operation. It should firstly contain a Frequency Checking Chart which will indicate what checks are to be made, how they are to be made and the frequency of the checks and records which must be made at each operation.

Application of Process Control

Statistical Quality Control is discussed at length in many specialised text books and the mathematical

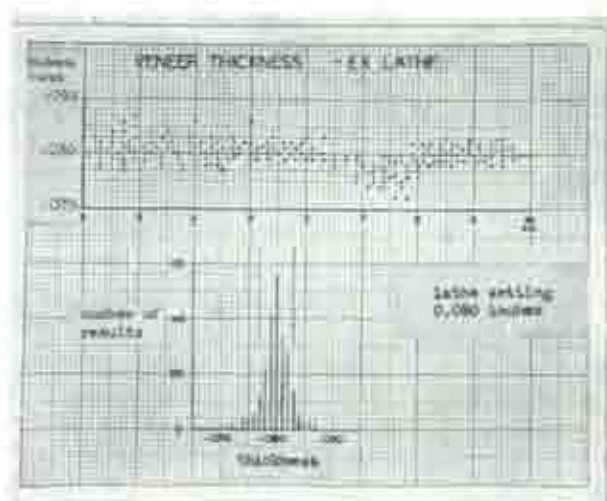


Fig. 4. Chart showing method of recording veneer thickness, also normal frequency curve derived from these results.

aspects, although an extremely interesting study, need not worry us greatly in our present work. A chart which will prove most useful, however, is simple to construct and gives a clear picture of what might otherwise be a confusing jumble of figures. The chart is the normal frequency curve or histogram. Its value is that it shows at a glance not only the average but the range (or spread) of a series of observations. Considerable information is available on the mathematics of the Gaussian curve which may be developed from the histogram and from the Gaussian distribution it is possible to estimate just how many of a given number of observations will fall outside a specified tolerance. Fig. 1 shows this curve.

The best approach to process control is to consider three major operations in a well-known manufacturing process, viz. the production of plywood of commercial grade in the United Kingdom to B.S. 1455:1945 (Type A.70) from tropical hardwood logs using a urea-formaldehyde adhesive. The sequence of operations will be:

- (a) Peeling the veneer
- (b) Drying the veneer
- (c) Pressing the packs

Figs. 2, 3 and 4 illustrate the operations, the checking equipment and the type of control chart suggested.

(a) *Peeling the Veneer.* The peeling lathe (see Fig. 2) has a most difficult task to perform;



Fig. 5. Checking veneer thickness by means of clock-face micrometer.

To peel veneer from a log by a rotary method is against normal woodworking principles and very slight irregularities of grain or hardness can upset a lathe-setting considerably. The main features desired in good quality peeling are (i) consistently uniform thickness of veneer, and (ii) uniform smoothness of the veneer and freedom from rough patches. Veneer thickness can be controlled with the aid of a control chart by taking regular checks of thickness across the full width of the veneer (Fig. 3) and plotting these on a time base chart. A series of such readings may be re-plotted as a "distribution" or "frequency". From the frequency curve it is possible to determine what tolerance limits are permissible for a certain "rejection factor" and also to what degree the process is under control. Our example (see Fig. 4) indicates that the control between 8 p.m. and 10 p.m. is more efficient than earlier in the period considered. The frequency diagram shows that the amount of "out of tolerance" i.e. veneer outside limits of $.080 \pm .003$, was excessive but if the two obvious regions of "out of tolerance" results could be eliminated the process would be very much more consistent. It therefore follows that more detailed attention must be given to the lathe and its operation to discover exactly what caused these obvious lapses.

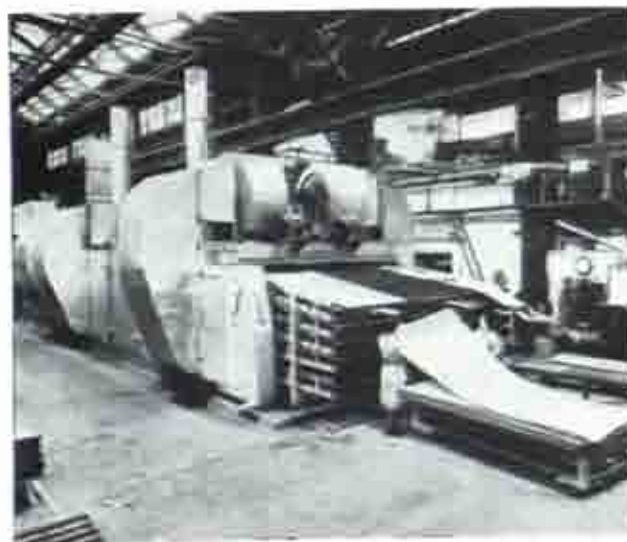


Fig. 5. Veneer drier.

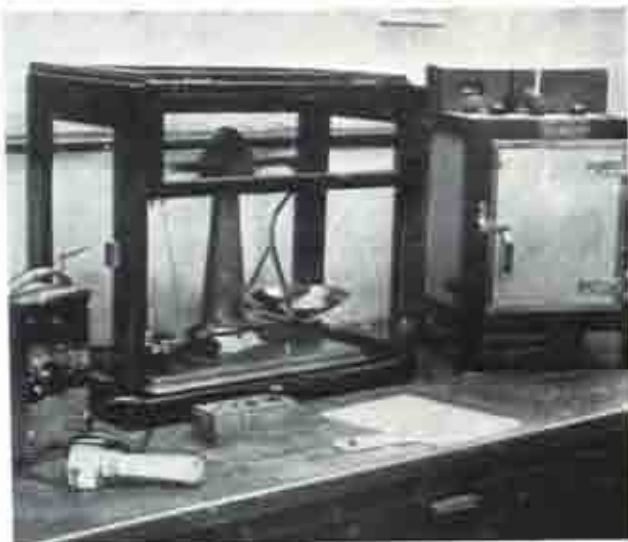


Fig. 6. Testing equipment for checking the moisture content of veneers.

The degree of rough cutting is, unfortunately, not presentable on charts so here the problem calls for direct analysis "on the job"—a technique I cannot cover in this brief talk.

(b) *Drying the Veneer.* This is probably the most important single operation in plywood manufacture. Moisture content influences bonding, stability and general durability of the product and every effort must be made to produce veneer uniformly dried within the tolerance decided from previous tests. The drying machine is, in this instance, a heated chamber with roller conveyors to carry the veneer and suitable controls for regulating temperature and controlling the speed of the conveyor. The earlier tests carried out on the machine have established the influence of various pressure-temperature relations, the effect of damper-settings and have finally made possible a "Standard Schedule of Operating Conditions" recommending through time settings for each thickness of each species to be dried. At this stage we are concerned only with maintaining consistent drying in accordance with the schedules. The testing equipment should consist of an oven (100°C to 105°C), a weighing balance and an interval timer. As a secondary and complimentary check a moisture meter should be available. The meter

must be checked against oven readings of moisture content regularly to ensure accuracy. The moisture content test pieces may be taken in sets of three at time intervals of five or ten minutes and should be taken so that all parts of the machine are regularly checked. (A convenient size for test pieces is 6 in. \times 3 in.) Results may be plotted on a time base and finally on a frequency curve to illustrate the degree of control. A convenient method is to use one chart for each eight-hour shift and group a week's charts on one sheet of paper so that comparisons are easily made. The Figs. 5, 6 and 7 illustrate this application and also show how a process out of control may be easily recognised.

(c) *Pressing the veneer packs.* Correct pressure (that is specific pressure—or pressure per in.² of board area) is a most important feature both technically and economically. The presentation of a formula involving ram area (total), gauge pressure and area (length and breadth of pack) will usually baffle an operator and a chart should be provided—this chart is preferable to graphic representation as the dependent variables, length and width can be separately indicated. The chart will be applicable to a given press working at a given specific pressure. Pressing records are best kept in the form of batch sheets on which the press operator enters details of each press load. Temperature recorders and a

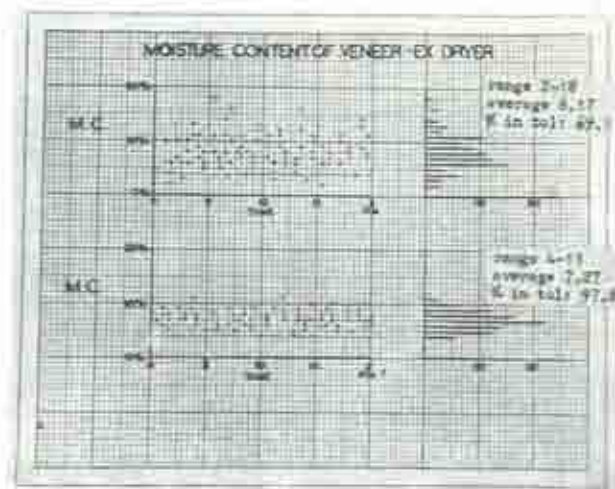


Fig. 7. Chart showing method of recording moisture content of veneers, also normal frequency curve derived from these results.

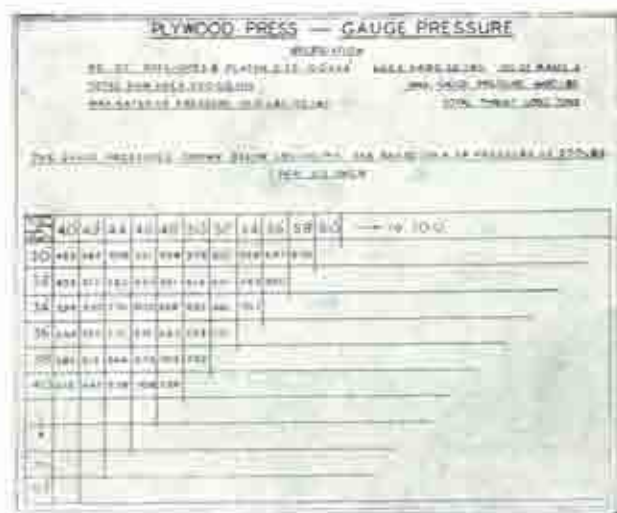


Fig. 8. Chart showing method of calculating gauge pressure required for any size pack, on a given press working at a given specific pressure.

pressure recorder, checked against a standard gauge should be fitted to the press. Utmost attention should be paid to uniformity of temperature and the elements of the temperature recording system placed in a position (either central or at the cooler end) where the temperature drop is known in relation to the recorder reading.

The recorder element should record *platen surface temperature* and pyrometer checks should be made to establish the true relationship between recorder and platen surface. Recorder charts are usually circular and should be marked with rings set at temperature limits, if no automatic controller is fitted to the press.

The loading of the press is important and two features must be watched carefully: (1) Speed of loading, if by hand, and (2) that racks are loaded directly in vertical alignment to avoid individual floating platens from being displaced out of a horizontal plane. To include these points our Pressing Instructions will give the following details:

(a) Details of Press

Ram area, maximum platen size, maximum gauge pressure

(b) Conditions of Operation

(i) Temperature $225^{\circ}\text{F} \pm 2^{\circ}\text{F}$

- (ii) Pressure—200 lb/in²—as shown by Chart No.
- (iii) Times under pressure—Thickness Time Notes on loading Notes on stacking after pressing, etc.

The press will be checked at the end of a shift (or day) by comparison of Recorder Chart, Batch Sheet and Standard Instructions so that as any incorrectly pressed material reaches the inspection stage it may be fully examined in the light of known data. A thickness check record should be kept of board being pressed but here checking is not frequent—it is sufficient to check three or four boards of each thickness from each shift. A chart should be kept on the basis of the Peeler Veneer Thickness charts and a collective chart prepared each month for each thickness. The value of this collective chart is experienced when a change is made in the construction of a certain thickness board, e.g. $\frac{1}{2}$ in. from, say,

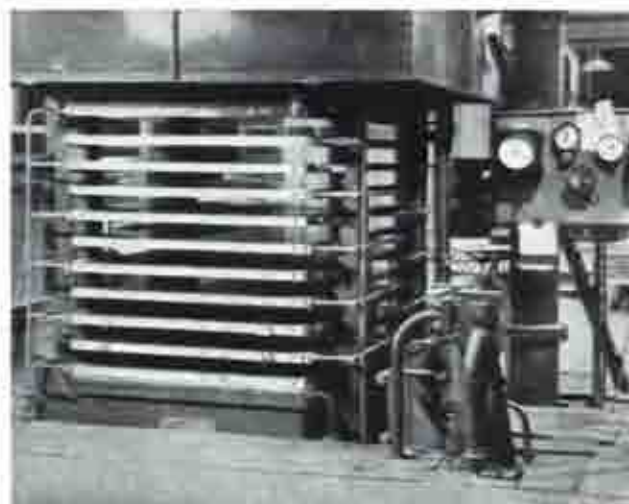


Fig. 10. Typical plywood press with steam heated platens.

5 @ .100 veneers to $\frac{1}{2}$ in. from 3 @ .080 and 2 @ .125 veneers. Figs. 8, 9 and 10 illustrate this operation.

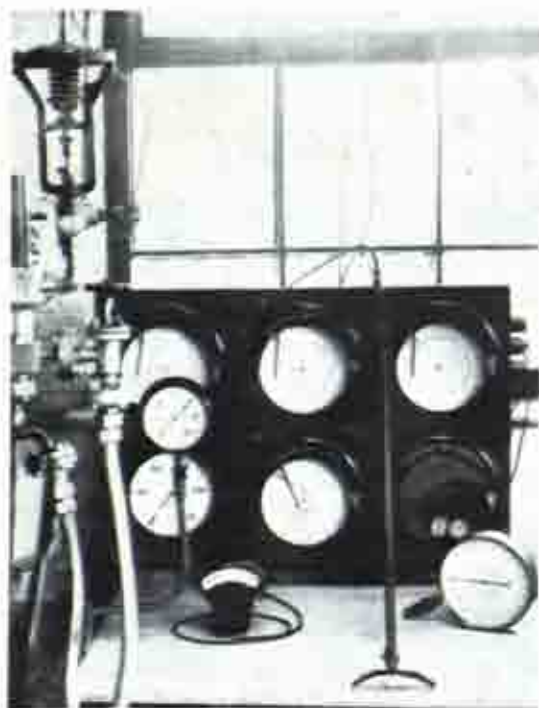


Fig. 9. Equipment consisting of pyrometer, recorder and standard pressure gauge used for checking press.

Testing of Products

There are two phases in the testing of plywood apart from those outlined as control tests in the previous pages. Material, such as adhesives being used in the process should be proved initially before use. In these days we are blessed with reliable adhesives but unfortunately we have retained to some degree our old idea that if it doesn't stick the glue is at fault. Adhesives, although tested by the manufacturer should have some form of acceptance test before being released into the plywood factory. The B.S. 1203/4 is an excellent basis for general comparison but an acceptance test using standard materials and the established procedure to be used is an excellent secondary check. A $\frac{1}{2}$ in. board made, say, 15 in. \times 15 in. in a laboratory press at the specified time and pressure and then tested as laid down in B.S. 1455 gives a satisfactory comparison and establishes that any trouble experienced is unlikely to be due to the adhesive.

The plywood is "batched" at the press and a batch limited by the number of sheets and by changes in the product. For example, Batch No. 500 will start at 6.0 a.m. on $\frac{1}{2}$ in. 6 ft \times 4 ft sheets and each load will be numbered consecutively 500/1,

500/2, 500/3 etc. until any one of the following is changed: size, thickness, the press operator, or the adhesive. This batching enables the production to be divided into small groups from which truly representative batch samples may be taken (usually one board for the first load in each batch and then every tenth load until a new batch is started). The batch board is trimmed on all sides to a solid board and then a 4 in. wide strip the full length of the board taken from one side for detailed examination and tests. The tests, a full record of which should be kept together with batch details, should consist of:

- (a) Adhesion dry (8 in. \times 4 in. test pieces tested to B.S. 1155)
- (b) Adhesion wet (8 in. \times 4 in. test pieces—3 hours in water at 70°C)
- (c) Moisture content
- (d) Thickness (to record compression loss)

A log book recording these tests and details of glue Batch Nos., species of timber etc. for each batch of plywood should be kept.

RECORD SYSTEM AND REFERENCE DATA

The process control charts prepared at the operation will be eventually collected, compared with recorder charts and certain information recorded in log books in relation to individual batches of plywood. Collective charts may be prepared monthly to indicate comparison with what will become established as "typical" charts and trends over long time periods will be evident.

Log books should be kept on:—

- (a) Adhesive acceptance batch testing
- (b) Batch testing of plywood
- (c) General log on plant.

The General Log Book should record major changes in machines, technique and material so that any inconsistencies can be "dated" in relation to changes.

From the foregoing you will appreciate that the mass production of plywood is given considerable attention throughout the process. This is a logical procedure in any product where quantitative *proof* testing is impractical and *test by representation* is the rule. The operative word is *representation* and process control is a major aid in obtaining consistent products which can be subject to the procedure of representative testing.

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STRIP-HEATING

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INTRODUCTION

EVERY method of applying heat to an assembly is of potential interest to glue users, and especially to users of synthetic resins as these glues have such exceptional sensitivity to temperature. Each has its own appropriate field of application, but it is my object to draw your particular attention to what I believe to be by far the most versatile of the methods now available, namely strip heating; and under this term I am including low voltage heating techniques generally.

Broadly, heating processes for glue setting can be divided into those of high thermal capacity, like hot-platen presses, and those of low thermal capacity, such as strip-heating, infra-red and radio frequency heating.

The former, whether operated by steam, hot water or electricity, are essentially constant temperature methods, and as such have the highly desirable characteristic that although there is no danger of overheating (assuming the operating temperature to have been suitably chosen), yet penetration of heat to the glue-line can proceed at the maximum rate since the surface of the work is immediately raised to the maximum safe temperature. Against this must be set the need for heavy and bulky platens, which are very expensive to make, almost prohibitively so for curved work; and the necessity for wasting much heat in attaining and maintaining the working

temperature. Their chief use, therefore, is for large scale production of flat material in standard sizes.

With systems of low thermal capacity, on the other hand, each cycle must start with cold heating elements, if any; the process must operate on a rising temperature; and special care is required to ensure that the temperature rises equally at all points. The energy is "pumped" into the assembly, so that in order to avoid overheating it is necessary to assign a certain maximum time of heating to each job, independent of the time of setting of the glue, for none of these methods has so far been provided with a satisfactory thermostat.

To offset these deficiencies, however, the processes in this group are extremely flexible, in all senses of the word; there are no heavy platens, so that the heating can be simply and cheaply adapted to surfaces of any size or shape, curved work can be easily tackled with inexpensive wooden moulds, and the heating is under instant control.

The three examples of systems of low thermal capacity that I have mentioned, while their fields of application overlap to some extent, are not always competitive. The outstanding characteristic of strip heating is its great simplicity. Infra-red or radiant heating competes with it in this respect but differs in that it is generally applicable only to the surfaces which are not under pressure. Radio frequency heating, of course, is for certain types of application in a class by itself in that it can induce

heating at depth and can cause ultra-rapid glue-setting; it is also, however, in a class by itself in its intrinsic complexity.

PRINCIPLES OF OPERATION

We are now in a position to consider strip heating in more detail. You will be familiar with the principles of operation, which are elementary; an alternating electric current, derived from the mains *via* a step-down transformer, is made to pass through a sheet of resistive metal which thereby becomes hot, and the assembly in which it is incorporated is warmed as a result of thermal conduction. Fig. 1 illustrates its well-known application to the setting of the glue in a laminated bend; two strips of galvanised iron or resistive alloy of about 24 gauge, of a width equal to that of the laminations, are assembled with the latter in a wooden jig, and connected to a transformer which supplies a current of several hundred amperes at a pressure of two or three volts.

Here we have the distinguishing feature of the process: a voltage so low that the elements are safe to touch with the bare hand, thereby eliminating nine-tenths of the difficulties of insulation usually associated with hot electric elements.

THE SETTING TIME

The time needed for setting a glue-line in an assembly consists of three parts: a heating-up time, a penetration time, which overlaps it to some extent, and a glue-setting time. When a cold-setting glue is being used, accelerated by heat, the glue-setting time also overlaps the others. The need for time for the heat to penetrate makes the strip heating process, on the

face of it, most suitable for applications where the glue-line is close to the heated surface, as in veneering, but its wide use in making laminated bends up to as much as 2½ inches thick shows that in practice the slowness of penetration is not a very great limitation.

With such a combination of simplicity, robustness, and complete safety, it is little wonder that the introduction early in the war of strip-heating, with which Dr. de Bruyne's name is closely associated, was rapidly followed by its extensive application throughout the wooden aircraft industry, where the need for the largest possible output of laminated bends from every jig was paramount.

HEATING LARGE AREAS

Strip Heating

Since the war, applications of low voltage heating have remained restricted to relatively narrow strips, although used for a much wider variety of jobs than laminated bends, but by about 1948 it had become clear at the Forest Products Research Laboratory that there was a growing need in industry for a

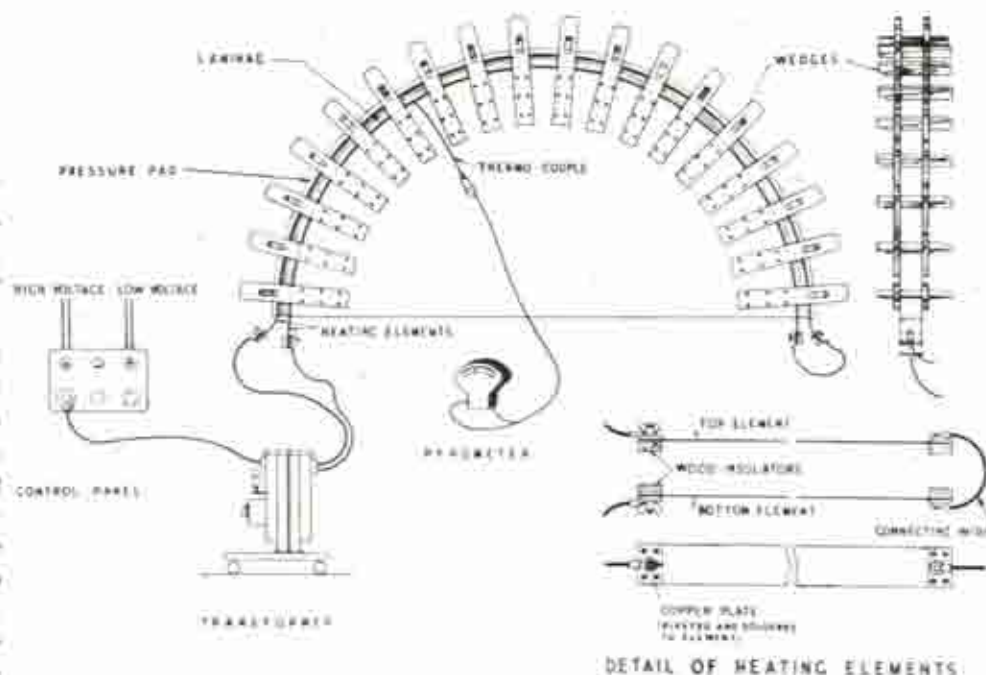


Fig. 1. Setting of laminated bends by strip heating.

flexible method of applying heat to larger areas, mainly as a help to the small manufacturer in accelerating the output from his cold press, but also to provide a solution to the perennial problem of applying heat in vacuum pressing; and it was thought that strip heating should be capable of extension to such areas, by the use of large sheet elements which would also serve as cauls for handling the glued items.

Mains Voltage Heating

The acquisition of the large scale plant was necessarily a lengthy business and the period of delay was used to investigate an alternative method referred to as "mains voltage heating". This was likewise based on the conception of an electrically heated caul, this time made of a laminated plastic sheet incorporating wire-wound elements which could be connected direct to the mains, and thus resembling a stiff electric blanket. This process has the advantage of eliminating the need for a transformer, but against this the elements have to be specially manufactured for each application and are much more expensive and less robust than sheet metal, and there is not the same complete natural safety as in a low voltage system.

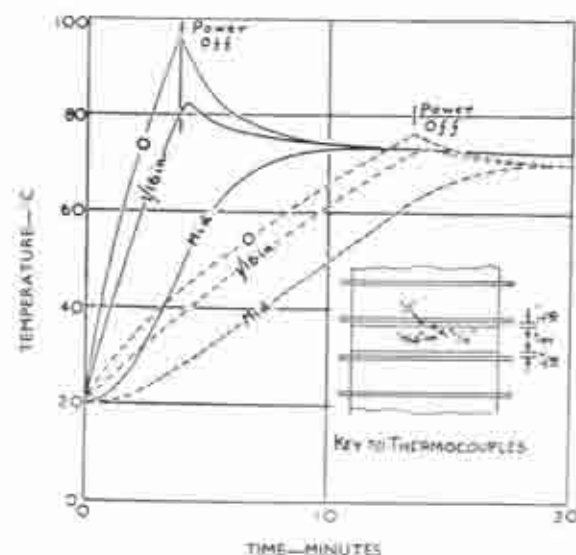


Fig. 2. Heating and cooling curves for $\frac{1}{2}$ -in. panels; full lines refer to 600 watts per sq. ft. rating, broken lines to 150 watts per sq. ft. (Mains Voltage Heating).

THE HEATING PROCESS

As regards the heating process, however, the two methods are practically identical, and the data obtained with the one are valid for the other. When power is switched on and the element, initially cold, begins to warm up, a steadily rising wave of heat travels from it into the wood on either side, and after a certain delay all parts of the assembly, providing it is not extremely thick, will be found to be rising in temperature at approximately the same number of degrees per minute, irrespective of depth—although of course, at any moment the temperatures are lower the greater the distance from the element. This is illustrated by the broken lines of Fig. 2.

This final, constant rate of heating, or slope of the curves, is proportional to the power concentration, being (for large areas) approximately $2\frac{1}{2}$ to 3°C per minute for every 100 watts per square foot. It will be seen that at $\frac{1}{4}$ -inch distance the curve is nearly a straight line through the origin, so that the effective period of delay here is zero. These curves refer to mains voltage heating; in low voltage heating the corresponding distance is approximately $\frac{1}{4}$ of an inch.

THE POWER REQUIRED

For any given heating curve the time required for a glue to set can be computed by the usual methods, i.e. by calculating what fraction of the setting has occurred in each successive minute of heating. If the glue line is near the surface, as in veneering, it will pay to use a high concentration of power, say 500 to 600 watts per square foot, so that a high temperature is developed quickly before the heat has had time to be carried away into the wood by thermal conduction. The higher rates of power consumption will be found to have been more than compensated for by the shortening of the heating time and setting time. The two experiments shown in Fig. 2 illustrate this point. It was arranged for exactly the same number of units of electricity to be consumed in the slow heating as in the fast, but under slow heating the glue took 13.5 minutes to set as against 7 under fast; the latter had obviously used the same quantity of electricity to better advantage. Incidentally, this quantity amounted to $1\frac{1}{2}$ units (kWh) per hundred square feet of veneered area—

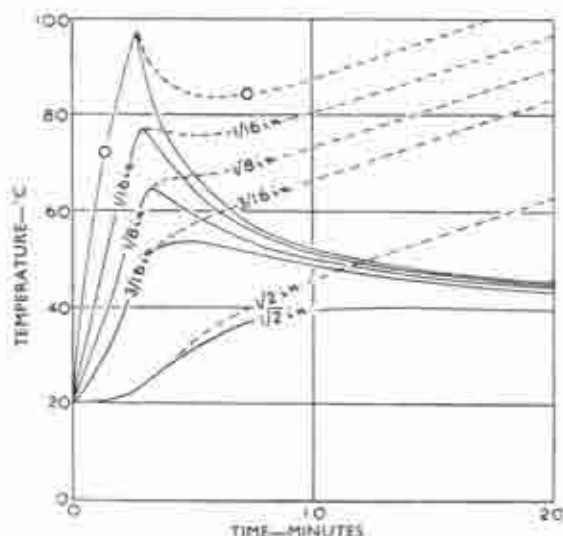


Fig. 3. Heating and cooling curves for 2½-in. panels showing, in broken lines, the effect on temperature of reducing power to one-quarter instead of switching off.

an area needing some 3½ lbs of glue. It will be noticed that in these instances power was switched off early in the heating cycle so that some of the glue-setting was effected by heat stored in the assembly, and this method of working, where it is capable of application, allows the best use to be made of high power concentration. An alternative is to change to low power, by suitable switching; the heating curves will then be of the type shown in Fig. 3.

In setting deep glue-lines, such as in laminated bends, by strip heating, there is little point in using very high concentrations, for the heating is bound to be slow at depth, and the surfaces will therefore have reached their maximum safe temperature very early in the heating cycle. In these applications it is not feasible to switch off before the glue has set—this would involve double timing on each of the jigs (which may be numerous) and so it is common practice to arrange the rate of heating at such a value, usually between 100 and 250 watts per square foot, that the deepest glue-lines are calculated to have set just before the surfaces have reached their maximum safe temperature. This maximum is approximately 100°C and if exceeded at the time of opening of the jig, there is a danger of burst glue-lines, for in this type of application comparatively high glue spreads are common. The rate of temperature-rise in laminated bends and similar narrow

assemblies is lower than that quoted earlier, owing to the effects of edge-cooling, and as it is not easy to calculate this effect, it is necessary to proceed by trial and error.

The experiments with mains voltage heating on veneering, and the experience of strip heating of thick assemblies, thus indicate the range of power concentration which may be required in large-area low voltage heating, viz. between say 100 and 600 watts/sq.ft according to the type of application, and 300 watts/sq.ft is a convenient working figure.

If, now, we apply this to a typical case, say the heating of both sides of a panel 6ft by 3ft, the total area being 36 sq. ft a power of 10.8 kW is called for, say 12 kW to include for the losses in the cables. As we are limited to 12 volts for reasons of safety the current will have to be at least 1000 amperes—so large as to require special methods of handling. The investigations into low voltage heating were therefore mostly concerned with the mechanical and electrical aspects of handling these large currents

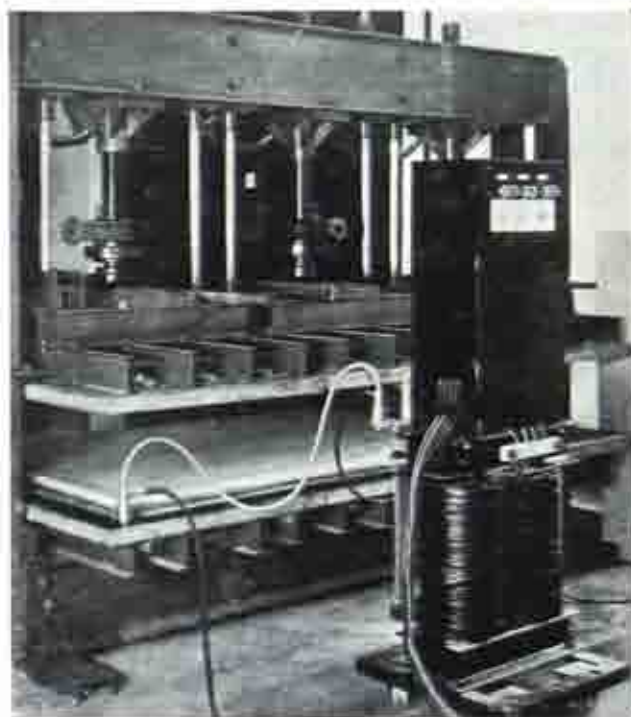


Fig. 4. Application of low voltage heating in the veneering of plywood: the top platen of the press have been raised for the purpose of the photograph. Power from the 18kW transformer (right) is delivered to the sheet-metal element via water-cooled cables and plug-unit-socket-connectors.

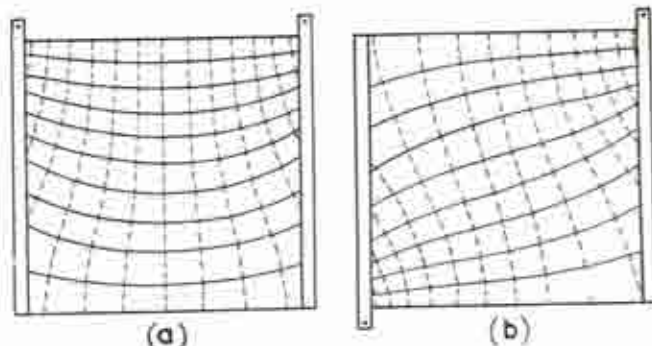


Fig. 5. Current flow in square element with insufficiently thick electrodes. Lines of flow of current are shown in full. The same amount of heat is developed in each square, irrespective of its size. In chart a feeding is at adjacent corners; in b, at opposite corners.

and making them flow uniformly through the elements, and the evolution of simple, robust, low-cost plant.

A transformer of 18 kW capacity was installed, delivering its output at a series of voltages to enable it to be applied to a variety of sizes of element. It occupies a floor space of little more than 18 inches square and is 4ft 6in. high including the switchgear compartment. Fig. 4 shows it in use in an application similar to the example given above, viz. the gluing of a veneer to one side of a sheet of plywood.

THE HEATING ELEMENTS

We may now consider how best to construct the heating elements, and while there is a certain amount of latitude in the choice of material, in that the transformer can be adjusted to suit it, there are also certain electrical limitations. For small areas the current is easy to handle by conventional means, although the cables have to be somewhat heavy, and there is little restriction in the choice of metal for the elements (even copper foil could be used). Galvanised iron sheet, say 20 to 24 gauge, is more suitable electrically and mechanically, and is commonly employed, as well as various types of alloy sheet.

With large areas, e.g. more than a foot in width, the current becomes so heavy that more highly resistive material is needed and the choice becomes severely restricted. If iron were available in very thin sheet it would be suitable electrically, but would be too fragile, and it is almost essential to use special

resistive alloys or stainless steel. Iron can, however, be employed in the form of light woven wire mesh, in cases where its lack of a smooth surface is of no consequence, and this material has the special merit of being able to conform easily to double curvature surfaces, thereby providing a much needed means of applying heat in vacuum and allied fluid pressure techniques.

Even if the material of the element is quite uniform, and not by any means all the sheet metal marketed is uniform in thickness, it will not heat evenly unless it is provided with heavy copper electrodes soldered or similarly attached at the ends. Fig. 5 illustrates what happens in the case of square elements which have been provided with insufficiently thick copper electrodes; the full lines are lines of current flow, and these are seen to crowd together near the points of attachment of the cables, whether these are at adjacent or opposite corners. It can be shown that the same amount of heat is developed in each of the squares whether large or small, so that a considerable amount of over- and under-heating takes place. If the electrodes are increased in thickness the pattern approaches the ideal of a square grid, and heating becomes uniform. Figs. 6 and 7 show actual temperature distributions in a

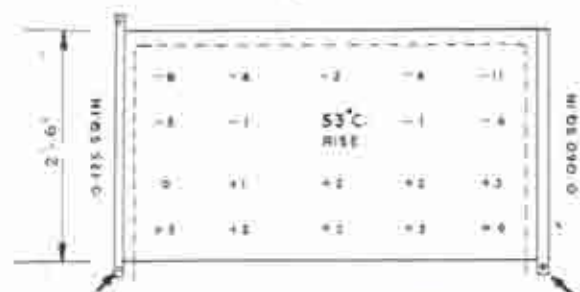


Fig. 6. Temperature distribution when using thin electrodes at ends of element.

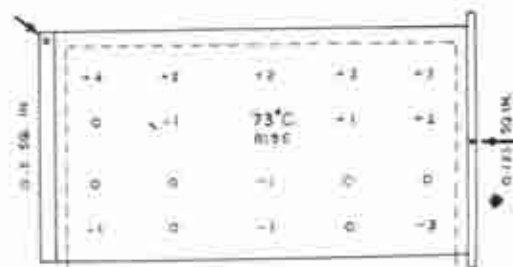
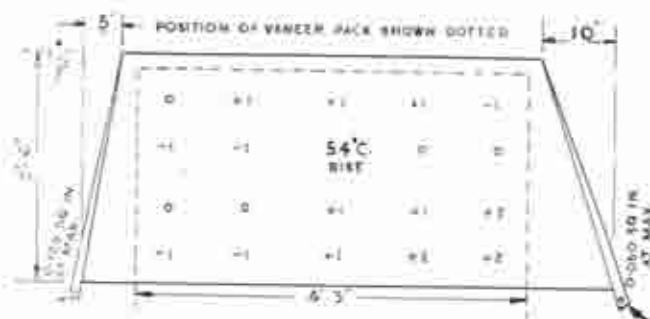


Fig. 7. Temperature distribution when using thicker electrodes.



sheet-metal element heated in the centre of a stack of veneers, when using thin and thick electrodes respectively (with different thicknesses at opposite ends). The temperatures are recorded as excess or deficiency compared with the quoted temperature rise near the centre.

Theoretical analysis shows that as an alternative to making the electrodes very heavy, 'perfectly' uniform heating can be achieved by tilting them, (and also tapering them to suit the graduated current flow), by an amount depending on, amongst other factors, their cross-sectional area; and the effect is illustrated by Fig. 8. This tilting ensures that the current which has to flow through the greater length of copper electrode is provided with a shorter path through the sheet-element material, so that all paths have equal resistances and carry equal currents. In the example given, very thin electrodes were fitted and hence exceptionally large tilts were needed. The temperatures measured in a trial are recorded and the variations are seen to be negligibly small. In practice it will usually be inconvenient to construct the elements and electrodes in this way, but the theory enables one to calculate what minimum thickness of electrode is necessary to ensure that the theoretical tilt is small enough to be ignored. Heating will then be sufficiently even for practical purposes. (Fig. 7).

In order to carry currents of 1000 amperes, however, a much larger cable would be needed which would be extremely heavy and clumsy, and it is best to incorporate water-cooling, which enables quite a light copper cord to be used. Its resistance causes an appreciable waste of power at such currents and so the length should be kept to a minimum. For attaching this cable a simple cooled terminal can be fitted, as in Fig. 10, or for quick action a water-cooled version of Fig. 9, and both can carry over 2000 amperes. Devices such as these enable low voltage heating to be applied to elements up to at least 3 feet wide.

With this extension of the process to large areas the scope of the low voltage technique becomes very greatly increased, and many operations which previously would not have been attempted without heavy capital plant are brought within the range of a very modestly equipped factory. One of the most difficult orders to handle is the small batch of large curved parts, required at short notice: the numbers

are too great to permit cold pressing except with numerous costly jigs, but not large enough to justify an outlay on steel dies or radio frequency equipment: strip heating can handle such work at a few hours notice—and with negligible risk of rejects.

Summarising the special qualities of the process, we see that it enables heat to be applied to any surface, large or small, flat or curved—even doubly curved: it is robust, safe and easy for operatives to understand; owing to its high thermal and electrical efficiency it is much more economical in current than other electrical heating methods; and its capital and maintenance costs too are probably lower than those of any comparable process.

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RADIO FREQUENCY HEATING

(PART I. FUNDAMENTAL PRINCIPLES)

J. Pound

INTRODUCTION

THE use of a radio-frequency electric field for the production of heat is not a new idea, for physicians have been employing it for a number of years in the so-called diathermy method of raising the temperature of parts of the human body. A logical development is to use these fields to raise the temperature of glue in a wood joint to produce quick setting.

Those who have had little or no experience of radio-frequency heating will naturally have a number of queries to be answered. It is the object of this lecture to answer some of these queries by explaining some of the underlying principles and applications of the process.

Radio-frequency heating, if correctly employed, can save the user money, and give an increased output, whereas if it is incorrectly applied the results may be costly and disappointing. In order that some of the difficulties may be appreciated and overcome, a few of the fundamentals of wood gluing are described in the following paragraphs.

GLUES

The main difference between animal and synthetic glue is that the former sets by cooling and loss of water, while the latter sets by chemical reaction. The rate of setting of a synthetic resin glue can be increased by raising the temperature of the glue line; this is shown in Fig. 1 for a typical urea-formaldehyde glue.

There are two main types of synthetic resins suitable for accelerated curing by radio-frequency heating. One is a phenol-formaldehyde (PF) and the other is a urea-formaldehyde (UF) resin. Both

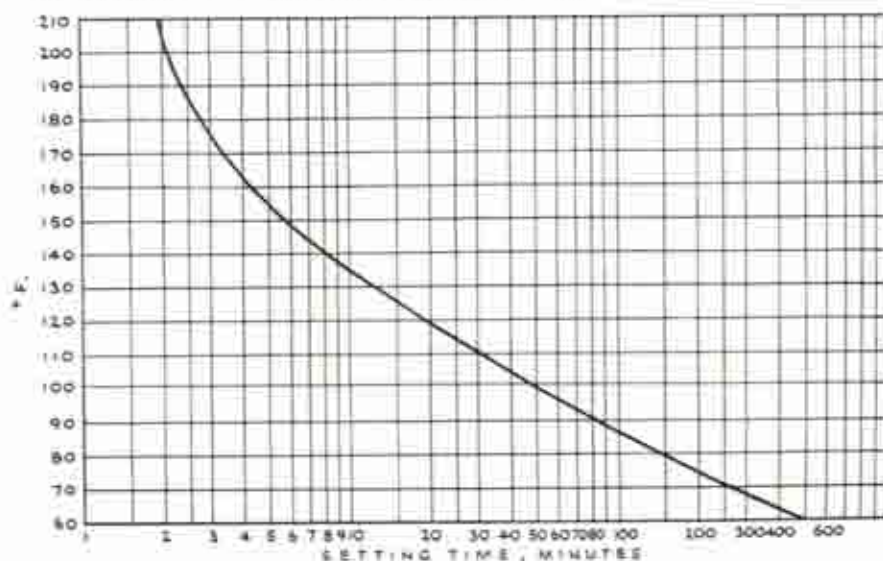


Fig. 1. The setting time against temperature for a typical urea-formaldehyde resin. "Aroclite K" and hardener CIA were used.

these glues can be obtained either in a liquid or in a powder form: the powder has the advantage that it can be stored for a very long time even in hot climates.

The setting of a synthetic resin is an irreversible chemical reaction which is accelerated by the addition of a hardener. The speed of this reaction depends on the chemical used as a hardener and on its strength. The speed is also governed by the temperature of the glue line: by raising the temperature a shorter setting time can be obtained. The characteristics of the hardener are determined by the resin manufacturer to suit the particular application for which it is intended and for all practical purposes these cannot be varied by the user. The raising of the temperature of the glue line is, for the purpose of this lecture, of most interest; this can be achieved in a number of ways.

We have already mentioned the types of glue most suitable for RF heating. Although a phenolic resin glue will give a glue line which can, if it is desired, resist boiling water, the curing time of this resin is necessarily longer than that of a urea-formaldehyde resin (which will itself withstand prolonged soaking in water at 158°F). Also phenolic formaldehyde resins generally require a considerably higher curing temperature than urea formaldehydes, and they are more expensive. The urea formaldehyde is therefore the resin in most common use (its properties of resistance are more than sufficient for most purposes) and it is to the curing of this resin that the data in this lecture refers.

CALCULATING SETTING TIMES

Using a typical UF glue and a certain hardener it is known that the glue will set in 4 hours at 70°F and in 2 minutes at 203°F. The simplest method of calculating the time required for the glue to set completely is therefore to add the time required to set the glue at the temperature at which the heating process operates (2 minutes at 203°F) to the time taken for the glue line to reach this temperature. This may be perfectly satisfactory if the time necessary to raise the temperature of the glue line is small compared with the setting time. When, however, it is long, curing takes place progressively as the temperature rises. As an example, it may

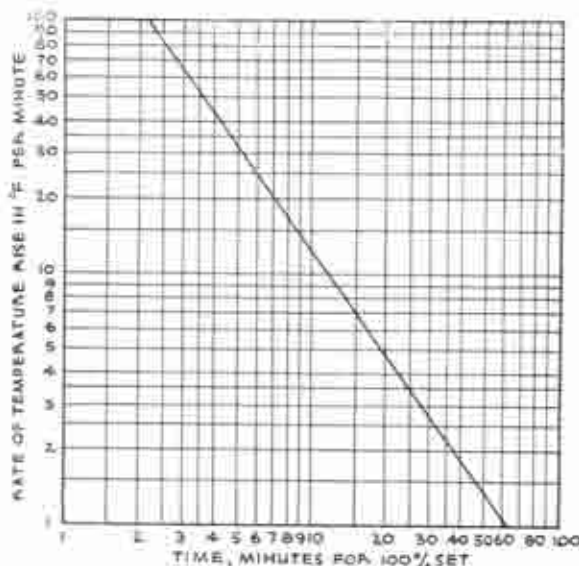


Fig. 2. Rate of temperature per minute/time in minutes to give 100% cure for a typical urea formaldehyde resin. "Aerolite" K and hardener CHA were used. (Ambient taken as 60°F.)

take a hot press 10 minutes to raise the glue line to 203°F. At this temperature the glue will cure in 2 minutes. But it is clear that the glue will already have become partially cured by the time it reaches 203°F. It is possible, however, to compute the setting time of the glue to give the exact moment that the glue is fully cured. To do this it is necessary to draw a graph of setting times against temperature as has been done in Fig. 1. From this it can be seen that at 119°F the setting time is 20 minutes, which means that in one minute we have a $\frac{1}{20}$ or a 5 per cent. cure per minute. Therefore, if the initial temperature and the rate of temperature rise are known we can calculate the percentage cure for each minute or fraction of a minute. As soon as the percentages add up to 100 the glue is cured and further time is unnecessary. As an example, using the above glue and a temperature rise averaging 20°F per minute Table I is obtained.

It will be seen that by raising the temperature of the glue line at the rate of 20°F per minute the glue sets in just under 7 minutes. Half-minute intervals were taken because the rate of temperature rise was relatively small. At much faster rates intervals as short as one-eighth of a minute should be tabulated in order to ensure sufficiently accurate results.

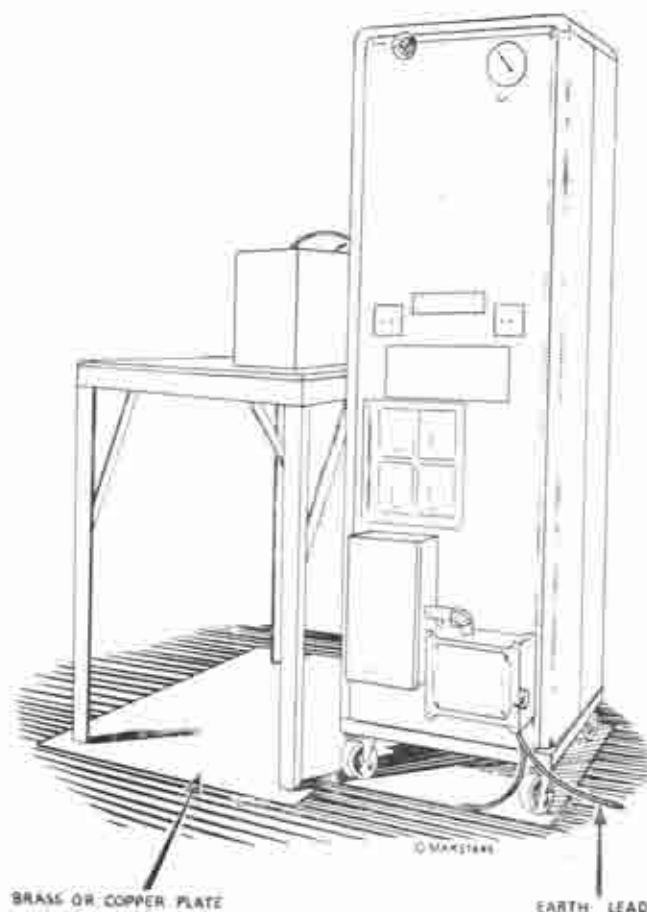


Fig. 3. An effective means of earthing a generator and jig by placing a sheet of metal under both.

Table I shows that the glue is cured before a temperature of 203°F is reached.

When a number of these tables have been computed for different rates of temperature rise, using Fig. 1, (setting being absolutely completed) the results give a graph, as Fig. 2, showing rates of temperature rise per minute against setting time in minutes.

The advantage of such graphs will be appreciated when making calculations for the time required to cure a glue in any particular job. The minimum time necessary could, of course, be obtained by experimental results but these are likely to be more costly in time and material.

It is sometimes possible to remove the joint from the press when it is only 80 per cent. cured, relying on the residual heat stored in the assembly to com-

TABLE I

At end of	Tem- perature (°F)	Average temp. over $\frac{1}{2}$ minute	Setting time at temp. in Col. 3 in minutes	% Set.
0 min.	60	—	—	—
$\frac{1}{2}$ "	70	65	350	0.1
1 "	80	75	190	0.3
$1\frac{1}{2}$ "	90	85	110	0.5
2 "	100	95	64	0.8
$2\frac{1}{2}$ "	110	105	39	1.3
3 "	120	115	24	2.1
$3\frac{1}{2}$ "	130	125	$15\frac{1}{2}$	3.2
4 "	140	135	10	5.0
$4\frac{1}{2}$ "	150	145	6.8	7.3
5 "	160	155	4.9	11.5
$5\frac{1}{2}$ "	170	165	3.9	12.8
6 "	180	175	3.0	16.6
$6\frac{1}{2}$ "	190	185	2.5	20.0
7 "	200	195	2.2	22.7
				104.2

plete the cure. The possibilities of using such techniques are, however, dependent on the type of work and method of production.

If a temperature greater than 212°F is reached in the glue line it is essential that pressure should be maintained until the glue has cooled to a temperature below the boiling point. Unless this is observed or other special precautions, such as releasing pressure slowly under control are taken, steam pockets may be formed, causing bad adhesion.

R.F. heating normally gives a linear temperature rise with time until the boiling point of the water in the material is reached. If, however, the material is under pressure or the water contains chemicals, the boiling point will be raised above the normal (212°F) and for the best results it should be arranged that the maximum temperature is slightly below this higher figure.

HEATING OF WOOD

There are two principal means of raising the internal temperature of wood: either by applying

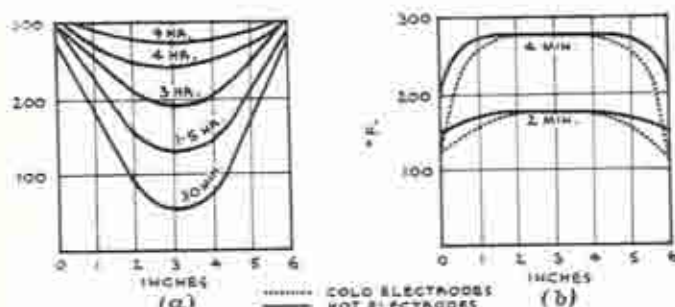


Fig. 4. Temperature gradients against time for hot platen and high-frequency heating.

heat externally ⁽³⁾ or by generating it internally. In the former method use is made of the thermal conductivity of the wood, which being low, necessitates raising the outside to a much higher temperature than the centre unless the heat is applied for a long period. The second method is to place the wood between two electrodes or plates to which a radio frequency voltage is applied, causing power to be lost to the medium, so raising its temperature, the heating effect being uniform throughout. Fig. 4 shows the temperature gradient for external and internal heating for different time durations.

Heating Effect

The increase of temperature of a material in a radio frequency field depends on :

- The power dissipation turned into heat.
- The weight of the material in lb.
- The heat absorbing property of the material, known as its specific heat (cal/gram/°C).

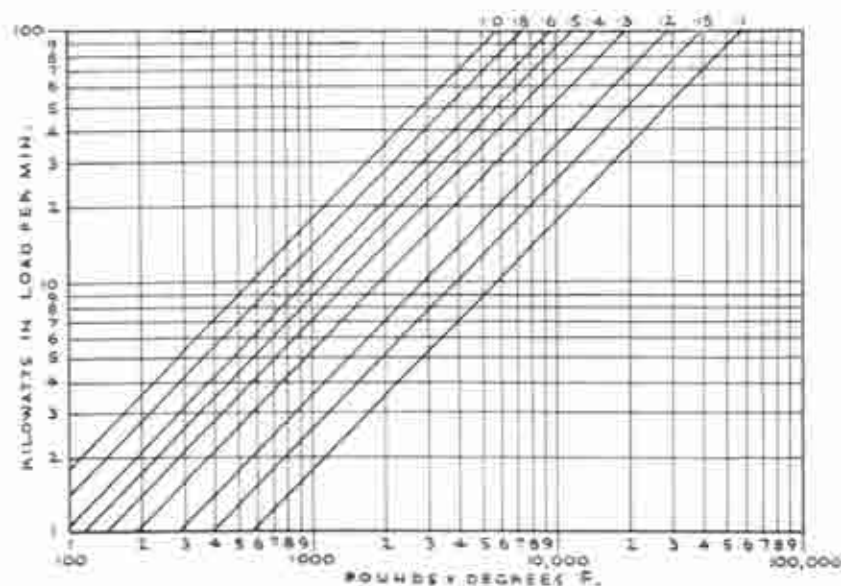
When the weight of the material, its specific heat, and the temperature rise (in degrees F) that is required, are known, the necessary power per minute into the material can be ascertained from Fig. 5. When only half the necessary power is available from the generator the time must be doubled, and proportionally for other power ratios. This method ignores loss of heat by radiation into the surrounding air, and by conduction to the electrodes, for, as the time is usually short, only a small percentage is thus lost.

The specific heat is a property of the material ⁽³⁾ being the amount of energy required to raise unit weight one unit of temperature, and is dependent on the moisture content. An approximate formula is given by Kollman ⁽⁶⁾, which has been plotted in Fig. 6, for moisture contents up to 100 per cent.

Example 1

It is required to raise 7 lb of wood, which has a specific heat of 0.4, from 60°F to 160°F. What power is required in the load to do this in 1 minute and in half a minute, and what time is needed if 3 kW is available in the load?

Fig. 5. Power required in load, knowing specific heat, weight and temperature rise.



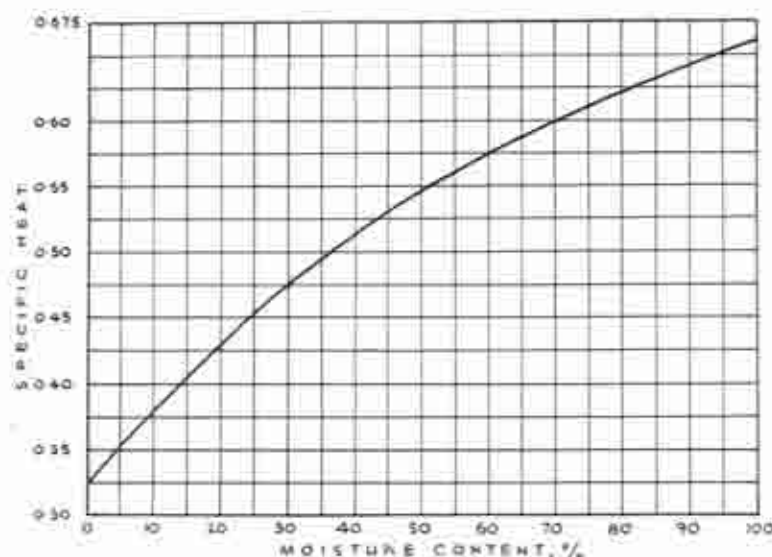


Fig. 6. Relationship between specific heat and moisture content for average woods.

$$S.H. = \frac{(m + 32)(m + 100)}{m} \quad \text{(Kollmann)}$$

m = Moisture Content %

Temperature rise ($160^{\circ}\text{F} - 60^{\circ}\text{F}$) is 100°F . Multiply this by the weight, 7 lb, giving a figure of 700. On Fig. 5 this line will be found to cross the line of specific heat, 0.4, at the same place as the line 5 kW in load per minute. Thus the power in the load required to do the work is 5 kW for one minute or 10 kW for half minute. With 3 kW the time needed is $\frac{1}{3} = 1\frac{1}{3}$ minutes.

Power in Load

The energy turned into heat in the load depends upon a number of items, of which the most important is the voltage, because, for example, if the voltage is trebled the heating effect is nine times as great. That is, the heating effect is proportional to the square of the voltage. The other important item is known as the power factor, and is a property of the material.

In order to get the maximum power into the load or glue line, the voltage across the electrodes should be as large as possible. The voltage that can be applied is in practice limited by the dimensions of the wood or glue line and the air gap. If too high a value is applied an arc will occur which will char the wood or glue line, and in bad cases even cause a slight fire. It is thus necessary to restrict the peak value to a safe limit, which can usually be taken as 2,000 volts per inch of material between the electrodes.

The Power Factor

Power Factor or "Loss Angle" of a material is a term used to denote the "goodness" of an insulating medium, and is usually expressed as a percentage or as a mathematical term ($\cos \phi$ or $\tan \delta$). In electronic engineering an insulator should have a low value of power factor which means that it has small heating losses. In dielectric heating where these losses are required this term should be as large as possible, approaching if possible its maximum value of 100 per cent (or $\cos \phi = 1$). As can be seen from Fig. 7, the smaller the value of the power factor, the more powerful must be the generator to get a certain wattage into the load. The term "Loss Factor" is one that is being used very considerably, this is the power factor multiplied by the dielectric constant of the material.

Example 2

If in Example 1, the power factor of the wood had been 10 per cent ($\cos \phi = 0.1$), what must be the generator power for 1 minute? What would be the required power if the power factor had been 1 per cent ($\cos \phi = 0.01$)?

From Example 1 the required power in the load was 5 kW. From Fig. 7 it can be seen that the line from 5 kW "power in load" cuts the 10 per cent

line at a point equal to 5 kW. If the power factor had been 1 per cent the generator power required would be 7 kW.

Capacitance

As an R.F. generator will only operate at its maximum efficiency when working into a load that is within certain limits of capacitance⁽⁹⁾ this will now be considered. When a pair of electrodes (two plates or tubes) are separated by air they form a condenser which has the ability to store electrical energy. The quantity of electricity that this condenser will hold depends upon its capacitance (capacity) and this is measured in mF or pF (micro-microfarads or picofarads). The value of the capacitance is dependent upon the area of the smaller plate, the distance separating them and the material between them. If the space between the plates is filled with air the condenser will have a certain capacitance, but should some other material be used, such as wood, a different value of capacitance will result. The material (air, wood, etc.) between the electrodes is called the dielectric and its property of altering the capacitance is called its "permittivity" or "dielectric constant" and is denoted by the Greek letter K . Should a condenser have a certain value of capacitance when the dielectric is air (permittivity is taken as unity) its value with a new material with a permittivity K is now K times that with air. Fig. 8 shows the relationship between capacitance in mmF and the dimension of the smaller plate over spacing for various values of dielectric constant.

When rods or tubes are being used for the electrodes the formula connecting their dimensions and the capacitance is different from that for plates. Fig. 10 shows the capacitance, per foot length, of three different diameter tubes, separated by the material having a dielectric constant of unity. The capacitance of an assembly equals the capacitance

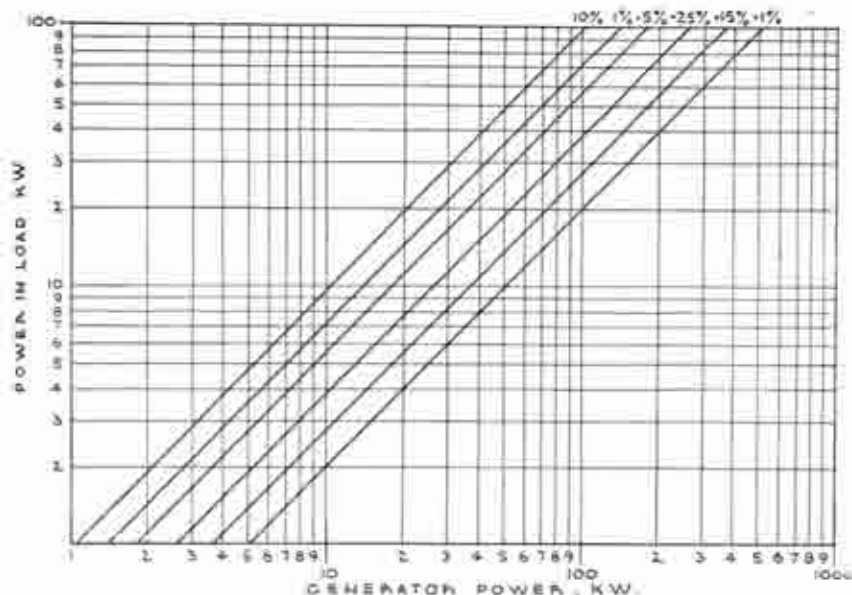


Fig. 7. Generator power/power in load for materials of different power factors.

per foot multiplied by the total length in feet of the shorter tube multiplied by the dielectric constant of the material between them.

It is most important that upon installation of radio frequency equipment there should be close co-operation between the user and the manufacturer. To most users the technique is quite new and the behaviour of currents at radio frequencies is so different from that at mains supply frequencies, that there is no obvious relationship.

The degree of success of an installation depends largely upon skilful electronic application engineering. It is upon this last point that success or failure will depend. We now come to Example 3.

Example 3.

If the lower electrode or plate of a jig is 24 in. \times 18 in. and the upper one 10 in. \times 9 in., what is the capacitance (a) when they are 1 in. apart in air, (b) 2 in. apart and the material between them has a permittivity of 6? The area of the smaller plate is $10 \times 9 = 90$ in.², so that in (a) area over spacing gives $90/1 = 90$. By using the line $K=1$ and 90 on the left hand scale is read 20 mmF on the bottom scale, which is the required result. In (b) the area is still 90 in.² and area over spacing gives $90/2 = 45$. This time using the line $K=6$ and 45 for the left hand

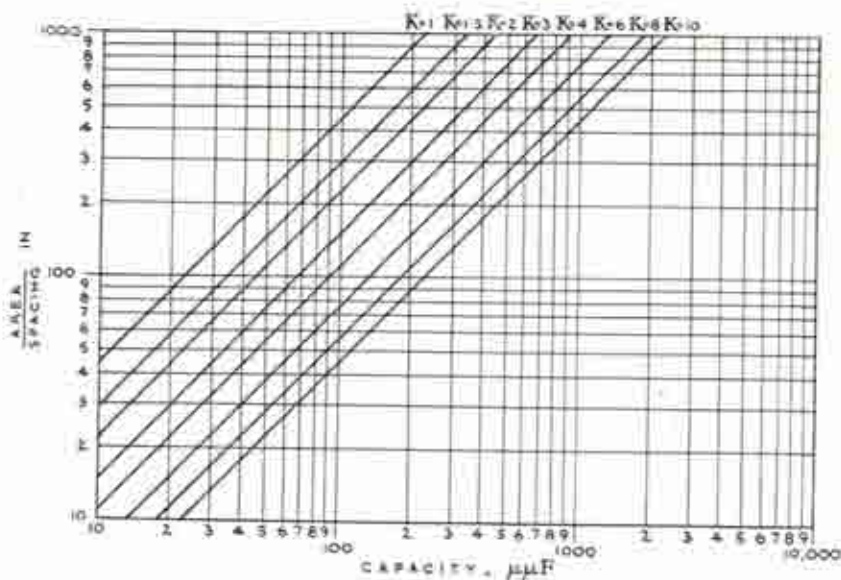


Fig. 8. The effect of electrode dimensions on capacitance for different values of K .

scale the result 60 mmF is read on the bottom scale.

What is the capacitance of a jig which has electrodes of $\frac{1}{2}$ in. diameter tube, the inner and outer lengths being 4 ft and 4 ft 6 in. respectively, and the

centres 0.6 in. apart when the dielectric constant of the material between them is 3?

The capacitance per foot from Fig. 10, for $\frac{1}{2}$ in. diameter tube on 0.6 in. centres is 7 mmF so that total capacitance is 7×4 (length of shorter tube) $\times 3$ (dielectric constant) = 84 mmF.

Table 2 gives representative figures of dielectric constant and power factor for some of the more commonly used woods (at various moisture contents)

and glues. As can be seen the resin glues have power factors and dielectric constant which are greater than those of the woods giving much larger value of loss factor.

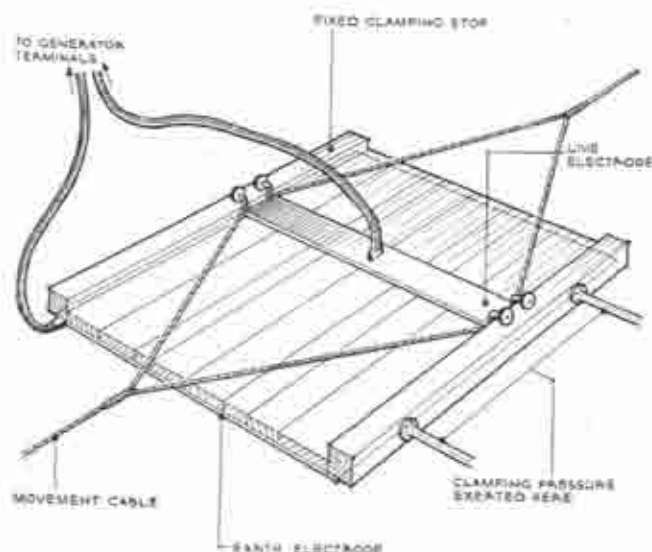


Fig. 9. Simple means of edge-jointing slats to form a board when the capacitance would be too high with a large upper electrode.

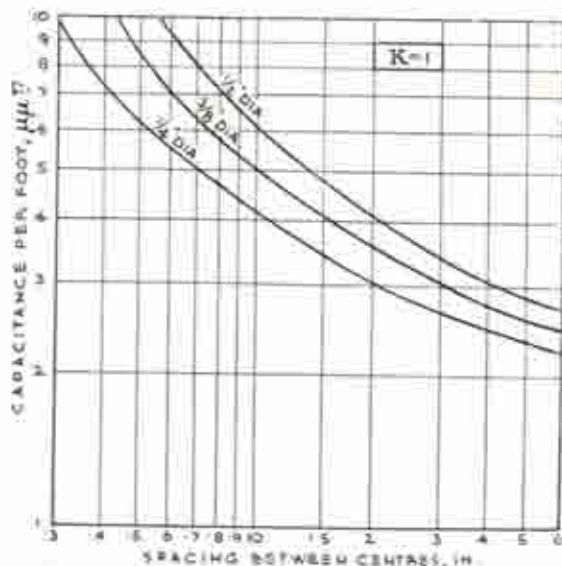


Fig. 10. Capacitance per foot of tubes having different diameter against their spacing with a material of $K=1$.

TABLE 2

Material	Moisture Content %	Permittivity	Power Factor	% Gravity	Spec. Heat	Source
Beech	0	2.0	2	.56	.32	10
Beech	8	5.0	11	.61	.36	10
Beech	10	5.0	38	.63	.39	10
Spruce	0	2.2	5.2	.37	.32	10
Spruce	8	2.5	7	.4	.36	10
Spruce	10	3.2	9	.42	.39	10
Walnut	0	2.1	3.6	(.57)	(.32)	1
Walnut	8	2.7	8	(.6)	(.36)	1
Walnut	17	5	14	(.63)	(.42)	1
Douglas fir	11.1	3.1	8.1	.45	(.40)	3
Douglas fir	11.4	4.0	10.5	.64	(.41)	3
Birch	10	2.6-3.0	1.4-6.3	.63	(.38)	3
Scots pine	15	3.0	19	.61	(.41)	3
Maple	10	2.2	8	(.5)	(.38)	4
Maple	15	3.8	11	(.51)	(.41)	4
Malagouty	10	2.4	71	(.50)	(.38)	4
Malagouty	15	2.7	10	(.51)	(.41)	4
Phenolic glue	—	10	50	1.23	.8	2
Urea glue	—	26	(cos $\theta = .85$)	1.5	1.0	2

1. Proceedings of the Institute of Radio Engineers (New York), Oct. 1943.
2. Electronic Engineering, Aug. 1945.
3. Trans. Liverpool Eng. Society Vol. LXIII.
4. Trans. American Society of Mechanical Engineers, April, 1943.

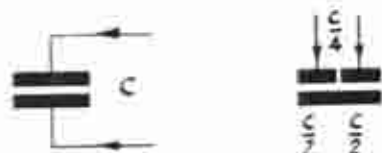


Fig. 11. Effect on capacitance of equally feeding via a split electrode.

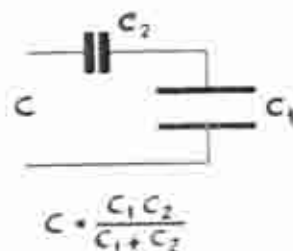


Fig. 12. Reducing the effective capacitance of a jig by adding a low loss capacitor in series with one of the leads.

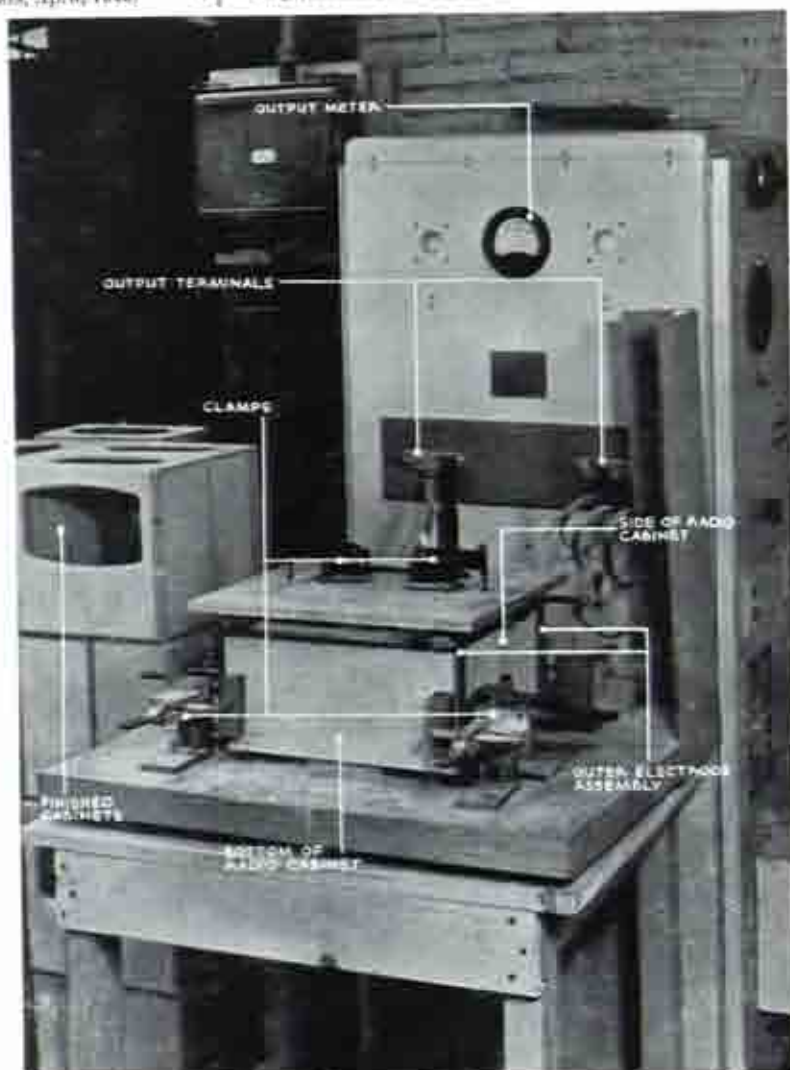
Fig. 13. Jig for making radio cabinet being loaded and shoring outer electrodes and extra coil in series as capacitance is low.

If the value of capacitance of a load is larger than that recommended by the makers of the R.F. generator it should be reduced by dividing the load into sections and connecting these in series, as shown in Fig. 11. If it is impossible to do this then a low loss ceramic capacitor should be included in one of the leads from the generator, this being shown in Fig. 12. The value of this capacitor can be calculated from the following formula:

$C_s = (CC_1)/(C_1 - C)$ where C_s = added series capacitor in mmF.

C = required capacitance of load and series capacitor in mmF. This should be somewhere in the range recommended by the generator manufacturer.

C_1 = Capacitance of load alone in mmF.



What value of capacitor must be added in series with a jig of 300 mmF to make the assembly have a value of 120 mmF?

In the above formula $C=120$ mmF and $C_1=300$ mmF, so that $C_2=(120 \times 300/300-120)=36000/180=200$ mmF so that the added capacitor must be one of 200 mmF.

Another method of reducing the effective capacitance of a jig is by connecting a coil (a number of turns of wire) across the assembly. With a large capacitance a small coil must be connected across it whereas with a smaller one a coil of large diameter and/or number of turns must be used.

When the capacitance is too small a coil can be added in series with the load which effectively increases its value. In this arrangement, the smaller the capacitance the larger must be the dimensions of the coil. Should it prove impractical to use an additional coil a low loss ceramic capacitor can be placed across the load. With the last method the total capacitance of the combination is the arithmetical sum of the two values. Should a jig have a capacitance of 20 mmF and a 50 mmF capacitor be connected across it, the combination will have a value of 70 mmF.

Electrodes⁽⁶⁾

In order that the best use can be made of an equipment it is necessary to understand the principles of the electrode assembly. The electrodes are of any metal by which power can be fed to the work where it is wanted. They are separated by the air gap or air gaps, wood and glue line as shown in Figs. 15 and 16, and may be made up of rods, tubes, plates or strips. They are usually made of brass or copper and, for greater efficiency at the higher frequencies, may be silver plated.

Fig. 17 shows two means by which a slat "S" may be glued to a board "B". In (a) the electrodes are at the top and bottom of the assembly so necessitating the heating of the whole volume of wood and glue in order to raise the temperature of the glue line. By placing the electrodes on either side of the glue

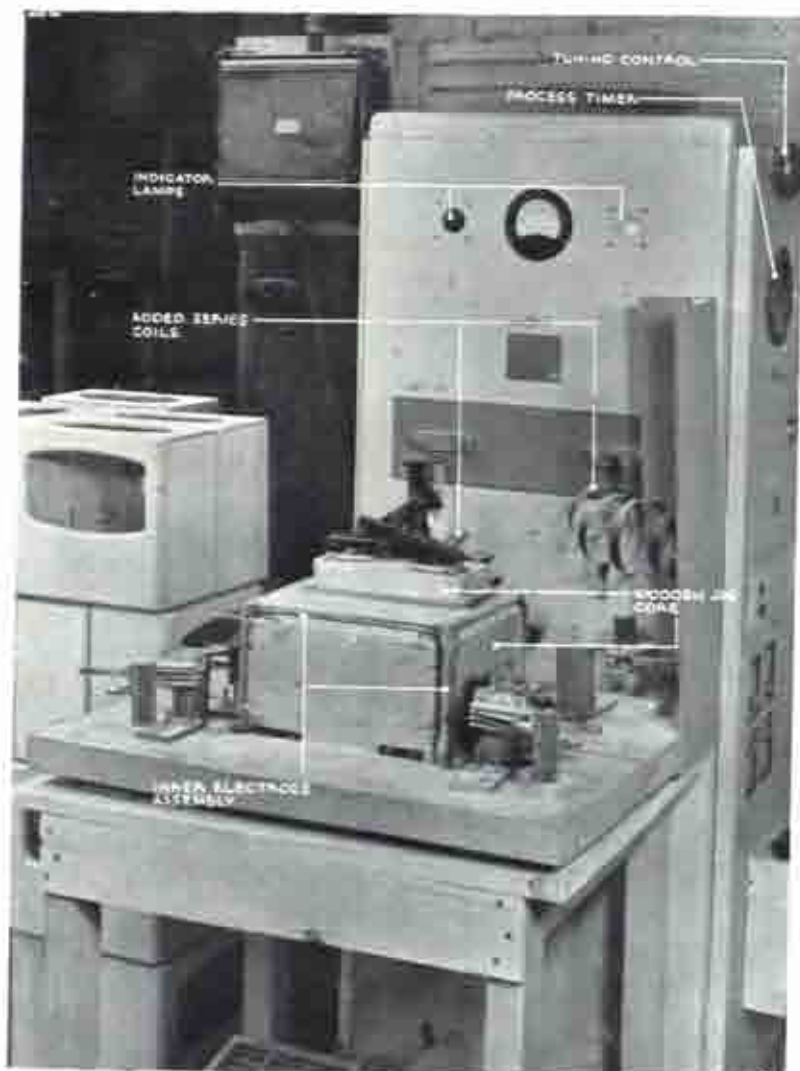


Fig. 14. Jig for making radio cabinets showing inner electrodes and extra coil in series because capacitance is too low.

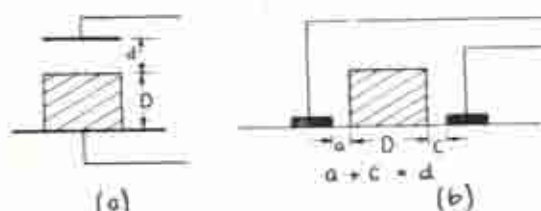


Fig. 15. Electrode assemblies with air gaps.

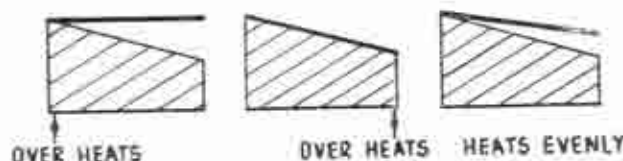


Fig. 16. How air gaps can overcome uneven heating when the surfaces are not parallel.

line, as in (b), its temperature rises much more rapidly than the wood, due to its large loss factor and only a small percentage of the wood is heated. This results in a saving of power or time, whichever is desired. This method has the added advantage that the means of exerting pressure on the joint need not be electrically insulated, as it does not form part of, or make contact with, the electrodes.

In Fig. 18 is shown a similar method of applying the greater part of the power almost direct to the glue line, again requiring less power than if the

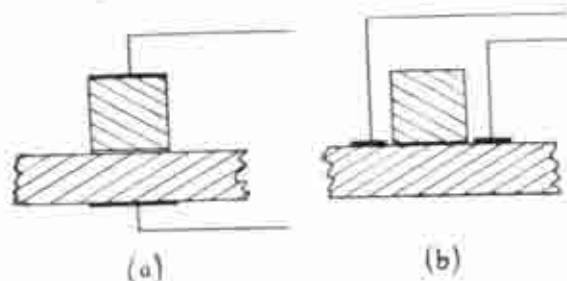


Fig. 17. Electrode assemblies for (a) transverse heating (b) longitudinal (glue line) heating.



Fig. 18. Simple means of exerting pressure on a glue line showing the position of the live electrode. The metal frame is the other electrode.

whole volume of the wood were heated. The necessary pressure along the glue line is obtained by means of a rubber-lined fire hose which exerts even pressure along the whole length when either water or compressed air is fed to it. In this arrangement only one additional plate is needed as the metal of the frame forms the "earthy" electrode (that is, the one connected to earth). Wherever it is possible, use should be made of any metal parts of the press or jigs as the earthy electrode, so the insulating difficulties are greatly reduced.

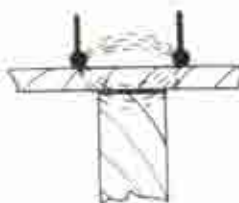


Fig. 19. Method of heating a glue line when the electrodes are separated from it by a ball or sheet.

VOLTAGE ON ELECTRODES

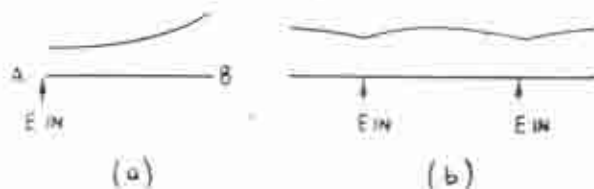


Fig. 20. Variation of voltage along electrodes.

Sometimes it is difficult or impossible to place the electrodes either side of the glue line or as shown in Fig. 17 and another method has to be employed. One means of overcoming this problem is as in Fig. 19, which shows the position of the electrodes and how the electric field reaches the glue line and heats the minimum amount of wood. This method is less efficient than true glue line heating, but better than that of Fig. 17 if the wood is not too thick.

In the manufacture of jigs it is essential that any metal used should be free from sharp edges, points and have circumferential ends.

If these precautions are not taken there is always a tendency for arcing to occur, so damaging the

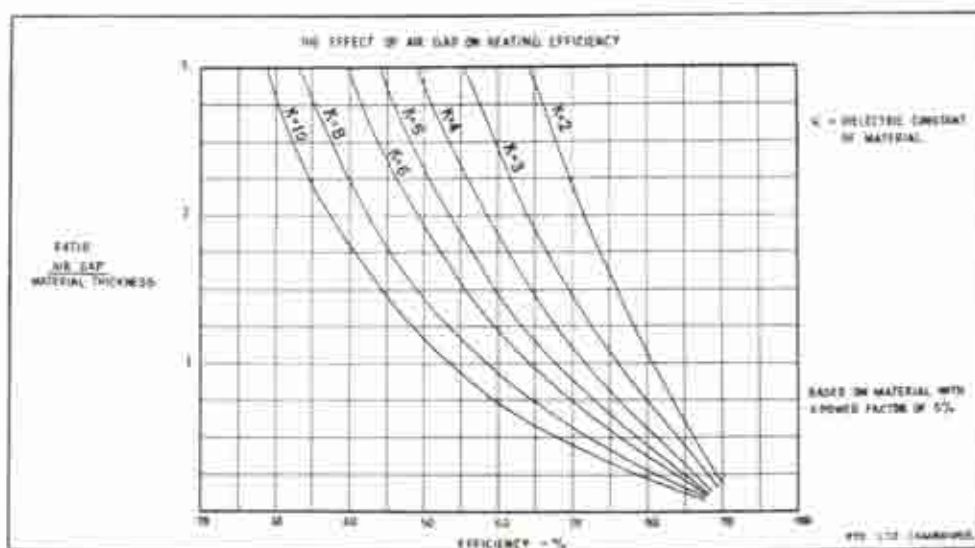
material and/or glue line, in the vicinity of any sharp edge or point. It is for these reasons that tubing is usually used in the making of electrodes, also it is both easy to handle and has enough rigidity to be self-supporting over long lengths. Although tubing has no sharp edges it can be joined in such a way that the junction forms an angle that is nearly a point instead of a radius. Consider an electrode placed so that one part of it is at a right angle to the other. In the incorrect method the angle is probably "mitred" whereas in the correct way the tubing is bent forming a radius. It should be noted that it is only the inner electrode that is bent and not the outer one, as this latter has to contain a right angle, so as to locate the runner or block in its correct position, without putting a radius on the corner of the wood. If the outer tubing is mitred, its "point" is so positioned that it cannot are to the other electrode. The termination of the tubing is another part of the assembly that can cause trouble, as it is here that a sharp edge can occur. The two principle methods of overcoming this difficulty are (a) by putting a radius on the end of the tubing or (b) by terminating the end in a hemisphere. This latter method can be easily accomplished by fixing a round-headed brass screw in the end of the tubing, which will give better results than that of "radiusing" the tubing and gives a better looking finish to the job.

Air Gaps

When the general electrode assembly has been decided upon, some more details must be considered. Due to the general tolerances on the woods and the presence of glue beads some form of air gap is necessary when longitudinal heating (Figs. 17 and 18) is used; as indicated in Fig. 15 by the letters d, or a and e. The result of these gaps is to reduce the effective power factor of the assembly, so lowering the efficiency of the electrode. There are two factors leading to this reduction of efficiency, firstly the dielectric constant of the wood, secondly d/D , that is, the ratio of the total gap size d , to the material size D ; and it is from these two factors that Fig. 21 was computed. As can be seen from this graph, the larger the value of K , the dielectric constant, the lower will be the efficiency of the jig with a stated value of gap ratio. It is evident that to get the best results the air gap must be kept as small as possible, a ratio of $d:D=1:10$ is quite within practical limits and this value should be aimed at.

In order to obtain uniform curing time over the complete glue line when of constant width it is important to keep the air gap ratio as uniform as possible or it will be found that where the ratio is least the curing will occur the more rapidly, causing this section to be over-heated or another section to be under-cured. As shown in Fig. 16, this effect

Fig. 21. Air gap/electrode relationship for material of different values of K .



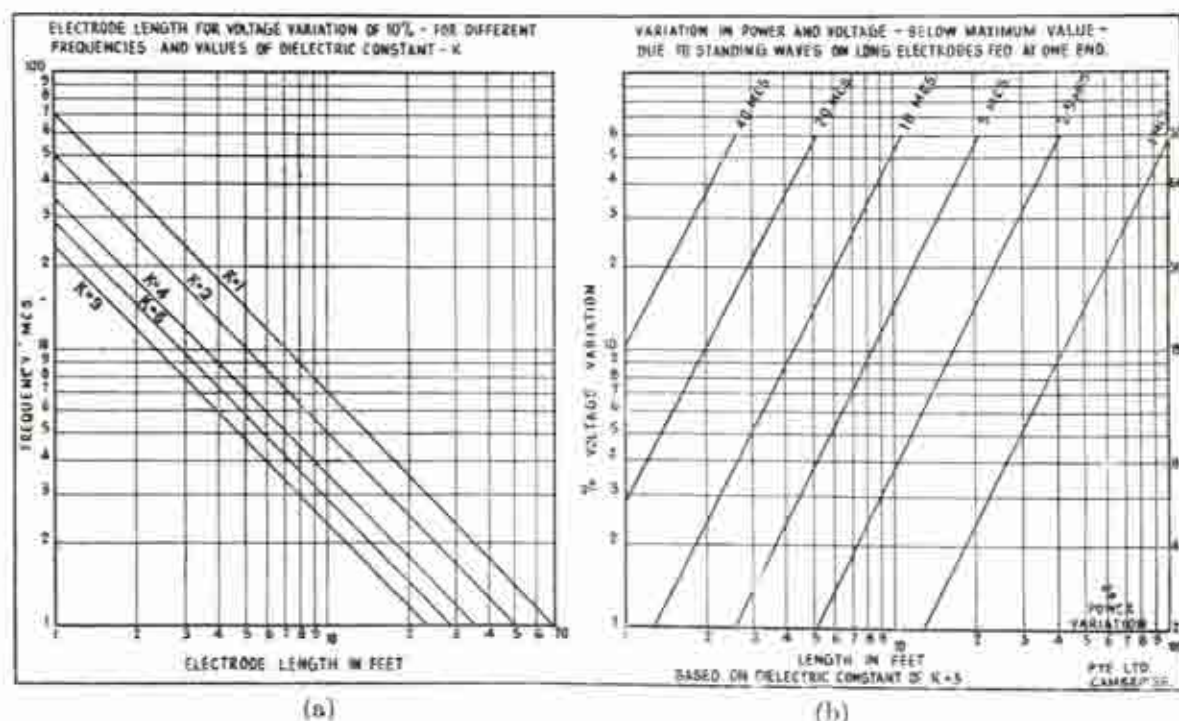


Fig. 22. Electrode length/voltage variation relationship for different frequencies and values of K .

may be used to counteract uneven heating in tapered sections.

Voltage Distributions

Another factor of importance is the length of the electrodes, due to the tendency of the voltage to follow a sine wave form. This means that if a voltage is fed to one of the electrodes, its value will become greater as the distance from the feed point increases, as shown in Fig. 20 (a), where A is the feed point and the maximum being reached at B. As the heat developed in the load is proportional to the square of the voltage (see under *Heating Effect* on page 112), it is customary to keep this voltage variation between maximum and minimum points, below 10 per cent which represents a maximum power variation of 10 per cent; maximum electrode lengths to restrict to this limit for various dielectric constants can be obtained from Fig. 22 (a). Fig. 22(b) shows the effect of electrode length, for a dielectric constant of 3, the average value for wood, on the voltage and power distribution, for certain

frequencies. The reason why the dielectric constant again enters into the calculations is because the wave-length of the voltage variations along the electrodes is inversely proportional to the square root of the dielectric constant.

Example 4

If a generator works on a frequency of 10 Mc/s, and the wood between the electrodes has a dielectric constant of 4, what is the maximum length of electrode from the feed point for 10 per cent voltage variation? As can be seen from Fig. 22(a) this is 4 ft.

Use Fig. 22(b) and the above generator; what will be the voltage variation with a dielectric of 3, for the wood with an electrode length of 6 ft? From this graph it can be seen that the voltage variation is 20 per cent. On the right hand side of the graph it can be seen that there is a power difference of 36 per cent along the work, so that certain parts of the work receive 36 per cent less power.

From the graph it is apparent that in order to reduce the maximum voltage variation, if above 10

per cent, either the frequency must be decreased or the electrodes shortened. One means of obtaining an effective shortening is by centre-feeding the electrodes, thus permitting twice the length of glue line to be set as compared with end feeding. The maximum electrode length may still be further increased by feeding in at more than one point: in Fig. 20(b) is shown a double feed, so enabling, if correctly arranged, 4 times the previously calculated length to be used.

Choice of Generator

In the choice of a generator or radio frequency heating unit there are a number of considerations of which the following are the most essential.

Of first importance is the output power, as this determines the amount of work that can be done in a specified time. If the output is more than is required the unit will not be used to its full efficiency, and the capital outlay will be unduly heavy. On the other hand, if too small a unit is employed time will be wasted, the jig operator having to wait for the curing time to be completed after having loaded the next jig.

Also of primary importance is that the unit should be simple to use, as the operator will probably be unskilled in electronics. This can be accomplished by having as few controls as possible: these can be limited to switches and a tuning or coupling control. The object of the tuning control is to cause the load circuit to resonate or "tune" (for definition see B.S. 204 and 205: 1943) at the same frequency as the generator, in the same way as a radio set is tuned to the frequency of the station that is to be received. The reason for this is that a large voltage will then be developed across the load, which is a necessity for high efficiency.

An efficient equipment can be built that has only one meter to give an indication of the power output. An operator does not then have to glance at three or four meters during every operation.

On a production line a timing control is another necessity and this should be of such a range that it will cover all the times likely to be encountered. It should be completely automatic, starting when the power is switched on, and should switch off the power after the predetermined time and reset itself

for the next cycle of operation, thus all the operator has to do is to press the "On" button after reloading.

A remote control switch that will control the equipment at a distant point is an addition that will save time, as it can be usually more convenient for the jig operator than the switch on the equipment or can be connected as an automatic switch on the safety guard.

ECONOMICS

A typical 3 kW R.F. generator should last about ten years so that depreciation, the maintenance costs, including new valves, lamps, air filters, etc., and electricity for running 40 hours a week, will average at the most £175 per annum. This means £3 10s. 0d. a week or 1s. 9d. per hour. Considering the time that can be saved on operations, both in material and labour, a generator will soon pay for itself. Each application and use in a factory will bring its own queries and differences but after a little experience the operator will soon know the jobs that will be economical and those that are better done by other methods.

In the sticking of thin veneers or making of thin plywood the use of radio frequency normally will be found to be more expensive than using hot platens, especially if heated by steam obtained from the burning of sawdust. This is due to the fact that the time taken for the heat to be conducted to the glue line is short whereas the internal heat in the wood quickly reaches and is dissipated by the cold electrodes used in the R.F. methods.

Where a ply type of bonding of a thickness of $\frac{1}{2}$ in. or more is to be cured, the rate of heating at the centre glue line is slow by means of thermal conductivity whereas by the radio frequency methods the heat is generated internally, so causing the centre to reach a high temperature at the same time as the other glue lines.

When a glue line has to be cured as in Fig. 17, there is great advantage with radio frequency heating as the electrodes can be arranged as in Fig. 17(b) or 19, so heating the minimum of wood. If the steam platen method is used almost the whole volume of wood has to be heated.

In the seasoning of laminae the rate of evaporation of the moisture is faster by radio frequency than by

steam ovens, due to the more rapid rise of temperature at the centre, but large powers are required and the final results are not as good as with the slower methods. (See Forest Products Research Laboratory, Radio Frequency Panel: Summary of Work done since third meeting, R.F.P.4/1, January, 1949.)

As a means of appreciating some of the advantages of radio frequency heating a few examples are given of what can be achieved:

A scarf joint in $\frac{1}{2}$ in. plywood, 2 ft wide, can be completely cured in 10 seconds.

All the runner glue lines, etc., on the back of a 6 ft wardrobe can be set 100 per cent in 80 seconds.

Two barrel staves each consisting of 8 laminae and one veneer can be cured in 2 minutes.

All the glue lines in the assembly of a radio cabinet can be cured in 62 seconds.

From the above figures, obtained with a 5 kW generator, it is apparent that there are distinct advantages to be obtained from the use of this new method of curing of resin glues.

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- (3) The penetration of heat into wood. *Aero Research Technical Notes, Bulletin No. 2*, Duxford, Cambridge, February, 1943.
- (4) Glossary of terms used in electrical engineering, B.S. 203/1943, and Glossary of terms used in electrical engineering, B.S. 204/1943, give roughly accurate definitions of these terms.
- (5) See Physical Tables (Kay and Laby); Smithsonian Physical Tables, Washington, U.S.A. and International Critical Tables

RADIO FREQUENCY HEATING

(PART II. PRACTICAL APPLICATIONS)

J. D. Cable

INTRODUCTION

THE use of Radio Frequency heating generators in the furniture industry for the rapid setting of synthetic resins is becoming increasingly widespread as the advantages of the technique become more generally realised. Possibly the most spectacular application of R.F. heating is in elaborate assembly jigs, where jobs which previously had to be clamped up for hours are removed from the R.F. press in under two minutes. As may be expected the manufacture of the jigs for this work, together with the design of their "electrode" systems requires a certain amount of care and knowledge if successful results are to be achieved. For the great majority of work the requisite knowledge is no more than is obtained from the instructions normally given by the manufacturers of the R.F. generator when the set is first installed. However, occasionally an odd job will come along which, for one reason or another, is not quite so straightforward. It is the purpose of this lecture to show how to tackle these oddities: the jigs which are too large, or too small; the glue lines which are too wide or awkwardly shaped. Wherever tedious mathematics are required, general formulae have been evolved and the results set out in the form of simple graphs. For those interested the formulae have been included in the Appendix.

R.F. GENERATOR

R.F. generators vary in some of their respects, but nearly all of them have two points in common. They

have a certain power output, expressed in kilowatts, which determines the amount of work they can do in a certain time, and a basic frequency which, within varying limits, states what is the rate of oscillation of the output voltage. The output of the machine may come from two terminals on the front of the set, from one "live" terminal and an "earth" connection or from some form of transmission line ending in a matching unit, but whatever system is used the jig maker will ultimately be confronted with two terminals to which he must attach his electrode system, and in most cases there will be some form of matching or tuning device.

HEATING METHODS

There are two main ways of heating glue lines by means of R.F. energy as shown in Fig. 1. Fig. 1(a) shows "transverse" heating, in which plate electrodes are used to raise the temperature of wood and glue together. This method is mostly used for making up flat or shaped plywood panels from veneers. Fig. 1(b) shows longitudinal or "glue line" heating, in which tubular or strip electrodes are laid in such a way that the electric field between them passes directly through the glue line. With the latter method the glue only is heated when power is applied to the electrodes, the wood remaining relatively cool. It is the most efficient form of heating, and is used in nearly all assembly work. Sometimes it is not possible to get an electrode right up to the glue line, and use is made of the stray fields that exist outside an imaginary line joining the

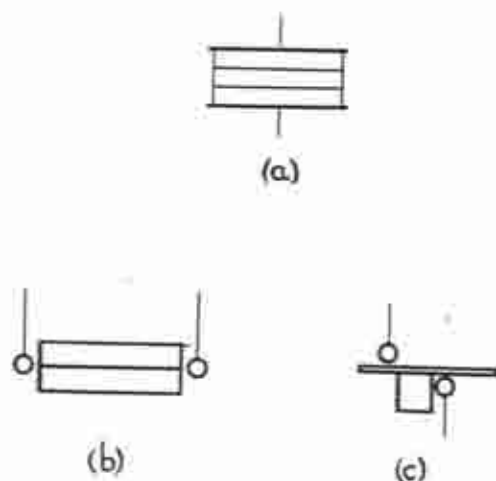


Fig. 1. Electrode arrangements: (a) transverse heating (b) glue line heating (c) stray field heating.

two electrodes. Fig. 1(c) shows such an arrangement, of which there are many forms. Combinations of methods 1(b) and 1(c) are sometimes used in the same jig.

JIGS

The furniture manufacturer will be familiar with assembly jigs. Modification for R.F. heating consists only in the provision of some means of rapid loading, application of pressure and unloading of the work, and the fixture of an electrode system. For large jigs, such as those for gluing the bearers and runners to a fitted wardrobe end, it is usual to construct a press which consists essentially of a steel girder framework which supports compressed air rams above a working table. This table is usually extended sideways at either end, so that the actual work assemblies, which are supported on small wheels, may be run in and out of the framework easily. The wheels drop into slots when the jig is in position for heating, so that the pressure is taken by its flat base.

Sometimes tandem arrangements are used so that while one job is being heated the next one is being glued up in readiness. When the heating cycle is finished the newly loaded jig is pushed forward, ejecting the finished job. For small work clamping pressure is often obtained by means of manually-operated devices, such as toggle action

clamps or wooden cams. In these cases it is best to mount everything on a wooden table and arrange a wire mesh cage to cover the complete assembly. The cage should have a hinged lid or door which is electrically interlocked with the R.F. generator, so that power can be switched on only when it is in the closed position.

Methods vary widely with the details of each job, but some basic points should be kept in mind. The jig has to serve the double purpose of holding together firmly the components to be assembled in their correct relative positions and also acting as a support for the electrode system that is to carry the electric field to the glue lines. The latter requirement must be kept constantly in mind during the design of an R.F. jig with allowance made for proper support and insulation of the electrodes, as well as the provision of connecting leads to the various parts of the electrode system.

ELECTRODES

The electrodes may consist of tubes, strips or flat sheets of metal. They should preferably be of copper or brass. Ferrous metals or alloys such as cupro-nickel should be avoided as they have high resistance to R.F. currents. Copper is the best material in most respects. It is not too costly, is readily obtainable and ductile enough to be bent easily into any required shape.

INSULATION

Since the R.F. voltages tend to heat wood, discretion must be exercised in mounting the electrodes. If they are to be screwed to the jig itself it should be arranged that any path from one electrode to its "opposite number" through the wooden structure of the jig is at least three times as long as the direct path between the electrodes through the glue line, otherwise power will be wasted in producing heat where it is not wanted. Similarly, there should not be a short path from an unearthed electrode or its fixing screws to the metal body of the press or other metallic structure.

If it is practicable, the electrodes should be mounted on some insulating support such as glazed

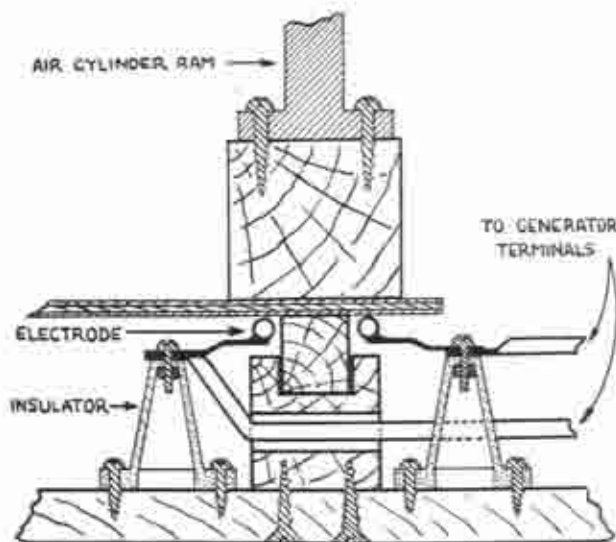


Fig. 2. Diagrammatic through typical fixture assembly jig. (Air gap exaggerated for clarity).

ceramic pillars or blocks of laminated Bakelite of a grade suitable for high-frequency work. If copper tubes are being used for the electrodes the usual method is to solder or braze on lugs which are fixed to the insulators.

The general scheme for a typical assembly jig is shown diagrammatically in Fig. 2. The length of lugs and width of air gap have been exaggerated for clarity of drawing. It should be noted that where a connector has to pass through some part of the wooden jig, it should come through an opening considerably bigger than itself and be supported on either side of the hole in such a way that it does not touch the wood. Points such as this do not have much effect when taken singly, but many small losses can waste a lot of energy.

AIR GAPS

Except in special cases where air gaps are introduced for a particular purpose, they should be kept as small as possible. If the electrode is a $\frac{1}{2}$ -in. outside diameter tube it should be possible to keep the air gap down to $\frac{1}{16}$ in. or less between each electrode and its glue line. This gives a maximum total of $\frac{1}{8}$ in., and the graphs which accompany the text are based on the assumption that such conditions obtain.

ELECTRODE ARRANGEMENTS

Before starting to construct an R.F. jig it is useful to make a sketch of the electrode layout, with clear indications as to where the connecting links will have to be, and where the connections to the R.F. generator will come. A good plan is to consider the generator terminals as being coloured, say red and blue, and then to obtain two appropriate pencils with which to sketch the layout, colouring all the electrodes that are to be connected to one terminal red and all the other blue. This may seem unnecessary in a lot of cases but in complicated layouts it is surprisingly easy to end up with two electrodes of the same "sense" on either side of a glue line!

Exact arrangements will vary with circumstances, but there are certain rules to be observed. The most obvious necessity is that every glue line has an electrode of opposite polarity on either side of it.

STANDING WAVES

Another requirement is concerned with the phenomenon known as "standing waves", whereby

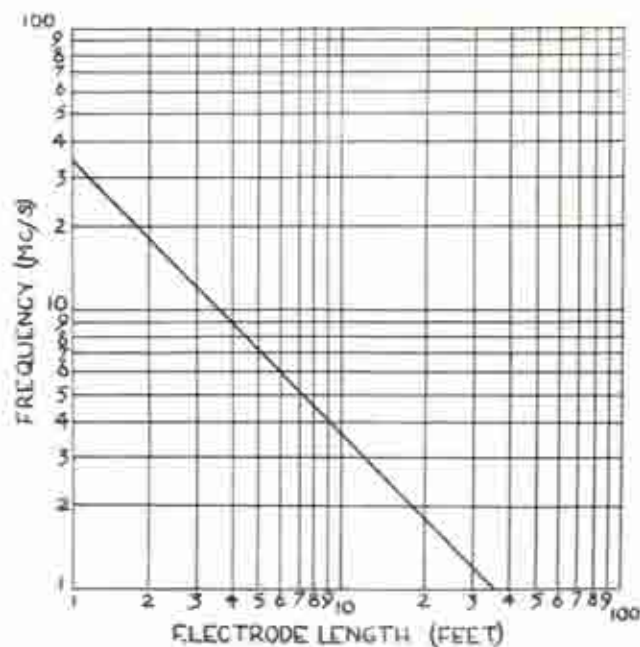


Fig. 3. Graph showing permissible distance from feed point to end of electrode for a glue line jig, at various frequencies.

if an R.F. voltage is fed to a pair of electrodes whose length is a substantial fraction of a quarter wavelength at the applied frequency, the voltage between the electrodes rises as the distance from the feed point increases. This means that if the jig is to heat the glue lines evenly the run of "free" electrode from any feed point must be kept as short as possible. In practice this means that electrodes must be so far as it is practicable, fed at their centres, or if very long at more than one point.

Fig. 3 is a graph which gives the maximum free run of electrode at various input frequencies for a voltage variation of 10 per cent. This implies a power variation of 19 per cent, which is considered to be the maximum permissible in normal circumstances.

From the graph it will be seen that for glue line arrangements at 10 Mc/s the electrode should not run more than 3 ft 6 in. from a feed point.

COLLECTION POINTS

If jigs are fairly lengthy it is generally best to arrange for distribution points from which will radiate feeders to the various parts of the electrode assembly. This ensures reasonably short runs of free electrode from any feed point.

In such an arrangement as that shown in Fig. 4, which represents the electrode layout for a chest end with two shelf bearers, the distances for calculating

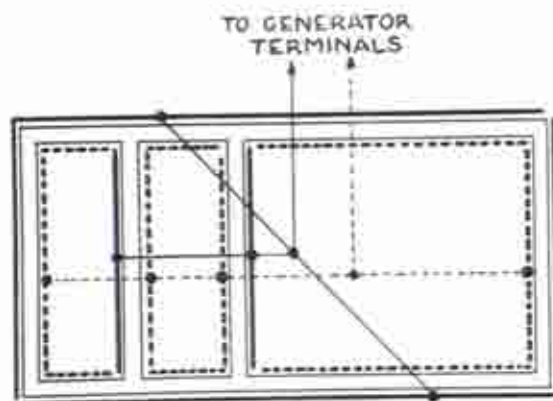


Fig. 4. Jig electrode connections, showing distribution points. Solid and dotted lines differentiate between electrodes of opposite sense.

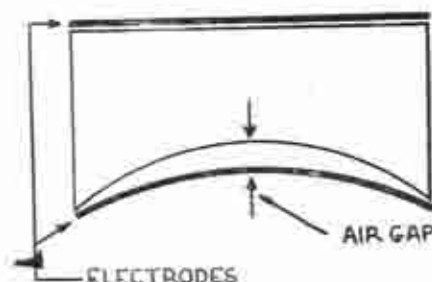


Fig. 5. Electrode arrangement for glue line of varying width showing compensating air gap.

standing wave percentages are not taken from the distribution points, but from the points of connection at the electrodes to the ends. Though it is not apparent from the drawing, the feeds to the two solid line bearer electrodes are kept substantially the same length as the feed from the distribution point to the two outer electrodes by making a downward loop in those connectors.

Where two electrodes of opposite polarity approach each other in a corner, the ends should be curved away from the glue lines. These ends should also stop short of the corner by at least 1 in., the small amount of lost "field" being of no consequence. The purpose of this precaution is to prevent the possibility of an arc through the glue line at a point where a high voltage could exist across a small gap.

Arcing, which is a disruptive discharge between electrodes, either direct or through some intervening conductive medium, should not normally take place in a well-designed jig, though occasional metallic impurities in the wood, or the presence of some substance which gives off a conductive vapour when heated, may sometimes start an arc.

Points to watch are: (a) avoid using any sharp corners or edges in the electrode system; (b) do not run a jig at the uttermost limit of voltage the glue lines will stand—it is better to take a few seconds longer for each curing cycle than to have interruptions while jigs are cleared, with a consequent break in the rhythm of the work; (c) do not use material which has previously been processed with substances conducive to arcing. Some forms of foreign-made blockboard are unable to withstand high R.F. voltages; synthetic glues using phosphoric acid hardeners are also bad in this respect. A few trials will soon indicate offenders.

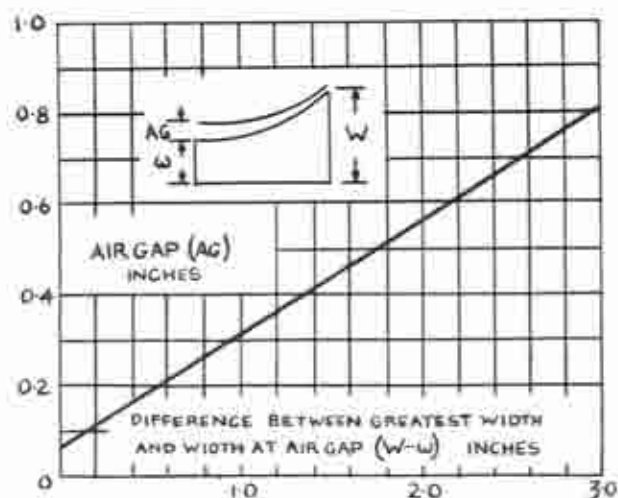


Fig. 6. Graph for obtaining required air gap for glue lines of varying width.

GLUE LINE OF VARYING WIDTH

It may happen that there are glue lines in a jig that differ in width along their length, such as that in Fig. 5.

The rate at which heat is generated by R.F. energy depends among other things, upon the square of the applied voltage gradient. Thus a substance which has 1,000 volts per inch applied to it will heat four times as fast as the same material with only 500 volts per inch. If the electrodes in Fig. 5 were put in position without any air gap and an R.F. voltage applied to them, the gradient at the narrow part in the centre would be higher than at the ends. Therefore, the material at the centre would get more heat. In order to compensate for this an air gap is introduced as shown. This effectively reduces the voltage across the narrower parts of the glue line whilst leaving the ends unaffected. The amount of gap that is necessary can be obtained from the graph in Fig. 6.

Example

A chair back has a rail which is curved on one side. The widest part is at the ends, which are 2 in. At the centre the rail is 1½ in. wide. What air gap will be necessary at the narrowest point? The difference in widths is 2 in. - 1½ in. = ½ in. From Fig. 6 this requires a gap of approximately 0.25 = ¼ in.

If the shape is more complex the gaps at several points along the length of it may have to be calculated separately.

GLUE LINES OF DIFFERING WIDTHS

The air gap method may be used in cases where there are glue lines of different widths occurring in the same jig. Fig. 6 may be used for the necessary calculations as before. However, it must be borne in mind that the large-scale use of air gaps in a jig introduces inefficiencies which may become too serious to be ignored.

If the air space is only to be applied to a small proportion of the glue lines in the job it generally presents the easiest way of dealing with the problem and the drop in efficiency is not enough to cause any concern, but a case may arise where there is only a small amount of wide glue line. For example, a wardrobe end may consist of a 1 in. rail, stiles and drawers, with four 1 in. shelf bearers and one 2 in. bearer. From Fig. 6 it is found that the 1 in. difference in width requires a ½ in. air gap in the narrow parts of the jig. This big gap distributed throughout the electrode system would cause a considerable drop in efficiency. In such cases as this a better method of equalising the voltage gradients is to have no air gaps, but to arrange for the electrodes at the wider glue line to have their voltage raised by the appropriate amount. Fortunately this can be done

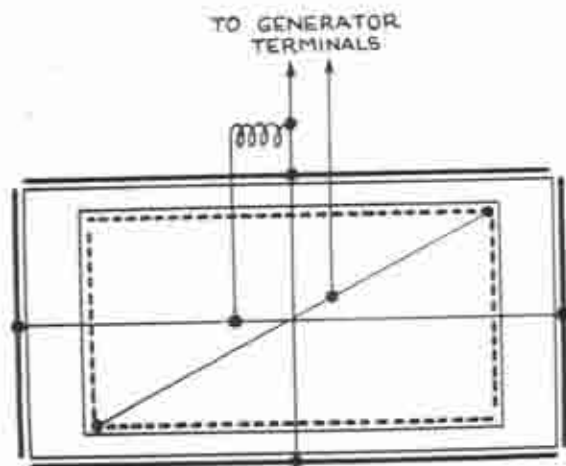


Fig. 7. Connection of coil to compensate for wider glue line.

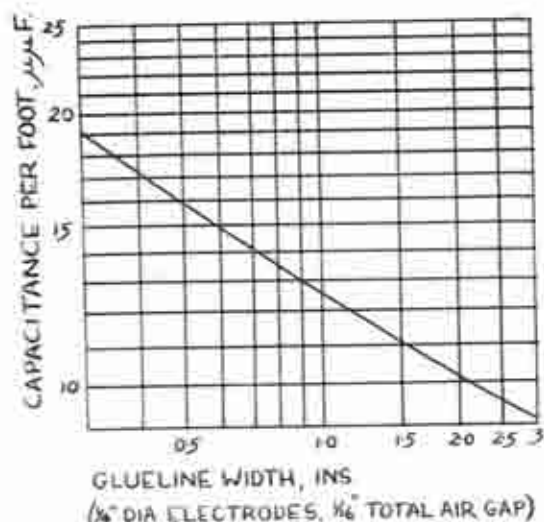


Fig. 8. Capacitance per foot of typical glue line electrode systems (with jig-banded) for various glue line widths.

quite simply by inserting a coil in the connecting lead to one electrode.

The method of connecting a compensating coil is shown in Fig. 7. At a particular frequency, the size of the required coil depends upon two things: (1) the ratio of widths at the wide and narrow parts of the jig, and (2) the capacitance of the electrodes which are to have their voltage raised. A good approximation to the latter can be obtained directly

from Fig. 8, which gives the capacitance per foot for glue lines up to three inches, assuming that $\frac{1}{4}$ -in. electrodes are being used with $\frac{1}{8}$ -in. total air space.

Having determined these two values, the inductance of the coil at 10 Mc/s is obtained from Fig. 9, and the actual dimensions from Fig. 10 which gives the required number of turns of $\frac{1}{4}$ -in. outside diameter tube or rod with a $\frac{1}{2}$ -in. pitch for various diameters.

Example

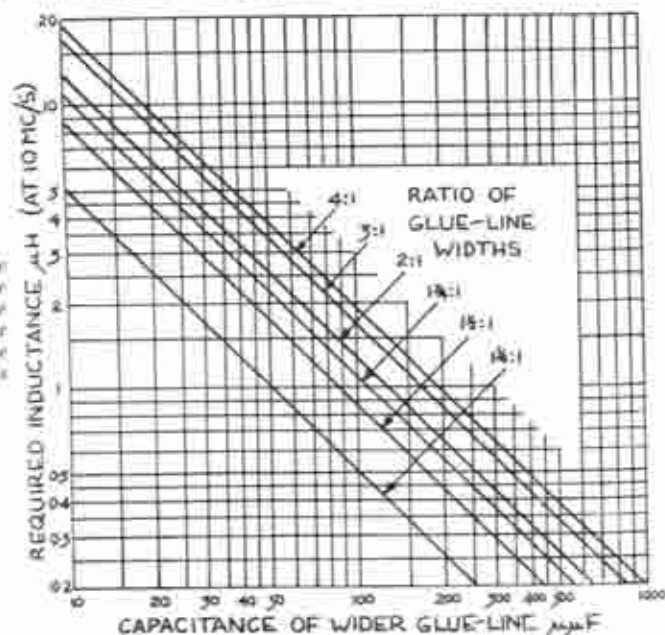
The end and side bearers in Fig. 7 are 2-in. and 1-in. wide respectively. The ends are 3 ft long. What coil will be required to raise the voltage at the ends to the correct value?

The ends are equivalent to 6-ft of 2-in. glue line. From Fig. 8 the capacitance per foot for a 2-in. width is approximately 10 pF. Therefore, the total capacitance is 60 pF. The necessary voltage ratio is 2:1.

Turning to Fig. 9, 60 pF is found on the base line of the graph and followed up until it intersects the 2:1 ratio line. From this point the eye travels to the left to read off the required inductance. In this case the figure is nearly 2.25 mH.

Fig. 10 shows that this inductance may be obtained by winding $4\frac{1}{2}$ turns on a 4-in. former, $6\frac{1}{2}$ turns on a 3-in. former, or $10\frac{1}{2}$ turns at 2-in. The choice of coil

Fig. 9. Graph for obtaining necessary inductance of the compensating coil shown in Fig. 7. After selecting appropriate ratio line note where a vertical line drawn from the point of the base of the graph corresponding to the capacitance of the wider glue line intersects it. From this point a horizontal line to the left-hand scale will indicate the required inductance. This graph applies only to a frequency of 10 Mc/s.



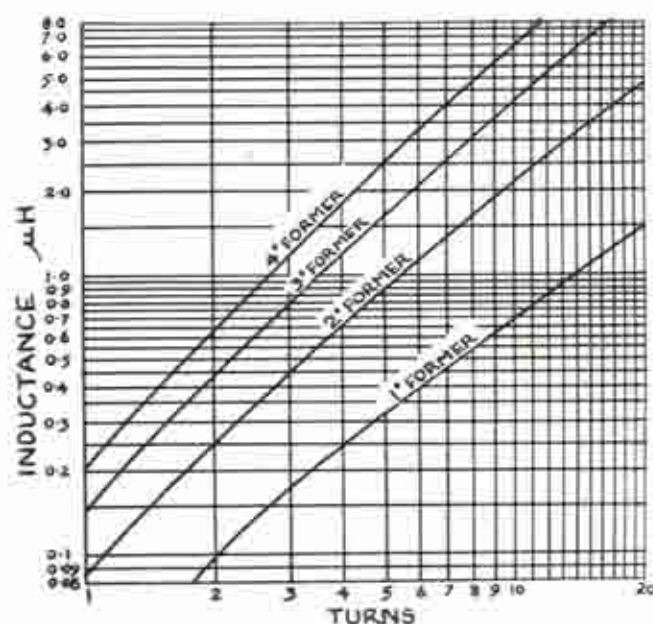


Fig. 10. Graph to obtain number of turns of coil required to produce the desired inductance. The curves referred to four sizes of former on which the coils may be wound. It is assumed that 1-inch outside diameter tube or rod is used, and that the turns are at $\frac{1}{2}$ -inch pitch (i.e. $\frac{1}{2}$ -inch between turns).

is determined by the space available. If this point is not important, preference should be given to the "squarest" coil, that is the coil whose length is most nearly equal to the diameter.

MATCHING

So far all the points dealt with have been concerned with the construction of a jig which will enable the glue lines of the job with which it is loaded to be heated efficiently and evenly when the correct R.F. voltage is applied to the terminals.

This voltage varies from one jig to another, and is determined by many considerations, such as the width of the narrowest glue lines, the rate at which it is required to raise the temperature, the power available in kilowatts, the amount of glue to be heated, the type of resin and hardener being used and other factors. If it is too high there will be overheating or arcing; if not high enough the job will take too long to heat. Somewhere between these extremes lies the correct figure.

Although this voltage is important, it is seldom measured directly, as this would necessitate the use of rather elaborate instruments, such as a valve voltmeter. Fortunately it is fairly simple to adjust an R.F. generator to a jig without knowing the voltage at the terminals by the process of "match-

ing". Before describing this procedure it will be useful to understand why it should be necessary.

The output voltage requirements of an R.F. generator may range from under one hundred to several thousand volts. Also the capacitance of the load may vary from tens to thousands of picofarads. For this reason the manufacturer of the machine must provide some form of output control that will enable these wide ranges to be covered. The usual method takes advantage of the phenomenon of resonance. Electrical and mechanical resonances are closely akin. Just as in a clock mechanism tiny pulses of power in the escapement can build up large potential and kinetic energy alternations in the hair-spring and balance wheel by virtue of being delivered at precisely the right moment to push the wheel in the direction it is turning at the time, so in electrical circuits containing inductance (the "balance wheel") and capacitance (the "hair spring") large currents and voltages can be built up if the applied pulses of electrical energy are delivered just when they are wanted.

When the jig is connected to an R.F. generator it becomes part of a complex circuit containing inductance and capacitance. This circuit includes some portion, usually an inductance, which is variable, and it is coupled in some way to the tank coil of the generator which is the heart of the machine, where

the R.F. oscillations are generated at a certain frequency.

If the variable part of the output is set so that the R.F. voltage peaks arrive always at just the right moment as in the clockwork analogy, then very large voltages can be built up across the capacitances and inductances of the output circuit. The possible voltage rise is limited by unavoidable losses, including the useful loss occasioned in heating up glue or wood.

As the circuit conditions differ more and more widely from the requirement for resonance, so the voltages across the components fall off. It is apparent that this presents a very useful method of control, as there will be some point between actual resonance and being right "out of tune" at which the voltage appearing across the jig (which normally represents nearly all the capacitance of the circuit) is exactly that required for the job. There is, however, a limitation in range. Every frequency has associated with it a certain figure which represents the product of inductance and capacitance which will be resonant at that frequency. For example, at 10 Mc/s it is just over 250, if measurements are in microhenries and picofarads. This means that any combination of inductance and capacitance whose product is 250 will be resonant at 10 Mc/s approximately.

A typical generator has a variable inductance in the output circuit which, together with the pick-up coil and internal wiring gives maximum and minimum figures of eight and two microhenries respectively. This means that at 10 Mc/s resonant conditions can be obtained within a range of capacitances from $250/8=31$ picofarads to $250/2=125$ picofarads, connected to the outside terminals. These figures may be extended somewhat at either end of the scale under working conditions, depending upon how close to resonance it is required to get in order to develop the particular voltage needed.

If the capacitance of a jig falls within the range of the generator's variable inductance, the process of matching is not at all difficult. Invariably some form of output meter is provided with the R.F. set. The jig is connected to the terminals and power is switched on. The meter reading is noted, and if it

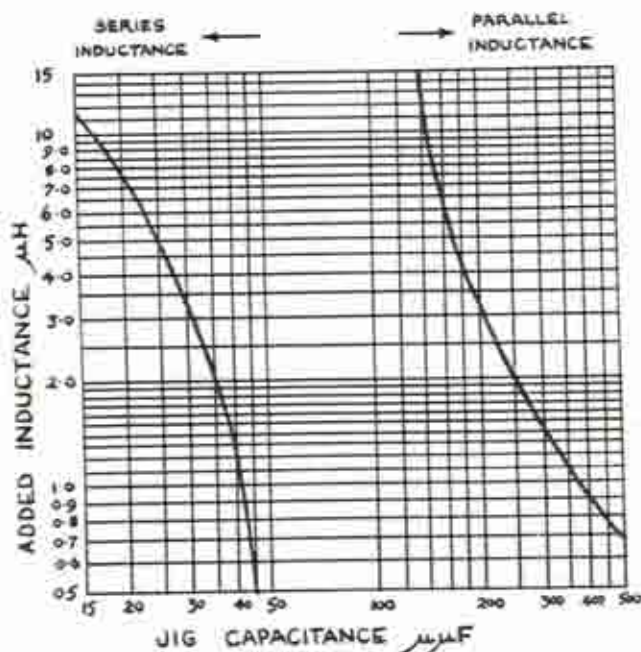


Fig. 11. Graph for calculations of series or parallel inductance required to compensate for too small or too large a jig capacitance. The series inductance curve indicates the coil needed to raise the effective jig capacitance to 50 pF, whilst the parallel inductance curve is for reduction of the effective capacitance to 120 pF. The graph is only applicable to a frequency of 10 Mc/s.

is below the required output figure the variable inductance or other tuning control, is altered. The direction of rotation of the control for an increase of power as indicated by the meter depends upon the capacitance of the jig. The power is increased by this means until the full output of the machine is being delivered provided that the job can absorb this amount of power. This is an important point which should always be borne in mind. The reduction of curing time by increasing power can only be taken to the point when the voltage being applied has risen to the maximum value permissible for the jig being matched. One indication of too high a voltage is first a slight crackling sound and eventually a breakdown in the form of an arc. In some cases damage to the job due to over heating may take place without the visible or audible indications of arcing.

On first setting up a job it is as well to ensure that if an arc occurs it is not due to some local irregularity in the electrode system, such as a sharp corner or edge, as discussed above.

No exact figure can be given for the power absorbing capabilities of any particular arrangement, as so many of the conditions are subject to wide variations, but as a very rough approximation one kilowatt per 50 sq. in. of glue line can be expected in well-designed longitudinal heating jigs.

Capacitance Too Large or Too Small

If when attempting to match a jig to the generator, as discussed in the last paragraph, it is found that moving the variable control to its fullest extent in either direction does not raise the power output sufficiently, it is probable that the capacitance of the job in hand is outside the normal matching range of the generator.

There are several methods of dealing with such a situation. The addition of suitable coils is undoubtedly the simplest, as they are easily made from materials ready at hand.

If very large corrections of capacitance have to be made it is better to consult the makers of the generator, who will advise on the best form of circuit, but for jigs in the range 15-500 pF a graph has been prepared (Fig. 11) which indicates the values of coil required at 10 Mc/s either to reduce large capacitances to an effective 120 pF or to increase small ones to 50 pF, these two figures falling within the matching range of most generators. It will be seen that capacitances which are too small require an added series coil, while those which are too large need a parallel coil. Fig. 12 shows method of connection.

It should be noted particularly that the graph in Fig. 11 applies only at a frequency of 10 Mc/s. For other frequencies recourse must be made to the formula, appearing in the Appendix.

After finding the required inductance from Fig. 11 the coil dimensions may be found from Fig. 10, as in the previous examples.

It is important that parallel coils should be connected as near as possible to the jig, particularly if long leads from the generators are in use.

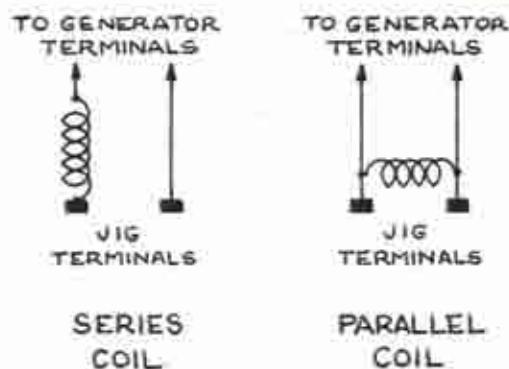


Fig. 12. Connection of series and parallel jig matching coils.

Example

A jig has four 1-in. glue lines 6 ft long. On attempting to match it to a 10 Mc/s generator it is found that reducing the variable inductance to zero still fails to raise the R.F. voltage to the jig sufficiently. What coil will be necessary to bring the effective capacitance within the range 50-120 pF?

From Fig. 8, 1-in. glue lines have a capacitance of approximately 12.5 pF per ft. In this case the total capacitance is $4 \times 6 \times 12.5 \text{ pF} = 300 \text{ pF}$. Looking at the bottom line of the graph in Fig. 11 it is seen that 300 pF is on the right-hand side, and intersects the parallel coil curve at a point corresponding to 1.4 microhenries. Fig. 10 shows that this can be obtained with $3\frac{1}{2}$ turns of coil on a 4-in. former, $4\frac{1}{2}$ turns on a 3-in. former or 7 turns on a 2-in. former. Any one of these coils may be connected in parallel with the jig terminals.

CONCLUSION

It is hoped that the foregoing has not given an impression that R.F. heating jigs are too complex to be tackled by the average furniture manufacturer. Such is definitely not the case. The great majority of jigs are quite straightforward and constructed on plain commonsense principles. The graphs and formulae are given merely to give assistance in those cases which depart from the normal in one way or another.

Undoubtedly the success of R.F. heating as a production tool depends more upon the jigs than on any other factor. The success of the jigs themselves depends very largely on careful, accurate and robust construction, with attention paid to the fundamental principles, particularly those relating to the causes of uneven heating and arcing.

After construction, the mechanical accuracy of a jig should be tested by loading it with the glued up parts, applying the correct pressures and allowing

the resin to set off by itself without the help of R.F. energy. It is possible by doing this to show up faults in the jig which might otherwise be attributed to bad design of the electrode system.

The authors wish to thank the directors of Pye Ltd., Cambridge for permission to give this lecture also to the Editors of "Wood" and "The Cabinet Maker" for using parts of articles that have been published in their journals.

APPENDIX

Fig. No.	Formula	Source
1.	$\sin^{-1} \frac{2.74}{S \sqrt{\epsilon}} \cos \frac{1}{2} \frac{E \text{ min}}{E \text{ max}}$ <p>where: $f \text{ mc}$ = Frequency in megacycles. S = Length of electrodes (feet). ϵ = Permittivity of dielectric is expressed in degrees.</p>	<i>Radio Frequency Heating</i> , by Brown, Hoyer & Bierwirth.
6.	$AG = \frac{W - w}{\epsilon} + ag \text{ min}$ <p>where AG = Air gap required (inches). $W - w$ = Difference between greatest width and width at air gap (inches). ϵ = Permittivity of dielectric. $ag \text{ min}$ = Existing air gap at W.</p>	Author
8.	$C = \frac{8.46 \epsilon}{\cosh d} \text{ pF}$ <p>where C = Capacitance per foot (pF). ϵ = Permittivity of dielectric. d = Distance apart of electrodes (inches). d = Diameter of electrodes (inches).</p>	<i>Reference Data for Radio Engineers</i> , compiled by W. L. McPherson, R.S.E., M.I.E.E., S.M.I.R.E.
9.	$L = \left\{ \frac{1}{4\pi^2 f^2 C} + \frac{w}{W} \right\} 10^{15} \mu\text{H}$ <p>where L = Required inductance. w = Width of narrow glue line (inches). W = Width of wider glue line (inches). f = Generator frequency (Mc/s). C = Capacitance of wider glue line (pF). <i>(This is a simplified formula ignoring the effect of the power factor of the load, which is a small figure occurring only as a square.)</i></p>	Author
10.	<p>The graphs were drawn from the formula $L = F n^2 d$, where F is a complex quantity depending on Nagaoka's constant, but a fair approximation is given by:</p> $L = \frac{\pi^2 n^2}{9r + 10} \mu\text{H}$ <p>where L = Inductance in μH. r = Mean radius of coil (inches). n = Number of turns. d = Length of coil (inches).</p>	<i>Radio Engineers' Handbook</i> , by F. K. Terman
11.	<p>Series inductance:</p> $L = \frac{10^9}{4\pi^2 f^2} \left\{ \frac{C \text{ min} - C}{C \text{ min} C} \right\}$ <p>where L = Required series inductance (μH). f = Frequency (Mc/s). $C \text{ min}$ = Required minimum capacitance (pF). C = Capacitance of jig (pF).</p> <p>Parallel inductance:</p> $L = \frac{10^9}{4\pi^2 f^2 (C - C \text{ max})}$ <p>where L = Required parallel inductance (μH). f = Frequency (Mc/s). $C \text{ max}$ = Required maximum capacitance (pF). C = Capacitance of jig (pF).</p>	Author

NOTE.—Where the term ϵ occurs in the formulae, it may be taken as 3.5 for glue-line jigs. In the formula for Fig. 3, the term $\cos \frac{1}{2} \frac{E \text{ min}}{E \text{ max}}$ is taken as 26°.

COURSE II

*ADHESIVES IN THE ENGINEERING, ELECTRICAL
MANUFACTURING AND ALLIED INDUSTRIES*

DESIGN FOR "REDUX"

H. Giddings

INTRODUCTION

IT must be some seven or eight years since my Company first considered the use of Redux in aircraft structures, but, in common with most other firms in the Industry, it did not make any active use of the technique on its designs for some time, in our case, not before the early part of 1948. Since that date, however, our design study and practical application has been intense, and the process now helps to build four of our current types of aircraft. It is mainly of this experience that I am able to speak, realising that other designers would be quite likely to evolve design solutions different from those that I shall describe.

The use of Redux in design does not involve any specialised theoretical treatment of its own, such considerations forming only a relatively small ingredient in the theoretical design processes applicable to general aircraft structural practice. Nevertheless, a realisation of the fundamental properties of any process is necessary for its proper application in design, and I shall therefore briefly review the basic characteristics of the Redux joint. I shall also discuss the application of Redux to the basic types of structural element in aircraft, to the stiffened panel of various forms subject to compression, shear and bending types of loading. The modern aircraft structure consists principally of this kind of element, which cannot be efficient unless the problems in its design are properly solved.

I believe that by far the greater number of design applications for Redux, will result not from general

theoretical considerations, but more from the invention of *ad hoc* solutions to particular problems, and these will multiply rapidly as experience of the process grows. I have therefore devoted part of my talk to the description of various particular Redux schemes that we have tried during these recent years. Another part of my lecture is devoted to the manufacturing aspects of the process which have to be considered from the point of view of design.

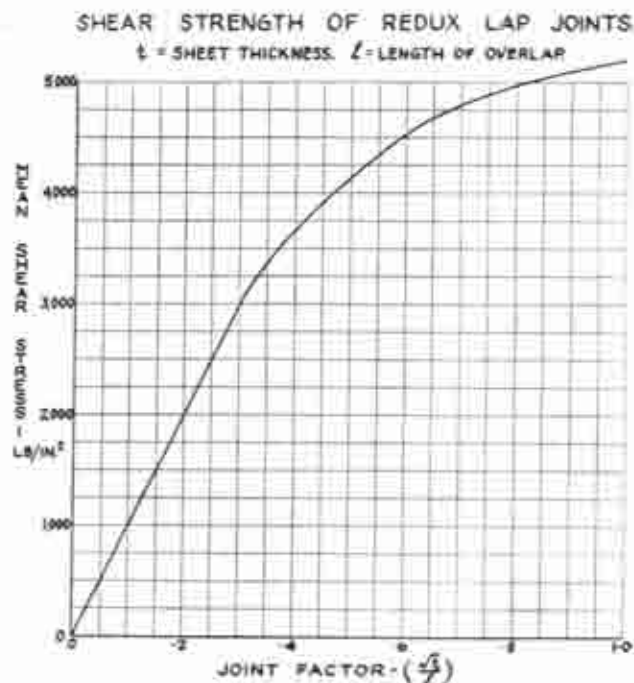


Fig. 1. Shear strength of Redux lap joints.

BASIC PROPERTIES OF THE REDUX JOINT

Static Strength

From the designer's viewpoint the most interesting strength property is that of shear. At room temperature, DTD.775 specifies that the strength of a standard single shear specimen (1 in. wide \times $\frac{1}{2}$ in. overlap \times 20 SWG DTD.546) shall be not less than 1500 lb, i.e. a mean shear stress of 3000 lb/in² must be developed. In practice, failing loads between 1700-2000 lb are normally achieved.

Some years ago Dr. de Bruyne pointed out how dependent the strength of the Redux-cemented joint was upon its dimensions. The shear strength is proportional to the width of the joint, but not to the length of the overlap, and it is also dependent upon the thickness of the members joined. Mathematical analysis and experiment have shown that the relationship between shear strength per unit width of joint, and thickness and length of overlap, is approximately as given in Fig. 1. This relationship is of the greatest significance in considering design applications for Redux, and several interesting curves may be deduced from it. Thus Fig. 2 shows

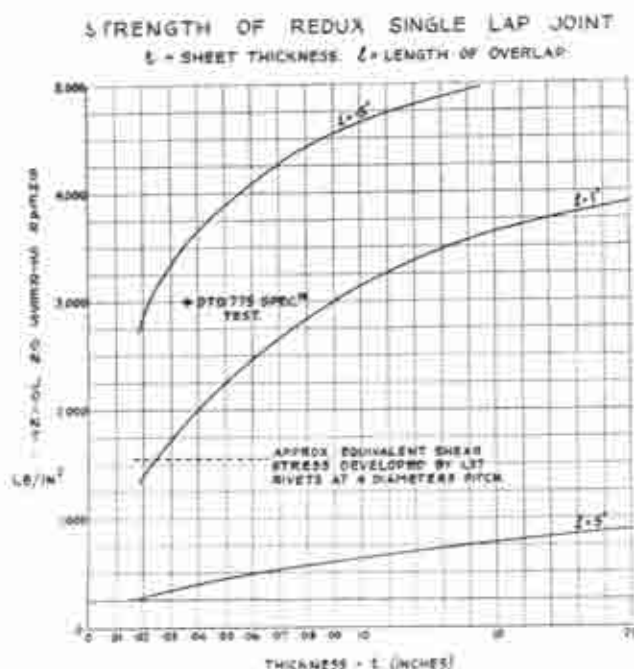


Fig. 2. Strength of Redux single lap joint (shear stress in joint)

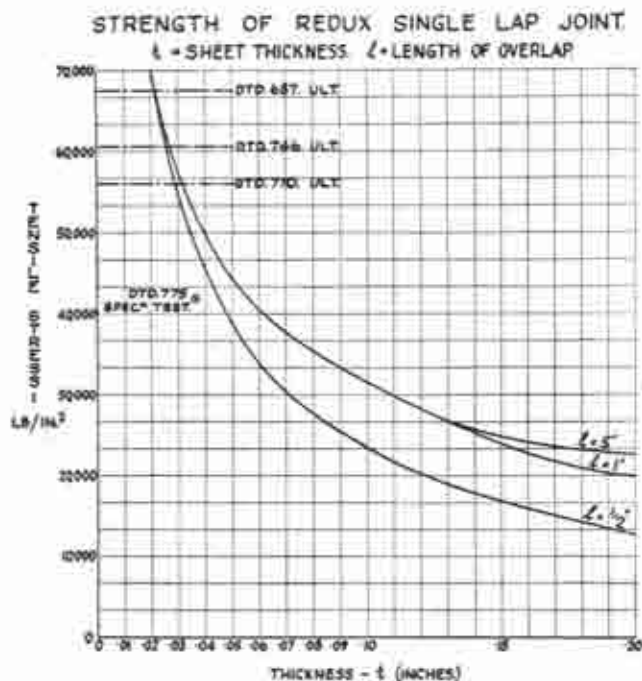


Fig. 3. Strength of Redux single lap joint (tensile stress in sheet)

the shear stress of sheet thickness for various lengths of overlap, and whereas at overlaps up to 1 in. the stress developed exceeds that of a riveted joint, for a 5-in. overlap it is only approximately 1/5th of that of the rivets in 20 SWG sheet. This indicates that the Redux joint cannot be used conveniently for large shear inputs requiring considerable overlap.

Fig. 3 shows the tensile stress developed in the sheet at shear failure of the Redux, against the same parameters. At thicknesses below about 22 SWG (.028in.) it is seen that failure of the sheet will occur and not failure of the Redux, but in thick gauges the stress developed is quite low and increase of lap is of little advantage. This indicates that the Redux joint shows the greatest efficiency when applied to thin sheet, say 16 SWG and below. Fig. 4 shows a similar result when tensile load per inch width of joint is considered and compared with the capacity of the sheet. It also shows that a limit of about 4000 lb/in. width of joint is reached in the Redux joint.

The conclusions are that Redux finds its most efficient applications with thin sheet needing quite short overlap when shear has to be transmitted.

STRENGTH OF REDUX SINGLE LAP JOINT. t = SHEET THICKNESS. L = LENGTH OF OVERLAP.

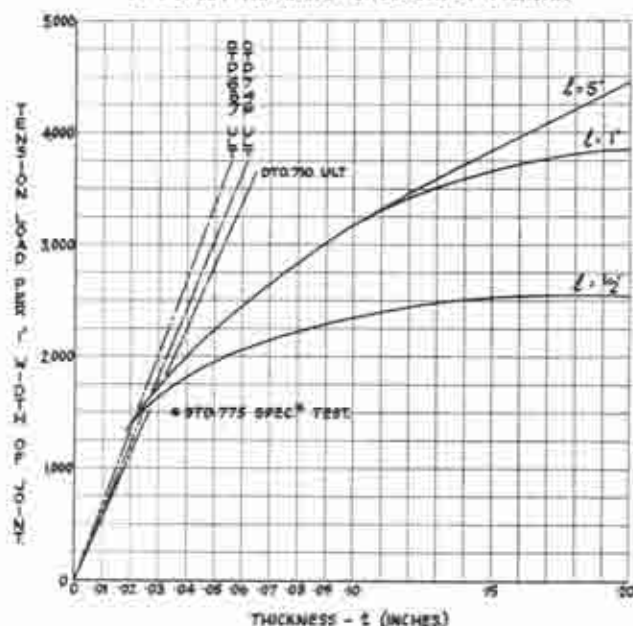


Fig. 4. Strength of Redux single lap joint (tensile load in sheet).

Pure tensile strengths considerably in excess of the shear strength figures can be obtained. The results are however, very dependent upon the uniformity of the loading and the absence of stress concentrations in the Redux. Due to this sensitivity, it is advisable in practice to avoid direct tensile loading of a Redux joint, as of course is normally the practice with a riveted joint.

The ability to withstand stress concentrations, such as may be obtained when one lamination of a joint is peeled from the other, is checked at B.A.C. by a standard "peeling" test. The minimum requirements for this test is 30 lb pull, representing gross misloading or mis-handling; in practice, such loadings are never normally contemplated in design. The "peeling" test thus tends to be a rather severe "quality" control test and is not really of direct interest to the designer.

Fatigue Strength

As far as I am aware the fatigue strength of the Redux joint in shear has not been fully explored, but what tests have been carried out suggest that its performance is little, if anything, worse than that of riveted joints. This view has been borne out by

operating experience, which has been quite satisfactory.

Fig. 5 shows a comparison of laboratory tests on single lap joints riveted or bonded with Redux. The Redux specimens consisted of $\frac{1}{16}$ in. wide $\times \frac{1}{8}$ in. overlap \times 16 SWG and 20 SWG DTD.610 type aluminium alloy, and the results showed no significant variation in strength with thickness.

The load cycle in the Redux tests is more severe, having a higher mean load than the rivet tests, so that it seems fair to claim that at low loadings the Redux life is about the same as rivets, while at high loadings the Redux joint is superior.

The results are plotted non-dimensionally in terms of ultimate strength and the variation of Redux strength with joint proportions should, of course, not be overlooked.

The Effect of Temperature

The range of normal air temperatures considered for aircraft operation is approximately -70°C to $+40^{\circ}\text{C}$. The metal structure of an aircraft parked in the sun on a tropical aerodrome might be expected to stabilize at a temperature some 50°C above the ambient air temperature, i.e. approximately $+90^{\circ}\text{C}$.

FATIGUE PROPERTIES OF REDUX AND RIVETED SINGLE LAP JOINTS. PULT = ULT. STRENGTH OF JOINT

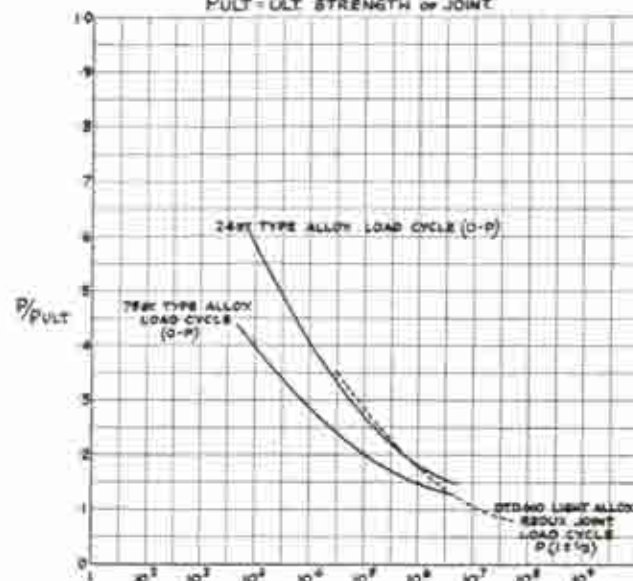


Fig. 5. Fatigue properties of Redux and riveted single lap joints.

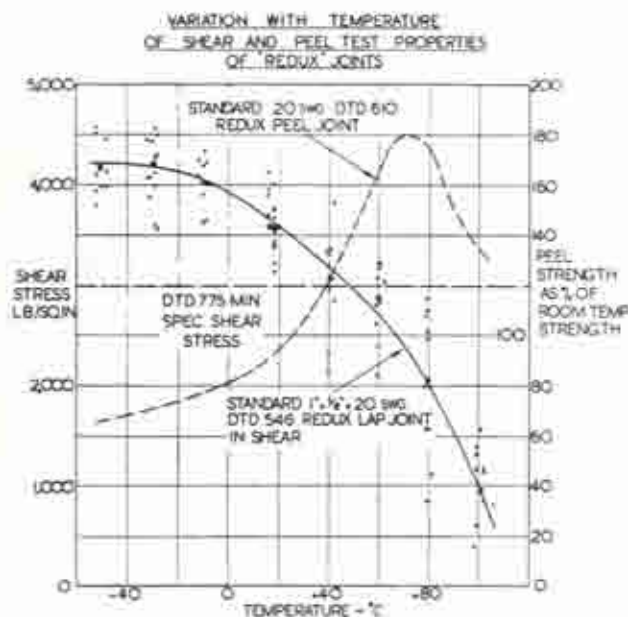


Fig. 6. The effect of temperature on Redux joint strength.

This might vary some $\pm 10^\circ$ depending upon whether the surface is painted or polished. Kinetic heating due to the motion of the aircraft through the air also gives a temperature rise of approximately $(V/100)^2$ in degrees Centigrade when V is the speed in m.p.h. Thus very high subsonic speed low down gives approximately $+50^\circ\text{C}$ rise, and a maximum temperature again of the order $+90^\circ\text{C}$. Thermal de-icing can also require structural temperatures of around $+70^\circ\text{C}$, and perhaps $\pm 20^\circ\text{C}$ depending upon the type of de-icing installation and structure.

The capacity of a Redux joint under this range of temperature conditions has been established in relation to the standard shear specimen, and is shown in Fig. 6. The fall in shear strength with increasing temperature above normal is most pronounced, and it will be appreciated that about $+80^\circ\text{C}$ is the safe useable maximum. Fortunately this is satisfactory for normal applications. Data on the effect of repeated load-temperature cycles are not available, but experience from aircraft in actual operation has so far been satisfactory. It is interesting to note that in peeling strength as opposed to shear strength the trend is reversed, i.e., there is some reduction at low temperature but an increase in strength up to about $+80^\circ\text{C}$.

The conclusion is that in general temperature does not present a problem in the Reducing of the normal aircraft structure, except at some points where conditions are abnormal such as in a de-icing system, or near to jet or exhaust pipes.

Aircraft to fly at supersonic speeds with operating Mach No. greater than about 1.5 would not be suitable applications for Redux bonding of the structure.

MANUFACTURING CONSIDERATIONS OF THE PROCESS

Conditions Required for Bonding

Successful Redux bonding requires the application of temperature and pressure to the joint approximately as follows:—

Temperature range	140–160°C
Pressure range	100–150 lb/in. ²

These conditions have to be maintained for approximately twenty minutes.

The pressure is primarily necessary to achieve mechanical contact between the surfaces to be joined and the Redux film, which has a final thickness of approximately .01 in. We have found that more satisfactory bonds are achieved with lower pressures (around 100 lb/in.²) in the autoclave, than in the rigid platen press.

Curing temperature may be reduced at the expense of increased curing time, but we have standardised on the above combination.

Two points are apparent: materials cannot be used whose properties are adversely affected by a temperature of $+160^\circ\text{C}$, and the type of structure and parts must be such as to allow the safe application of at least 100 lb/in.² in either platen press or curing chamber. With regard to the high temperature, the heat-treated high strength aluminium alloys are just about satisfactory in this respect. Magnesium is also satisfactory from this point of view, but is difficult in another respect, that of preserving "cleanliness" of the surface prior to application of the Redux.

The Application of Pressure

In order to apply the required pressure, the design must either be stable enough to carry it in direct

compression, or must permit the insertion of packing blocks to relieve part of the load. This aspect is illustrated in Fig. 7.

(a) shows a light corrugated construction which is cured in the autoclave. A rubber blanket is used to seal the corrugations, and air pressure is applied over the whole area including the unsupported portion, which must therefore be designed not to wrinkle under the pressure.

(b) shows another construction of sandwich type with corrugated filler. It is obviously impractical to make the transverse faces of the corrugations stable under the pressure of the Redux press, and inserts have to be used. The component thus has to be such that these pieces can be inserted and removed. For this type of work, open sections rather than "hats", and Z's or angles rather than channels are preferred.

In deciding upon particular designs and Reducing methods, care should be taken to minimise elastic distortion under the curing pressure, otherwise "spring back" will occur after curing, with resultant bad finish.

Break-down of Components

Most methods of Redux curing involve the use of fixed plant, presses or autoclaves, and the component has to be taken to these for the curing operation. Thus breakdown of components is necessary for the process, and final assembly has to be effected by the usual methods of riveting and bolting.

Where the autoclave is being used, then the component and bonding jig have to be inserted into the curing chamber and size is therefore limited. Our largest autoclave will take components 10 ft x 4 ft in size, and we find this convenient for most applications. There is also a limitation where press curing is employed, the component must be capable of insertion between the press platens. The area to be bonded may, however, extend beyond the platens and more than one curing operation be employed, with a certain amount of overlap. Recuring of the overlapping portion does not appear to affect the quality of the resulting bond.

The dimensions of the platens of our largest Redux press are 10 ft x 4 ft, and again we find that this serves for a wide range of work. A useful supple-

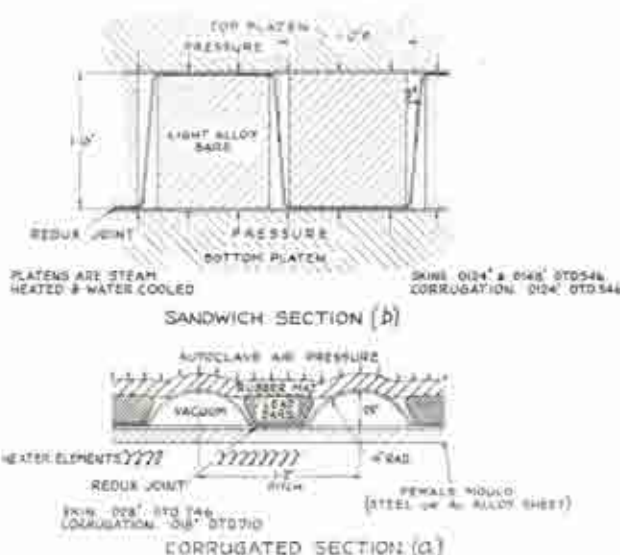


Fig. 7. The application of pressure to Redux joints.

mentary press which we call the "edging press" is used for long narrow strip work, and has dimensions of 17 ft 6 in. x 6 in. and is capable of bonding a reinforcing strip along the edge of the full length of the largest normal sheet.

Portable curing equipment has been developed for Redux bonding *in situ* in the assembly jig, but I have had no experience of this. It is, I believe, quite successful, but I should imagine it would need designing around a particular curing operation and not necessarily form an item of general equipment.

The autoclave is a most useful item of general equipment and parts with double curvature may be bonded in it, the limitation generally being the normal one of shaping the separate parts to be bonded. Air pressure is used in the curing chamber to force the parts into a female metal mould which also contains electrical heating elements. Very exact shape reproduction is possible if the mould is accurate. The moulds need not be expensive and may normally be fabricated from aluminium alloy or steel sheet material, and not machined from the solid.

Tack-riveting

I do not consider that tack-riveting is necessary to reinforce the strength of the Redux bond in any way but it is necessary for two other reasons:—

- (1) As a temporary measure to locate and hold the parts being bonded together after application of resin and powder before the curing operation.
- (2) As a preventative against tearing of unsupported edges comprising a Redux joint, but eventually destined for assembly with other parts. This damage may occur quite easily by knocking against floor or bench etc., between the operations, and is difficult to rectify.

For both purposes, $\frac{1}{8}$ -in. dia. soft aluminium rivets are suitable, these may be left in, or may be removed upon completion of the assembly. I regard tack rivets as rather analogous to the provision of tooling holes on conventional construction, and not primarily a design matter. Locations are suggested by the Planning Department and the Design Office "vet" these and eventually incorporate them on the drawing.

Forming of Redox Joints in Curved Components

Where components have slight curvature in one direction only, then two methods of approach are possible not needing the more complicated procedure of the autoclave.

- (1) The separate parts (e.g. stringer and skin) may be formed to contour, pressed out flat for the curing operation in the press, and then allowed to spring back to the required curvature on removal from the press. The method obviously does not produce very accurate contours, but is quite satisfactory when the part is rather flexible and its final contour is going to be determined by assembly into a rigid supporting structure.
- (2) By curing flat in the press in the normal way and carefully rolling the sheet, including the Redux joint, to contour afterwards. We have found that the Redux bond will stand a surprising amount of work in this way with no apparent deterioration.

In both methods no general rules can be given, an empirical approach to each particular job is necessary.

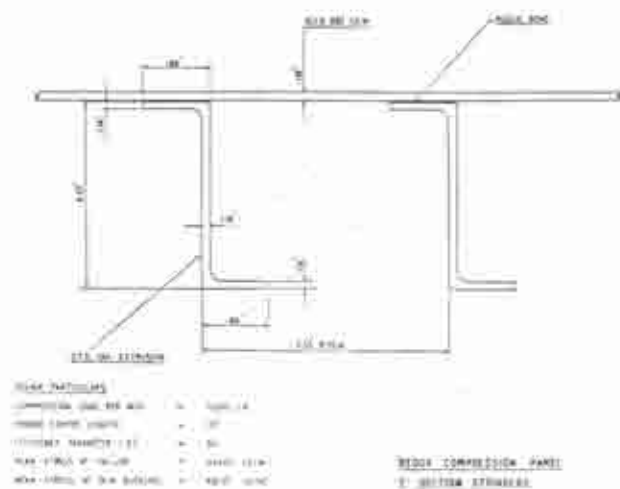


Fig. 8. Reduct compression panel—Z section stringers.

DESIGN APPLICATIONS

General

Apart from the questions of strength the manufacturing aspects of the process suggest that primary joints in a structure do not form suitable applications for Redux. On the other hand there are large areas of structure where strength and manufacturing conditions are both favourable to the use of the process. Thus most present day aircraft structures consist of relatively thin skins or sheet, with large numbers of stabilizing members (stringers, stiffeners, etc.) attached. The requirement for the joint between the sheet and stabilizing member is not generally that of strength, but rather of stiffness and continuity. These requirements are ideally satisfied by the Redux joint, whereas the riveted joint has more than adequate strength, and usually enough stiffness, but is obviously completely lacking in continuity. Possibly some 50-60% of present day structural riveting fulfils this stabilizing function, and could be redesigned for Redux with reduction of weight and improvement in finish.

Riveting gives rise to two types of distortion, one due to setting of the rivet, the other due to buckling under load, and both may be eliminated by proper use of the Redux bond. The continuity of the joint also gives a more uniform stress distribution than is

COMPRESSION STRENGTH OF REDUX BONDED SKIN-Z STRINGER COMBINATIONS.

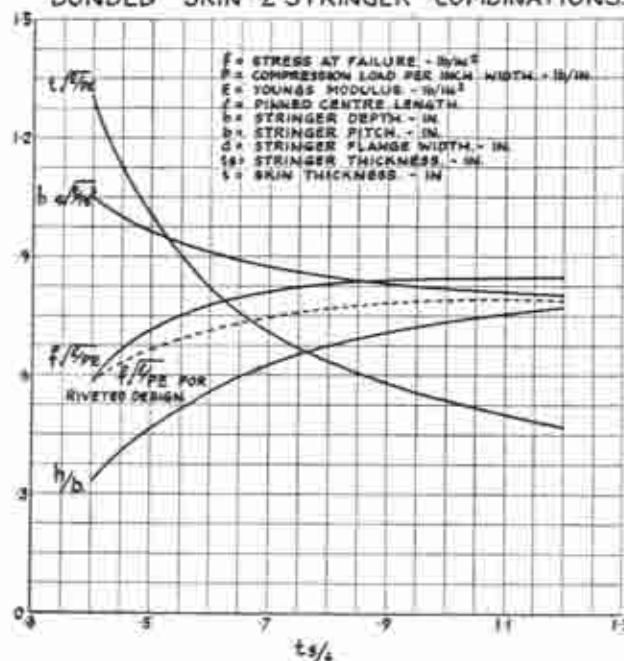


Fig. 9. Compression strength of Redux bonded skin-Z stringer combinations.

obtained by riveting or bolting, and an improvement in fatigue life, particularly with aluminium alloys of high strength, may be expected. Thus thinner materials may be used, e.g. on secondary leading and trailing edge surfaces, fairings, control surfaces, etc., where the minimum thickness would otherwise be dictated by considerations of fatigue cracking at rivets.

The Redux joint obviously has advantages over riveting or bolting in cases where sealing is necessary, such as pressurised fuselages, integral fuel tanks, or flying boat hulls.

In general no new design theory is necessary, but I now propose to discuss briefly the effect of the Redux joint on various types of stiffened skin, where the joint is carrying out a primarily stabilizing function.

Compression Structure

The significance of the Redux joint in the design of stiffened skins in compression is best considered in relation to a particular type of design, and I have chosen the 'Z' stringer for this purpose. Fig. 8 shows a particular design which will serve to

illustrate my general remarks, and I will also be referring to it again later.

Notation b = stringer pitch
 h = stringer depth
 d = width of stringer flange
 t_s = stringer thickness
 t = skin thickness
 l = pinned centre length
 f = design stress at failure
 P = compression design load per inch
 E = Young's Modulus
 K = Compression efficiency parameter

Considering the various types of instability:-

Local instability of the skin (skin buckling), stringer web, or stringer flange is given by the usual relationship.

$$f_c = AK \left(\frac{t}{h} \right)^2 \quad (1)$$

and A is a coefficient depending upon the edge conditions of the skin, web or flange as the case may be, and therefore upon the proportions of the combination. R.Ae.S. Data Sheet 02.01.25 gives values for this, and this solution is not modified by the use of Redux to bond stringer to skin.

Rotation of the stringer section about an axis in the plane of the skin, gives rise to 'torsional instability', strictly only true when the axis is also in the plane of the stringer web. In practice lateral distortion of the stringer usually takes place involving movement of the axis of rotation along the skin plane. This combined type of "torsional cum lateral" instability is more pronounced in the case of riveted panels as a certain amount of lifting of the stringer "heel" from the skin is possible.

Torsional instability stresses are given by a similar relationship to (1), thus

$$f_c = BE \left(\frac{t}{h} \right)^2 \quad (2)$$

and B may again be obtained from R.Ae.S. Data Sheet 02.01.25. In this case however we have found that the Data Sheet results are realised by Redux bonded designs, but not by riveted ones, due to the increased lateral distortion mentioned above.

The types of instability considered so far assume continuous attachment of stringer to skin, and are therefore appropriate to Redux bonded combinations. With riveted designs however, a further

mode of instability involving relative displacements of stringer and skin between rivets may occur (inter-rivet buckling). With proper design of the riveting it is possible, more or less, to eliminate this buckling, so that there need be no difference in this respect between riveted and Redux panels. In cases where insufficient riveting was provided, however, the substitution of Redux bonding would obviously give greatly improved results.

The final type of instability considered, that of overall flexure between the supports, is usually treated on the conventional Euler theory, and is not modified by the use of Redux. Where skin buckling occurs prior to flexural instability, but without precipitating collapse, then allowance is made for this in the Euler calculation. Our practice at Bristol has been to use "optimum" designs based on coincidence of the theoretical instability stresses in the above different modes, at the required failing stress. The application of this condition defines the proportions of the design, and the result for Z designs is given in Fig. 9. A comparison between riveting and Redux for this particular solution is shown. The best results are achieved for values of d/h between .3-.35 and this is not greatly affected by the type of attachment.

The stress at failure is given by

$$f = K \sqrt{\frac{PE}{I}} \quad (3)$$

where K is the efficiency parameter of the design. It will be noted that there is a maximum of "optimum" value, corresponding to a particular geometry. The maximum value for riveted designs is about .79, while that for the Redux design is .84 (both at $t_{\text{min}} \approx 1.0$). The combination shown in Fig. 8 is based on this method of design and has been tested at B.A.C. The mean realised failing stress from two panels was 46,000 lb/in.² compared with the predicted 44,200 lb/in.².

Based on the same design principle the following combination was also tested :-

Skin	18 SWG (.048 in.) DTD.746
Stringers	1.2 in. x .43 in. x .048 in. extruded DTD.364
Pitch	1.50 in.
Pinned support length	= 21.4 in.
Load per inch	$P = 3,890$ lb/in.
	$f = 37,200$ lb/in. ²
	$K = .83$

The achieved mean stress from two tests was again higher than predicted at 41,000 lb/in.²

Panels have been tested in DTD.687-683 materials up to stresses of 50,000 lb/in.² with satisfactory results. Tests have also been done on designs where skin buckled at approximately one-quarter of the ultimate stress. Values of $K=1.0$ are achieved in this type of design. We have also repeated some of these tests at elevated temperature (+80°C) at stresses around 47,000 lb/in.², and the reduction in strength was insignificant (approximately 4%).

Compression fatigue tests with deliberate "bow" of the panel under load, have been made with satisfactory results. All panels tested withstood the design requirement of $1.0g \pm .38g$, for 2×10^6 cycles, without any observable deterioration.

As a result of our investigations we conclude that the Redux bond is in every way satisfactory for such applications in highly stressed compression skin-stringer combinations of "unbuckled" or "buckled" types. Also that the results are predictable by the normal theoretical methods, and that with correct design, improvement over riveted design is possible.

One word of warning—there is some evidence to show that where "plastic" failure of the material is expected at very high compression stresses, as distinct from elastic instability, then the Redux bond is not so tolerant as the riveted joint. Thus designs for stresses in excess of 50,000 lb/in.² in aluminium alloy can be approached with rather less confidence, on our present evidence.

Although my remarks have been based upon the "Z" design, similar considerations and conclusions also apply to the other types of stringer design e.g. the "hat", "Y" and angle designs. The latter type are usually chosen for very lightly loaded applications involving thin skins and sections, and there is some evidence to show a relatively greater improvement with the use of Redux in this type of design than in the other cases. It is difficult in this type of application to get sufficiently close riveting to eliminate inter-rivet buckling.

When considering a "sandwich" type of construction for compression loading, "Redux" bonding again shows to advantage. For a given compression load the use of the sandwich involves splitting the load-carrying material into two faces and a stabilizing core. Thus the thicknesses available are

less and the problem of local instability is worsened. Adequate riveting for an efficient design is again usually not practicable, and has to be "blind", whereas Redux gives very good support conditions for the thin faces.

Fig. 7(b) shows the general proportions of this type of sandwich.

- t_c = thickness of core material
- t = thickness of face material
- h = depth of sandwich
- b = pitch of core corrugations
- k = Radius of gyration per inch width.

Then the local instability of the faces is given by

$$f_{Lc} = CE \left(\frac{2t}{b} \right)^2 = CE \left(\frac{t_c}{h} \right)^2 \quad (4)$$

$$\text{giving } \frac{b}{2h} = \frac{t}{t_c} \quad (5)$$

In practice the use of Redux bonding in this type of design gives nearly clamped edge conditions for the local instability and $C \approx 6.0$.

The proportions of the section may then be determined by equating the local instability and flexural instability stresses, the latter being given by the usual Euler formula,

$$f_E = \frac{\pi^2 Ek^2}{l^2} \quad (6)$$

The type of design shown in Fig. 7(a) may also be used in compression. Local instability is again important and Redux bonding gives effective edge conditions better than riveting.

- t_c = thickness of corrugation
- t = thickness of face material
- R = radius of curvature of corrugation
- C = width of corrugation
- d = width between corrugation.

Local instability is given by

$$f_{Lc} = DE \left(\frac{t_c}{R} \right)^2 \text{ for the corrugation} \quad (7)$$

$$f_{Lc} = FE \left(\frac{t}{c} \right)^2 \text{ for the face across the corrugations} \quad (8)$$

$$\text{and } f_{Lc} = HE \left(\frac{t + tc}{d} \right)^2 \text{ for the face between corrugations} \quad (9)$$

For the proportions indicated D will have a value of approximately .25.

If local instability of both parts of the face is designed to occur at the same stress, then F and H

will have equal values appropriate to pinned edge conditions.

$$F = H = 3.62 \quad (10)$$

$$\text{and } \frac{c}{d} = \left(\frac{t}{t + tc} \right) \quad (11)$$

If f_{Lc} is designed to be large compared with f_{Lc} , then F will approach that for clamped edge conditions ($F \approx 6.0$).

Further consideration of the design may be made on the basis of equation (6) as previously described for the sandwich.

Shear Structure

Redux bonding may be conveniently used for the attachment of shear stiffeners to spar webs and diaphragms under shear loading. No change in design procedure to allow for the Redux is necessary, the proportions being determined in the same way as for riveted construction, the considerations being

- (a) adequate stiffness to prevent combined panel-stiffener buckling under panel shear.
- (b) adequate strength and stability to support the tension field pull in the panel.

A flange proportion of about 30% of the depth of Z, angle, or channel type stiffeners is satisfactory for the Redux attachment.

Corrugated stiffening may be used for shear panels, but very deep corrugations are not practicable due to the necessity for closing the end of the corrugations to take the complementary shears.

We have carried out a shear test on the corrugated section shown in Fig. 10 and failure of the Redux bond and collapse of the corrugations occurred at a shear stress of 23,000 lb in.². Visual buckling occurred at about half this stress.

The corrugated design of Fig. 7(a), and sandwich design of Fig. 7(b) can also be efficiently used in shear and give similar results.

Shear reinforcing plates on spar webs etc., are very efficiently attached by Redux, the buckling stress being that appropriate to the combined thicknesses. Thus a "doubling plate" will increase the shear buckling stress by nearly 4 times.

This is extremely useful where stiffness is important, as there is an effective drop in the shear modulus of some 30-40% immediately buckling takes place. This is particularly important on spar webs which

usually make a big contribution to the torsional stiffness of a wing.

Bending Structure

The corrugated and sandwich type designs of Fig. 7(a) and 7(b) may also be used for bending loads such as would arise from lateral loading of panels due to aerodynamic, pressurisation loads etc.

Similar considerations of local instability as discussed under compression-loading apply. In this case, however, they have to be combined with the consideration of bending strength, determined in the usual way.

Based upon these considerations the proportions of the sections may be varied to give minimum weight, noting that as overall depth of section is increased, for a given bending moment, the weight of face material is reduced, but the weight of stabilizing or core material is increased. There are thus optimum proportions for the given bending strength. The particular design of Fig. 7(a) has been tested to a failing B.M. = 125 lb/in. per inch width, while that of 7(b) failed at 1100 lb/in. per inch width.

Fig. 10 shows a design which has been evolved for a fuselage pressure diaphragm. The factored design pressure loading was 22 lb/in.² giving a B.M. of 184 lb/in. per inch. The design was tested to failure at the design B.M., giving a compression stress in the crown of 29,000 lb/in.². The buckling stress in the crown of the corrugation under the bending distribution of stress is given approximately by

$$f_L = .12E \left(\frac{t_c}{R} \right)^2 \quad (12)$$

A difficulty about these corrugated designs of the deep type arises at the support, i.e. where there is a concentrated shear input. Effective measures must be taken to get the local load into the corrugated section, other than by pure crushing of the section locally.

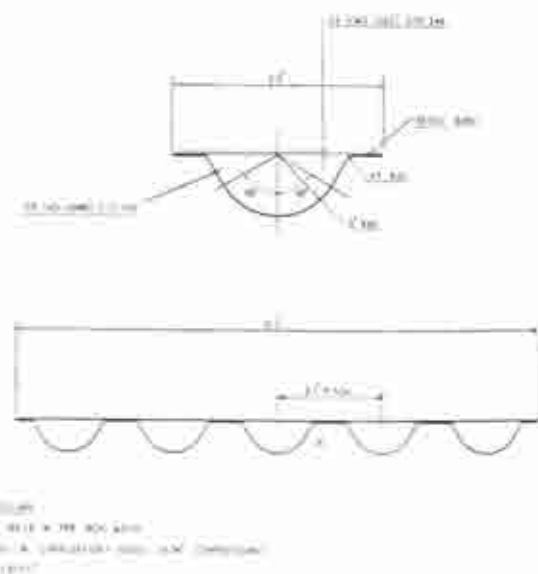
THE USE OF LAMINATIONS

The advantage of the use of Redux for the attachment of shear reinforcing plates to spar webs etc. has

already been referred to. Redux may also be used with advantage to reinforce tension members. Riveting reduces the efficiency of a tensile reinforcing plate, whereas with Redux the full areas of main member and laminations are retained, and also the effect of rivet-slip avoided. The fundamental properties of the Redux joint must however be remembered, the reinforcing being built up from thin laminations and small overlaps. Thick laminations must not be used.

We have used this technique very successfully in the very arduous application of tensile fatigue specimens where the problem is to prevent fatigue failure at the grips instead of at the test section. In this application the Redux-bonded laminations have successfully stood up to a great deal of fatigue testing.

Another important application for Redux bonded reinforcing strips is in building up the sheet thickness locally to that necessary to compensate for the effect of the holes in a primary riveted or bolted joint, or to allow the use of simple cut-countersinking in providing a flush surface.



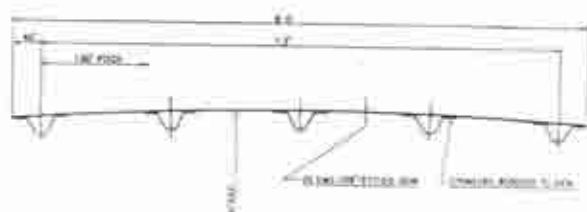
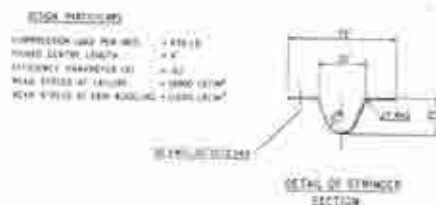


Fig. 11. Redux bonded skin-stringer combination for helicopter blades.

MISCELLANEOUS DESIGN EXAMPLES

Metal Helicopter Blades

The principle design requirements for a helicopter blade are as follows:—

- Static bending strength
- Static tensile strength
- Flexural and torsional stiffness
- Accurate finish
- Accurate balance
- Fatigue strength
- Low weight.

A metal blade satisfying these requirements is a difficult proposition, but the use of Redux bonding is of considerable help. Our solution consists of extruded and machined aluminium alloy leading-edge spar and trailing-edge sections, light pressed-ribs, and a Redux bonded light stiffened skin riveted to these members by a special process.

A section of the stiffened skin is shown in Fig. 11 and the very light, almost "miniature wing" construction should be noted.

The rib pitch is 4 in. and the 26 SWG (.018-in.) skin is Redux-laminated locally on the inside for attachment to ribs and spars by cut-countersunk riveting. Avdel rivets are used and the heads are milled flush after setting. The skins are also heavily reinforced at the root by Reduxed laminations for attachment to the root fitting.

Compression tests have been carried out on the skin panels with the following results:

f_{mean}	= 10,000 lb/in. ²
f_{buckling}	= 11,000 lb/in. ²
Compression load P	= 436 lb/in.
Efficiency parameter K	= .62

A fatigue test has also been successfully carried out on a complete blade section, with a fluctuating torsional load superimposed on a steady tensile load. Fatigue failure of the skins eventually occurred without failure of the Redux bond.

The finish achieved on the blade is excellent.



Fig. 12. Redux bonded "Freighter" wing specimen.

top and bottom skins and completed as panel assemblies, the spar webs being assembled in position subsequently, using Avdel riveting. An alternative design of braced intermediate or stabilizing spars is also possible.

The leading edge uses an interesting Redux technique to bond the densified wood ribs to the metal skin: this may also be used for other applications. Strips of paper are Redux-bonded to the inside of the skin in the appropriate rib positions while the skin is flat. The skin is then formed to the leading edge contour and the paper lightly buffed off leaving the cured Redux film. The ribs are then glued in position to the Redux film using ordinary wood gluing technique.

The trailing-edge structure is built as a Redux bonded sub-assembly of top and bottom skins, flanged ribs, and rebated trailing edge section. This is all Redux-bonded in one curing operation in the flat press with suitable internal and external packing blocks. The leading and trailing edge sub-assemblies are then Avdel-riveted to the main spar box structure, the rivets being milled flush after setting.

Servo-tabs

Control-surface servo tabs have to satisfy mass balance requirements to prevent flutter. These requirements are normally satisfied by the addition

of mass balance weights at the leading edge. The main control surface, including tab, also has to be mass balanced, so that the weight added to the tab is also multiplied and added to the main control surface. These mass balance weights can easily amount to hundreds of pounds in weight per aircraft, and the most profitable method of reduction of this is by reducing the moment of inertia of the tab.

The requirement for the tab mass balance takes the following form

$$X \frac{m\bar{x}}{I_c} < Y - Z \frac{I_T}{I_c} \quad (12)$$

where X, Y and Z are constants

$m\bar{x}$ = tab mass moment about tab hinge line, +ve when tab C.G. is behind hinge.

I_T = Moment of Inertia of tab about tab hinge.

I_c = Moment of Inertia of control surface and tab about control surface hinge.

Generally $m\bar{x}$ will have a positive value, (without the extra mass balance) and it is possible to satisfy the above equation, not by adding mass balance, but by reducing I_T (tab moment of inertia).

It should be noted that adding tab mass balance increases I_c i.e. makes the criterion more difficult. Also, that if by bad design I_T is made large then the extra mass balance required is also large. The requirement can be met, and extra mass balance dispensed with, if the tab is built of very light skin, and this can be done much more easily if Redux bonding of skin to the supporting structure is carried out.

Fig. 14 shows a Redux bonded servo tab which we have designed with the above requirement in mind. The construction is quite simple, consisting of a shaped leading edge 22 SWG (.028 in.) skin Redux-bonded to light flanged ribs; a one piece trailing edge 30 SWG (.012 in.) skin Redux-bonded to close pitched (3 in.-4 in.), but very light flanged ribs, and these are both Avdel riveted to a relatively heavy spanwise channel spar approximately on the hinge line.

The finish is very good, the tab is quite "solid", strength and stiffness requirements are met, and no mass balance penalty is incurred.



Fig. 14. Redux bonded servo-tab.

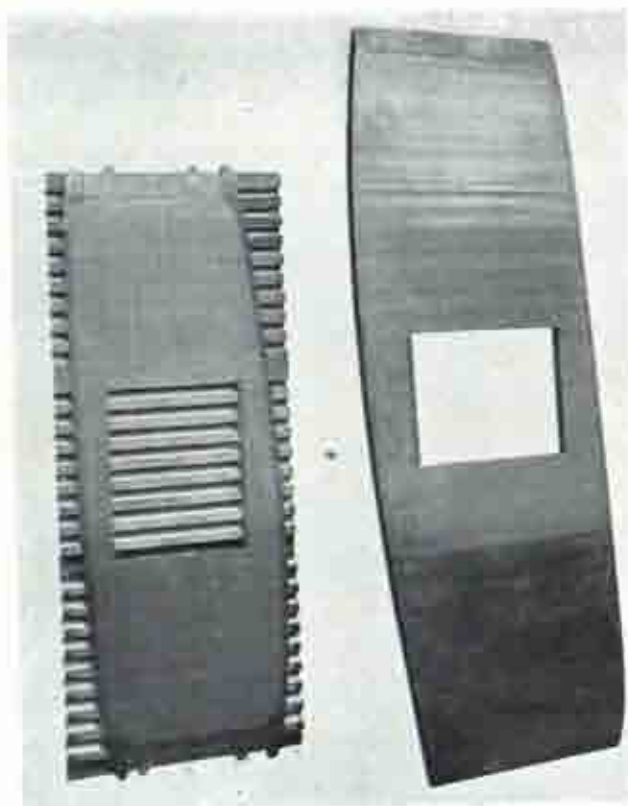


Fig. 15. Redux bonded wing rib.

Wing Inter-Spar Tank Ribs

Lightweight flexible bag type fuel tanks are now fashionable for civil aircraft, and it is important that the walls of the tank cells should be smooth. Normally, wing interspar ribs and spars form the tank cell walls, and the design requirements for the ribs become quite difficult, as follows :—

- (a) Shear strength.
- (b) Tensile-compressive stiffness in vertical plane of rib to stabilize wing skin and stringers.
- (c) Crushing strength across rib for 'high g ' case, tanks full on both sides of rib.
- (d) Bending strength of rib for high ' g ' case, tank full on one side, empty on other side.
- (e) Flush finish.
- (f) Light weight.

The sandwich design of Fig. 7(b) is a very efficient solution to the problem, and a picture of a complete rib is shown in Fig. 15. The design of this type of sandwich has already been discussed and its applica-

tion to this particular case is quite straight-forward. The comparison of the specific weight of the Redux sandwich and alternative riveted design previously used is as follows :—

Conventional riveted design	1.5 lb/ft ² area
Redux bonded sandwich	1.2 lb/ft ² area

Fuselage Pressure Bulkheads

The fuselage of the modern pressurised aircraft usually contains large areas which, from the layout point of view need to be flat, and also have to carry a high pressure differential. This may be as high as 10 lb/in.² operating, and 20 lb/in.² factored. The operating pressure is sustained for long periods during flight, and also is repeated in every flight, thus having a fatigue aspect. Flat skins supported conventionally are subjected to quite high bending and membrane stresses at the point of support, and we have found it impracticable to reduce these stresses below the elastic limit of the material at the operating pressure, without a severe weight penalty.

The most attractive solution is to provide a distributed support to the panel, and Fig. 10 shows a convenient way of doing this with a Redux bonded corrugated design. The stresses in the panel at operating pressure are quite satisfactory from the fatigue point of view, and the weight is equivalent to that of an 18 SWG (.048 in.) thick single unsupported diaphragm (.7 lb/ft²).

CONCLUSIONS

Summarising the results of this experience, I believe that, despite fundamental limitations of the "glued" joint, and present manufacturing limitations, there is a wide field of aircraft structure where Redux bonding offers a more efficient design solution than conventional fabricating methods.

It is reasonable and convenient to adopt the Redux process in two stages :—

- (1) Firstly, on secondary structure such as internal floors and bulkheads, leading and trailing edge surfaces of wings and tail units, fairings, cabin and undercarriage doors etc.
- (2) Secondly, for secondary joints in primary structure. The principle example of this application is the bonding of the stringers to wing, fuselage and tail-unit primary structures.

Whereas these form the principle applications, there is no lack of reliability in the process to preclude use in primary joints where suitable applications can be found.

No new design principles are involved in the use of Redux bonding, but careful appreciation of the strength and manufacturing characteristics of this type of joint must be made at an early stage. Conversion of orthodox designs does not give the best results.

Improved finish, less weight, and better fatigue performance should be obtained.

The weight saving on the applications in stage (1) above may be as high as 25%, and in stage (2), relatively less at some 5-10%.

Finally I would thank the Bristol Aeroplane Co., for permission to give this lecture, also those of my colleagues who assisted me in its preparation, and those who have taken part in the developments with which I have dealt.

PROCESSES USED IN BONDING METALS

F. H. Parker

This lecture is based upon a Paper read before the Royal Aeronautical Society and is reproduced by kind permission of the "Journal of the Royal Aeronautical Society".

INTRODUCTION

THE Bristol Aeroplane Company first took an active interest in metal bonding at the beginning of 1948. Naturally a start was made on available materials which were fully approved under DTD.775 and the combined use of these materials is known as the "Redux" Process. We started, and have since found no reason for change, by using the combination of "Redux" Liquid K.6 and Powder conforming to 30-52 screen, B.S. 410-1943 and except where otherwise stated these are the materials discussed. Experiments over the past three years have disposed of many doubts regarding the reliability of bonded structures for aircraft and we have now satisfactorily determined what is and is not important.

I will now endeavour to describe the steps taken to reach this satisfactory position.

CURING EQUIPMENT

The Miniature Press

Our first press was quite miniature. It consisted of a laboratory moulding press, with a platen size 7 in. x 7 in. This equipment proved quite useful in reaching first approximations but anyone starting the method is advised to set up a rather larger pilot plant capable of curing ten specimens simultaneously as a more representative number. This press should have all the mechanical and heating settings capable of being accurately pre-set and controlled, thus allowing a methodical check on the several factors outside its mechanical operation, for example, control of glue thickness, exact repetition of loading, heating cycle, etc.

As stated, we accepted the standard shear strength figure of 1,500 lb (D.T.D. 775) as a minimum for the selected resin and our first task was to try out the sequence of processes on a small scale in accordance with the manufacturer's instructions using first the press curing technique.

At the outset we realised that the flat platen press had a limited application, thus, we decided that a method capable of wide application would need to be developed to cover, for example, the case of surfaces having severe double curvature. This led through stages to be described to the present successful Autoclave method.

Both in the description above of elementary apparatus and in the ones that follow, it will be noted that no figures for pressure and temperature are given. This subject is dealt with in the section of the paper headed "Curing."

First Pressure Box

Concurrently with the press work described we put in hand the first experiments with fluid pressure curing. A box was used consisting of two chambers capable of being clamped together one on top of the other. The lower chamber was used as a steam cavity to heat the work specimen. The space in the upper chamber was loaded first with a metal die conforming to the shape of the part to be formed, then the component, on top of which, and restrained by the walls of the chamber, was placed a rubber bag which, when pressurised from a supply, gave the required pressure on the work specimen. With increase in size this equipment would become more and more unwieldy, whilst the rubber bag would be very expensive and easily damaged.

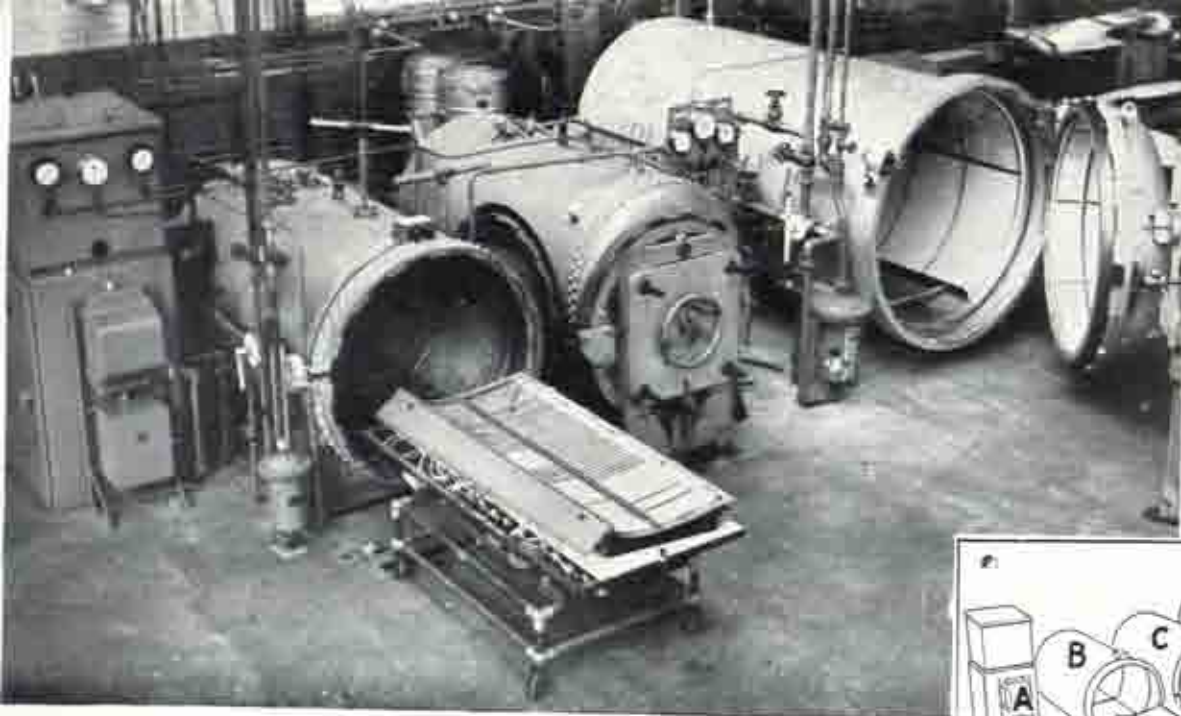
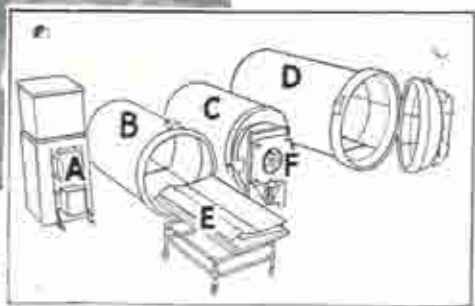


Fig. 1. Autoclaves for Redux bonding (The Bristol Aeroplane Co. Ltd.)

A Electrical control gear, B Autoclave No. 1, C Air receiver, (Common to both Autoclaves), D Autoclave No. 2, E Offloading trolley with jig-assembly, F Door for Autoclave No. 1.



This crude start established the principle of fluid curing and the necessity for fitting accurately male and female dies with the attendant great cost, was avoided, whilst uniformity of pressure all over the component was assured.

The Autoclave

The next obvious step was to abandon a system in which the air pressure was applied unilaterally and to evolve a bilateral method in which it provided its

own reaction. This was done by immersing the parts to be bonded in compressed air, taking special care that no air could get between the faces to be joined together so that this cavity remained at atmospheric pressure. Thus the autoclave process was evolved.

A miniature test autoclave was made from an 8-in. diameter steam pipe 18 in. long, together with a special type of electrically heated jig, and a process

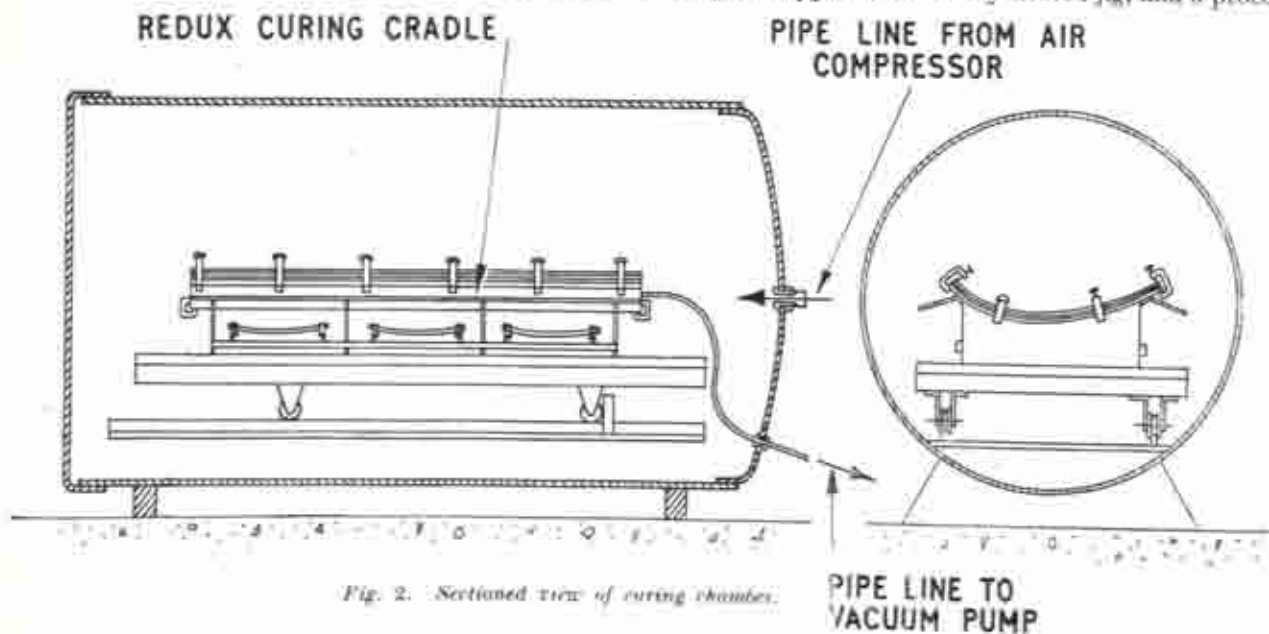


Fig. 2. Sectioned view of curing chamber.

was evolved which proved satisfactory and capable of being reproduced immediately afterwards to a larger size without any further difficulties arising. Thus in one step, with practically no change of method, the full-scale equipment was established.

Fig. 1 shows the full size equipment. Reading from left to right is the first full size autoclave with door open and a jig ready for entry. The next unit is a high pressure air accumulator which, using only a small capacity compressor, allows a very quick charge to be made to the autoclave: to the right is a larger autoclave also charged in sequence from the same accumulator.

The next illustration, Fig. 2, gives an idea of the arrangement of the jig within the autoclave, whilst a further drawing, Fig. 3, illustrates the make-up and operation of the jig. This consists of a light (14 s.w.g.) aluminium alloy plate conforming to the final shape of the component, attached to a number of cradle frames to hold it to form. Immediately under the jig plate, woven electric elements are fitted to provide the necessary heat.

The component to be cured is laid on top of the jig and this in turn is covered with a thin $\frac{1}{4}$ in. thick rubber sheet which is clamped down around its edges. A vacuum line is attached to the base of the jig communicating with the cavity between jig and rubber blanket. The sequence of operation is as follows:—

The jig is loaded as described, electrical and vacuum connections are made outside the autoclave. Vacuum is then applied: this evacuates the rubber blanket and in addition completes the edge sealing of the rubber thus creating the required differential pressure across component and jig, which on being confined in the autoclaves can be brought up to any required curing pressure.

It should be noted that with the form of structure illustrated, in calculating the required curing pressure on the joint, consideration must be given to the proportion of surface being bonded to the total area under uniformly distributed air load since the glue line area provides the sole reaction for the whole of this force; thus with a typical corrugated structure as shown, where glue area is approximately a third the total area under pressure, only 60 psi pressure is required in the autoclave to give a bonding pressure on the joints of 180 psi.

In passing it should also be noted that all electrical connections to the supply source are made automatically when the curing-jig cradle is passed into the autoclave and all the necessary safety precautions both with regard to compressed air supply and electrical supply are incorporated in the door-closing mechanism.

The Platen Press

While the autoclave process was being thoroughly established, the platen press was not neglected. At the moment a 250 tons press fitted with 2 in. thick precision steam heated platens 6 ft x 3 ft is in use.

This is shown in Fig. 4 and consists of a four-post, double-ram, rising-bottom platen machine. The steam-heated platens are mounted on 1 in. thick insulating material and work is fed into and out of them from feed tables on either side of the machine. All controls, including a curing-cycle-time warning clock, are conveniently grouped, so that the operator has all the controls and the components under observation.

Two larger presses are about to be installed, one being a long narrow open face press which will be used for bonding edge reinforcements to skin panels.

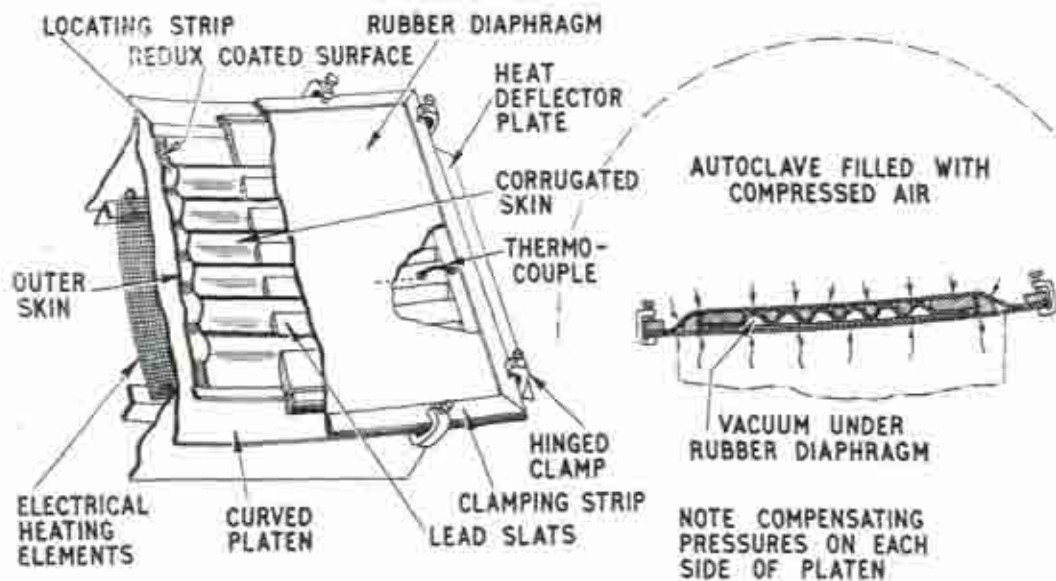
PREPARATION FOR CURING

Having described the evolution of the equipment used for the actual curing we may now describe the two stages leading to the application of heat and pressure. These are:—

- (a) Pre-treatment of the metals to be joined and
- (b) The application of the liquid and powder adhesive.

Pretreatment

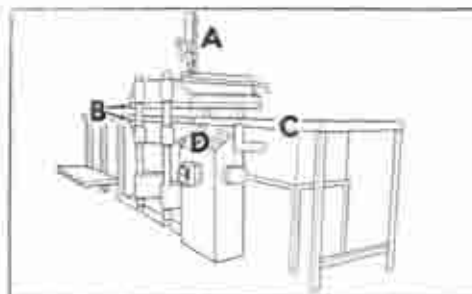
From the outset it was known that the pretreatment stage was of vital importance, but experience has shown that the control is not so exacting once production is under way. Use is always made of pickle to DTD, 915A even if this is subsequently followed by anodising to DTD, 910B. We have found in addition to vapour degreasing that the use of an aqueous degreaser (Collex) is also advisable. Aqueous degreasing effectively removes adhering solids which are frequently left by vapour degreasing.



AUTOCLAVE CURING JIG ASSEMBLY

SKETCH SHOWING HOW PRESSURE IS APPLIED TO THE COMPONENT

Fig. 3. Autoclave curing jig assembly and principle of pressure application.
Fig. 4. Hydraulic flat-platen Redux Curing Press (The Bristol Aeroplane Co. Ltd.)



A Steam and water feed pipes.
C Loading stands.

B Steam-heated platens.
D Control panel.

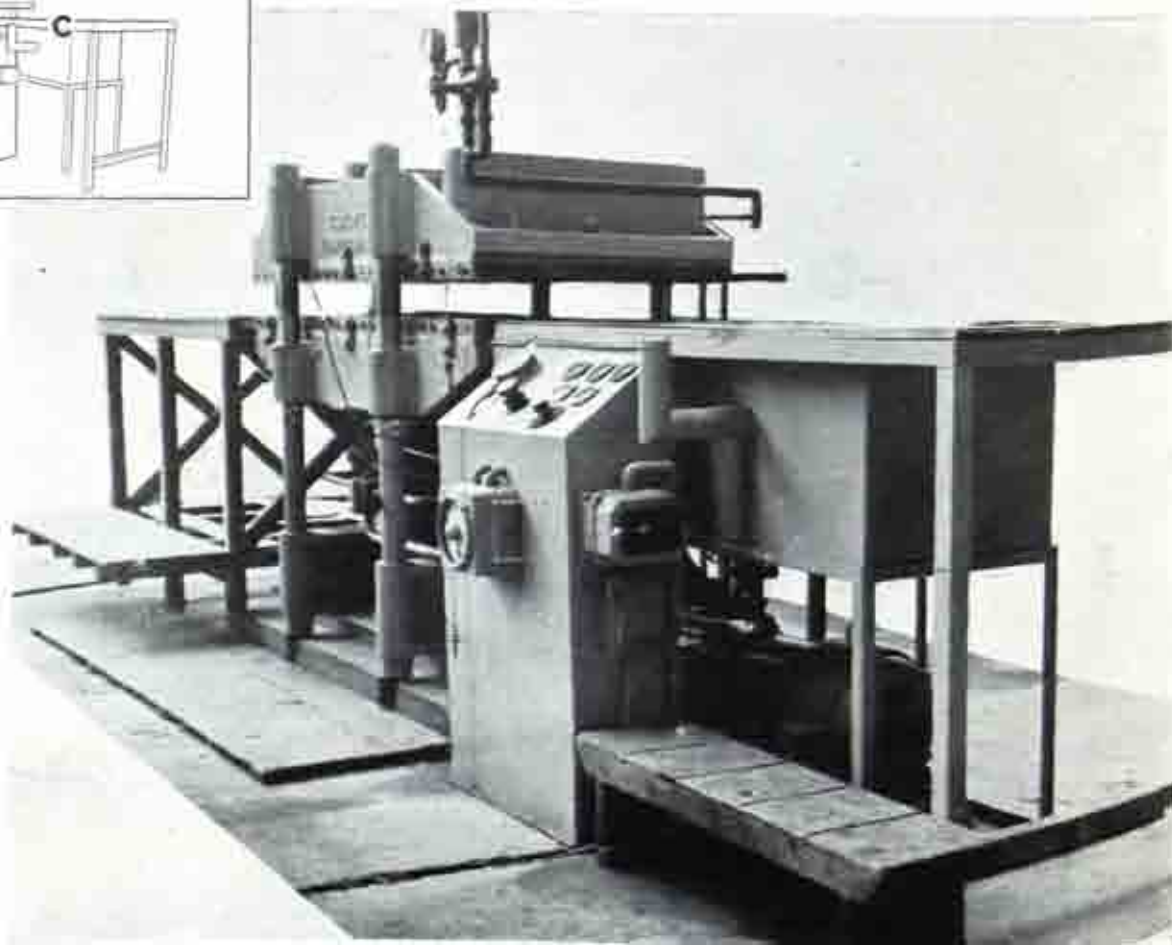
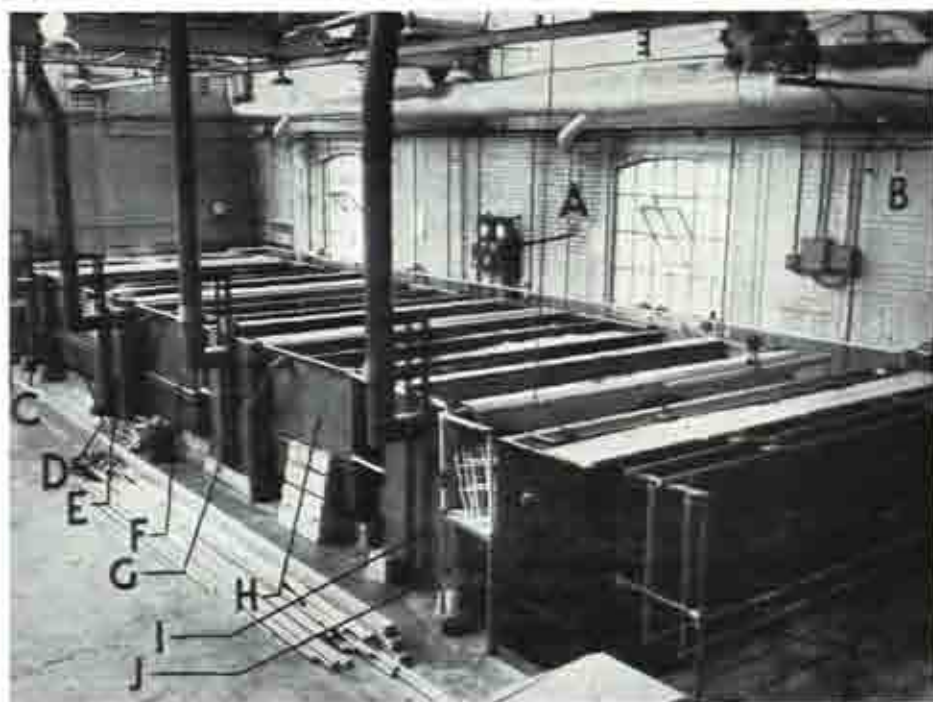


Fig. 5. *Redux* Pre-treatment Plant.
(Bristol Aeroplane Co. Ltd.).

- A Control Panel.
- B Bath for "pig".
- C 3% by weight "Collex" aqueous degreasing solution.
- D Counter current cold-water swirl tank.
- E D.T.D. 915A pickling vat.
- F Counter current cold-water swirl tank.
- G D.T.D. 910B chromic acid anodising vat.
- H Counter current cold-water swirl tank.
- I Cold-water final swirl.
- J Hot-air drying oven.
- K Bath for "pigs" showing typical frame "pigs".



With the exception of the vapour degreasing which is carried out at any convenient point between the raw material store and detail manufacturing stage, all the pretreatment plant should be installed in the Metal Bonding Department and its use should be the responsibility of those responsible for all other stages of the process. Careful record must be kept of the operating conditions, e.g., time, temperature, bath concentration, etc.

The sequence of the operations and the compositions of each bath used is given in Table I (the plant is shown in Figure 5).

During early tests both on the press and in the autoclave pre-treatment was suspect for every failure. Water impurities were exhaustively examined. Results following different methods of drying were tabulated as were the results following ordered variations in bath concentrations. In short, all the variables were systematically explored with the result that a method of pre-treatment was standardised, the application of which requires only a slightly more exact shop control than is necessary for a normal plating shop, but the bonding plant and pre-treatment baths should be completely separate from any other operation.

All the above investigations will be found recorded in Ministry of Supply Scientific and Technical Memorandum No. 7/49, while a further S. & T.M. to be issued shortly should provide a really full picture of this vastly important phase in the sequence of processes. The above memorandum contains many references to the full subject to which your notice is drawn.

TABLE I

BATH SEQUENCE, COMPOSITION AND OPERATING CONDITIONS OF "REDUX" PRETREATMENT PLANT

Sequence	Bath	Composition	Operating (Time)	Conditions (Temp.)
1.	"COLLEX" DEGREASER	3% by wt. "Collex" aqueous degreasing solution	20 min.	40°C
2.	SWILL (Double)	Filton bore hole water	5 min.	ambient
3.	PICKLE	Pickle to DTD 915 A (5% by wt. chromic acid, 13% by vol. sulphuric acid)	Min. 20 min. Max. 30 min.	60°C
4.	SWILL (Double)	Filton bore hole water	5 min.	ambient
5.	ANODISE	Chromic acid anodise to DTD 910 B (5% by wt. Chromic acid)	1 hr.	40°C
6.	SWILL (Double)	Filton bore hole water	5 min.	ambient
7.	SWILL	West Gloucestershire supply water	Dip	ambient
8.	HOT-AIR OVEN		30 min.	Approx 60°C

Application of the Resin

From pre-treatment and after drying, the prepared material is then taken over by the process operator for resin application.

Furthermore, the bonding operator himself handling the job at this stage is responsible for ensuring that bonding faces are not contaminated. The method of resin coating is that of brush application of liquid K.6 and subsequent dip-application of powder, the residue after consolidation on the resin face is lightly shaken off. Mating parts are then either wired together or rack stored ready for curing.

CURING

The curing process has received much examination and it was evident throughout development of the press and autoclave that despite identical pre-treatment and subsequent resin application the appearance of joints made on the press was noticeably different from those cured in the autoclave, furthermore, the autoclave joint always had higher properties particularly in regard to peel strength. The joint when separated by hand shows much more uniform and ductile properties.

At first this was thought to be associated with uniformity of contact resulting from air pressure curing as well as due to other factors present.

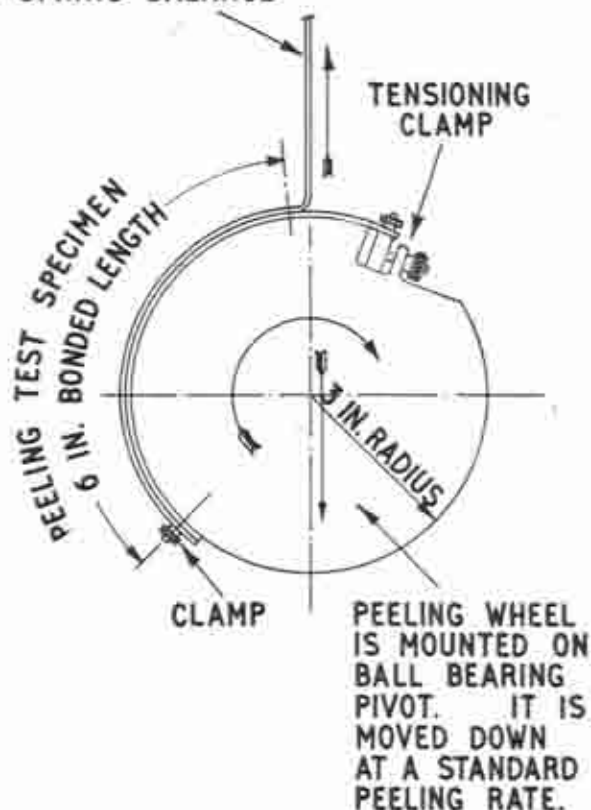
On both systems the curing pressure was 200 psi for 15 to 20 minutes at a temperature from 145°C up to 150°C maximum with an open assembly time (the period between application of resin and curing) of about one hour. This short interval was introduced to avoid shop contamination.

Press curing under these conditions resulted in peel strengths of great irregularity and the visual appearance of broken joints was unsatisfactory. The press technique, however, could not be abandoned as it had some advantages and offers a slightly shorter cycle whilst jigging is normally cheap and simple for flat assemblies, for example, in the case of many sheet-stiffener combinations.

Pre-treatment was re-explored and every mechanical variation in the press and heating equipment was perfected. The outcome was the use of a longer open assembly time and a reduced curing pressure at 100 psi for use in the press method.

The facts are that uniformity of pressure and even

**SINGLE OUTER LEAF
OF SPECIMEN CLAMPED
TO LOADING POINT OF
A SPRING BALANCE**



**NOTE. THE BONDED SPECIMEN IS COLD
ROLLED TO A RADIUS OF 3 IN. BEFORE
FITTING TO PEELING DRUM.**

Fig. 6. Basic principle of the "single drum" peeling test.

temperatures over the full area of the parts to be joined are essentials to successful curing, thus the platens must at closure fit most accurately and the steam passages through them must be sufficiently numerous and so disposed that the temperature is truly uniform.

The essential of a good joint is strict control of all factors which influence the flow of the adhesive. Excessive flow causes undue loss of adhesive from the joint often accompanied by a disturbance of the proportion of resin to powder. It is, therefore, necessary to control rise in temperature, pressure, and to ensure evaporation of all solvents before the joint is closed. In the autoclave this evolution is

met since the pressure is applied at a uniform and compensating rate and thus the resin is partially cured and consolidated before the full pressure is reached. On the press harsh mechanical crushing can occur at the commencement of the cure.

Thus the introduction of autoclave curing and lower pressure press curing has, on the whole, increased the overall strength of "Redux" bonded joints while scatter has greatly reduced, this has resulted in higher average strengths than were obtained originally. Average values are 2,200 lb shear on a joint 0.5 in. \times 1 in. and 60 lb peel.

Press pressure may be still further reduced providing the component being cured does not itself require considerable force to bring the mating parts into uniform contact.

With the autoclave working on thin gauge material excellent bonds have been obtained using atmospheric pressure only, that is, the pressure has been that arising from the use of the vacuum between the cradle and the rubber sheet.

PEEL TEST

The peeling test was developed by Aero Research, Limited, and has been established as the main control test in the absence of any known form of non-destructive examination of the bond. The test consists of peeling against an autographically recording loading device. Fig. 6 shows in diagrammatic form the method of applying load to the specimen. In this you will see that the peel specimen is clamped to a circular drum, the free end is held in a suitable clamp. The drum is then pulled hydraulically, which caused the specimen to rotate and peel the two component strips apart.

As a result of thousands of tests a minimum peeling load of 30 lb has been established on a specimen made from 20 gauge DTD, 610. In this connection lies the chief limitation of the single drum test. If the test figures are to have any significance for comparison purposes the test must be confined to one gauge and material specification, since, by nature of the geometry of the test, any change in the gauge of material or specification alters completely the peeling strength.

A further disadvantage is the fact that the actual radius which the specimen takes up as it leaves the

drum varies with stiffness of the material and increases the loading moment on a specimen of low strength, while decreasing it on a specimen of high strength, thus scatter of the results so obtained is so severe as to make them meaningless; the need, therefore, for standardisation of gauge and specification of material is essential when making comparisons.

Means, however, are being developed to eliminate these limitations and a peel test will soon be available which will allow immediate inter-comparison of test results on materials of different gauges and specifications up to, of course, a certain limit when the peel test becomes virtually impossible. But even with these limitations the single drum peel test is an excellent means of checking the process since we have found that it shows up immediately any slight variation in pre-treatment or other bonding conditions and, therefore, we regard it as one of the most valuable checks on the quality of a joint. It is interesting to note that the A.I.D. are likely to establish this test as a standard requirement for accepting "Redux" bonded joints. We do not, however, suggest that the peel test has any significance as a design criterion unless perhaps it is associated with endurance against fatigue.

On the other hand, it is well known that the shear strength of "Redux" bonded joints is very insensitive to processing conditions. There is abundant evidence of joints with no apparent peel strength easily meeting the shear strength requirements of DTD, 775.

INSPECTION PROCEDURE

Inspection procedure is a difficulty with metal bonding since there is no non-destructive test which can be intelligently applied and evidence of quality is limited to a test on a separate specimen. It has, therefore, been found necessary to introduce strict inspection routine at each stage of the method and although at first sight this appears to call for a high percentage of inspection to production labour, that is amply met by the low overall manning required. The following is of interest in this connection.

A metal bonding plant producing, say, 1,000 components of different design and sizes per month requires initially a production manning of about 25 operators, with 6 to 8 inspectors in addition. As

JOB HISTORY

STAGE 1 PRETREATMENT

TYPE	Pickle & Anodize
TIME OUT	1:30 p.m.
DATE	17-5-50

STAGE 2 REDUX APPLICATION

DATE	17-5-50
TIME	3:30 p.m.

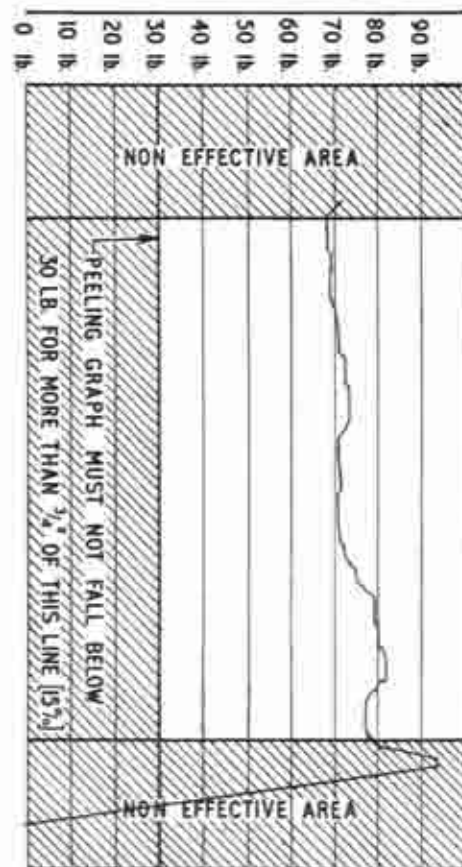
STAGE 3 CURING

PLANT	Autoclave
DATE	18-5-50
TIME IN	8:50 a.m.
TIME OUT	9:10 a.m.
TEMP.	150°C.
PRESSURE	150 lb. sq. in.
VACUUM	21 Mercury In.

STAGE 4 FINAL INSPECTION

ACCEPTED BY	
DATE	22-5-50

SERIAL NO. 149
DRG. NO. H20303 NDS
M.O. 26463
SEQUENCE 1/695
NO. OFF 1.07
DESCRIPTION
Redux S.A. Fluid
Diaphragm F.O.



THIS AREA TO REGISTER
WITH DRUM CLAMP

Shear Test - 2,095 lb.

Fig. 7. Face and reverse of standard peel test graph form.

the operators become experienced and if the rules are properly followed the inspection manning can safely be reduced by half; even so the inspection ratio is higher than for the older methods of assembly, but the overall manning is very much less.

As to the inspection control, this consists of a stage by stage viewing throughout the several processes. The inspector's last dual jobs are the

shear and peel tests which in each case is on one test piece per component per pre-treatment batch. A typical peel graph is shown in Fig. 7—each graph is signed by the inspector. The back of each graph, which will be seen on the left hand side of the picture, also carries the routine check records which the inspector has made, thus, the completed slip stamped by the inspector gives a permanent record of the process history of the part to which it applies.

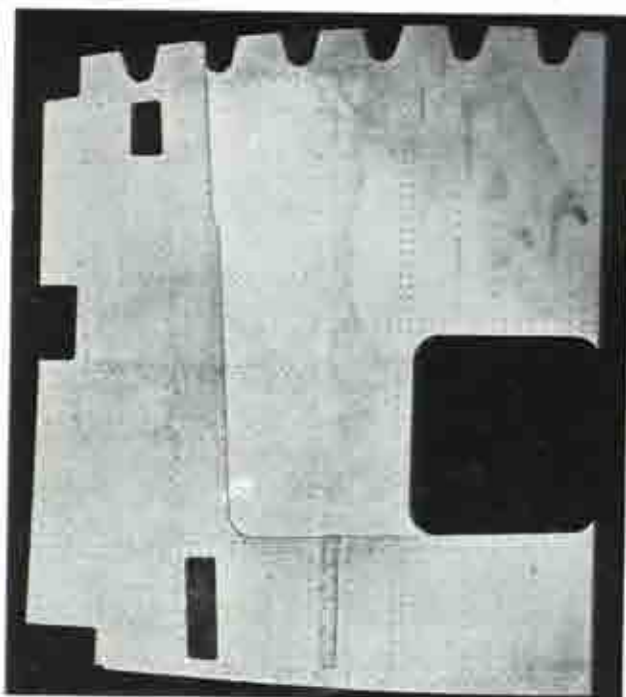


Fig. 8. Wing rib diaphragm, edge-reinforced by Redux bonded laminations.

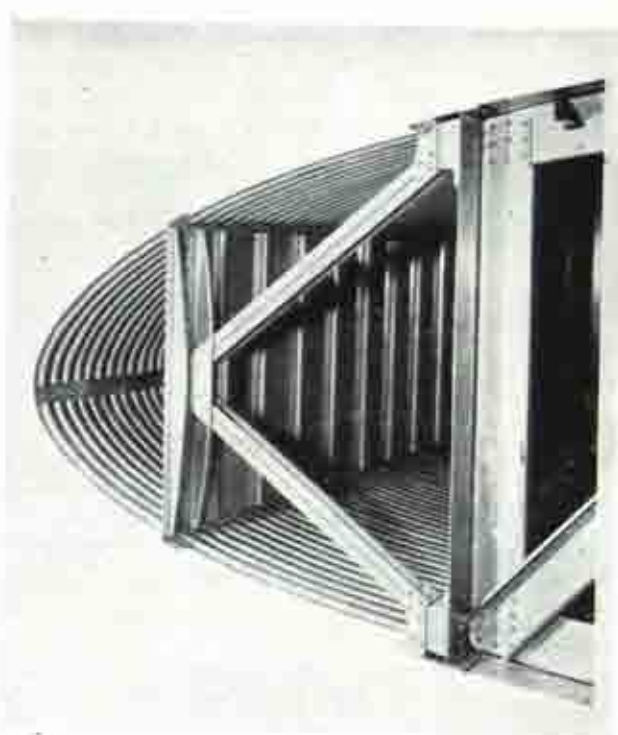


Fig. 9. Section of wing leading-edge assembly.

DESIGN AND WORKS CO-ORDINATION

With metal bonding the closest design, development and production collaboration is essential. The design must be appropriate for the method from its inception, its adoption merely as an alternative to riveting is often no advantage, that is, the essential requirements for good bonding must be realised by the designers and catered for in component layout.

Apart from overall considerations such as the very obvious one that panel sizes should fit autoclaves, there are a number of considerations such as the strip reinforcement of thin sheet edges by bonding, thus permitting the use of fewer rivets at panel edges, which also makes possible cut-countersinking for final assembly with its attendant economies. Edges thus thickened permit great economies in weight over the main panel area while allowing loads to be taken through the reinforced edges. This feature is well illustrated in Fig. 8.

In short, local load concentrations can easily be accommodated through laminations secured by the metal bonding which, in some cases, is particularly useful where stringers and rib members terminate on thin panels.

SOME "REDUX" BONDED STRUCTURES

Two very important applications were apparent in the initial design of the Bristol Type 175.

- (1) The wing leading-edge reinforced with an internal corrugation, the multiple channels thus formed acting as ducts for hot-air de-icing purposes (Fig. 9).
- (2) The assembly of large interspar ribs, particularly where smooth surfaces are requisite to prevent chaling on flexible petrol tanks.

Another valuable application lies in the use of thin materials with reinforcing members attached so as to ensure a large bonding area, avoiding stress concentrations and thus minimising fatigue possibilities.

ADVANTAGES OF METAL BONDING

The use of metal bonding has four main advantages:—

- (1) Reduction in structural weight.
- (2) An improvement of surface finish.
- (3) The reduction of stress concentrations.
- (4) Reductions in cost.

It would be wrong to assume that all advantages follow automatically on the adoption of the method, for example, if minimum structural weight is the first objective, thin highly stressed surfaces are a necessity which, in many cases means closely reinforced thin sheets, but no means have yet been evolved of producing such structures without very perceptible external waviness, thus if smoothness is the first consideration then some sacrifice in weight must follow. There is no difficulty in getting relatively thick (say 18 s.w.g.) sheet bonded to stiffeners without any visible surface deformation but this may be achieved only at the expense of some structure weight. Clearly in the case of the large aircraft with high wing loading these conditions should easily be fulfilled, but in other cases a choice one way or the other must be made.

Possibilities relating to stress concentrations have already been made and are referred to again in the next section of the lecture concerning reduction in cost.

COSTS

These are early days for a discussion on this important subject, but one may mention some relevant factors. For comprehensive application of method, initial capital cost of the plant is an item to be taken very much into account. On the other hand, maintenance and replacement charges should be less than those incurred by the older methods of fabrication for metal aircraft. Designing for the use of the method should lead to simpler constructions than hitherto, there should be fewer parts and the components on the whole should be lighter. All this should show to advantage in the final cost account. Designers must realise that the costs associated with curing-time are as large for a small component as for a large one and attention to that consideration should have its effect on overall cost, and that within reason, whatever complications are built into the product the cost of curing is not affected. Obviously, once in routine production, reductions in cost should follow the adoption of the method. Profit raising of aircraft operation which should follow the realisation of greater disposable load follows in the wake of the weight saving that should accrue. Examples of weight saving are

those which must inevitably arise from the reinforcing of sheet edges, leaving the main body of sheets of the desired original thickness, and similarly reinforcing of stringers, due to which large weight savings are known to have been made.

SOME RESULTS TO DATE

Large numbers of panels in a variety of sizes from the small laboratory specimen to full-scale aircraft panels have been tested both for static and fatigue strength.

We have found that shear and compression tests made on panels "Redux" assembled are at least equal to similar riveted structures and, indeed, in many cases the load carried is 30 to 40% in excess of riveted assemblies. Sometimes an original riveted design has been copied in which the distribution and size of panel elements has not necessarily been optimum for a bonded assembly. Even so, such assemblies have shown some advantages,

Typical figures are:—

<i>Compressive Failing Loads</i>	
Bonded	Riveted
44,000 lb	42,000 lb
37,000 lb	34,000 lb
53,000 lb	50,000 lb

It would appear that the principle factor contributing to added strength in the case of stringer-sheet combinations is continuity of contact or the avoidance of inter-rivet buckling, which can be a source of premature failure in riveted structures. In some cases where the riveting pitch has been rather wide the strength difference has been most marked. As one would expect, when a bonded panel is progressively loaded, failure develops from some region of instability but parting of the "Redux" joint is never the criterion and does not occur until final collapse of the specimen is imminent.

A major advantage of the use of metal bonding lies in reducing centres of stress concentration, thus there is scope with intelligent layout to add considerably to the fatigue life of many structures. A good example of this is shown in Fig. 10 which shows a helicopter skin with bonded stringers and local rivet reinforcements required to attach the skin to the rib

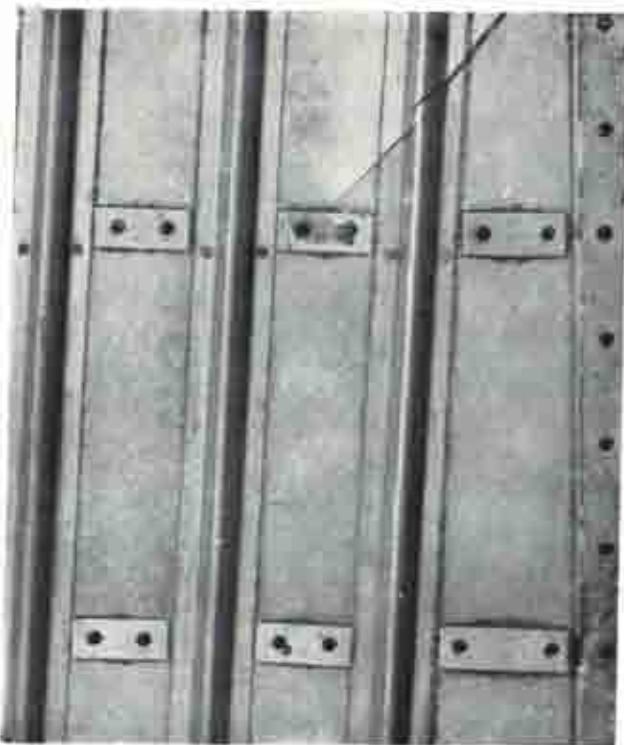


Fig. 8. Fatigue failure in Redux bonded skin panel (skin 20 s.w.g., stringer 30 s.w.g.) Note undisturbed bond where crack traverses stringer.

structures. This part failed at a riveted joint, after 150 million cycles.

As has been made clear, two of the fundamental conditions for "Redux" curing are the application of pressure and heat, thus "panel" construction is obligatory and at this stage of development the contiguous panels have to be connected at their edges by riveting and/or bolting. Careful attention is necessary in the design of these joints if full advantage of the bonds is to be obtained. I refer, of course, to the efficient transfer of load from one edge to another.

No question in relation to "Redux" has received so much publicity as that of the fall in strength with rise in temperature. The wing leading edge shown in Fig. 9 was tested at room temperature and also at 100°C through the use of infra-red lamps. It is known that "Redux" loses two-thirds of its shear strength at 100°C, yet the two structures failed at nearly identical loads both appreciably above the design load. In neither case did the "Redux" bond fail. The reason is that in this, as indeed in

most cases the bond is subject to low intensities of stress, but that may well not always be the case and the problem of low strength at elevated temperature certainly needs solving at an early date. The increase in peeling strength which accompanies plasticity under heat is not the answer.

OTHER BONDING MATERIALS

Many other bonding materials are available and have been considered. Among these are Araldite, also made by Aero Research, Ltd., Hydunite, Cycolac, the Glenn Martin Adhesive known as F.M.45, Scotch Weld, Convair Metabond and a variety of Bostik derivatives. We find that the single part adhesives have a common fault. They are, with the exception of the Bostik group, extremely good adhesives when bonding relatively thick materials but they are brittle and, therefore, may not be too safe in structures which are flexible and then fatigue life would be suspected.

If an attempt is made to bond together two thin materials it will be found that none of these adhesives has any appreciable peeling strength and a parting once started rapidly runs the whole length of the joint.

Some adhesives, Araldite for instance, have shear strengths as good as, if not slightly better than, "Redux" giving over 2,200 lb on a standard single shear test joint $\frac{1}{2}$ in. \times 1 in. Our tests on the American adhesives, have not been conclusive, due to shortage of supplies, but to date the shear strengths obtained have varied between 1,000 and 1,400 lb or roughly half the value of "Redux", but again there seemed to be a lack of peel strength.

The Bostik and Boscoprene family, on the other hand, due to their more plastic nature exhibit promise of high peel strength but so far their shear strength is low ranging from 400 to 1,000 lb on a standard single shear specimen. Also on adhesives of rubber or similar base, evidence of joint "creep" at comparatively low stresses have been found.

MATERIALS BONDED

Tests have been made on the quality of "Redux" bonds on a number of materials and satisfactory joints have been produced with all the following:—

Foremost, of course, are the aluminium alloys used in aircraft construction, all bond well within their elastic range. Then the magnesium alloys, including magnesium zirconium; steels including stainless; rubber; asbestos based materials, for instance Ferrodo or Ferobestos; Durestos; Tufnol and similar phenolic impregnated materials. There is no trouble with any of them providing the appropriate and adequate precautions are taken at the pretreatment stage. "Redux" also gives a very satisfactory bond between metal and glass cloth laminates made up with the Marco range of resins.

Magnesium zirconium, a relatively new and interesting material, is likely to find considerable use in the aircraft industry. Our present knowledge indicates, however, that when this metal is used special attention should be placed on the avoidance of stress concentration; thus metal bonding is an admirable process for fabrication and has further advantages in the matter of subsequent protective treatment within the joint. The best pretreatment of the surface prior to bonding is still a matter for exploration, but it is anticipated that a really satisfactory chemical pretreatment will be found, and that this material will be bonded with sufficient joint strength to permit the manufacture of structures of considerable economic attraction.

A further useful application is in bonding paper or a fabric face to metal which, when prepared in this way, can be cold glued to wood or any other suitable surface, although in the case of paper it is necessary to sand it away leaving only a film of "Redux" to develop optimum joint strength.

SUMMARY AND CONCLUSIONS

I shall have done a considerable disservice to anyone contemplating the adoption of this method of jointing if I have given the impression that by reading the available literature on the subject they can, at once, be sure of getting the desired results

immediately the plant is installed. There is no royal road to success in this matter and the best state of mind for anyone at the outset is that of a pioneer. On the other hand, there is no great mystery about the process and the fact that the efforts of those who have persevered have been rewarded by success should in itself give ample confidence and encouragement.

As already indicated, the first requirement is to install a pilot plant, including a pre-treatment pilot plant with vats sufficiently large to remove it somewhat from the sphere of the chemical laboratory, introducing something of the "shop element", but not so large as to make early and frequent changes in compositions uneconomic. We used baths of about 50 gallons capacity which proved a good compromise.

The pilot plant should be set up in the department in which the full-scale work will be carried out, and put in charge of the carefully selected nucleus of personnel with whom it is finally intended to run the job. This is important since the idea of sticking metals together does not come easily to people with long experience of the hitherto almost universal methods of metal jointing. It therefore needs as long an association as possible with the process before everyone concerned acquires the necessary confidence in his task. One feels that the early successful use of the "Redux" bonding process by the de Havilland Aircraft Company was in no small measure due to their long background of experience of gluing practice on wooden aircraft and their transition from wood to metal adhesion and finally metal to metal without the very definite break in adhesive methods that everyone else experienced.

In conclusion, I would like to express my appreciation to The Bristol Aeroplane Company, Limited, for permission to give this lecture and to the technical staff of Aero Research, Limited, for their help in the developments we have made, and particularly to my colleague, Mr. Hulbert, who has worked closely with me and has done a great deal of the basic work on this project.

RECENT DEVELOPMENTS IN ETHOXYLINE RESINS

E. Preiswerk *

PLASTICS AS WORKING MATERIALS

THE technological applications of synthetic resins are almost bewildering in their number and variety: nevertheless it is possible to classify them under three main headings as shown in Fig. 1. Beginning at the top, we have the large group of applications which can perhaps be summed up by the term *Plastics as Working Materials*. It covers the whole range of manufactured, profiled articles which are made by plastic deformation—whether they are sheets, tubes, rods sections, strips or foils—whether they are cups, fancy goods, electrical installations or many other things. We are not concerned here with whether the final material is a thermoplastic or a thermosetting resin and it should be noted that the term “plastic deformation” is intended to cover pressure moulding, injection and casting. There is no time to go into the differences between these processes more thoroughly but the properties listed below will be found to be of importance in all of them and in the finished products:—

- (1) *General Mechanical Qualities*—such as impact strength, hardness and heat resistance (these three properties are possessed, to give an example, by a pressed piece manufactured from a melamine-resin moulding preparation).

- (2) *Dielectric and Electric properties*—such as the insulating power of Teflon foil or the tracking of a moulded melamine article.
- (3) *Ease of Processing*—such as is offered by the styrol injection moulding preparations, and *Good Workability*—such as is found in the methyl methacrylates.
- (4) *Chemical Resistance*—as possessed in a high degree by vinyl chloride and Teflon products.

Nowadays, these properties are all constantly checked: they are standardised and are guaranteed, within certain limits, by the makers of synthetic resins.

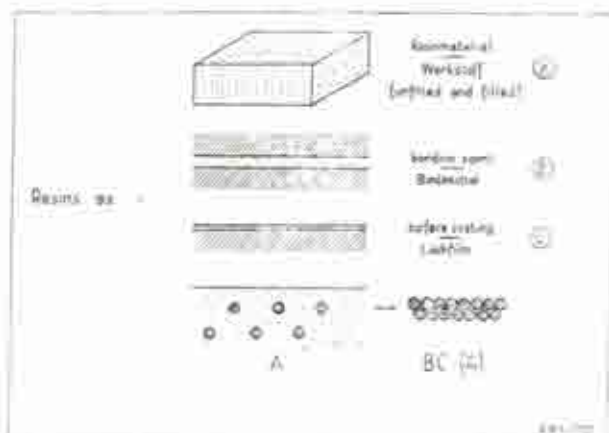


Fig. 1. The three main classes of application of synthetic resins.

* Chim. Ind., Basle.

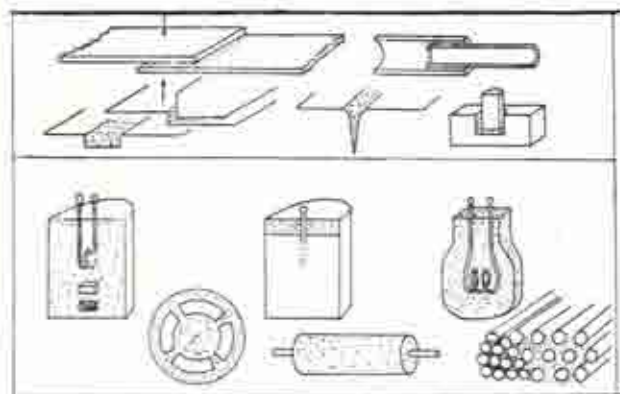


Fig. 2. Some principles of bonding and casting (potting).

PLASTICS AS BONDING AGENTS

The second group of applications for the resins is the large class of "bonding agents." It would be carrying coals to Newcastle, or taking synthetic resins to Duxford if I were today, at the end of this course, to stress the importance of this section. I should only like to remind you that the durability of the glued joint, its mechanical quality, and the ease with which the glue can be processed are all important considerations.

PLASTICS AS SURFACE COATINGS

The third range of application is that which is covered by the term "surface protection". The synthetic resin is usually used here in the form of a thin film to cover another material, such as metal or wood. The uses of this coating can be very diverse; it may be used, for instance, to protect the material from corrosion, or perhaps merely to change its appearance. Sometimes a layer of electrical insulation is also required. In all these cases, however, properties of the coating resin such as the degree of adhesion to the surface of the material, the mechanical and dielectric qualities, the degree of plasticity and elasticity, and the resistance to chemicals are all taken fully into consideration.

It has also been found that there are various applications which fall between the three main groups illustrated; I have shown some of these in the two bottom examples. In both cases objects

made of the material (e.g. wires or thin rods) are embedded in resin. If we look at the left-hand picture, we see that here the resin is put to the kind of use which we have described under *Plastics as Working Materials*. In the right-hand picture the properties expected of the resin are those we have described under *Plastics as Bonding Agents* and *Plastics as Surface Coatings*. And there may also be cases where properties from all three categories are called for.

GENERAL REMARKS

This short survey may have given you some idea of the extraordinarily wide range of applications there are for synthetic resins, and of how various the requirements may be technically.

The chemist working on synthetic resins strives constantly to improve the properties of his products or to produce new substances which will fulfil new technological needs. The mechanical or dielectric properties are corrected and adapted to the purpose in view and the method of application is simplified, or at least modified, to suit the working conditions of the user. And last but not least, the chemist is trying to lower the production costs of the resin by using ever simpler and more systematic processes, so that low cost may make possible a continued widening of the fields of application.

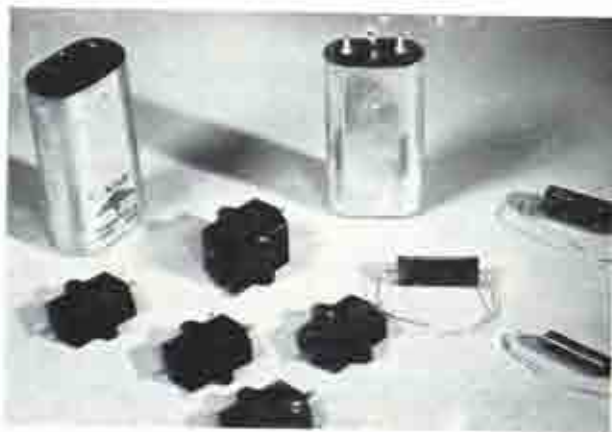


Fig. 3. "Araldite" Casting Resin B for insulating and potting applications.

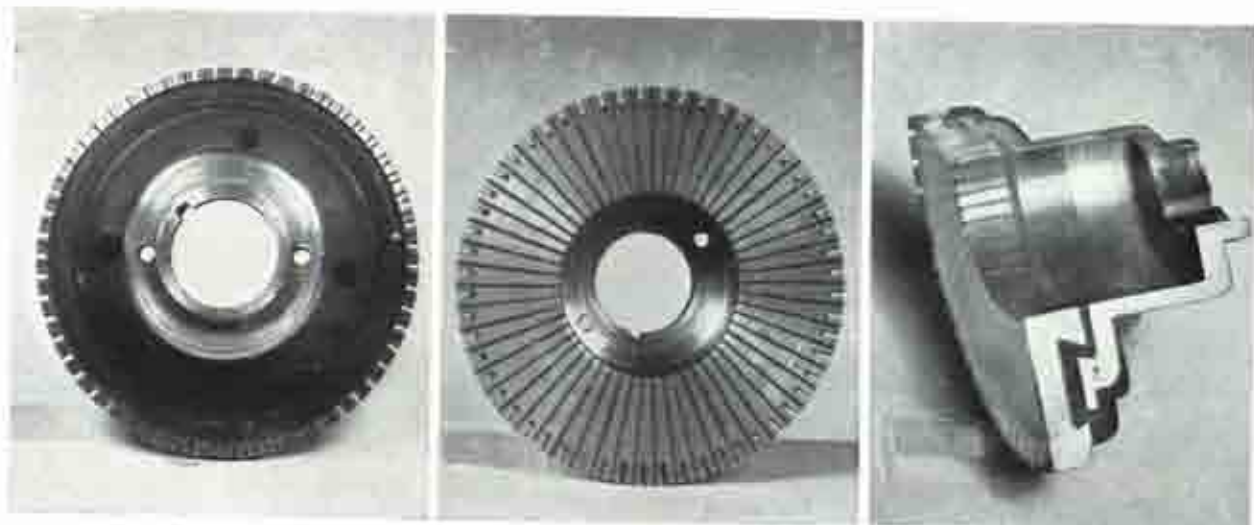


Fig. 4. Different parts of a rotor combined in a compact mechanically and dielectrically high grade unit with the aid of "Araldite" Casting Resin B.

Now that we have learnt something of the possible applications of synthetic resins, and have also seen which properties are of importance in their application, the question arises of how these new materials produced from synthetic resins compare with the classic materials such as metals, wood, ceramics, etc. Is it possible that the classic materials should be partly replaced by the new materials? However, I do not wish to go into this question here. It has already been sufficiently discussed, and such speculations always end in the conclusion that each material has its own special field of application, and that it is really meaningless to talk of a "plastics era" or a "light metal era". In fact, it is shown in practice that designers in all the various branches of technology must pay more and more attention to the simultaneous use of the new developments in various materials, according to their characteristics. If, in this connection, we again refer to Fig. 1, we can see that the need for such simultaneous use of different materials is particularly evident from the examples given at the bottom of the picture, and it is a need which has yet to be met.

From the above observations it is clear that the simultaneous use of different materials having been postulated, technology must now see to it that those different materials can be joined together. What is the present situation as regards the bonding processes available for the various types of materials?

METHODS OF JOINING METALS

Let us first review briefly the methods of joining metals. Here the classic methods of joining are screwing, riveting, welding and soldering. These processes have been carefully evolved and improved through the years, so that to-day the technician has at his disposal a useful and proved method of joining metals together. At least this was so while it was a case of joining metals of the same kind and type. But even here there were already new requirements to be met! The light metal specialist was looking for processes of joining which could replace soldering in light metals. In aircraft construction new problems arose, in which the joints between light metal parts were no longer satisfactory when carried out by any of the usual methods of joining, such as riveting.

METHODS OF JOINING WOOD

On proceeding to the second class of materials, wood, we discover that here, with the help of synthetic resins, the methods of joining have developed so far that there is little left to be desired; but again we must add that this is only the case when it is a question of joining wood to wood. The joining of paper and of textiles with synthetic resins has also been considerably developed, so that here too there are few requirements still to be met.



Fig. 5. A heat exchanger unit completely bonded by "Araldite" Type I.

THE JOINING OF UNLIKE MATERIALS

It can therefore be seen that in joining like materials to like, there are useful methods ready at hand. The situation is quite different, however, when it is a question of joining materials from the different classes to each other, e.g. heavy metal to light metal, metal to wood, metal to ceramics, etc. Here the classic methods of joining are only practicable in exceptional cases, and if one were to look around for a bonding agent, such as a glue—and glues, based on synthetic resins, have, as we have seen, proved excellent with wood—it would soon be clear that it still remained for technology to produce such a bonding agent. At first sight this may be surprising! And yet all attempts in this direction which were made with synthetic resin glues already on the market had negative results. It was necessary to use a resin possessing completely new properties, if it was to be considered as a metal bonding agent, or as a *solder based on synthetic resin*.

The Properties Required in the Adhesive

If the properties which should be possessed by such a resin are studied in more detail, we discover that they must fulfil the following conditions:—

- (1) The resin must show outstanding adhesion to the surfaces of the materials.
- (2) The setting of the resin must take place with the least possible release of volatiles. If this is not the case, the formation of blisters or bubbles in the

glued joint is unavoidable. This phenomenon occurs because in the case of metals and ceramics the materials to be bonded are impermeable to volatile substances and also are incapable of absorbing them. It is true that the formation of blisters or bubbles in the joint can be suppressed during setting by means of pressure, so that on the one hand the adhesion and on the other the mechanical stability of the glue film can be guaranteed. However, the use of pressure, quite apart from the expensiveness of any pressure process, is in many cases impracticable, as, for example, in the joining of tubular bodies.

(3) The shrinkage of resin after setting should only be slight. Otherwise strong internal stresses are set up in the glue film, which are detrimental to its function as a bonding agent. If shrinkage should unfortunately occur through "plasticifying" of the film, this usually results in loss of heat resistance or other properties.

(4) The mechanical quality and stability of the glue film must be of such a quality that, right from the beginning, adhesive strengths can be expected which will make possible its use as a bonding agent for metals, and which will bear comparison with the strength offered by riveted, welded or soldered bonds.

(5) The desired bonding agent must in addition be—

- (a) Neutral in behaviour towards metals, non-corrosive.
- (b) Harmless to the skin—non-productive of irritant fumes.
- (c) Easily workable, adaptable to the demands and possibilities of the workshop and of factory production.



Fig. 6. Current transformers manufactured with the aid of "Araldite" Casting Resin II.

TABLE I. SUMMARY OF PROPERTIES OF ETHOXYLINE AND OTHER CASTING RESINS

Property	ETHOXYLINE RESINS (ARALDITE TYPE B)		OTHER CASTING RESINS (VALUES DETERMINED BY APPROPRIATE ASTM TEST METHODS)				
	Test Method (European, See Footnote)	Values	Cast Phenolic ^a	Polyester ^b	Allyl ^c	Acrylic ^d	Polystyrene ^e
STORAGE LIFE	—	Practically unlimited	Limited	In many cases limited	Practically unlimited	The monomer: product limited	—
CURING PROCESS, POLYMERIZING	—	No volatile substances are split off; no special precautions; no precise temperature	Volatile substances are split off; careful curing necessary	No volatile substances are split off; in many cases presence of air inadmissible; careful curing	No volatile substances; careful curing	Careful curing	—
CURING PROCESS OR POLYMERIZING CARRIED OUT BY	—	Resin manufacturer or user	In many cases user must prepare resin himself	Resin manufacturer or user	Resin Manufacturer or user	Resin manufacturer or user	Resin manufacturer
ADHESION TO THE SURFACE OF DIFFERENT MATERIALS	—	Outstanding ^f	None	Appreciable	Slight	None	None
SHRINKAGE DURING CURING	—	0.5–2.5%	>1%	Varies in some cases up to 10%	Varies in some cases up to 10%	10–20%	10–15%
TENSILE STRENGTH	VSM 77101	6.5–8 kg/mm ²	4.2–6.4 kg/mm ²	2.5–6.4 kg/mm ²	3.6–4.3 kg/mm ²	5.7–7.0 kg/mm ²	6.0–6.4 kg/mm ²
FLEXURE	Schopper test bar 120x15x10mm	900–1200 kg/cm ²	770–1200 kg/cm ²	600–1200 kg/cm ²	420–920 kg/cm ²	1050–1200 kg/cm ²	850–1120 kg/cm ²
IMPACT STRENGTH ^g	Schopper test bar 120x15x10mm	10–20 cm/kg mm ²	0.25–0.40 ft-lb/in.	0.3–0.4 ft-lb/in.	0.2–0.4 ft-lb/in.	0.4 ft-lb/in.	0.25–0.4 ft-lb/in.
MODULUS OF ELASTICITY	—	25–35,000 kg/cm ²	20–35,000 kg/cm ²	20–57,000 kg/cm ²	20–45,000 kg/cm ²	25–36,000 kg/cm ²	35–42,000 kg/cm ² (Tension)
SPECIFIC GRAVITY	VSM 77109	1.1–1.2	1.3	1.3–1.46	1.3–1.4	1.18–1.19	1.05
HARDNESS	Vickers kg/mm ²	20–24	M93–120	M85–115	M95–M119	M96–M102	M165–M175
THERMAL COEFFICIENT OF EXPANSION, LINEAR MAX. PER DEG. C	Special test	60x10 ⁻⁶ with high percentage of extenders 25–30x10 ⁻⁶	60–80x10 ⁻⁶	80–100x10 ⁻⁶	50–100x10 ⁻⁶	90x10 ⁻⁶	60–80x10 ⁻⁶
HEAT DISTORTION	Test by Martens, test bar 120x15x10mm	135–120C	74–80C	60–116C	80–88C	90–100C	95–100C
WATER ABSORPTION per cent.	7 days test bar 120x15x10mm	0.1–0.14	0.15–0.4	0.15–0.6	0.034–0.44	0.2–0.4	0.64–0.95
DIELECTRIC STRENGTH	VSM 77107 (Short time)	55 kilovolts/0.5mm	350–400 vpm	380–500	380	450–900	>400
VOLUME RESISTIVITY	—	10 ¹⁵ –10 ¹⁷ ohm-cm	1.0–7.0x10 ¹⁴	—	>4x10 ¹⁴	>10 ¹⁵	(10 ¹⁴ –10 ¹⁶) (Type I)
DIELECTRIC CONSTANT	—	50 10 ³ cps	60 1000 10 ⁷ cps	60 1000 10 ⁷ cps	60 1000 10 ⁷ cps	60 1000 10 ⁷ cps	60 1000 10 ⁷ cps
		25C 3.2 3.6	6.5 5.5 4.9	3.0 3.2	2.8 3.45	3.35 3.6	3.5 3.9
		50C 3.9 4.1	7.5 6.0 5.5	4.36	3.7	5.0	5.0
DISSIPATION FACTOR	—	50 8x10 ⁻⁵ 10 ⁻³ cps	60 1000 10 ⁻³ cps	60 1000 10 ⁻³ cps	60 1000 10 ⁻³ cps	60 1000 10 ⁻³ cps	60 1000 10 ⁻³ cps
		25C 0.007 0.007 0.027	0.1 0.01 0.04	0.003 0.009	0.009 0.009	0.01 0.028	0.05 0.05
SURFACE RESISTIVITY	—	High	—	—	—	—	—
		High	—	—	—	—	—
TRACKING RESISTANCE	SEV publ. No. 177, page 9, 1st edition	Good	—	—	—	—	—
DECOMPOSITION	SEV publ. No. 177, page 4, 1st edition	340C	—	—	—	—	—
ASH CONTENTS	SEV publ. No. 177, page 7, 1st edition	0.02%	—	—	—	—	—

Note: Values taken from current technical literature. Wherever possible and practicable all values are calculated in metric measures. Standard test methods are given where known. As noted, test methods in the second column, applicable to ethoxyline resins, refer to European standards. VSM refers to Verein Schweizerischer Maschinenindustrieller (Society of Swiss Machine Builders) (SEV refers to Schweizerischer Elektrotechnischer Verein (Swiss Electrotechnical Society)). ASTM methods were used for the other casting resins.

^a Mechanical and chemical grade, type I.*

^b Rapid quality.*

^c Cast allyl.*

^d Cast resin, heat-resistant type II (b).*

* Heat resistant.*

* No adhesion to moulds when properly pretreated.

* Generally speaking the differences of impact strength are small.

* Source of property values cited in table is the Plastics Materials' Manufacturers Association (Technical Data, May 1948).

(6) Not only "thin" glued joints but also more thickly glued joints must be practicable and these must also give useful values for mechanical stability.

The Ethoxyline Resins

By extensive research and development work, the laboratories of Ciba Ltd., in Basle, have succeeded in producing, in the Araldite class, a type of resin which has allowed the problem to be approached from a new angle. The ethoxyline resins are supplied as fusible resins built up from aliphatic-aromatic chain compounds with terminal ethylene oxide groups, which can be brought to the final hardened condition by heat or even at room temperature, by the use of suitable hardeners. Besides excellent surface adhesion, they also show all those characteristics which are necessary for their use as bonding agents for materials such as metals, ceramics, etc.

In the spring of 1946 we first brought a representative of this type of resin on to the market. At first we produced hot-setting bonding agents, in the form of powder or rods, for those who were interested. It was not by chance that these bonding agents were first used in the field of light metals, and that the new process—the *soldering of metals by plastics*—should have proved to be its first application. This relatively young light metal industry recognised quickly that the new method would be not only a welcome aid in joining light metals to each other, but also for joining light metals to other materials. From early on, thorough tests were carried out, the results of which were published in *Sheet Metal Industries* (1949); these laid the indispensable foundation for the engineer planning new designs.

These tests were carried out by the E.M.P.A. in Zurich. The results of the tests were positive throughout and, together with examples drawn from practical work in the meantime, presented a valuable foundation for further progress.

Adhesives in Electrical Engineering

From the beginning the electrical industry has been among those interested in synthetic resin bonding agents. This industry has since its origin had a very special interest, first in natural resins, and then in synthetic resins. In fact, the insulating properties of these products were found to be very



Fig. 7. Sectional view of a frequency filter. The different parts are potted in "Araldite" Casting Resin B.

valuable, indeed almost essential. We must not forget how important the natural amber resin was in the early history of electricity. If we observe the requirements of this important branch of modern technology from the point of view of bonding problems awaiting solution, we are confronted by a new subject which needs to be carefully explored.

The demand for bonding not only metals to each other, but also to plastics, to ceramics, to glass, etc., occurs perhaps more often in the electrical industry than in any other. And the process of joining can in many cases not be achieved by using a thin glue layer: very often for constructional reasons or for reasons of insulation technique, there are considerable gaps between the materials which must be filled by a glue which has, in the best sense, *gap-filling* properties. One can see that this bonding must be at the same time a casing and a means of fixing and so the idea of pouring in and around is necessarily arrived at—that is, of a casting resin which, besides the purely bonding job, will also carry out the function of an embedding material. Such materials are not known in electrical engineering. The compound materials have for a long time been very useful in electrical engineering. However, the limited mechanical and dielectric properties of these products allowed only primitive and in many cases questionable applications, and forbade their use everywhere where special qualities such as heat stability, adhesive stability, and uniform mechanical and dielectric values were called for.

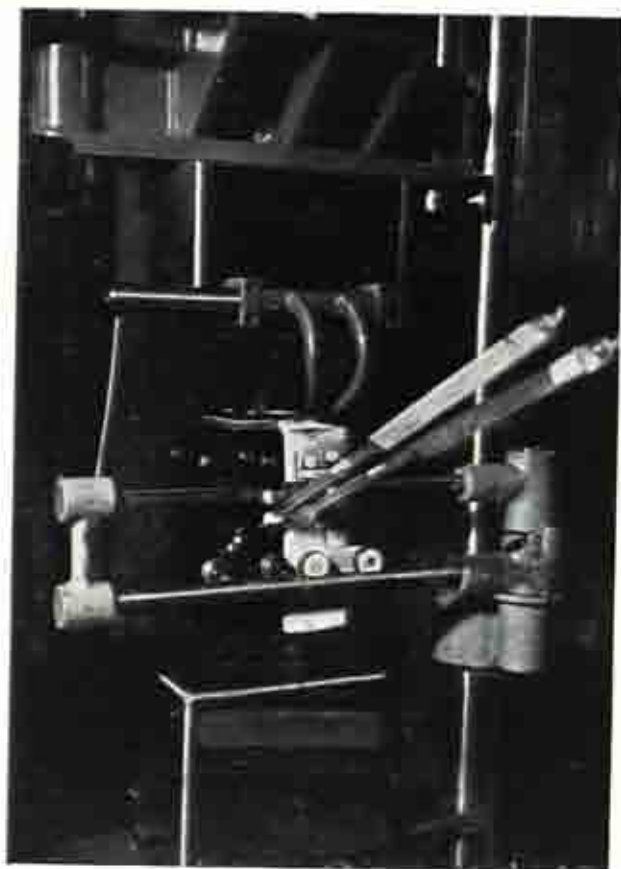


Fig. 8. Shear strength test of "Araldite" Type 1 bonded strips at a temperature of -70°F (-60°C).

Here again the ethoxyline resins made possible the creation of casting resins which were made available to those interested for the first time in the year 1946.

With ethoxyline bonding and casting resins, electrical engineering had come into possession of products which permitted parts of any material to be joined in a bond of high mechanical and dielectrical value, by means of a simple process of coating, casting, dipping or centrifugal processing.

The outstanding characteristics of these materials as bonding agents, the small degree of shrinkage on setting, the high heat stability, the remarkable mechanical and dielectric values, and the simple methods of application, meant that electrical engineering could tackle problems which before this

were out of the question. One of these is the whole idea which is known in English as "potting". Similar developments are taking place with polymerisation resins such as, for example, the so-called Polyesters. It has, however, been reserved for the ethoxyline resins—thanks to their special characteristics such as their bonding properties, their small amount of shrinkage on setting, to name only a few—to start a development of which the further results can still not be gauged to-day.

If we survey these different tendencies, the idea of a "bonding agent" must be taken somewhat further, and in particular where ethoxyline resins are concerned—so long as the bonding and casting resins are in question—it would probably be better to talk of "uniting agents".

It was evident that the excellent properties of ethoxyline resins also called out to be used in the field of surface protection. Here too, in the ethoxyline coating resins, were developed products which gave outstanding performance as coatings for boxes, tins or even wires. At the same time the ethoxyline resins were also finding uses in the U.S.A., as the so-called "epoxide" resins, for coating resins, and the good results obtained in Europe were confirmed.

CONCLUSION

Looking back to summarise the progress of these five years, in a field which to-day is in the course of being fully developed, we can state to-day that the ethoxyline resins have fulfilled expectations and play a useful part as an indispensable aid to modern engineering constructions. And if you refer once more to Fig. 1 you will realise that technology to-day, in the ethoxyline resin, has a synthetic resin at its disposal which in its different forms of application can fill the needs of all three sections, and especially of those cases which lie in between them. And this is not only so with the materials which are permeable to volatile substances, but also with the important materials: metal, ceramics and plastics.

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ADHESIVES IN THE ELECTRICAL INDUSTRY

R. F. Archer

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INTRODUCTION

In the earlier lectures of this course, attention has already been given to the development of adhesives, to their properties and characteristics, and to the processes and requirements involved in promoting adhesion. It is therefore no part of the purpose of this present paper to discuss those subjects as such, but rather to review some applications of adhesives in the electrical industry, particularly with a view to relating specialised requirements in the industry to the properties which have already been described.

Although adhesives find applications for general and structural purposes in the electrical industry, such applications are usually common to other industries; applications which are peculiar to the electrical industry are concerned with the subjects of electrical insulation, magnetic cores, and sealing and filling. It is such applications which form the subject matter of this paper.

ADHESIVES FOR MICA

One of the basic materials for electrical insulation, and certainly the one on which we largely depend for the insulation of large generating equipment, is mica. Occurring as a mineral, mica has to be mined, sorted, cut, and split before it comes to us in the form of flakes of varying area and thickness, in which form the material is mostly used. The flakes will generally be of the order of 1 mil in thickness, and a commonly-used grade of splittings will have

an average of $3\frac{1}{2}$ square inches. Such flakes are not easy to handle, and have to be applied as insulation over large areas in strange shapes. Despite the difficulties of handling and processing, mica is used because of its high thermal and chemical stability, its flexibility in the form of thin flakes, its high electrical strength and low power factor. To hold the mica flakes in position, not only as a means of processing but also in the finished insulation, an adhesive is required. For many years the adhesive commonly used has been shellac, applied as a varnish or as a dry powder, and in many mica products today shellac is still the favoured adhesive. The main features which make shellac desirable as an adhesive for mica products are:

- (1) its good electrical properties,
- (2) the comparative ease with which the solvent (methylated spirits) can be removed,
- (3) its property of being initially thermoplastic and ultimately thermosetting.

It is the last of these three features which is particularly interesting and which, until recent years, has probably been unique. It is this property which makes it possible to lay one, two or three layers of mica splittings (bonded with shellac varnish) on a suitable backing material, for example paper, and then, after the solvent has been removed, to wrap such insulation round, say, a bar, and under the influence of heat and pressure to form the insulation into a hard mass conforming closely to a designed shape. The coils of many large motors and

small generators are insulated in this way. Similarly, commutator vee-rings, as made from mica, are only possible because of the flexibility of the flakes combined with the initial thermoplastic property of the shellac bond which they employ.

As already indicated, when shellac is subjected to heat for great periods of time, it tends to become thermosetting, and is no longer capable of flowing under the action of heat. It is therefore not surprising that other bonds for mica have been introduced, so as to give a product of more enduring flexibility. In particular, the mica insulation on the high-voltage stator bars of large turbo-alternators is generally bonded with a varnish based on bitumen. The insulation of such machines for an operating voltage of, say, 33 kV calls for many layers up to a radial thickness rather greater than 0.4 of an inch; in addition, the length of the high-voltage coils will be considerable, say about 15 ft. The expansion and contraction of such coils under operating conditions require that the insulation must also be capable of movement without fracture or electrical weakening. Hence the use of a bonding medium which has the appropriate electrical characteristics combined with the mechanical property of accommodating the change in length of the conductor to which it is applied.

The bars of a large stator, insulated as described with bitumastic mica, will usually be impregnated with a bitumastic varnish or compound. In other cases, for example in motors for high-temperature service, the machine may be impregnated in a high-temperature alkyd varnish. In such cases, compatibility between the impregnating varnish and the mica bond may be achieved by bonding the mica insulation also with alkyd varnish, and it is now quite common to find glyptal varnishes used as adhesives for mica.

More recently, in the development of Class H insulation for operation at temperatures up to 175°C, the Silicone materials have been used as bonds for mica, with varying degrees of success.

Although there is such a long tradition of use behind the use of mica in electrical insulation, there are still problems of bonding to which a final solution is yet to be found. One such problem concerns the bonding of micanite for the insulation of commutator segments. In general, micanite of a

low shellac content is used for this purpose, but as the commutator is built and pressed the micanite continues to yield under repeated applications of pressure, and whilst in practice the number of applications of pressure in the building process may be limited to four or five, it is almost certain that under severe conditions of service the commutator bars of a finished machine may tend to loosen. Fortunately, such troubles are infrequent, but the very fact of their occasional incidence leads to at least a feeling of discomfort amongst the engineers concerned.

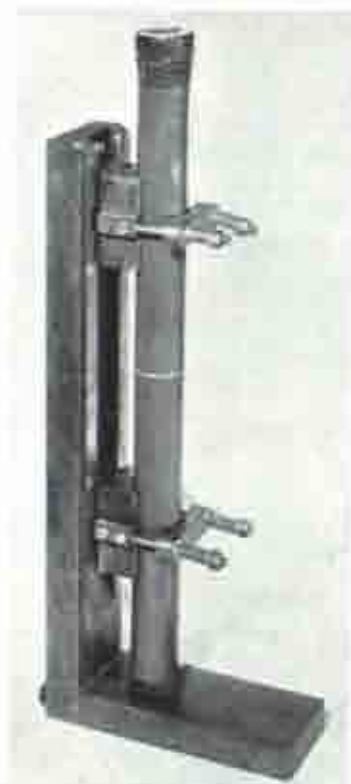
The micanite in question can conveniently be made using an adhesive agent in the form of a dry powder. The powder is mixed by an air flotation process, with small clean flakes of mica, and consolidation is effected by the application of heat and pressure. The bond is mainly shellac, with small additions of other natural resins.

Since Araldite Type 1 is available in powder form, it has been considered that it may form a suitable alternative to the shellac-type dry bond generally used in making commutator-segment micanite. Araldite bonded micanite has been prepared by pressing for 1½ hours at a temperature of 165°C and a pressure of 800 lb/sq.in. The initial samples showed promise: they had good electrical characteristics, and mechanically they were hard by virtue of the thermosetting quality of Araldite. Particularly, they were much less affected by moisture than the conventional shellac-bonded micanite. Further developments in this direction should prove of great interest.

BONDING OF CERAMICS

Ceramics form a very important class of insulation in the present day electrical industry. The range of usage of ceramic materials extends from small parts of low dielectric loss, as used in the radio industry, to large porcelains with weathersheds as used in switchgear, and all these applications are characterised by the need for employing good and permanent electrical material upon which varying atmospheric conditions have the minimum effect. In recent years there have been some interesting developments in the application of adhesives to porcelains, particularly the larger ones as used in switchgear.

Fig. 1. Strength of adhesive joints in porcelain rods: assembly of test specimens.



As a result of the great post-war demand for electrical equipment of all kinds, adequate supplies of large porcelains of electrical quality have been difficult to obtain and, due to the conditions of manufacture of such porcelains, it has also been true that the larger the porcelain the more difficult has been the supply position. As a result of this situation, some importance is attached to the possibility of assembling large porcelains by the jointing of a number of smaller ones. For example, one may consider a porcelain in the form of a truncated conical shell with weathersheds, the length being about 8 ft and the diameter over the weathersheds being about 3 ft at the bottom and about 2 ft at the top. If such a unit could be made by bonding together four or six units, end to end, it would almost certainly result in a considerable saving of time in obtaining the finished item. The usefulness of such a technique is not limited to assemblies as large as the example just quoted, but whatever the size of porcelain to which the technique were applied, the features required of the adhesive to be used would be somewhat critical.

In the first place the technique of application of the adhesive must be relatively simple. Prolonged thermal curing would obviously be a disadvantage, particularly for large items with high thermal capacity. Furthermore, any thermal curing of adhesives on large assemblies will be an embarrassment if it must be accompanied by arrangements to apply any substantial pressure to the joints during the cure. As regards the properties of the joints when completed, their strength in shear and in tension must be high; if possible the strength should be as high as that of the basic porcelain. Likewise, the shock strength of the joint should be high. The need for such properties as these is dictated by the circumstances in which the porcelains are to be used, including the possibility of subjecting porcelains to an internal hydraulic pressure of up to 1000 lb/sq. in. Other properties which are required of such adhesive joints are that they should be completely stable to the varying atmospheric conditions of temperature and moisture encountered in almost any part of the world, and that they must not introduce any electrical weakness or serious discontinuity or have any deleterious effect upon switch oil or transformer oil with which they may come into contact.

There may be a number of adhesives which will produce joints having most or all of the properties just enumerated, but in general the problem of application, particularly in respect of curing the adhesive under pressure, has been extremely difficult of solution until the introduction of Araldite. The fact that joints can be made with Araldite under contact pressure only has simplified the problem of making joints in large porcelain assemblies to such an extent as to bring such assemblies well within the range of practical possibility.

Experiments have demonstrated that, in respect of mechanical strength, and thermal and chemical stability, joints in porcelain using Araldite Type 1 as the adhesive are quite satisfactory. In this connection it is interesting to note that the strength in tension of an Araldite joint between two porcelains is usually such that when the joint is pulled the porcelain fractures rather than the joint. This has recently been demonstrated by preparing a range of test specimens in the form of 1-in. diameter rods of porcelain jointed at the centre in a plane normal to the axis. The nature of the test specimens and the

fixture in which they were prepared can be seen in Fig. 1. It should be noted that this fixture was so arranged as to bring the joint faces together parallel to each other, and the upper half of each rod then rested freely on the lower half. Three sets of samples of special interest were those in which joints were made with Araldite Type 1 in the form of powder, cold-setting Araldite Type 101 with Hardener No. 951, and Redux Type K6. With the exception of Araldite Type 1 the curing of all the samples was started from cold as follows:

Araldite Type 1—cured for 1 hour at 190°C.

Araldite Type 101—cured for 1 hour at 90°C.

Redux Type K6—cured for 5 minutes at 180°C.

These samples were tested to destruction in a tensile machine with self-aligning jaws, and except in the case of Redux Type K6 the joint itself was not fractured; when fracture occurred at the joint it was usual to find that the break had occurred just within the porcelain adjacent to the joint. In many cases the porcelain had broken in positions well away from the joint, as for example in the case shown in Fig. 2.

With joints made of Araldite Type 1 the mean value of the breaking load was 1 ton; with the other two materials the breaking load was .9 ton and .4 ton. The high value of the breaking load of the joints prepared with cold-setting Araldite cured at a moderate temperature is particularly interesting.

Further tests on similar samples have shown that they are not seriously affected by exposure to open steam, and tropical tests which have been in progress for some months indicate that no loss of joint

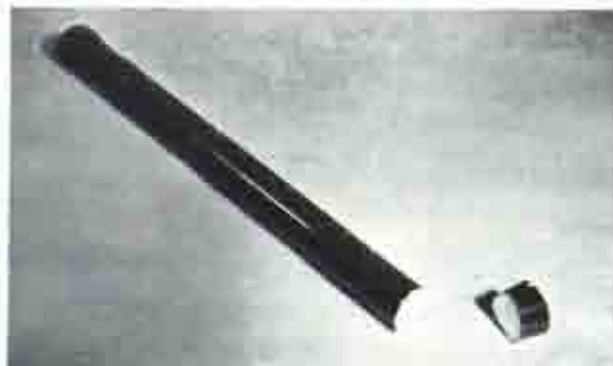


Fig. 2. Strength of adhesive joints in porcelain rods: specimens in which an Araldite joint was stronger than the porcelain.

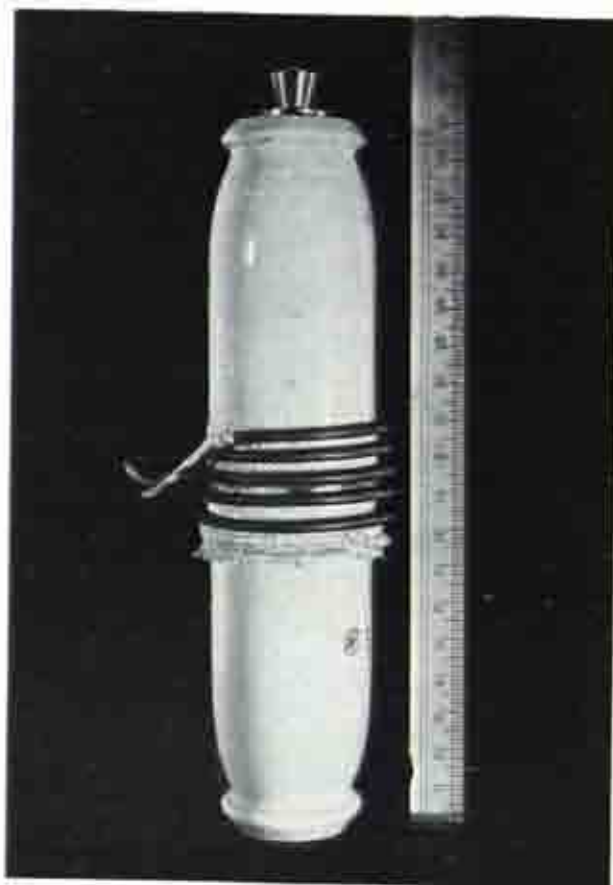


Fig. 3. Adhesive bonding of porcelain assemblies with Araldite Type 1: arrangement for curing.

strength is to be expected as a result of prolonged exposure to conditions of high humidity.

Other tests have demonstrated the suitability of Araldite Types 1 and 101 for use in transformer oil.

It would appear that, so far as properties are concerned, Araldite joints are entirely suitable for application to large porcelains.

As regards the practical problem of making the joints, the advantage of the Araldite adhesives in that no applied pressure is required, has already been mentioned. A further simplification of the technique of making the joints has been sought by using external heating arrangements so as to avoid the need for an oven. Fig. 3 shows a simple arrangement in which joints were made between pairs of porcelains using Araldite Type 1 as the adhesive, the heat being applied to the joint by means of a sheathed heating element in the form of a



Fig. 4. Adhesive bonding of porcelain assemblies with Araldite Type 1; result of tensile testing.

coil. The diameter of these porcelains was about 5 inches and the width of the annular jointing face was approximately $\frac{3}{4}$ inch. Joints were made using the Araldite in both forms: using the stick material the porcelains were, of course, heated before applying the adhesive, but using the powder material the adhesive was sprinkled on the jointing face and the porcelains were brought together before heating was commenced. The coil was supported around the joint by a simple packing of asbestos rope, and, on this relatively small assembly, no special care was taken to provide thermal lagging. The temperature was measured with a thermocouple placed on the inside edge of the joint face. It was found that, using a 1-kilowatt heater, the temperature was raised from ambient to 185°C in approximately 1 hour, and when this point was reached the supply to the heater was regulated so as to maintain the temperature steadily at 180-185°C for 1½ hours. The assembly was provided with brass studs at either end so that the strength of the joint in tension could be determined. In two experiments with this particular assembly the joint has not failed: in one case, one of the brass studs fractured at the root of the thread under a load of 2.6 tons; in the other case the porcelain broke on its smallest diameter under a load of 2.54 tons (approximately 4 ton/sq. in.). This second example is shown in Fig. 4.

Although this experiment was on a small scale, it may be concluded that its translation to a larger-scale operation would not present any major

difficulties, particularly having in mind the fact that the samples described were not lagged in any way during curing.

The adhesive jointing of ceramics is not, of course, limited to bonds of porcelain to porcelain. There are many cases of electrical designs which include ceramic and metal assemblies. Fig. 5 shows two such examples in which ferrules are bonded to rods and shafts. It is common practice in switchgear to make lifting rods and mechanical links in synthetic-resin bonded paper or synthetic-resin impregnated and bonded wood laminates. In such cases ferrules and end-caps may be screwed or cemented to the rods, and they are generally also pinned as an additional safety measure. It has been shown that, compared with previous practice, ferrules bonded with Araldite on to synthetic-resin bonded paper rods are so much more secure that, were it not for fear of the failure of the human element, the use of pins could be dispensed with. There are some electrical designs, however, in which the properties of synthetic-resin bonded laminates are inadequate: when the electrical conditions demand a superior material, resort must be made to something in the class of ceramics, in which class, for present purposes, I include glass. The larger item in Fig. 5 is a tie-rod made of glass-bonded mica, familiarly known as Mycalex, to which is bonded a brass ferrule at one end and a steel one at the other. This is a tie-rod used in the construction of a 300-kV oil-filled resonant transformer for use in a piece of medical X-ray equipment. The ferrules are bonded to the rods with Araldite Type 1 and the joints have been

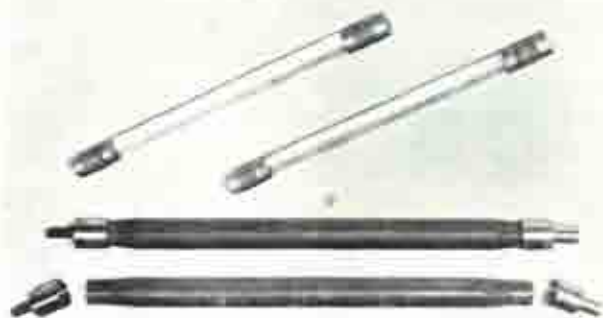


Fig. 5. Bonding of metallic ferrules to Mycalex and glass rods, using Araldite Type 1.

found to be perfectly safe in service. The smaller items are glass drive-rods to which flexible-type tubes have been bonded with Araldite Type 1; these drive-rods are used in the television transmitter at Sutton Coldfield. Other cases could be cited in which ferrules have been bonded to the ends of glass tubes, again using Araldite Type 1 as the material which would give the optimum strength of joint. Such cases introduce an interesting consideration of the relation between the coefficients of expansion of the materials used, and it is sometimes necessary critically to choose the dimensions of the mating parts in relation to the curing temperature, so as to avoid the danger of obtaining a joint which is not self-stressed (if not broken).

In discussing tensile tests on joints between porcelain rods it was noted that the strength of joints made with cold-setting Araldite cured at 90°C was not very much lower than that of joints made with Araldite Type 1. Where it is possible to accommodate the lower strength of such joints it is a great convenience to be able to effect the cure of the adhesive at the relatively low temperature of 90°C—this temperature being used to enhance the strength of joints made with Araldite Type 101 as compared with setting at room temperature. An example of the application of cold-setting Araldite cured at a moderate temperature is shown in Fig. 6.

The porcelain cylinder, which is 18 in. long, is closed at each end with a tinned copper cap, and houses a stack of spark gaps and current-limiting Metrosil units. The end-caps are bonded to the porcelain tube by means of Araldite Type 101 with Hardener 951, cured at 75°C for 2 hours. In the development stages this assembly was subjected to a most rigorous series of vacuum tests, pressure tests, and temperature cycling tests, in order to prove the value and permanence of the bond as a seal. In the vacuum tests the pressure was reduced to that of 2 centimetres of mercury; in the pressure tests nitrogen was admitted at a pressure of 10 lb./sq.in.; and in the temperature cycle tests the assembly was subjected to temperatures ranging from -40° to +70°C. It was found that bonding the end-caps in the manner described gave a seal which was vacuum and pressure-tight within the design requirements, and such units have proved satisfactory in production and service.



Fig. 6. Scaled porcelain casting for gap assembly: tinned copper end-cap bonded to porcelain tube with Araldite Type 1.

Adhesives for Laminates

Laminates of paper, fabric and wood are very widely used in the electrical industry. Such laminates are usually formed by treating the base material in sheet form, with a thermosetting resin, and then pressing together stacks of treated sheets at a temperature suitable for converting the resin. Under suitable conditions, this process produces boards which are hard and strong, of good electrical properties, and generally free from signs of delamination. The most commonly used boards are bonded with mixed phenol and cresol formaldehyde resins.

It is sometimes necessary to bond together parts made from laminates, and in the past the adhesive generally used has been either shellac or a syrup based on phenol and cresol formaldehydes; in the latter case the bond requires thermal curing. In either case the bonds have been of doubtful strength and engineers have generally endeavoured to avoid the use of such bonds in their designs.

The introduction of adhesives combining both thermosetting and thermoplastic components has provided the means of bonding laminates in a more satisfactory manner than was possible with either of the two adhesives previously used. The two-component adhesives, as exemplified by Redux, overcome at once the thermoplastic nature of shellac and the brittleness of the synthetic-resin films. It is also possible to bond laminates successfully by means of Araldite, and this, of course, under contact pressure only. However, to cure Araldite in a short time requires a temperature which is generally too



Fig. 7. Synthetic rubber volume compensators for use in sealed oil-filled equipment.

high for the laminates in question. Even at a temperature of 150°C there is a serious danger of most electrical forms of laminated material distorting and delaminating. This danger can be avoided by using, for example, Redux liquid K6 with accelerator and Redux powder; by this method joints can be made in a matter of ten minutes at temperatures as conveniently low as 120°C . Such joints have to be made under pressure, but having regard to the resultant strength and the shortness of the cure we have here a most useful means of making strong bonded assemblies of laminates in a manner not previously known.

Bonding of Rubber

Natural and synthetic rubbers find many applications in the electrical industry, ranging from their use as dielectric materials in cables to their use for mechanical purposes such as in the provision of flexible mountings. Amongst these uses there is one to which attention is now drawn, in which the problem of bonding is of more than ordinary significance. In certain types of oil-filled equipment it is necessary to seal the container, excluding all gas and also avoiding the creation of a partial vacuum in the container. This is particularly true of oil-filled equipment which, in normal service, may be inverted. Obviously, in such circumstances the

use of the customary conservator, as employed with many oil-filled transformers, is quite impracticable. Air must be excluded from the container because otherwise there would be a danger that when the equipment is inverted air-pockets might gather in regions of high electrical stress, and lead to breakdown. Two cases where these considerations apply are, firstly oil-filled transformers for air-borne use, and secondly, the oil-filled transformer for the medical X-ray set already mentioned; in the second example the whole unit has to be capable of rotation about a horizontal axis in order to facilitate application of X-radiation to the patient. When such sealed equipments are subject to temperature variations of more than about 50 degrees Centigrade, the thermal expansion of the oil becomes a serious consideration and means must be employed to accommodate variations in the volume of the oil; when the temperature of transformer oil is changed by $100^{\circ}\text{deg. Centigrade}$ its volume changes by about 10 per cent.

A convenient method of dealing with this problem is to include in the oil-filled assembly an oil-resisting synthetic-rubber sac, the inside of which is open to atmosphere by means of a suitable breather tube or nipple. When the maximum volume of the sac is a little greater than the maximum change in volume of the oil, and provided also that the initial inflation of the sac is controlled in relation to the temperature at which this initial inflation is performed, then such an arrangement acts as a volume compensator, avoiding both the danger of the creation of a partial vacuum at low temperatures and the danger of building up an excess internal pressure at high temperatures.

In designing such an arrangement, it usually transpires that the shape and size of the rubber compensator are such that it is not possible to mould the sac in a single operation; most probably the sac will have to be moulded in two parts which must subsequently be bonded together. Examples of such volume compensators are shown in Fig. 7. The larger circular sac has an overall diameter of about 2 ft and has been formed by bonding together two halves, the joint being in the centre-plane. The smaller examples have been bonded together by means of a reinforcing strip around the seam,

In making compensators of this kind it is important that the adhesive joint shall be mechanically strong as the parent material, that it shall be unaffected by transformer oil over the range of operating temperature to be encountered, and that it shall not leak. Such joints can be made by using a solution of the parent material as the adhesive. By this method it is necessary to semi-cure the two halves, paint the jointing faces with the adhesive solution, and having brought them together under pressure, the cure of the mouldings is taken to completion at the same time as the adhesive joint is cured. This process is made more difficult by the fact that the second half of the curing has to be performed with an internal pressure applied to the sac in order that its natural shape may be that corresponding to maximum inflation, i.e. correspond-

ing to the condition of minimum temperature when the equipment is in service. Clearly the process is one calling for great care, and in fact the rejection rate of compensators made by this process is uncomfortably high.

A considerable improvement has been achieved by using Ardux 120 as the adhesive in place of the synthetic-rubber solution. In the first place, when using Ardux 120, the joint can be made after the half-mouldings have been completely cured. This, of itself, results in a considerable simplification of the manufacturing process. The use of Ardux 120, however, carried with it the further advantage of improved joint strength, which more than offsets the slight inconvenience of acid-cleaning the joint faces before making the joint.

Referring to the large annular compensator, tear-

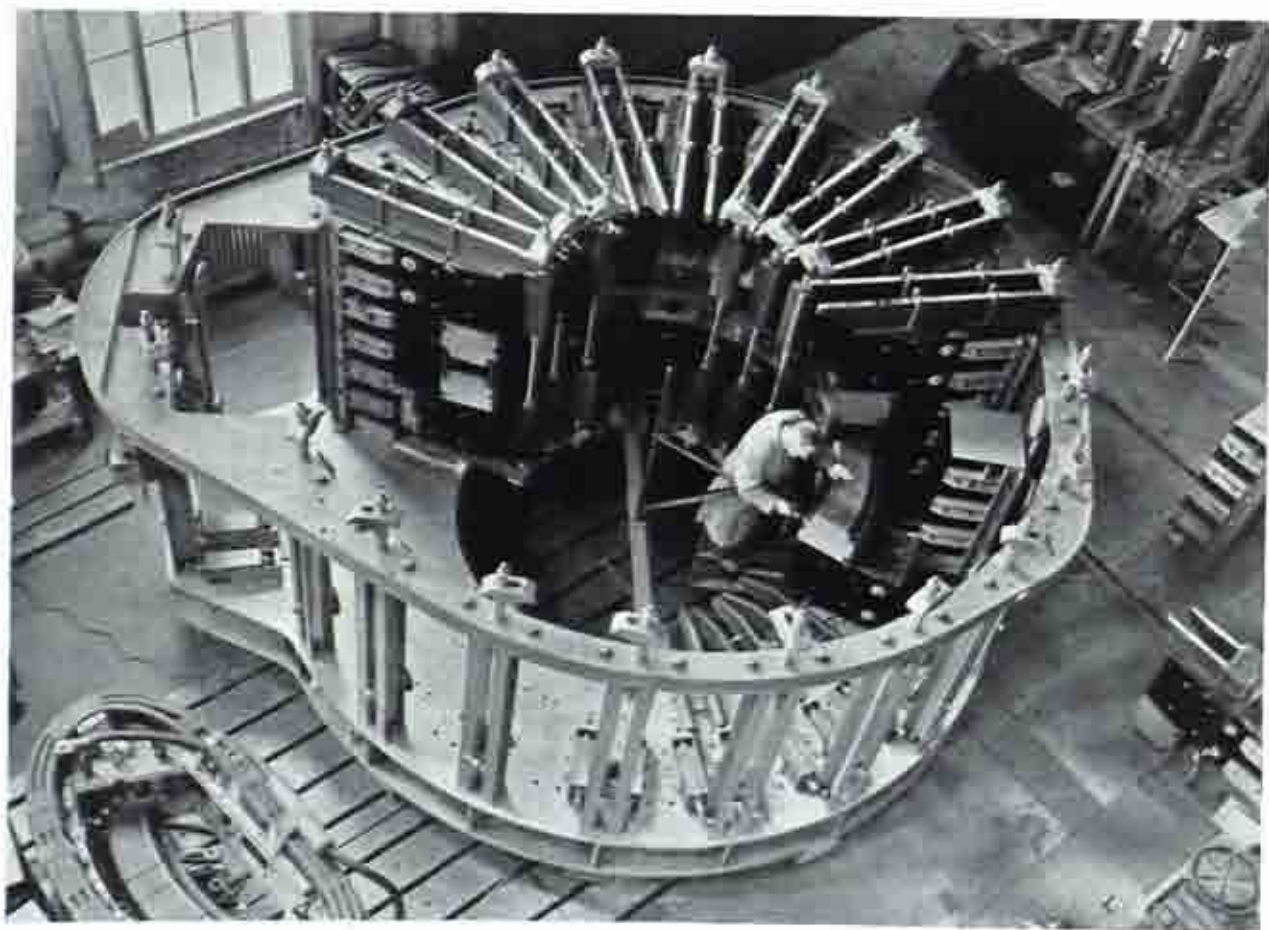


Fig. 8. Partly-assembled core of 300 MeV Synchrotron: core laminations bonded with M.V. 302 adhesive.

ing tests across the joint indicated that joints made with Ardux 120 were at least twice as strong as those made with synthetic-rubber solution, and that after such joints had been immersed in transformer oil for six months at a temperature of 60°C the strength of the Ardux joint was reduced by about 25%, whereas the strength of the synthetic-rubber joint was reduced by about 70 per cent. In many of the tests on the Ardux joint it was found that the moulding itself failed before the joint.

In this connection it is also of interest to note that the curing time of joints made with Ardux 120, particularly when the accelerator is added, is only a fraction of that for the synthetic-rubber solution at the same temperature.

The use of Ardux 120 is not confined to the bonding together of similar types of natural or synthetic rubber compounds, but also includes the bonding of rubbers to metals and other materials. An example is shown in Fig. 7 of a rubber dolly bonded into a cup made from laminated wood. A series of these assemblies is used to support the 'donut' of a large synchrotron, and the application is of interest in that this item is used under conditions which tend to tear the joint. In view of the fact that the tearing condition is the most arduous to which any joint is likely to be subjected, it should be noted that up to the present no dollies have been pulled out of their cups: the Ardux 120 joints have proved entirely reliable.

ADHESIVES IN MAGNETIC CORES

The use of adhesives in magnetic cores is no new feature. Years ago it was general practice to provide insulation between the laminations of the cores of transformers and large machines by sticking thin paper on to electrical sheet-steel by means of starch pastes and similar adhesives. The advent of flash-enamel coatings on electrical steels has not entirely displaced paper insulation, still applied by the old method.

In assembling the cores of electrical apparatus, it is almost an invariable practice to hold the steel together by clamps and tie-rods and other similar mechanical arrangements. There are cases, however, in which conventional mechanical clamping arrangements may be inconvenient or indeed may be

inadequate, particularly with regard to the generation of noise. Two examples may be quoted which, though differing very widely in scale, exemplify the possibilities of using the adhesive bonding of steel laminations as an alternative to the usual clamping arrangements. In the first example, a small core is used as part of an electromagnetic detector head: the core is made from U- punchings, $\frac{1}{2}$ inch wide and with a length of limb of approximately 2 inches; these laminations are built up to a thickness of $\frac{1}{2}$ inch. This detector head, forming part of a Turbo-visory equipment, is mounted within and close to the shaft of a steam turbine. It is thus exposed to elevated temperature conditions and to the combined action of oil and water vapours. Further, because of the function of the device it is important that there should be a high mechanical stability of the components of the magnetic circuit, despite the fact that the mounting arrangements for core itself are not such as to permit the laminations to be clamped really tightly. The problem has been met by bonding together the laminations of this core with Redux. The positioning of the laminations with respect to each other is ensured by the use of a suitable jig, and the solidly bonded-core which has been obtained has proved to be suitable in respect of both mechanical and chemical stability.

Whereas the cores just described weigh only a few ounces, the weight of steel used in the second example to be described is 120 tons. A 300-MeV synchrotron has been constructed by the Metropolitan-Vickers Electrical Company Limited to be installed at the Glasgow University. In designing the main core of the synchrotron it was realised that unusual measures would be required to minimise the risk of undue vibration and noise. At the same time it was important to provide a core in which the inter-laminar insulation resistance was such as to keep down eddy currents to a minimum. It was felt that the problem of vibration could not be solved by mechanical clamping alone, and a solution was sought and found in combining mechanical clamping with adhesive bonding of the electrical steel. The coreplate insulation was provided by double flash-enamelling the steel.

The adhesive which was used for this purpose was one which, like Redux, combines the thermosetting and thermoplastic components, but which, at the

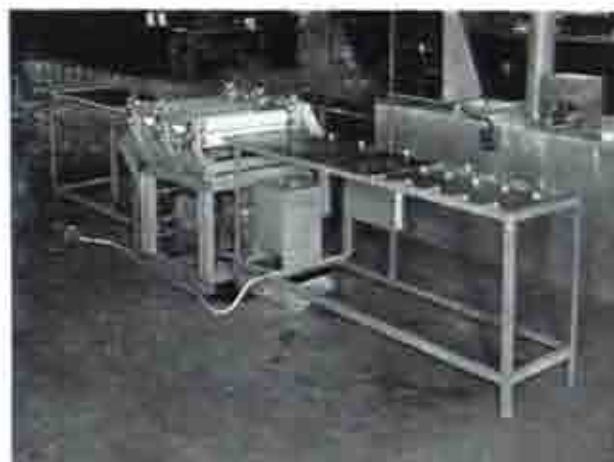


Fig. 9. Machine for applying adhesive to electrical sheet-steel. sacrifice of some adhesive strength, contains both components in a single syrup. The advantage of the single-solution adhesive (which was made by M-V.) will be obvious when the scale of the application is considered. Fig. 8 shows a partly-assembled core of the synchrotron. Each leg is made up from one vertical and two horizontal blocks of laminations, together with two laminated pole-pieces; the height of each leg is about 3 ft and the cross-section roughly 18 inches square; thus each block is made from about 1800 laminations. The complete core is made of 20 legs.

The process which was adopted for bonding these laminations consisted of four operations. A double film of adhesive was applied simultaneously to both



Fig. 10. Rollers of machine for applying adhesive to electrical sheet-steel.

sides of each individual sheet. Secondly, the solvents were driven off, and the adhesive was dried in an oven at 150°C for five minutes. Thirdly, the sheets were stacked in suitable jigs and pressed into slabs 1 inch thick, the pressure being 50 lb/sq.in. and the cure being effected at a temperature of 150°C for five hours. Finally, the 1-in. slabs were brushed with the adhesive and bonded together under the same conditions of cure as before. Fig. 9 shows a general view of the machine which was made for applying the adhesive to the individual laminations. As each sheet came off the machine it was collected in a light steel frame which was loaded into a truck; when the truck was full this in turn was pushed into an oven at a temperature of 150°C, and as one truck

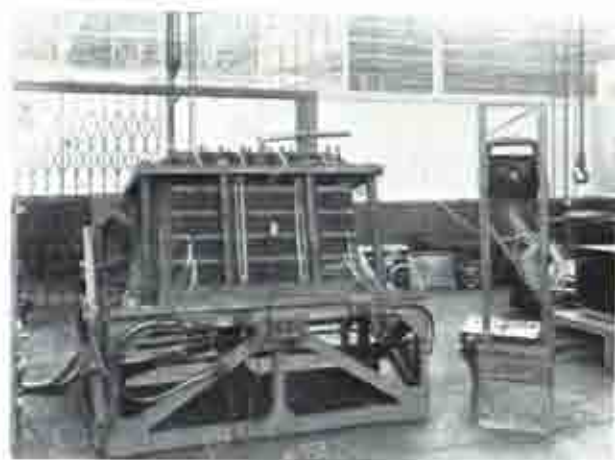


Fig. 11. Pressing and bonding of 1-in. thick slabs of laminations for 300 MeV Synchrotron.

was pushed into the oven at one end, an earlier truck was pushed out at the other end. The arrangement of rollers which was used to apply the adhesive to the sheets is shown in Fig. 10. Three pairs of synthetic-rubber rollers were employed, the first pair being driving rollers, the other two pairs each applying adhesive. The bottom roller of each of the last two pairs was running at its lowermost point in a trough of adhesive, and it should be noted that the adhesive in the trough was kept in constant circulation by means of a circulating pump below, there being an adhesive reservoir also included in the system. It was found that the middle pair served merely to wet the surface of the flash-enamel with adhesive, and in this connection it is interesting to

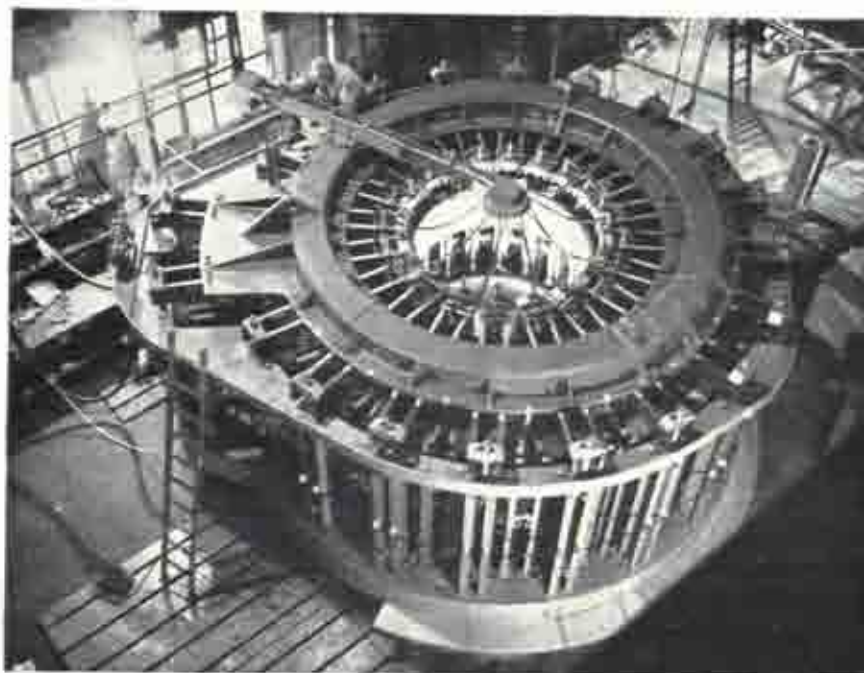


Fig. 12 Fully assembled core of 300 MeV Synchrotron.

note that any undercuring of the flash-etchant was immediately revealed by the appearance of patches which were not wet by the adhesive. The last pair of rollers built up the thickness of the film of adhesive to approximately 3/10 thou. per side, this being controlled by the pressure of the rollers and the viscosity of the syrup.

After the film of adhesive had been dried in the oven, the sheets could be stacked until required for pressing without any danger of their sticking together. The pressing of the sheets in 1-inch blocks is shown in Fig. 11. Pressure was applied by screwing down the top platen, and throughout the stack were spaced at appropriate intervals electrically-heated platens whose temperature was controlled at 150°C.

By this means, slabs were obtained whose spacer factor was no worse than 85 per cent (this based on laminations of thickness 0.014 in.) and in which the insulation resistance was at least 33 ohms/sq.in. per interface.

The finally-assembled core is shown in Fig. 12, and although this machine has not yet been run as a complete assembly, initial tests on the legs bonded in the manner described have indicated that the

technique which was adopted should meet all the set requirements.

ADHESIVES AS DIELECTRICS

Some of the adhesives to which reference has been made have proved to be suitable for use as dielectric media, particularly in combination with suitably chosen fillers. Electrical tests on slabs of $\frac{1}{4}$ -inch thickness prepared from Natural Araldite Type 1 in the powder form, show that it has an S.I.C. of 4.1, a power factor at room temperature of 0.004, and a breakdown strength of approximately 300 volts per mil. Moreover, these properties are not significantly changed after exposure to two of the conventional tropical cycles. At 90°C, the power factor rises to 3.5%, the S.I.C. to 4.0 and the breakdown strength falls to 260 volts/mil. These figures indicate that Araldite Type 1 is a good electrical insulator, particularly resistant to moisture and suffering no serious loss of electrical properties at temperatures up to 90°C.

When Araldite Type 1 is used in conjunction with zircon sand as a filler, in the proportion 1 to 3, the S.I.C. rises to a value of 6.7 at 20°C, and the power factor to 0.017, whilst the electric strength falls to 240 volts per mil. The use of a filler such as sand

has the advantage of strengthening the insulator mechanically, and particularly in respect of abrasion resistance, whilst largely preserving the good electrical qualities; it also has the advantage of greatly cheapening the material.

Reference should also be made to the fact that Araldite is available in the form of a casting resin, which may also be used in combination with fillers to give dielectric materials of good quality.

Materials of this class, and other solventless resins, are being used on the Continent as a means of insulating dry-type instrument transformers, including both current transformers where the mechanical strength of the insulation is important, and voltage transformers rated up to 60 kV where the electrical strength is important. To employ filled resins in such circumstances is particularly advantageous from the point of view of simplification of the manufacturing process. The conventional means of insulating such transformers is based on a somewhat laborious hand-taping, with materials which are by no means cheap. The use of casting resins goes far to reduce the labour required for the process of insulation, and, judging by present reports, gives a product whose performance is in no respect inferior to that of the type of transformer which is insulated by taping. The adoption of this

means of insulation may well impose certain limits on design in respect of methods of construction and no doubt the full significance of such limitations will only be seen when the range of applications has been more fully explored.

An application of sand-filled resins which may be of some interest is the preparation of guide-bars for use with the belt of the 4 million volt Van der Graaf generator which has recently been constructed at the A.E.L. Research Laboratory at Aldermaston. The guide bars, which are about 18 inches long and which are $\frac{1}{4}$ inch in diameter, were required to be smooth, to be resistant to the abrasion of the belt passing over them, and to have high electric strength having regard to the d.c. stress to which they would be subjected. As a core for the guide-bars, a steel tube was used of $\frac{1}{8}$ inch diameter, and this, in relation to the finished outside diameter of $\frac{1}{4}$ inch, imposed an upper limit on the curing temperature, because of thermal contraction on cooling from the curing temperature. It was found that the cure should not be performed at a temperature higher than 150°C, and in order to avoid a lengthy cure at this temperature the insulation on the guide-bars was made from Araldite Type 1 natural powder, mixed in the proportion of 1 part of Araldite to 3 parts of Zircon sand. A mould was prepared, as shown in Fig. 13, which also shows the centre steel tube and the finished guide-bar. The mould with the steel tube in position was heated to a temperature of 180°C and was then placed in a heated and sand-lagged tray. The Araldite powder and the sand had previously been well-mixed in a closed container and the mixture was sprinkled slowly into the mould; when the mould was full it was placed in an oven at 150°C for 5 hours. When the casting was cold, it was knocked out of the mould, which had previously been lubricated with colloidal graphite; it was then rough-machined and finally ground to size. The d.c. breakdown strength of bars made by this method was 57 kV. An indication of the abrasion resistance of the sand and Araldite mixture is given by tests which were performed on a slab of the material by loading on to it a rotating steel wheel and measuring the length of the groove worn in the material by the wheel during a given number of revolutions at a given speed. Whereas the length of groove worn in a common glass was 6 mm, under a given set of

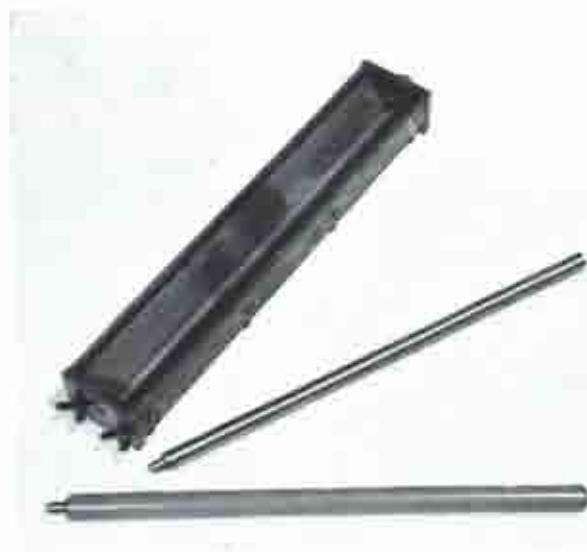


Fig. 13. 4 M.V. Van der Graaf generator guide bar, insulated with a mixture of Araldite Type 1 and sand; the centre tube and mould are also shown.

conditions, the length of groove worn in sand-filled Araldite under the same conditions was only 2.5 mm. These guide-bars have been in operation for some months, and apart from the fact that their electrical performance is satisfactory, it is also interesting to note that the frictional wear on them is very slight indeed.

CONCLUSION

With the advent, during recent years, of materials which promote adhesion marked by great strength and thermal and chemical stability, such as those offered by the Company which has promoted this Summer School, it may be concluded that there is now available to the electrical engineer a considerable extension to the range of design possibilities. These

new adhesives cannot be classed or dismissed as mere stickers; they are engineering materials, and I trust that the nature and range of the examples which have been discussed in this paper will have been such as to demonstrate that in the electrical industry the field of possible applications of true adhesives is not only wide but can be exploited to great advantage.

ACKNOWLEDGMENT

The author expresses thanks to Dr. C. Dannatt, M.C., O.B.E., M.I.E.E., Director of Research and Education and to Mr. B. G. Churcher, M.Sc., M.I.E.E., Manager of the Research Department, Metropolitan-Vickers Electrical Company Limited for permission to publish this paper.

THE BONDING OF FRICTION FABRICS

G. S. Learmonth

INTRODUCTION

THE bonding of friction fabrics to their metallic supports is one of the latest developments in the use of organic synthetic materials to replace more orthodox methods of fastening. While it has in fact a short prior history, the process owes its success mainly to developments in the use of these adhesives during the last war, chiefly in connection with the aircraft industry.

The nature of the problem and its state of development are such that it is not possible to give a highly scientific discussion on the subject, which is essentially a practical one. There is no theory involved which does not already apply in the normal bonding of metals to any organic (wooden or plastics) material, (i.e. one porous and one non-porous surface). This means that the bond will be a combination of mechanical and specific adhesion on one side, and of specific adhesion only on the other. The applications involved are grouped under three main headings:—

- (1) Automotive and industrial brake linings.
- (2) Clutch facings, mainly automotive.
- (3) Friction discs and miscellaneous bonds.

BRAKE AND CLUTCH FACINGS

—COMPOSITION

Nearly all brake linings are composed of asbestos fibres bonded together with a resinous, oil-based, bituminous or rubberised medium. In order to

obtain the correct coefficient of friction and durability the amount of the binder is strictly limited in that it forms in the neighbourhood of 30% of the finished product.

Without going too far into the manufacture of brake linings it is essential to elaborate this point as it has an important practical bearing on the bonding process. The asbestos may be used in one of two forms; as long fibres spun into heavy yarns and woven into thick fabrics; or short fibres in random assembly.

The cloths used, in the first method, may be either about $\frac{1}{8}$ in. thick (1.5 mm) and built up into the finished article by laminating under the influence of heat and pressure, or, alternatively, may be solid-woven, up to 1 in. thick, and processed by impregnation and subsequent consolidation under heat and pressure, and sometimes in addition by a baking process.

It has for some years been common practice to use the second method in U.S.A. and in this country; this employs short-fibre asbestos incorporated with a binder, either in the dry state or dispersed in solvents or water, which is formed by moulding, extruding, sheeting etc. Sometimes the asbestos fibres are previously formed into sheets of "mill-board".

For woven brake linings the binding medium may consist of phenol or cresol formaldehyde single-stage resins, or more frequently of a composite varnish which may contain one or more of the following materials: oil-modified resins, vegetable oils, bitu-

mens and natural resins (Congo copals, cardolite products etc.).

Moulded materials may contain phenolic single or two-stage resins (occasionally oil-modified) cardolite products, rubbers and oils.

Other materials may be added to the moulded products, usually in the nature of powdered fillers in order to achieve certain desired effects, but these do not normally appear to affect the bonding process in any way.

All friction fabrics are distinguished by the possession of a resinous skin, i.e. the surface layers are richer in organic binder content than the interior, this is, of course, true more or less of all plastic mouldings, but the woven asbestos products are particularly troublesome in this respect. The working surface is always ground off or otherwise removed by machining, but the back which is, of course, the surface used in bonding is normally left more or less untouched. With all moulding processes this skin is thin and readily removed, but the woven ones are often not only highly rich in organic matter but very rough owing to the coarse weave used, and special preparation for bonding is necessary.

CONSTRUCTION AND TYPES OF SHOES

Automotive Brakes

The main brakes on automobiles are, without exception, of the internal expanding type in which the asbestos facings are carried on two or three aluminium or steel shoes pressed by hydraulic, mechanical or pneumatic leverage on the inside of the brake drum. Three main types are in common use :—

(1) *Cast Shoes.* These shoes, usually die-cast aluminium, are carefully designed and have thick webs adequately reinforced where necessary and are extremely rigid and accurate as to dimensions. They are ideal for bonding.

(2) *Rolled Steel Shoes.* This type of shoe is rolled by patented processes from Tee-section steel with moderately thin web and periphery. It has adequate rigidity and accurate dimensioning and does not give trouble in bonding.

(3) *Fabricated Shoes.* One common type of brake has shoes of which the periphery and web are formed

separately from strips of steel assembled together by riveting or welding. In some cases the web has a narrow portion right in the centre of the shoe. This is designed to give good rigidity in the normal manner of operation of the brake, but with some bonding processes it has been found that the pressure applied in the middle of the shoe is sufficient to give some distortion and special precautions are necessary.

Self-Adjusting Shoes. One brake has a special self-adjusting device in which part of the lining is loose and is kept in constant light contact with the drum by means of a spring. This portion cannot, of course, be bonded unless special properties of the brake are dispensed with.

Band Brakes. The emergency brakes on some American cars and the brakes on certain types of industrial, agricultural and earth-moving machinery are of the external contracting type, or alternatively, of internal expanding type in which the friction fabric is fitted to a flexible steel band. Both types have been satisfactorily bonded using the normal equipment or in some cases special jigs.

Industrial Brakes

These are often of the external contracting type and sometimes of great size. This makes them rather unsuitable for bonding, especially as the sizes are not standard and the number of units involved of any one size is small. There is, however, no theoretical reason against bonding, and it has in fact been used for special purposes, even with rigid shoes.

CLUTCH PLATES

There are four common types of clutch plates all with slightly different construction, and all can be bonded under certain circumstances.

The commonest automotive clutches are of patented manufacture and fitted not only with sprung centres to assist in smooth take-up of the load but also with slotted and shaped plates. These are difficult to bond in the original form and unless special press tools are used the only alternative is to apply two main clutch-discs and slot afterwards. Sometimes plates or replacement plates are formed

without slots or without shaped segments or without both, and in this case no difficulty arises. Motor-cycle plates are often fitted not with discs but with small trapezoidal segments inserted in the plate. These segments can be bonded in place or alternatively discs can be used on either side.

Cone clutch segments can be bonded without difficulty providing suitable tools are available, but the remarks made in connection with industrial linings apply also here.

FRICTION WHEELS, etc.

Bonding has been applied not only in the mounting of friction discs and wheels, but also in their construction. In one specific example the centre portion is made of (cotton) fibre and constitutes the driving face, while the shrouds and centre boss are made either of steel or laminated plastic material assembled together with the aid of a synthetic adhesive.

In certain types of brake blocks (used with steel-wheeled vehicles) the main friction element is held to the mechanical part of the brake by means of wedge grips. These have been successfully assembled by bonding instead of shaping directly from the main friction block.

The duty expected of friction fabrics varies enormously according to the machine to which the brakes are attached. The lightest duty of all is probably found in cycle and autocycle linings which are very small and operate at low speeds and under light pressure.

In automotive work the range starts from the average light car where the braking loads are quite small, and the temperature reached is low. Though brake linings are made from asbestos this is so well consolidated that the conduction of heat is quite high. It has been found by experiment that the difference of temperature between the working face and the bonded back surface may be only some 10°C at a working temperature of 110°C.

The next heavier duty is found in the heavier type of commercial vehicles—trucks and lorries—and the heaviest normal duty is in passenger carrying vehicles working in large towns, and particularly in buses fitted with pneumatic brakes. In other heavier vehicles the higher stopping loads are usually allowed for by the provision of increased brake

working-surface. In the heaviest duty the working face of the brake may reach 300-350°C or even higher. Properly designed and operated clutch facings do not generally have to operate under such arduous conditions and very high temperatures are unusual.

It must be emphasised that the chief element destructive to the bond in all these applications is the heat generated as, when properly applied, the shear loads met with are well within the capacity of the adhesives used. Before leaving this subject oil must be mentioned. Brakes do not, of course, normally work immersed in oil (though clutches may do so) but in ordinary automotive work trouble is experienced periodically through the leakage of oil, especially on rear wheels, and while there is some evidence that no harm will be done provided that the brake lining itself is resistant to oil it is recommended that these conditions should be avoided as a matter of normal prudence.

HISTORY

Though bonding of friction fabrics is of recent development, and has only been carried out commercially since about 1947, it originated some years ago. In fact a British patent was granted to an American citizen in 1930. It is not proposed to review the patent position in general but it may be mentioned that this particular specification (BP 36561) had apparently in mind the use of a natural rubber composition as a bonding agent, and at the same time as a cushion between the lining and the shoe. One recent British patent (BP 617766) describes the injection moulding of brake linings directly on to a shoe which has been pre-coated with adhesive, and a further one of more importance covers the use of an adhesive in strip form in which the base is "a network of cellulose fibres .001-.005 in. thick with the object of providing for easier removal of the old lining."

In the period from 1935 to 1940 important developments were taking place with thermosetting synthetic adhesives with the object of securing efficient adhesion to metals and these were forced to early fruition by the wartime conditions which followed. In the aircraft industry particularly, both in Britain and in U.S.A., it was found possible in

many cases to eliminate riveting and to replace it by synthetic resin bonds which were not only as good as the riveted joints, but had certain specific advantages, for example, the slight degree of resilience in the resinous bond was found to give better resistance to vibration. These adhesives will be discussed briefly later on.

Work on the bonding of brake linings to shoes appears to have started in real earnest in the U.S.A. in 1934 and the project was carried at this time to the stage of development where a satisfactory synthetic rubber-resin bonding agent was evolved and to the carrying out of pilot scale production trials (on emergency brakes of the transmission brake type). The linings were in fact cured by R.F. heating procedure in some 2 min. and were found to give approximately twice the life of the riveted assembly, on the dynamometer. The same method was then applied to wheel brakes, and at the same time improved adhesives were tested with good results both on the testing machine and on the road. Wartime conditions then caused this investigation to be held over until 1945, when Buna N-phenolic resin adhesives were used and R.F. heating was abandoned in favour of oven curing and later the so-called "hot-shot" process was developed. These methods were thoroughly tested and it was found that in one test an increase of 100% in service life was possible. A large scale test was then carried out with light commercial vehicles. At this time too, the practical position with regard to operating the process both at the factory and in the field was correctly appreciated and the various forms in which the cement could be used were described.

During the same period the first recorded British applications of the bonding process used were made. Some difficulty was experienced with the clutch assemblies of certain tanks due to separation of the friction facing from the metal backing plate, and it was found that considerably better results were obtained by using "Redux" to bond the two together. It was found that the riveted discs disintegrated at about 5000 r.p.m. whereas bonded discs could be run at over 6400 r.p.m. without apparent harm resulting. Furthermore the service life of the riveted joint was some 200 hours while a bonded one operated for over 2000 hours. In

addition, when a disc was run to destruction the steel disc broke and the bond remained intact.

Meantime, other interests became involved and by about 1946 a three-pronged attack on the bonding problem was in full force in which the manufacturers of brake linings and the producers of adhesives and equipment took part (sometimes in collaboration with each other) and by mid-1948 the position was such that the rivet manufacturers saw fit to publish a strong counter-offensive in "Brake Service". By mid-1947 the brake service specialist or garage was being offered bonding ovens and hot-shot machines, bonding tape and adhesives from several manufacturers, and brake linings specially prepared for bonding, and in some cases pre-cemented ready for use. At least one manufacturer of brake linings offered replacement shoes at the same time. In 1948 it was announced that all Chevrolet $\frac{3}{4}$ - and 1-ton trucks were fitted with bonded linings, and a system of factory replacement of lined shoes was started, which meant that shoes were not re-used.

The present position is apparently that there are at least five proprietary brands of bonding tape, three or four makes of pre-cemented lining, and seven makes of ovens available. The manufacturers of original equipment are now using conveyor ovens and line production and not only commercial vehicles but also passenger cars have bonded linings as original equipment.

In England the chronological record is not too clear, as little information has been published and progress has been slower. Undoubtedly a large number of experiments have been made for a number of years mostly dating from the first announcements of the appearance of the process on the American market: the first public announcement was made early in 1949 when one of the makers of brake systems offered replacement shoes lined by bonding.

At the Motor Show in 1949 one maker of brake linings offered a replacement service and in 1950, after a hesitant start, another manufacturer not only offered relining service but gave technical service in the fitting up of any brake service agent with the necessary tackle and linings. Considerable sales resistance has been met with in Britain; most motor cars are fitted with proprietary brakes made by one of two manufacturers and no strong lead has been

given from any of these sources. Manufacturers of brake linings, in the advertising field at least, are dominated by one firm, which has so far thrown cold water on the process. There are indications however that preparations are now in hand for an all over change to bonding.

In the heavy vehicle field there has been little progress. Strangely enough in England this is the field which has shown the greatest interest in the process but apparently the problems involved have not yet been completely mastered. These problems are two: temperature, and the securing of adequate contact between the liner and shoe. The firm which I represent has been in a position to undertake small scale relining for over two years and a constantly growing business has been built up. Major achievements are the bonding of over seven thousand band brakes in one season for agricultural machines, the fitting of the whole fleet of the leading hire car service and successful trials on motor cycles at speeds up to 120 m.p.h. Up to the present time all these endeavours have been on a relatively small scale, but signs are now becoming evident of preparations for really large scale production.

TECHNIQUE

Adhesives

Adhesives for the cementing of metals to metals or to organic materials commonly consist of a phenolic resin modified by the addition of a thermoplastic material such as a vinyl derivative or a synthetic elastomer. In some cases also a synthetic rubber may be used with another type of resin, and the bond stabilised by vulcanising the rubber.

The adhesives found suitable for bonding of friction fabrics have been of these types. Without going deeply into the theory of adhesion it may be assumed that the function of an adhesive in a joint is a combination of "sticking" and "load transmitting" and that except in very thin layers of adhesive the strongest part is immediately adjacent to the surface while in the centre of the adhesive random orientation will occur. When an insoluble thermoplastic material is added to the adhesive it acts as a filler whose particles are of molecular dimensions and the strength of the whole bond is high, comparable with that of the surface layers. In addition a

certain amount of cross linking will occur between the thermoplastic material and the resin. Whatever the combination of these two factors, the fact remains that excellent adhesion may be obtained using adhesives of either of these two types.

It is believed that in virtually all the American work combinations of phenolic resins with acrylonitrile rubbers such as Buna N, Hycar, Chemigum, Perbunan, Chemigum N are used. These were developed by the Goodyear Rubber Co. Ltd.

The adhesives are prepared and marketed in three forms:—

- (1) As solutions in volatile solvents. These are applied to metal and fabric surfaces, the solvent removed, and the two then united. In this form the usable life is about three months more or less.
- (2) As precemented liners. These, of course, start as in (1) and in general the cemented liners will be available from the assembly lines manufacturer of the lining or brake. The life is about 12 months.
- (3) As precemented tape. The tape may be made of various materials, such as kraft, and one particular process claims to use a base composed of laminated asbestos and natural rubber. The absorbent bases are impregnated, and the rubber one coated on both sides with the adhesive.

In all cases once the solvent has been removed from the adhesive the process is virtually the same.

Similar adhesives are available in Britain, though the present difficulty in supply of synthetic rubber is a handicap.

The process with which the author has carried out most work is of the "Redux" type. This is of the type comprising a phenolic resin modified with a polyvinyl formal. Normally, the resin is supplied in solution in meths and the PVformal separately as a granular powder. The two are mixed in the application process and mutually dissolve when the bond is heated. It can also be used by both the tape and the precemented liner process.

Araldite

This new series of resins has been successfully used in bonding of friction liners, and has the advantage of requiring little or no pressure. It has however a very long baking time at high temperatures and is rather costly.

APPARATUS

Convection Oven

This equipment calls for no great comment, and the design is not at all critical. The only two factors which must be taken care of are firstly constancy of temperature and secondly even distribution of temperature. In a gas oven these two factors look after each other to a considerable extent and very good results have been obtained using an oven taken from a derelict domestic cooker. When an electric oven is used, however, some care is required to ensure that the proportion of convective heat transmission to radiation is high. In practice it has been found that the only reliable method of ensuring this is to have an indirectly heated oven with forced air circulation.

Infra-red Oven

This type of oven differs in principle and practice from that mentioned above as the heat transfer is predominantly by radiation, and necessitates the spreading out of the assembled liners and shoes in a flat layer either horizontally on a wire mesh tray, or alternatively vertically on hangers. The infra-red method has two major advantages, firstly it is ready instantaneously on pressing a switch and secondly the rate of heating is much higher than with convection. However, the liner/shoe is by no means an ideal subject for infra-red heating, as the source temperature, and the temperature which can be quickly reached by the work is very much higher than that at which either the cement or indeed the brake lining will spoil. This means that the cooking of the adhesive is on a time and temperature basis and not a time basis alone, and also that there is a strong probability of local overheating of the brake lining.

Conveyor Ovens

For really large scale production there is no doubt that the conveyor oven is ideal, and in this connection the remarks made with regard to infra-red are not applicable. In fact it makes an ideal heating unit for this type of oven. Mention might also be made of the "camel oven" in which the units are carried by a chain conveyor up into an oven-shell heated indirectly by gas.

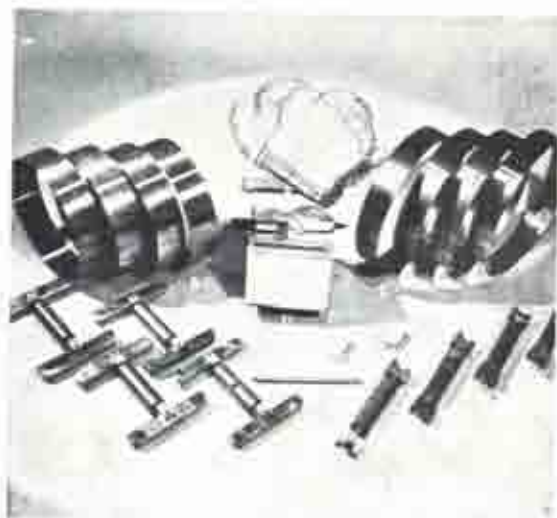


Fig. 1. Set of equipment for use in bonding linings to shoes

"Hot-shot" equipment

This is an American device whose function has been somewhat misunderstood. It may, in fact, be used as the sole curing unit in a relining unit, but is most efficiently used in a large scale production line simply as a means of setting the cement to a limited extent only, and requiring an oven to complete the cure. It consists of a heated anvil which is at rather a high temperature and which is fitted with jigs to carry the various sizes of shoes to be bonded. (Incidentally, it should be mentioned that the number of different sizes used in America is much smaller than here.) The shoes are preheated in an oven, placed on the anvil and the pre-cemented brake lining is quickly fitted and clamped down on the shoe by means of a toggle press fitted with a yoke and flexible band. After a short period depending on which adhesive is used (30 secs. in the original process) the assembled liner-shoe is removed and placed in an oven to complete curing.

In the first three types of curing equipment jigs are required to carry the linings and shoes, and as the curing process may require up to an hour when production is large the numbers necessary may be quite great. Several types have been used, but all are relatively simple in nature and readily available.

- (1) Spring plates and clamps.
- (2) Individual screw loaded and spring jigs.



Fig. 2. A brake shoe assembly ready for curing, using pressure bands and expanders.

- (3) Flexible bands and screw- or wedge-loaded expanded pieces (some are also spring loaded).

Other equipment necessary includes grinders for preparing shoes and preferably radius grinding equipment for the final stages.

EQUIPMENT REQUIRED

Permufose

- (1) Oven.
- (2) 8 each 10-in., 11-in., 12-in., rings.
- (3) 8 jacks.
- (4) 8 spacers for Bendix shoes.
- (5) Sanding drum with 10 sleeves.
- (6) Shears.
- (7) Air hammer and chisel.
- (8) Asbestos gloves.
- (9) Assembly plate.
- (10) Bonding tape.
- (11) $\frac{1}{2}$ -h.p. motor.
- (12) Bench.

Gandy

- A. Asbestos gloves for removing assemblies from the oven.

- B. Pressure bands of $\frac{1}{8}$ -in. steel. Two sizes are generally sufficient to start the service, one set of $9\frac{1}{2}$ -in. \times 2-in. and one set of 12-in. \times 2-in. Other sizes to suit individual requirements can be added in the light of experience gained.
- D. Adhesive. The shelf life of this adhesive is four months.
- E. Expanders. Type E, being for use with normal & brake shoes and type F with the special adaptors.
- F. to avoid distortion of light weight pressed steel shoes such as the Bendix.
- G. Tommy bar for tightening the adaptors and applying the pressure.
Also oven and radius grinder.

THE BONDING PROCESS

Preparation

The first stage in all bonding processes is the preparation of the shoe.

Where shoes are being relined the old lining is removed by means of a chisel or a rough grinder etc.

The shoe is degreased, preferably with trichloroethylene vapour, and the bonding surface is prepared by grinding till bright and free from all foreign matter including paint and all types of plating or anticorrosive treatment. Care is taken to keep this prepared surface clean till required for use. In the American process no further treatment is given to the shoe, but in order to ensure freedom from contamination of the metal surface it may be found desirable to apply at this stage a thin coat of adhesive.

The next stage is the preparation of the surface of the lining, and it is here that the first divergence between the various methods occurs.

Firstly, the lining must be in a fit condition for bonding. In all cases it must be free from paint and other foreign matter and it has usually been found an advantage to grind lightly to remove the resinous surface skin, which may contain exuded matter and also mould lubricant. In addition, in the case of some woven linings a rather heavier cut will give a flatter surface by removing some of the cavities which normally appear in the weave.



Fig. 3 Grinding face of liner after bonding to shoe.

Liquid-Cement Method

The cleaned lining surface is given two (or with woven linings even three) coats of adhesive by brushing or spraying or with a special spreader. A drying interval is given between coats, and the final coat is left an hour or preferably considerably longer to allow solvents to escape. This stage has been found very important and it is well worth while to have a low temperature oven to ensure efficient drying.

Film Method

When strip adhesive is used it is only necessary to apply a strip or strips of tape. The tape has a limited life but a reactivating solution is usually provided to soften it.

Precoemented Liners

These are prepared as for liquid cement, and no further operations are necessary. These may be stored up to one year at less than 100°C.

Curing-oven Method

The linings are now assembled in the correct position relative to the shoe and pressure is applied. The assemblies are then baked for the required period. Special care is necessary to avoid under-curing.

Curing "Hot-shot" Method

This method has just been described under equipment.

Finishing

The final stages are the cleaning of the edges and grinding of the face to the correct radius. This is especially important with bonded liners owing to the much greater solidity and rigidity which is obtained with them.

AMERICAN PROCESSES

				(°F)	(min.)
Pyrobond	Worldbest Cycloweld Chevrolet	Precoemented	Oven	350	30
		or tape	Hotshot	500	4
	Barrett	Precoemented		400	cont.
		or tape			
Saflibond	Grizzly	No details available			
			Precoemented	400	50
				450	40
				500	3
Durabond Pick		No details available	Oven		15
Permatase Unibond Cycloweld	Permatase	Tape	Oven		40
Chrysler			Oven	325	15
				375	10
				400	5
				425	3
			Hotshot plus	300	1 1/2
			Hotshot oven	350	15
Unifuse Plastlok	Amen	Tape No details available	Hotshot oven	350	5
			Infra-red	350	20
			Hotshot	400	20
			(plus oven treatment)		4
			Oven	385	30

BRITISH PROCESSES

				(°C)	(min.)
Girling Broomer Gandybond	Redux	Oven		150	60
			Hotshot	250	2

EXPERIMENTAL RESULTS

Linings

It has been found repeatedly that at the lower end of the temperature range woven linings under favourable conditions give the highest figures for shear strength with a decided lowering as the temperature is raised. This is thought to be due to the fact that under all conditions covered in these tests the strength of the adhesive layer is much greater than that of the brake lining material. All woven

linings are rather erratic in behaviour and due to the type of impregnant used are greatly weakened at the highest temperatures. Considerable fluctuations have also been observed from time to time with woven linings owing to variations in the degree of bake, in resin content, and also in the mechanical properties of the surface used for bonding. It has been found that a certain popular type of impregnating medium for some reason gives poor bonding, and liners made from this type of material are totally unsuited to the process. No other method of detecting this fault other than the purely practical one has been found and tests must be made of each type of lining to verify its suitability. Most moulded linings are suitable for bonding, and have a good surface free from excess resin and other deleterious matter. They usually show a lower shear at room temperatures, but maintain it much better than the woven ones at higher temperatures.

Temperature

The chief agency resulting in failure of brake linings is temperature and the temperature reached may range from freezing to 100-150°C on light car and commercial vehicle applications and to as much

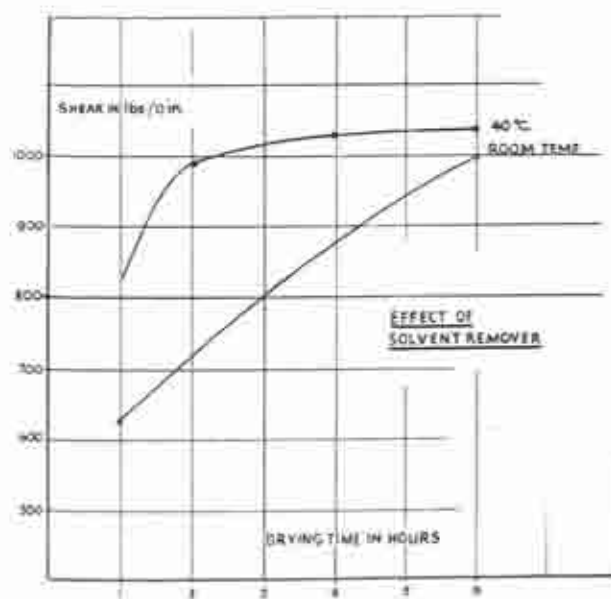


Fig. 4 Effect of solvent removal on strength of cured joint between brake linings and shoes.

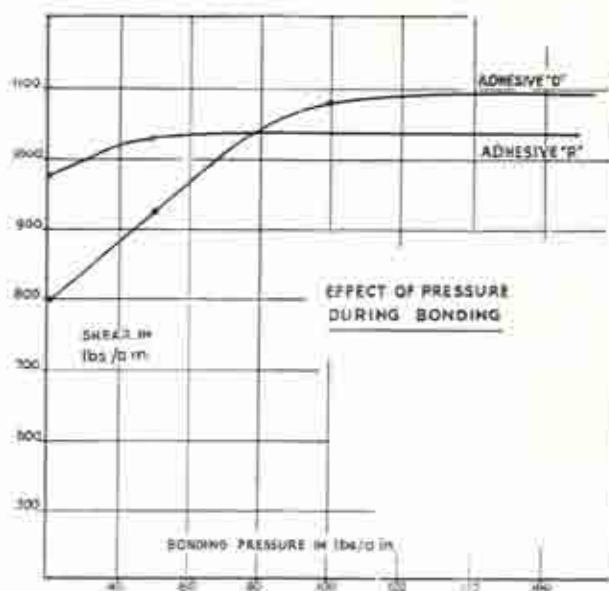


Fig. 5 Relation of shear strength to bonding pressure using two different adhesives.

as 350°C or over under extreme conditions with commercial passenger and goods vehicles. It was therefore necessary to test the bonding process for resistance to such temperatures. It was first of all established that the temperature of the bonding surface was surprisingly near that of the working face, about 10°C at 110°C, and tests were therefore carried out at room temperature, 150°C and 300°C with various linings. Under favourable conditions a moulded liner showed as much as 90% retention of shear strength even at 300°C while a woven material lost 90%. At 100°C however the difference is not great and in fact many woven liners have given excellent service results.

(It should be mentioned again that the strength of the adhesive under these conditions is greater than that of the lining, and it is very rare to have a pure glue-line failure, providing the layer of adhesive is not too thick).

Solvent

It is of great importance that most of the solvent should be removed from the adhesive film before bonding, and for this reason alone there is some advantage in precoating liners. Excess of solvent will have the effect of lowering the viscosity of the

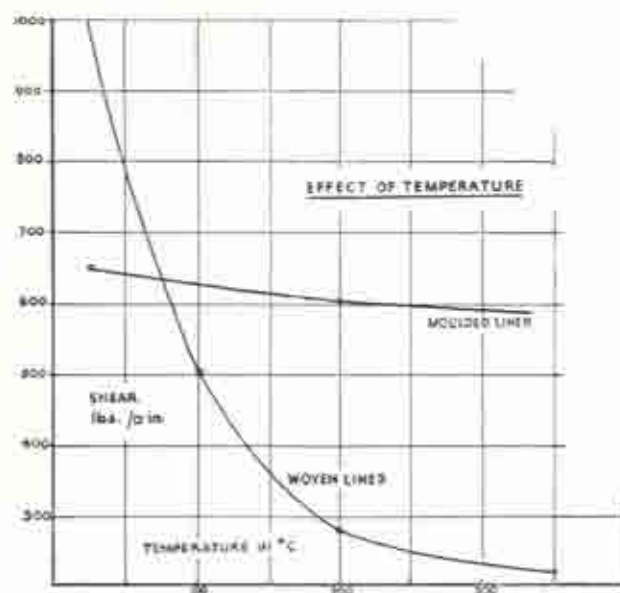


Fig. 6. Graph showing how the strength of the cured adhesives varies in relation to the curing temperature.

adhesive at bonding temperatures, with the result that an undue ejection of resin from the glue-line will take place resulting in a starved joint. Considerable bubbling and blistering may also occur in extreme cases. This may all be avoided by oven treatment under controlled conditions of the cemented liner and shoe. Treatment for 30 min. at 60°C or 1 hour at 40°C is more effective than 12-15 hours at room temperature.

Pressure

The effect of pressure during bonding differs greatly with different adhesives, but in practice, provided that there is sufficient pressure to bring the liner and shoe surfaces together with a glue-line of 21 thousandths and that the pressure is well maintained during curing, 30-40 psi is the minimum desirable, a good bond will be obtained though with some adhesives an appreciable loss will be suffered unless this is increased to 100 psi.

Baking-time Temperature

The strength of the bond increases very rapidly in the initial stages, and as will be seen from the graph, after about an hour under the particular conditions used the rate of increase fell off, though

appreciable increase took place for at least a further hour. As will be seen, a difference of some 10°C doubles the curing time, and it is generally found that better bonds are obtained at the higher temperatures, and though the significance of this is not clear, it may be due to the glue-line passing more quickly through the liquid stage, with rather less loss by exudation.

Oil and Grease

The adhesives used appear to be for all practical purposes resistant after curing to all common oils and grease, but some linings are affected and the apparent bond strength may be seriously diminished.

COMPARISON OF BONDING WITH RIVETING

A riveted joint does not fail by shear but by a combination of tensile failure of the lining and the rivet pulling through the elongated hole. The rivets almost never fail. The figures given are therefore a reflection of the effect of temperature on the lining alone, and will vary greatly with the lining.

One pair of rivets 20°C—920 lb, 150°C—100 lb, 300°C—40 lb.

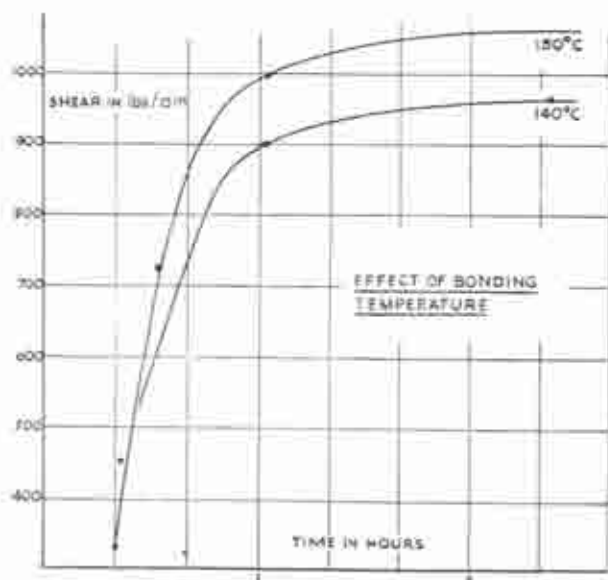


Fig. 7. Graph showing the effect of elevated temperature on the strength of moulded and woven liners.

A brake lining $1\frac{1}{2}$ in. \times 9 in. will normally have five pairs of rivets giving total strength of 4600 lb. A similar bonded liner has a total strength of (minimum at room temp.) 600×16 i.e. 9600 lb.

Advantages

- (1) Eliminates rivets.
- (2) No scoring due to rivet heads.
- (3) Improves heat dissipation increases life.
- (4) No scoring due to grit in rivet holes.
- (5) 10% increased braking surface due to no rivet holes.
- (6) Twice bond strength.
- (7) Over twice life as lining can be worn right down as far as take-up.
- (8) No gap between lining and shoes gives more solid feel.
- (9) Antisquel due to better contact.
- (10) No drilling required.

Disadvantages

- (1) Skill required.
- (2) Plant required.
- (3) Security.
- (4) Limited life of cement.

Proof-test Method

- (1) Girling—100% proof stress to all liners.
- (2) Chrysler—special shear test.
cyclic shear test.

dynamometer tests

fade test 7 times,
shock stop once,
endurance several
hundred
repeat fade test 7
times.

car tests six months.

- (3) Chevrolet—shear 400 lb/liner
- (4) Permafuse—air-cylinder
- (5) Gandy—strip off 5% or 10%
shear off 1 sq. in.

Practical Test Results

General motors—tested at 200–400°C with satisfaction.

Permafuse—over six years experience with 10 service stations 95% of relining work by bonding.

Girling—100% stronger than riveting.

Chrysler—11-in. liner riveted 1200 lb bonded 13200 lb.

Goodyear—6 times stronger than rivets.
Taxicab life increased from 12000–25000 miles N.Y. 2000 stops from 50 m.p.h. at 18 ft/sec/sec.

Chevrolet—double life.

Gandy—60 stops in 10 secs from 90 m.p.h. at 350°C. 15000 bands bonded.
Taxicab service.

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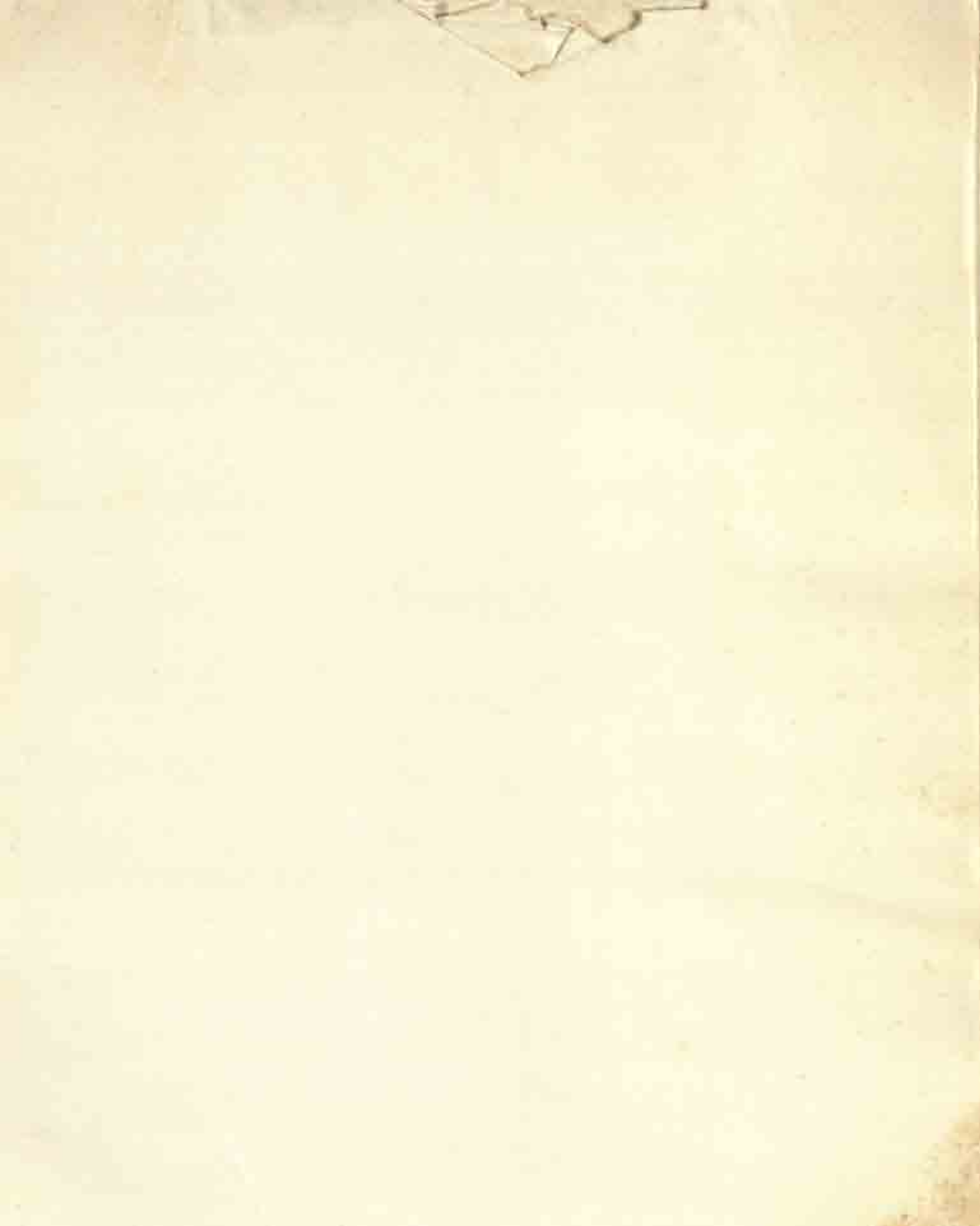
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