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SUMMARY

A description is given of the cementing together of two 20-ton steel discs to form a composite 40 ton rotor, 139 in. in diameter and 20 in. in thickness, which functions as a two-turn winding of the homopolar generator at the Research School of Physical Sciences of The Australian National University. The bond between the steel discs is required to withstand a 200 volt difference in potential and large mechanical forces due to temperature differences and short circuit currents. The bottom rotor pair was cemented first, followed by the top rotor pair.

CONTENTS

INTRODUCTION

As part of the research programme at the Research School of Physical Sciences a large homopolar generator[1] is under construction to deliver pulses of current of about 1 second in duration and 1.6 million amperes peak value. As the output voltage is 800 volts, the impulsive volt-ampere product is 1,300,000 KVA. This output is obtained from a series connection of two counter-rotating armatures, rotating about a common vertical axis in the vertical magnetic field of a large electromagnet. Each armature has two electrical 'turns', and consists of a 40 ton rotor, 139 in. in diameter and 20 in. in thickness, formed by cementing two 20 ton mild steel discs together with the aid of epoxy resin. Electrical connexion is made by slip rings consisting of liquid metal jets at the outside edge and near the centre of each disc as shown in Figure 1. The voltage developed between the slip rings of a disc is 200 volts at the maximum disc speed of 900 r.p.m. The bond between the discs in each rotor is required to withstand this voltage, as well as the expected forces due to temperature differences and short-circuit currents of 5 million amperes.

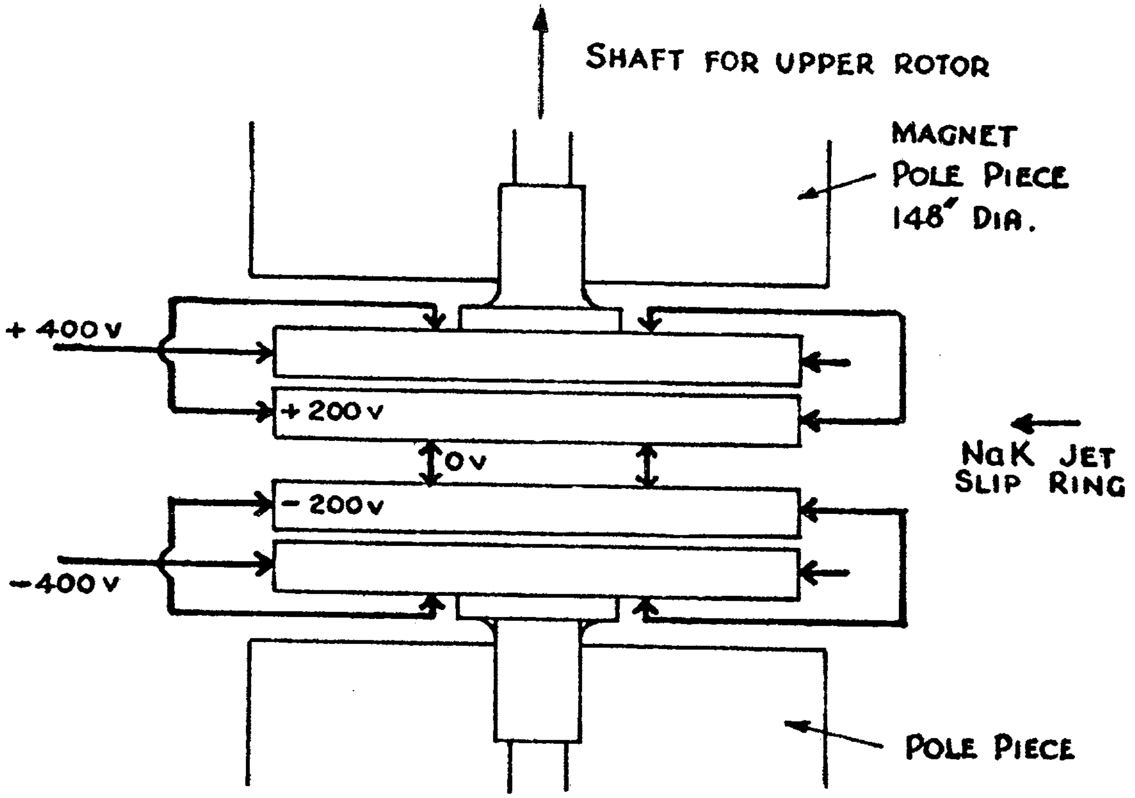

Figure 1. Electrical Circuit of Homopolar Generator

A single $1\frac{1}{2}$ in. diameter bolt passing through a central hole attaches one disc of each pair to its coupling as shown in Figure 2.

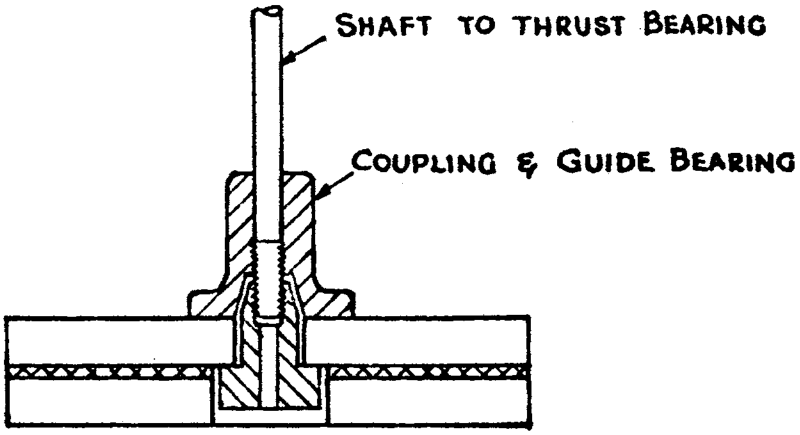

Figure 2. Method of Bolting Rotor to Coupling

At 900 r.p.m. the circumferential stress developed at the edge of the central hole is equal to the yield stress of mild steel. This is the factor which determines the limit of rotor speed. The presence of additional holes suitable for bolting the discs together, would necessitate a reduction in speed and hence in the stored energy in the generator. It is for this reason that the discs have been cemented together. The purpose of this paper is to outline the problem involved in cementing together such massive objects. The use of adhesives for structural purposes is a relatively new and expanding field and the techniques and experience described here should be of value to others.

STRUCTURAL ADHESIVES

The development of resinous adhesives which bond to metal surfaces with strengths comparable with those of the metals themselves is of recent origin and the principles are little understood. The precise chemical nature of proprietary formulations is obscured by trade secrecy as with most commercial products, however, the basic chemistry and properties are described in the literature,[2,3,4,5] and no purpose will be satisfied in discussing it here. For our purpose the primary classification of adhesives is with regard to the contact pressure required during application. The area of one face of a steel disc is over 100 sq.ft and a contact pressure of 3 p.s.i. over the whole of this area amounts to a total force of 20 tons. Only one of the basic structural adhesives is capable of being applied at pressures as low as this. This is the class of resins known as epoxy, epoxide, or ethoxyline and marketed under the trade names Araldite,[6] Epikote,[7] Epon,[8] Epiphen,[9] Epophen,[10] Epi-Rez,[11] Cardolite.[12] These resins require no pressure and experience very little shrinkage on curing. Other resins that adhere strongly to metals require pressures ranging from 50 to 1000 p.s.i. during cure in order to achieve a satisfactory result. The use of such resins does not provide bond strengths in excess of those obtained with the best epoxy adhesives at normal temperatures. A few epoxy formulations will retain a bond strength of 1000 p.s.i. at a temperature of 100°C. On the other hand other[3] adhesives can provide a similar strength at temperatures as high as 250°C.

The next most important classification for our purposes is with regard to the temperature of curing. Here again the epoxy resins demonstrate superior properties in that some formulations give excellent strengths with room temperature cure, although there are always advantages in curing at somewhat higher temperatures. Because of the large dimensions of the steel discs high curing temperatures give rise to serious application problems. For this reason an epoxy resin with a moderate curing temperature (70°C) was finally adopted.

The greatest problem associated with the use of structural adhesives in an application of this type is that of acquiring the necessary confidence that the desired result will be achieved. Probably all persons who have made use of adhesives have experienced unexplained set-backs even in applications which do not appear to demand strong adhesion. Furthermore in many instances an initially satisfactory job has failed a year or so later and the reason for failure has never been explained. It is also difficult to accelerate a life test without prejudicing the result in one way or the other. In a problem such as this which demands complete success at the very first application, it is necessary, in order to acquire the necessary confidence, to carry out a large number of tests aimed at understanding

1. the intrinsic properties of the adhesive
2. the necessary surface preparation of the materials
3. the process of resin application
4. the process of closing the joint
5. the process of curing the resin
6. the possibility of testing the result

Some hundreds of tests were carried out, ranging in size up to one quarter of full scale, before the above factors were sufficiently understood to allow the full scale operation to be completed satisfactorily.

REQUIRED BOND PROPERTIES

The primary purpose of the bond between each pair of steel discs is to keep the discs together so that they behave mechanically as one rotor. The most obvious force which the bond is subjected to is the weight of one disc. If the whole area available for bonding is employed this amounts to only 3 lb per sq. in. and is negligible compared with other forces experienced. A more important force is the shear when one disc tends to rotate relative to the other. Under normal conditions of acceleration and deceleration this is small compared with the force which can exist if an internal electrical short-circuit develops across one turn of the generator. It is assumed that the maximum value of such a short circuit current would not exceed 5 million amperes for a small fraction of a second, however this would give rise to an electromagnetic retarding torque of about 3,700 tons-feet acting on the rotor and one half of this will be developed on the inter-disc bond. If the bond is a uniform elastic medium over the whole surface this will give rise to a shear stress which has a maximum value at the outside radius of 100 p. s. i. Other stresses which are important arise from thermal differences generated in each rotor by windage and other losses. One form of this is a difference in temperature between the two discs of a rotor, and another is a symmetrical temperature change in the rotor from the bonded to the free faces. The former gives rise to thermal expansion of one disc relative to the other, producing radial shear at the bonded interface. The latter causes the two discs of a rotor to bow towards or away from each other. If this is restrained by the bond some areas will be in tension and others in compression. Both of these stresses will be dependent on the magnitudes of the heat transfer into the disc faces and the extents to which the consequent distortions are restrained by the bond. Thus 'hard' or inelastic bonds will give rise to large stresses and 'soft' or elastic bonds will produce only small stresses. In both cases the stresses tend to be concentrated towards the disc periphery. The lowest bond stresses will obtain if the bond elasticities are so matched to those of the steel discs as to restrict thermal distortions only to the necessary degree. Only a bond elasticity which is uniform over the whole interface will be considered here. Some other forms have been examined but were not considered to have overall advantages. For the purpose of analysis the bonding medium will be assumed to obey Hooke's Law for both tension, compression and shear, and to have the same modulus for tension as for compression. In considering distortion of the steel discs the discs will be treated as thin plates as is usual with such a ratio of diameter to thickness. In this case the equations for bending are similar to those for beams and if M_r, M_t are the bending moments in radial and tangential directions, in general

$$M_r = D(C_r + N{}^{C}{}_{t})$$

$$M_t = D(C_t + N{}^{C}{}_{r})$$

where N is the Poisson's Ratio (0.3 for steel),

C_r, C_t are the curvatures (reciprocals of radii of curvature) and

$$D = \frac{Eh^3}{12(1 - N^2)}$$

where E is the Young's Modulus (3×10^7 p.s.i. for steel) and h is the disc thickness (10 in.). For spherical bending $C_t = C_r$ and $M_r = D(1 + N)\ C_r$ however for plates substantially restrained from spherical bending $C_t << C_r$ and $M_r \doteqdot D\ C_r$. We are concerned only with axially symmetrical bending with conditions intermediate between these two cases. In general a simple analysis will be given here in which the detailed effects arising from C_t are ignored. Some individual results have been checked satisfactorily against a more precise theory allowing for curvature of plates in association with an elastic, medium, using methods and solutions given in Timoshenko 'Plates and Shells'[13]. In each case the solutions were not of general utility, being in the form of series in which small differences between very large numbers were involved and a substantial amount of effort is required to compute results for one arbitrary set of initial conditions.

Considering first a situation with different heat inputs to the two faces of a rotor we see that one 'steady state' effect of this is to cause heat flow from one free face to the other, setting up a uniform temperature drop across the bonding and insulating material separating the discs of a rotor. The uniform temperature gradient will cause both discs to bow and expand together as in Figure 3(a) in such a way as to give rise to no loading of the bond. This gradient will be ignored.

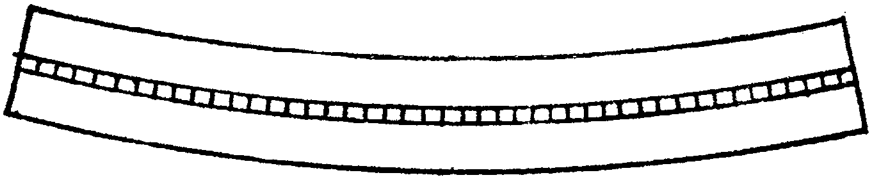

Figure 3(a). Stresses Due to Elastic Shear of Bond Medium

A temperature drop T across the insulation on the other hand will cause one disc to expand relative to the other, giving rise to deformation in shear of the bonding material in a zone at the outside edge. This in turn will act on the steel discs to expand one and contract the other and to bend both so that the relative radial movement v of the disc surfaces at the interface will diminish from the outside edge inwards as illustrated in Figure 3(b). In Figure 3(c) the stress conditions in a section of unit thickness close to one edge are shown.

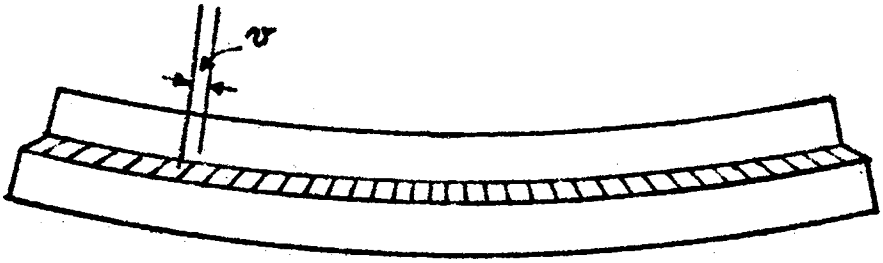

Figure 3(b)

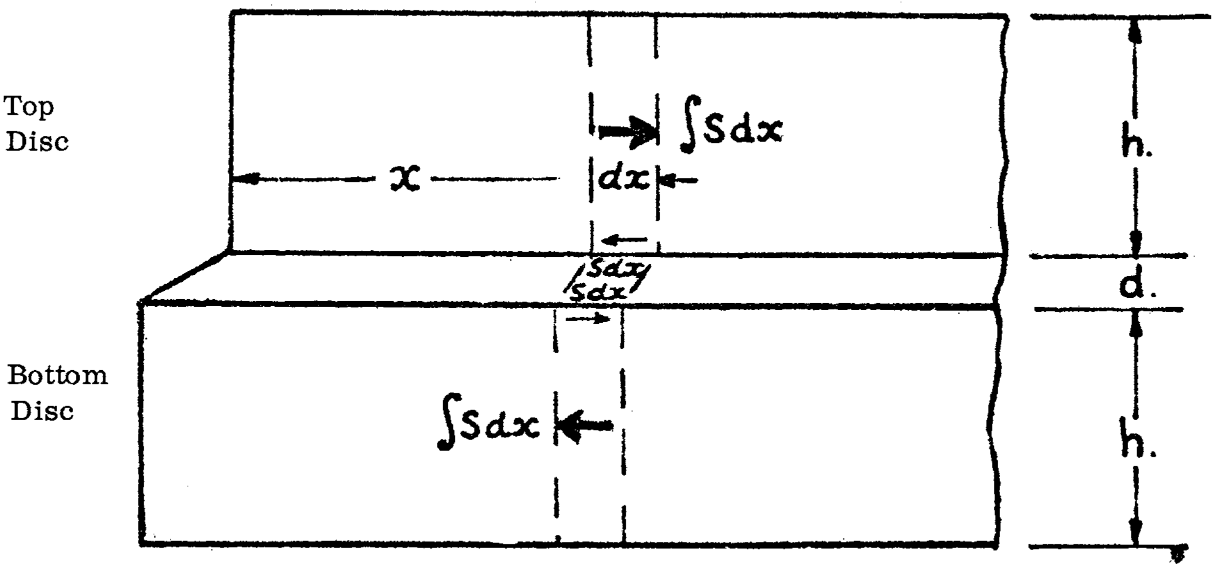

Figure 3(c)

Stresses Due to Elastic Shear of Bond Medium

In this the shear strain v/d in the bond at a distance x from the edge gives rise to a shear stress S = Gv/d where G is the coefficient of rigidity of the bond medium. This acts on both discs but in opposite directions. If G/d is large the stresses will fall off rapidly from the edge and a two dimensional geometry can be assumed. Now the accumulated shear force $\int_0^x$ S dx over the band of length x will be balanced in each steel disc by a reaction distributed over the disc thickness but equivalent to a concentrated force. $\int_0^x$ S dx located on the central plane. The shear and reaction stresses together produce a bending moment $\frac{h}{2}\int S\,dx$ at x causing both discs to bow equally in the same direction with a curvature of $\frac{h}{2D}\int S\,dx$. The elastic strain at a disc face arising from this bowing is $\frac{h}{2}\cdot\frac{h}{2D}\int S\,dx$ or $\frac{3(1-N^2)}{Eh}\int S\,dx$ and the relative strain at the adjacent faces of the two discs is - 2 times this. There is a similar local relative strain due to the average direct stress $\frac{1}{h}\int S\,dx$ in the discs and this is equal to $\frac{-2(1-N^2)}{Eh}\int S\,dx$. The resultant of the two is thus $\frac{-8(1-N^2)}{Eh}\int S\,dx$. To this we must add the relative thermal strain aT, where a is the thermal expansion coefficient for the steel disc. The change of v with x arises from the combination of the thermal and elastic strains and we must have

$$\frac{-dv}{dx} = aT - \frac{8(1-N^2)}{Eh}\int S\,dx = \frac{-d}{G}\cdot\frac{dS}{dx}$$

If we assume T to be independent of x, differentiation gives

$$\frac{d^2S}{dx^2} = \frac{8G(1-N^2)\,S}{Edh}$$

and the required solution is

$$S = \frac{GaT}{dK}\cdot e^{-Kx}$$

where $K = \sqrt{\frac{8G(1-N^2)}{Edh}}$

A more accurate solution is $S = \frac{(1+N)GaT}{dK}\,e^{-Kx}$ (1)

Let us consider as an example a bond of 'rigid' plastic such as phenolic sheet or epoxy resin of thickness d = 1/8 in. and having a value of G of the order 5.10^5 p.s.i. This gives $S = 214Te^{\frac{-x}{3.6}}$ p.s.i. The shear stress in the bond thus has a maximum value of 214T p.s.i. at the rotor edge and falls to 1/e of this value at a point 3.6 in. from the edge. The stress varies as $1/\sqrt{d}$ and the characteristic distance as $\sqrt{d}$, thus reducing the bond thickness by a factor of 4 would give 428T p.s.i. and 1.8 in. respectively In general however this would also reduce the temperature difference T by a factor of 4 so the maximum stress would be 107T p.s.i.

For a temperature difference of 2°C to occur across a bond of 1/8 in. thickness we would require a heat flow from one disc to the other of 1.2 kilowatts, assuming a thermal conductivity of 5×10^{-4} cals. cm^{-1} sec^{-1} $^{o}C^{-1}$. If we take the heat transfer coefficient at the gas-steel interface as 50 B. T. U. ft^{-2}. $^{o}F^{-1}$. $hour^{-1}$ this heat unbalance would require the gas temperature at one rotor face to be 4.3°C hotter than at the other and could be avoided in practice; however design considerations should, if possible, cover the worst conditions that might occur during normal running or through unforeseen circumstances and should also allow for later modification in running conditions. Thus, although the intention with the homopolar generator is to operate in a continuously cooled helium atmosphere in order to avoid excessive heating and loss of power, and the normal cycle of operations will not require running at the maximum speed of 15 r.p.s. for appreciable lengths of time, yet all initial development will be done with nitrogen without adequate cooling and may involve prolonged running at speeds above the mean in the process of diagnosing troubles. If we take the worst of these conditions and make various assumptions about the nature of the windage losses a peak windage power approaching 160 kW is obtained[14, 15, 16] for both rotors. Under normal cycling in nitrogen the mean windage loss should be less than 70 kW. With a loss of 160 kW it would only be possible to operate the generator for short periods. Without external cooling the gas temperature would rapidly rise to about 15°C above that of the rotor surface at which temperature difference most of the power would be flowing into the rotors. Thus even with this extreme condition of operation it is not likely that a difference of 4.3°C could be produced between the gas temperatures at the two faces of a rotor. We may thus regard a 2°C temperature drop across the bond, giving 430 p.s.i. maximum bond stress, as a safe design figure.

The basis of derivation of expression (1) for shear stress variation in the bond is reasonably correct for the values of parameters considered here. If however much harder bonds are considered, i.e. much smaller insulation thicknesses, the expression would be inadequate because a more local elastic deformation of the steel would play a part. If much softer bonds, such as rubber, are considered, the bond shear stress would be spread over a much larger fraction of the radius and the above approximations would be invalid. In the extreme case the steel can be considered to be unaffected by the bond stress and the latter can be deduced directly from the bond shear strain and will vary as $\frac{GarT}{d}$ where r is the distance from the disc centre. For rubber a value of G of the order of 200 p.s.i. is typical and with the above figures T = 2°C, d = 1/8 in. we would have a maximum radial shear bond stress of only 2 or 3 p.s.i.

We will now consider in a similar manner the bond stresses produced by an inflow of heat of constant value H per unit area into the free face of each steel disc. An exact solution for the temperature θ at a point distant x from the bonded face and time t after the application of H is given[17] by

$$\frac{\theta}{H} = \frac{t}{hCw} + \frac{x^2}{2kh} - \frac{h\cos}{2k} \quad \frac{\pi x}{h} \cdot \frac{\frac{-(\pi)^2 kt}{e\,h^2\,Cw}}{(\pi)^2}$$

(Continued)

$$+ \frac{h}{2k} \cdot \cos \frac{2\pi x}{h} \cdot \frac{e^{\frac{-(2\pi)^2 kt}{h^2 C w}}}{(2\pi)^2} + \ldots . \tag{2}$$

where k, C, w are respectively the thermal conductivity, specific heat and density of a steel disc. In our case the values for the first two time constants of (2) are 490 and 122 seconds respectively, so that within about 15 minutes the distribution of temperature will be given quite well by

$$\frac{\theta}{H} = \frac{t}{hCw} + \frac{x^2}{2kh} \tag{3}$$

Thus the 'steady state' temperature gradient $\frac{d\theta}{dx}$ is equal to $\frac{Hx}{kh}$ and varies linearly from zero to a maximum value of $\frac{H}{k}$ at the free edge. The temperature distribution $\frac{Hx^2}{2kh}$ gives rise to a corresponding thermal expansion strain $\frac{aHx^2}{2kh}$ at each point and in this case it can easily be shown that the resultant curvature of an unconstrained disc is related only to the average temperature gradient and is equal to $\frac{aH}{2k}$. With a disc of radius R the extent of the bow arising from this curvature is $\frac{R^2aH}{4k}$ and for our case is 0.0135 in. for $\frac{H}{k}$ equal to 1°C per in. This represents a power input to each disc of 17 kW under the influence of which a pair of discs would bow apart by 0.027 in. and the temperature difference between the free and bonded faces would be 5°C. These are the conditions approximating normal cycling in nitrogen with little external cooling of the gas or walls. This would be permissible for some hours at a time, the limit being set by the temperature rise given by the first term of expression (3), in this case 7.4°C per hour giving four hours'operation for a mean rotor rise of 30°C. Likewise operations with the extreme windage loss of 160 kW would give a 30°C rotor temperature rise (50°C gas temperature rise) in 1.75 hours and an overall disc to disc bow of 0.062 in. if unconstrained.

In Figure 4 conditions are shown near the edge of a partially restrained pair of outwardly bowing discs. Once again a parallel section of unit thickness is taken and the bending moment in each disc at a point A, distant x from the edge, is considered. This will be caused by the vertical bond stresses in the zone between A and the disc edge. If the bond thickness at a point A, distant x from the edge, is considered. This will be caused by the vertical bond stresses in the zone between A and the disc edge. If the bond thickness at a point P, distant x' from the edge, is d + u and the elastic modulus of the bond medium in direct tension and compression is K, the force acting on a band dx' is $\frac{uKdx'}{d}$ and the bending moment at A is

$$M = \int_{o}^{x} \frac{(x-x')\,uK}{d} \, dx'$$

giving rise to a curvature M/D as before.

The resultant disc curvature $\frac{d^2u}{2dx^2}$ arising from this bending and the thermal curvatures will be

$$\frac{d^2u}{2dx^2} = \frac{aH}{2k} - \frac{1}{D} \int_{o}^{x} \frac{(x-x')\,uKdx'}{d}$$

whence $$\frac{d^3u}{dx^3} = \frac{-2}{D} \int_{o}^{x} \frac{uK\,dx'}{d}$$

and $$\frac{d^4u}{dx^4} = \frac{-2K}{Dd} \cdot u$$

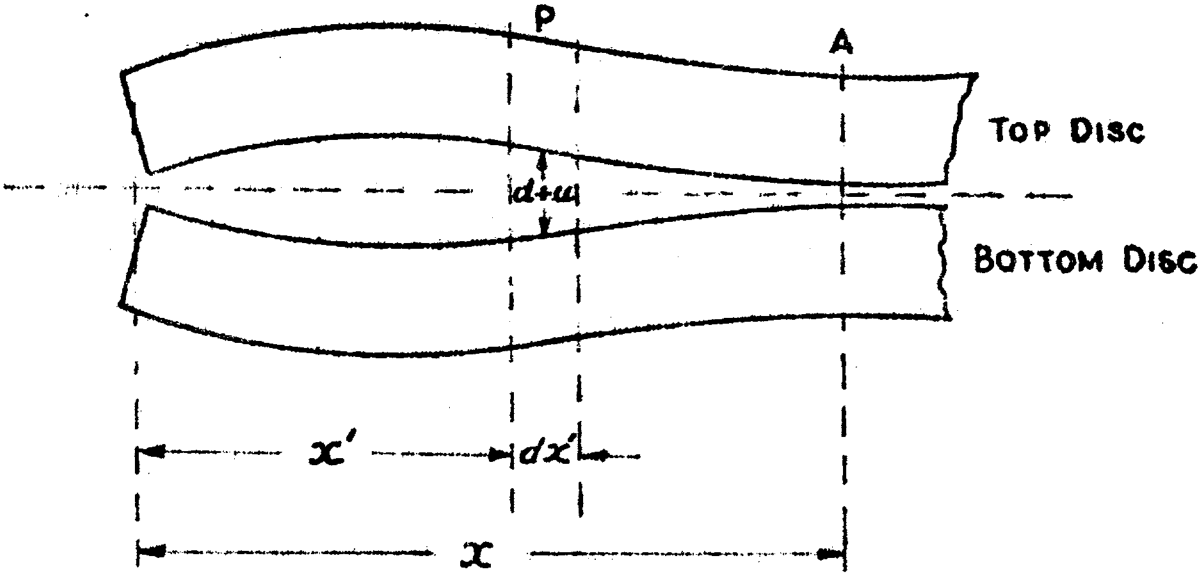

Figure 4. Thermal Bow of Discs

The solution of this is $u = u_o e^{\frac{-x}{x_o}} \sin\left(\frac{x}{x_o} + b\right)$

where $$x_o^4 = \frac{2Dd}{k}$$

b follows from the fact that the resultant vertical bond force is zero, i.e. $\int u dx = 0$ which gives $b = -\frac{\pi}{4}$.

The original equation gives

$$\frac{d^2u}{2dx^2} = \frac{-aH}{2k} \quad \text{at} \quad x = 0$$

whence $$u_o = \frac{aHx_o^2}{k\sqrt{2}} = \frac{aH}{k}\sqrt{\frac{Dd}{K}}$$

Thus the solution is $$u = \frac{aH}{k}\sqrt{\frac{Dd}{k}} \;.\; e^{-\frac{x}{x_o}} \sin\left(\frac{x}{x_o} - \frac{\pi}{4}\right)$$

and the bond stress is $$\frac{uK}{d} = \frac{aH}{k}\sqrt{\frac{DK}{d}} \;.\; e^{-\frac{x}{x_o}} \sin\left(\frac{x}{x_o} - \frac{\pi}{4}\right) \qquad (4)$$

If we put $K = 10^6$ p.s.i. we find $x_o = 5.1$ in. and the bond stress pattern consists of a compressive band followed by a tensile band with widths of $\frac{5.1}{4}$ and 5.1 in. width respectively. The effect of these two bands is to develop the required bending moment needed to straighten each disc over its central region. The peak stresses in the two bands are

$$\frac{aH}{k}\sqrt{\frac{DK}{2d}} \quad \text{and} \quad \frac{aH}{k}\sqrt{\frac{DK}{2d}} \;.\; e^{-\frac{\pi}{2}}$$

respectively and if we again take $H/k = 1^{o}C$ per in. we have 1,200 and 250 p.s.i. respectively. These are the stresses pertaining to normal cycling in uncooled nitrogen. For the extreme windage figure of 160 kW we would have 2,700 and 560 p.s.i. respectively. For bonding purposes only the tensile stress has to be considered, however under conditions of cooling the stress pattern is reversed in sign so the outside band is the important one. In this case, however, the absence of any powerful cooling agency comparable with the 160 kW windage heating means that the tensile stress will be much lower than the 2700 p. s. i. figure and does not require extra consideration. The stresses given by (4) vary as $\sqrt{\frac{K}{d}}$ and there are some advantages to be gained by using a thick bond medium with low elastic modulus. The limit to this is set by allowable distortion, however it is possible to reduce K/d by a large factor before this limit is reached since, even with the stress of 2700 p. s. i., the value of u in the above example is only 3.4×10^{-4} in. The expression (4) is reasonably applicable to any homogeneous bonding material which completely fills the inter-disc gap. This even includes rubber since with full constraint against sideways movement the effective elastic modulus K is high, being approximately equal to the bulk modulus. If very low elastic moduli are required it is necessary to consider a form of sponge structure with holes or slots into which the medium can move by elastic shear. This will be examined in the following but will necessitate a more accurate treatment as the stresses are no longer localised in a band near the periphery of the disc. The deformation v at radius r of a thin disc under equal and opposite line loads distributed uniformly round the circumference of a circle of radius b and the outer periphery of the disc is given by the following expressions[13]

$$v = \frac{P}{8 \pi D} \left[(b^2 + r^2) \log_e \frac{b}{a} + (a^2 - b^2) \frac{(3+N)a^2 - (1-N)r^2}{2(1+N)\, a^2} \right] \text{for } r > b$$

$$= \frac{P}{8 \pi D} \left[(b^2 + r^2) \log_e \frac{r}{a} + (a^2 - r^2) \frac{(3+N)a^2 - (1-N)b^2}{2(1+N)a^2} \right] \text{for } r < b$$

where a is the disc radius, P is the total magnitude of each line load, and D and N are as before.

In order to compute the resultant shape of a disc under the effect of thermal bowing restrained by a uniform elastic medium a procedure similar to the following was adopted. Nine plots were drawn of v as a function of r for different values of b equal to 0.1a, 0.2a etc. to 0.9a respectively. A resultant disc shape was guessed and the elastic loading produced by the bond medium computed for each zone of radius centred on the chosen values of b. The resultant deformation at all points due to this loading was then applied to the free thermally bowed disc shape and a new distorted disc shape derived. The above procedure was then repeated and an almost exact closure was obtained showing that the shape was correct. The elastic modulus of the bond medium in the above procedure was chosen to allow a resultant disc bow which was 20% of the unconstrained bow i. e. with 70 kW and 160 kW windages the resultant bow of a disc would thus be 0.0027 in. and 0.0061 in. respectively. The movement of one disc relative to the other would not be twice this as the disc edges move towards each other, in fact the actual relative movements are found to be 0.0015 in. and 0.0035 in. respectively and the elastic modulus to achieve this degree of control is 2650 p. s. i. for 1/8 in. thickness. The appropriate maximum tensile bond stresses in the two cases are found to be 32 and 73 p. s. i. respectively.

The required bond strengths discussed in the preceding section are capable of being achieved with a wide range of bond media. However the theory indicates that, other things being equal, a low elastic modulus is to be preferred. In addition to intrinsic bond strength and elasticity there are a number of factors which are involved in making a choice of material and adhesive. First and foremost, mention has already been made of the requirement for low pressure which led to epoxy resin adhesive as a first choice. This precluded the use of thermoplastic materials since reliable bonding with epoxy or, for that matter any other adhesive was not considered to be a possibility. The use of a thermo-setting plastic material such as phenol-formaldehyde, urea-formaldehyde, etc. sheet does not suffer from this trouble provided that the sheet has been well cured. It does, however, call for a reliable bond strength over a large area which should be several times greater than 560 p. s. i. Also in order to avoid weaknesses in laminated sheet material it would be preferable to cut narrow strips and utilise them with the grain normal to the rotor discs. This is not objectionable since the provision of numerous cavities for surplus resin to squeeze into is necessary in any case, and one of the simplest ways to achieve it is by using narrow strips spaced slightly apart. The use of epoxy or polyester resin as a medium with or without glass fibre is also an attractive possibility and in the case of epoxy resin could serve also as the adhesive. Various of these possibilities were studied, paying particular attention to the application procedure and a substantial number of tests were carried out before making the final choice of rubber strip as the bond medium.

The rubber strip which was used was obtained from the Dunlop Rubber Company of Australia and was specially made to their specification 4648, with a modified deoxidant to suit an operating temperature of 70°C. It is a fairly standard mix of natural rubber with a Shore hardness figure of 80 and was initially selected because it was known to have good strength when vulcanized to metals. Softer rubbers give much lower strengths and have no compensating advantages since the choice of strip width allows an independent control of the effective elastic modulus. For all tests of rubber performance an operating temperature of 70°C was adopted. It is not intended that the rubber temperature in service should ever rise above 50°C, but in order to accelerate life tests of creep behaviour etc. the higher figure was chosen. This has also been found to give a more sensitive indication of surface adhesion deficiencies and, in fact, many quality control tests were subsequently done at 90°C in order to show up defects more readily. The use of natural rubber was recommended by the manufacturers as giving strength performance at a temperature of 70°C superior to that of any artificial rubber. The choice is contingent upon its use in a non-oxidising atmosphere as the deterioration of rubber is primarily caused by oxygen. This is not an onerous requirement since the homopolar generator must likewise operate with a non-oxidising gas and the inter-disc space which must be sealed against NaK ingress, can have its cavities filled with nitrogen. This requirement of course favours the use of spaced rubber strip rather than foam or special mouldings without connected gas pockets. Residual oxygen contamination can be met by the extra deoxidants and progressive leak of oxygen into the bond space is obviated by the NaK seal and by the strongly reducing action of the NaK which mops up all oxygen leaking into the homopolar generator.

It is not practicable to discuss in detail all the factors for and against this choice of medium and the adoption of epoxy resin adhesive for use with it. The following observations however will give some indication of the weight of argument in its favour. During the implementation of this program of work many previously unrealised advantages were noticed and are listed here. These factors are considered to be by no means trivial.

Probably the main advantage with rubber is the reduction of bond adhesive strength required. In the early stages a lot of attention was given to methods of cleaning steel areas of the order of 30, 000 sq. in. initially covered with oil, turning marks and rust. Notable successes and equally notable failure were found when seeking consistently reliable bond strength in excess of 1000 p. s. i. and this experience played a big part in favouring a rubber medium for which a few hundred p. s. i. bond strength represents a substantial factor of safety.

A further advantage derives from the fact that the two steel discs of a rotor experience a mutually attractive force due to the magnetic field through them. This has been estimated to produce 30 p. s. i. average compressive stress in the bond medium and relieves the tensile bond strength requirement. The improvement is very substantial compared with 70 p. s. i. and small compared with 500 p. s. i. Again, with rubber there is added safety since the radial shear stress arising from different disc temperatures is negligible. Another advantage is that the whole and not a small part of the disc area participates in the bond and local failure over a small area due to contamination or deficient technique will not precipitate overall failure. This is a very important factor if the bonds are susceptible to peel failure. In general this is the weakest feature of epoxy adhesives and is a consequence of brittleness. Similar trouble occurs in most rigid laminated materials in which tensile strength and ductility are excellent in certain planes and the bonds between the planes are brittle. The use of glass cloth in bonds of large area is a source of particular danger in this respect. These difficulties as such are also relatively absent when a rubber medium is used. This is probably because of non-linear elastic behaviour of rubber which tends to minimise stress concentration in the rubber and at the external bond. Also because, although sheet rubber is made by a lamination process, the resultant produce should be homogeneous. One of the quality control checks applied to the rubber for this job was to look, visually and by means of bonding tests, for inter-ply defects. Between 5% and 10% of the rubber supplied was rejected because of these checks.

Another strength consideration which favours the use of rubber for this application arises from its very great resilience. It is a common experience with medium scale adhesive work involving steel members that the designed strengths to meet the known loads are seldom adequate to cope with contingencies arising from impact forces which occur when objects are dropped or are bumped by other objects, concrete walls, etc. during handling. It is not always possible to allow for contingencies of this type however, where it is easy to do so, factors of safety of 100 or more are often found beneficial. In the main field of application of adhesives, i. e. aircraft construction, these problems do not arise as lapped sheet aluminium joints can easily be made with strengths greater than the aluminium sheet itself. The experience is very different however when steel pieces of thick section are bonded and, whatever the mechanism, it is a simple matter to demonstrate the superiority of a rubber medium by bonding thick pieces of steel together by various processes and hitting them with a hammer. As often as not dropping on the floor is sufficient to break the joint. With a rubber medium the joints defy destruction by such means.

The actual elastic curves and strengths obtained with the rubber bond medium are related to time of loading and temperature. At 70°C in air the rubber deteriorates badly in a few weeks, becoming hard and brittle. Thus very long term creep, etc., tests must be carried out in a non-oxidising atmosphere. With the rubber dimensions finally adopted for this application, i.e., 0.250 in. width by 0.120 in. thickness, typical elastic curves measured at room temperature are shown in Figures 5(a) and (b).

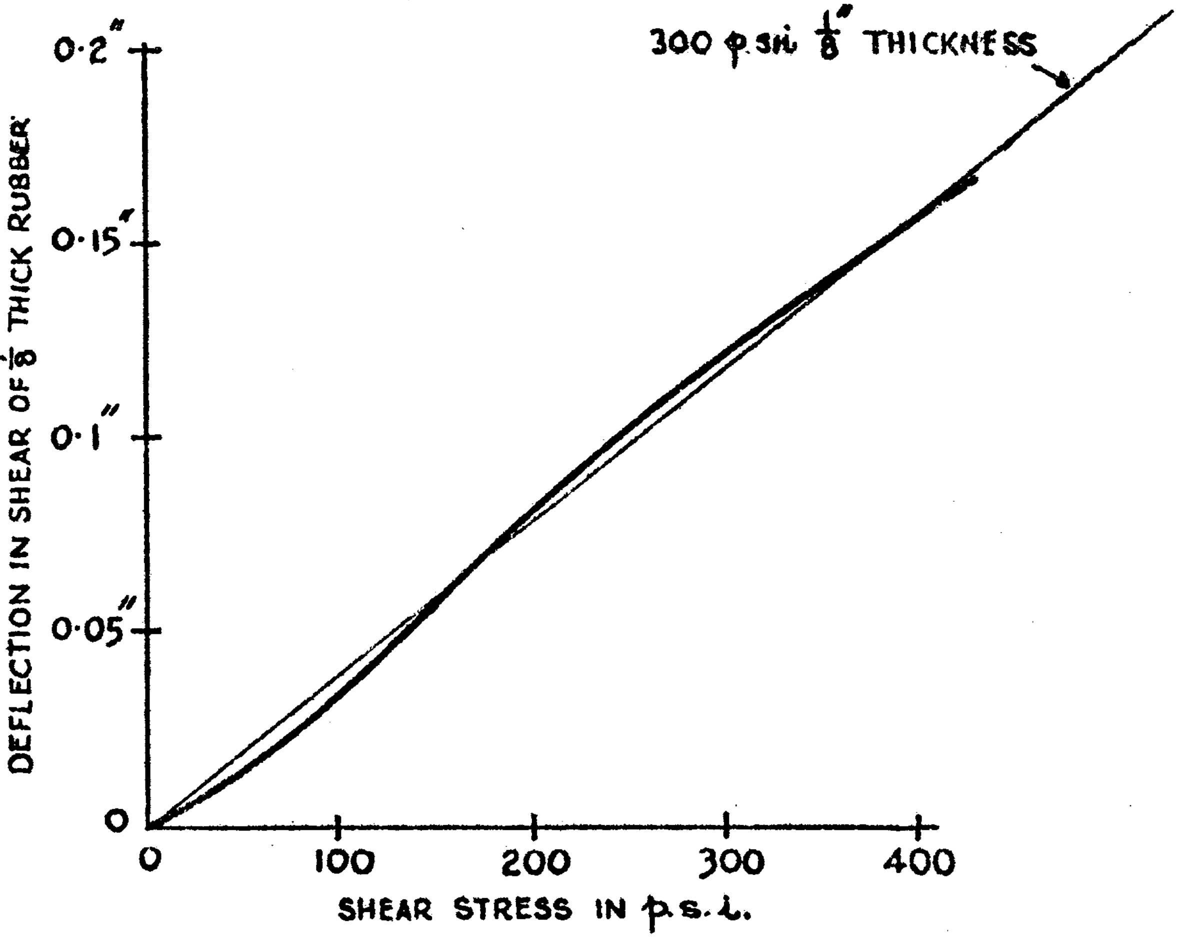

Figure 5(a). Elastic Deformation of 1/4 in. x 1/8 in. Rubber Strip in Shear-at Room Temperature strengths greater than the aluminium sheet itself. The experience is very different however when steel pieces of thick section are bonded and, whatever the mechanism, it is a simple matter to demonstrate the superiority of a rubber medium by bonding thick pieces of steel together by various processes and hitting them with a hammer. As often as not dropping on the floor is sufficient to break the joint. With a rubber medium the joints defy destruction by such means.

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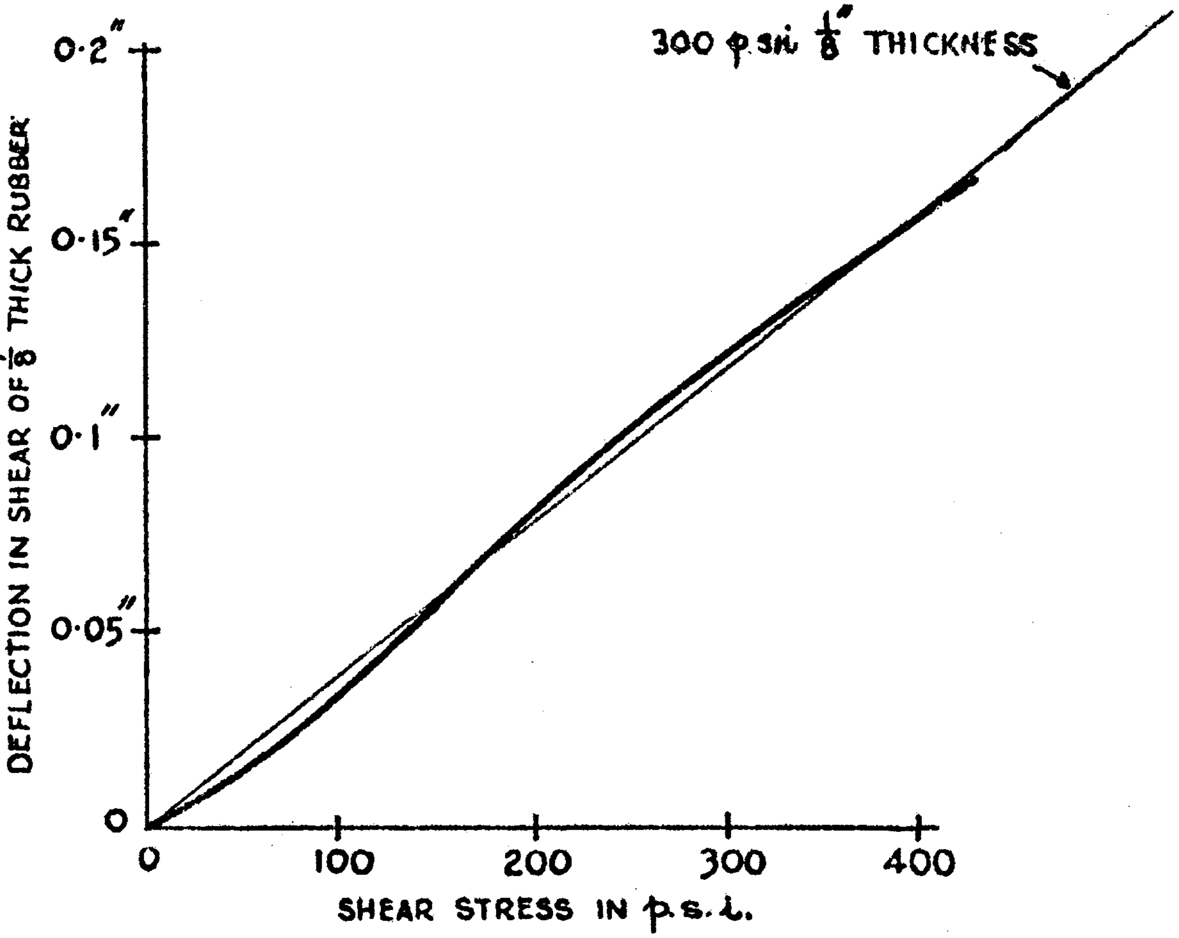

Figure 5(a). Elastic Deformation of 1/4 in. x 1/8 in. Rubber Strip in Shear-at Room Temperature

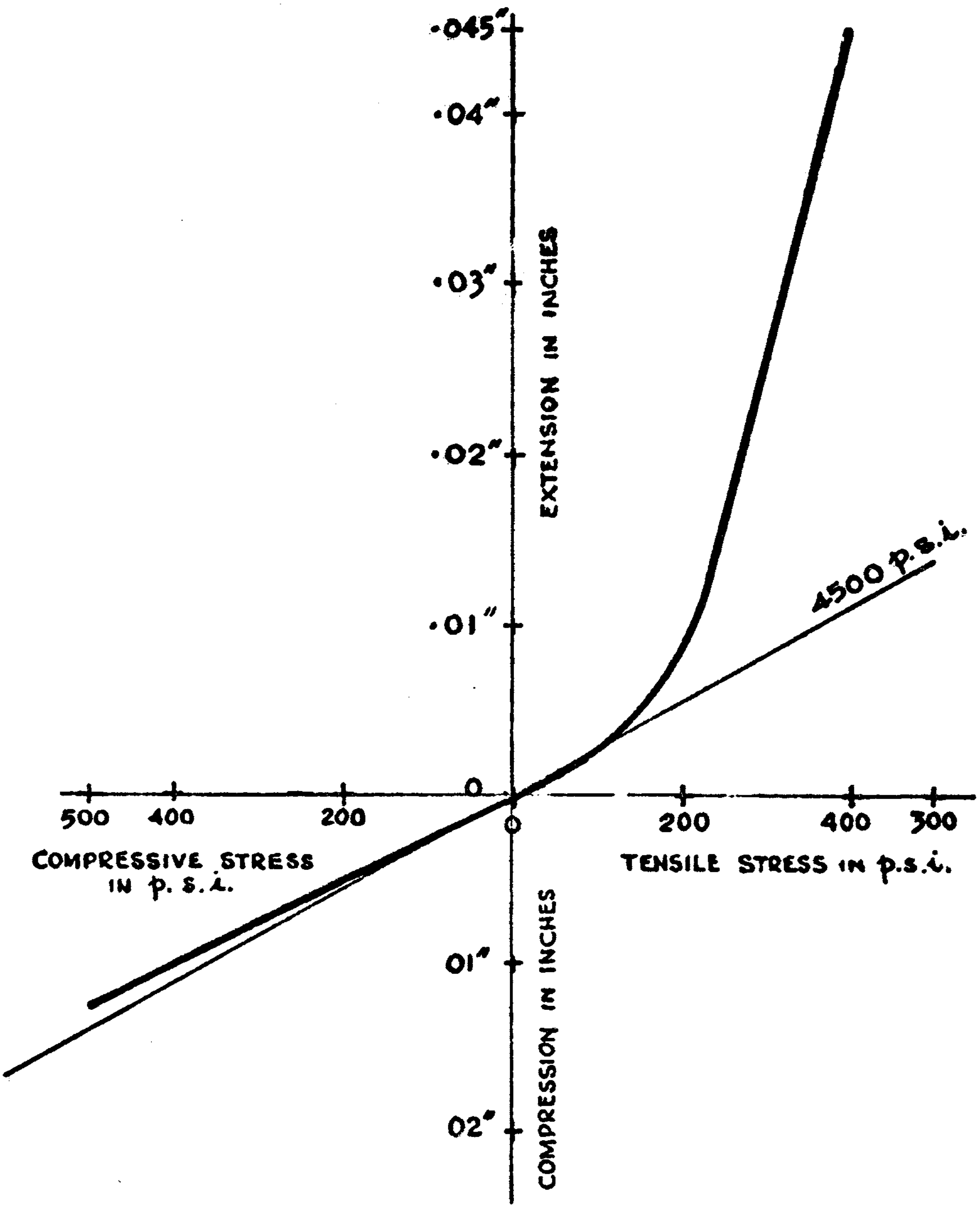

Figure 5(b). Elastic Deformation of 1/4 in. x 1/8 in. Rubber Strip in Tension and Compression - at Room Temperature

The shear curves obtained are the same whether the rubber is sheared along or across the direction of the strip and is fairly linear having a modulus of about 300 p. s. i. The tensile curve is non-linear above 100 p. s. i. and has an elastic modulus of the order of 4, 500 p. s. i. over the range we are interested in. Each of these curves was taken over a period of time of between 5 and 10 minutes. Because of creep effects lower values of modulus will be obtained if the loads are sustained for longer periods or if the temperature is raised. If a strip to strip spacing of 1/16 in. is used the above elastic moduli must be multiplied by 0. 8 to refer to the disc area, giving 240 and 3600 p. s. i. for shear and tension-compression respectively. Short-term strength figures obtained at room temperature for both shear and tension ranged from 700 to 1200 p. s. i. with an average of about 1000 p. s. i. These tests were completed in a matter of minutes and individual figures varied with speed of loading and other factors. Most of the tests were done with rubber bonding together 2 in. steel cubes. In all cases the failure was in the rubber, unless a fault in bonding technique occurred. Initially there were plenty of these faults but with experience 100% success was achieved. Higher strength figures could undoubtedly be achieved by more rapid loading, as the time taken to complete destruction after initial substantial failure is usually quite a few minutes with a fraction of the rubber area holding the full load. The rubber has the peculiar ability to yield greatly above 200 p. s. i. as in Figure 5(b) and yet to harden very much before breaking. The latter is a well known phenomenon attributed to the formation of a crystalline structure at high stress. The above non-linear behaviour adds greater safety against catastrophic failure of the composite rotor since, in the event of any factor tending locally to push the operating point around the bend of Figure 5(b), the disproportionate yield will avoid excessive stress. This is similar to the ductile behaviour of metals which renders them superior to nonmetals for constructional purposes.

The variation of tensile strength with time was investigated more closely at higher temperatures in order to standardise accelerated testing procedures. The results of many tests in air at 70, 80 and 90 degrees C are shown in Figure 6. It will be seen that at 70°C, despite oxidation, a lifetime of some months can be expected at loads of 300 p. s. i., while at 80° and 90°C the lifetimes are reduced by factors of 10 and 1000 respectively. A number of spring loaded test specimens have been sealed in nitrogen and helium with loads up to 200 p. s. i. and are still intact after two years at 70°C. The creep behaviour of these has been observed by using a travelling microscope to measure the variation of gap between pairs of opposing points as shown in Figure 7 and the average results are given in Figure 8. It will be noticed that the non-linear extension apparent above 100 p. s. i. in Figure 5(b) is greatly offset in Figure 8 by reduced creep over the first day. It follows from Figure 8 that a wide variation of 'elastic modulus' is possible depending on the temperature and the duration of application of a load. For instance over a period of one day at 70°C the movement under 100 p. s. i. loading would represent a modulus which varies from about 5000 to 2500 p. s. i. On removing a load which has been applied for some hours it is found that much of the residual creep will recover within a short period however, on re-loading, the deflection will soon return to the value it reached before the unloading. Thus to some extent the creep movement will continue to accumulate. The effect of this is to progressively lower the 'elastic modulus' with time until the creep ceases. Referred to the disc area the resultant 'modulus' for a load cycle of 100 p. s. i. at 70°C could thus vary from an initial value of about 4000 p. s. i. to a final value after 20 load-days of about 1200 p. s. i. Since temperatures of 70°C are not to be allowed and thermal tensile stresses will in practice be considerably less than 100 p.s.i. (probably 40 p.s.i.) the range of variation of the 'modulus' should in practice be well within these limits and should not deviate unduly from the 'target' value of 2650 p.s.i.

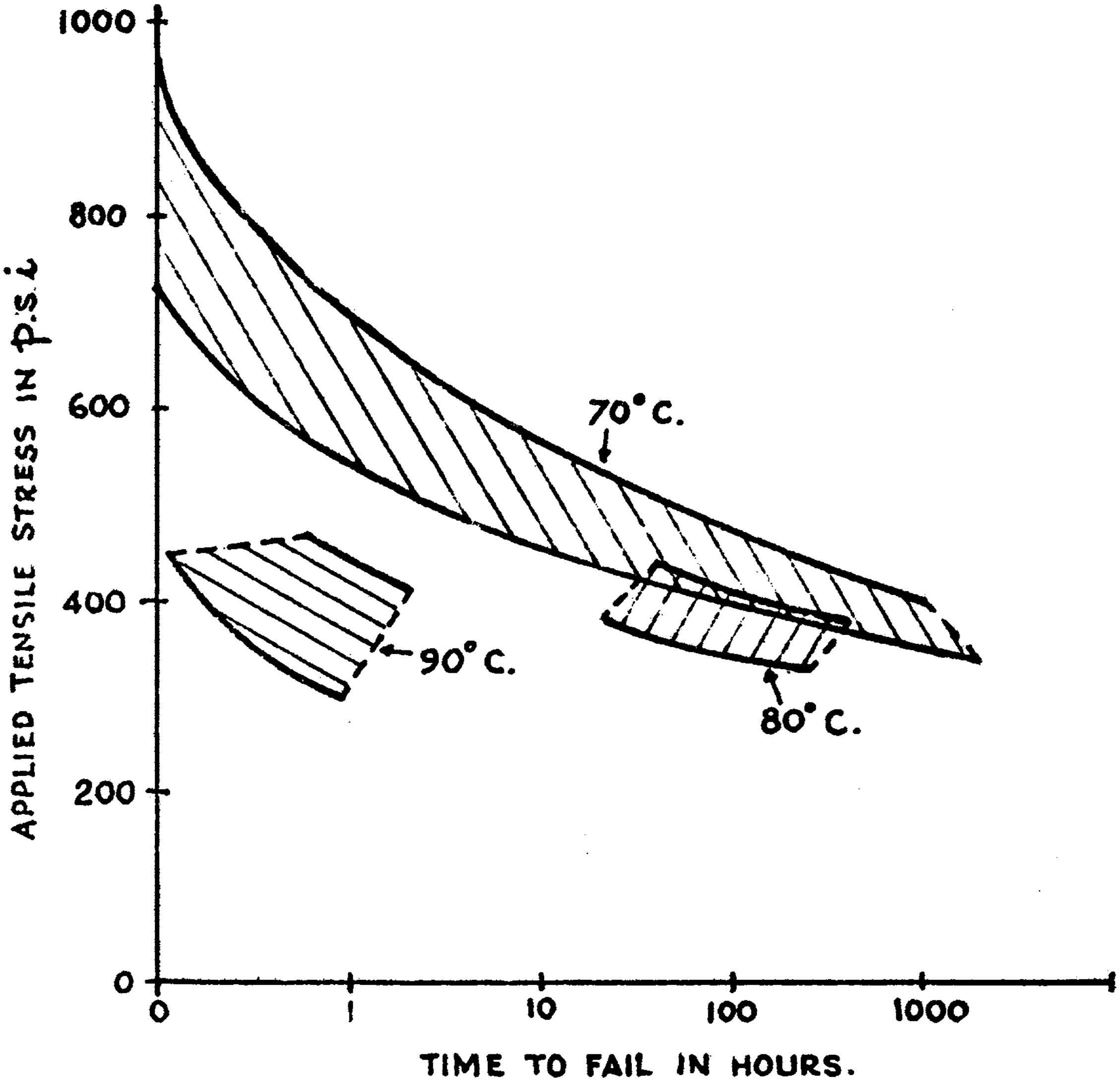

Figure 6. Lifetime in Air of 1/4 in. x 1/8 in. Rubber Strip Specimens at Different Tensile Stresses and Temperatures

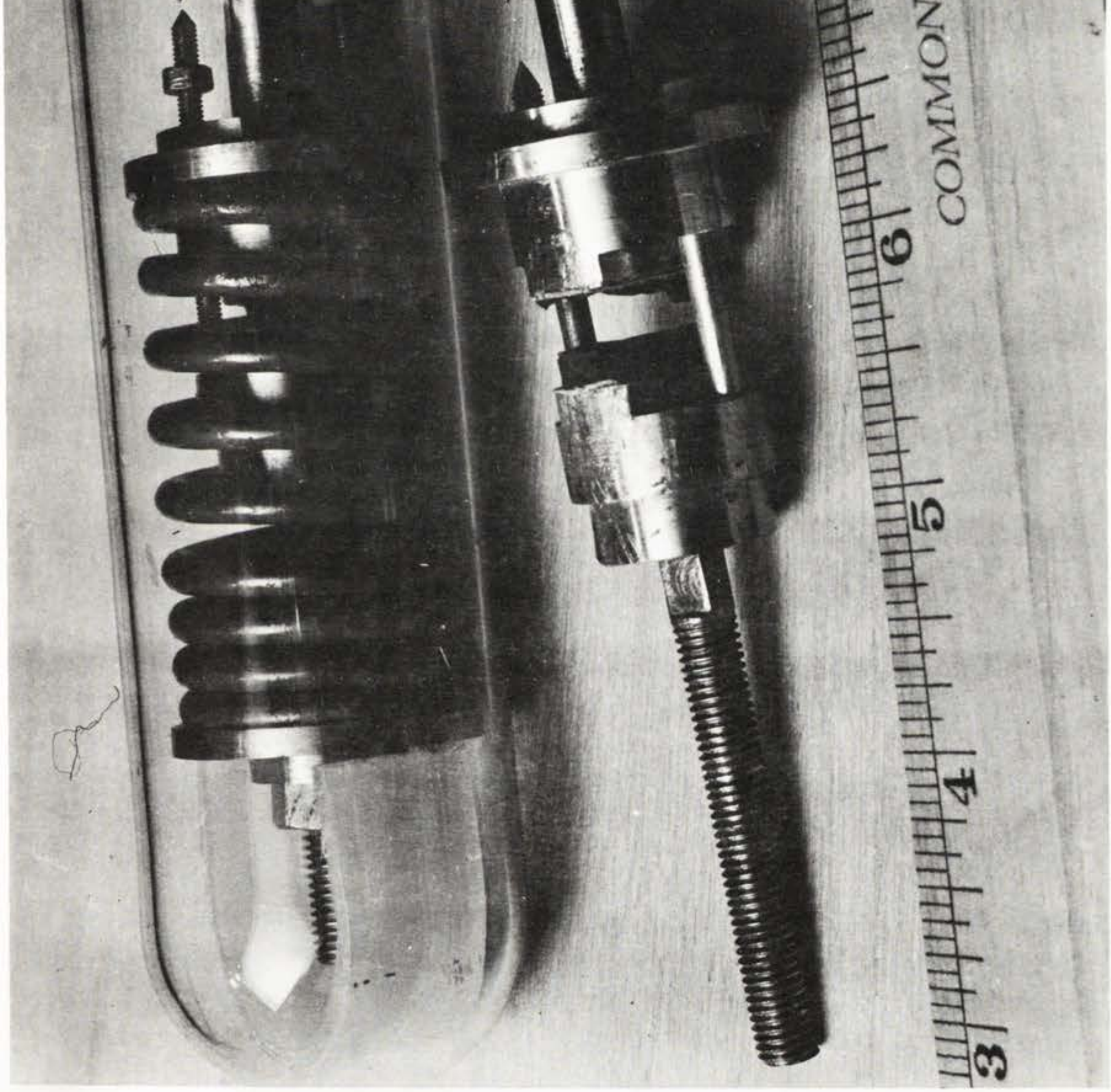

Figure 7. Spring Loaded Creep Test Specimens

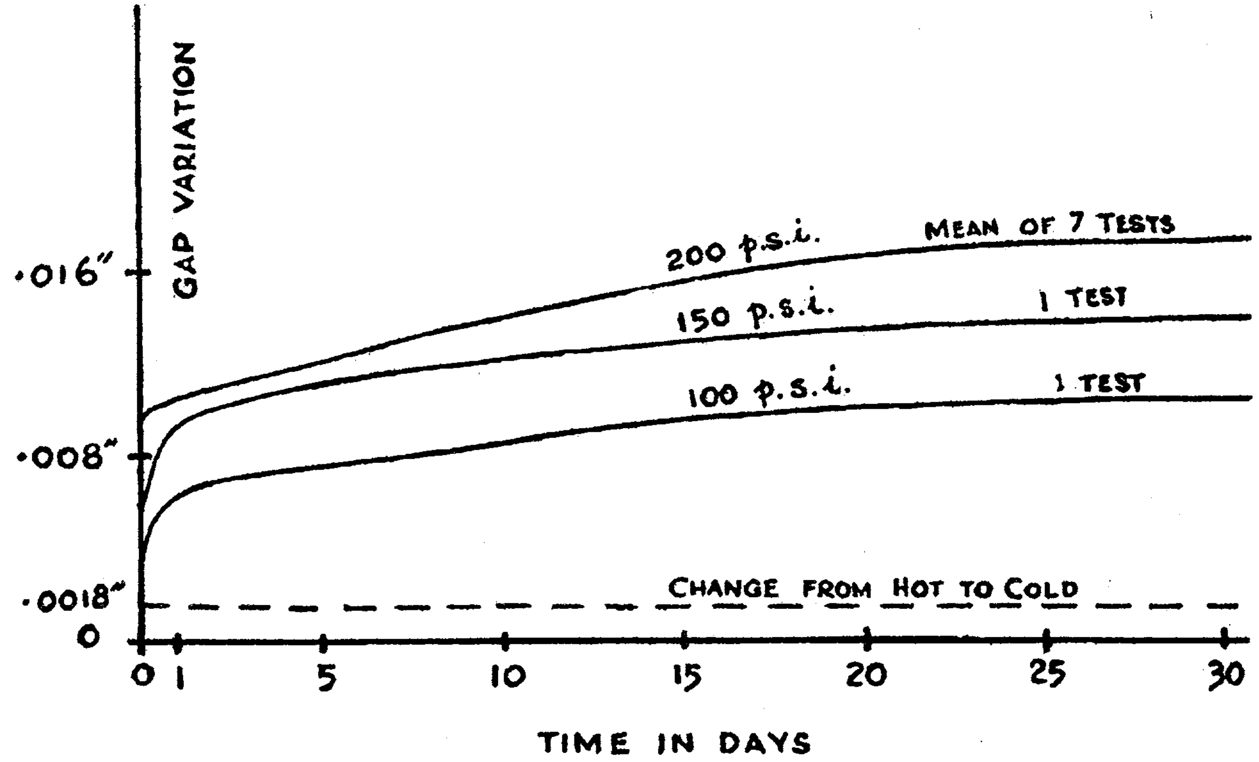

Figure 8. Tensile Creep at 70°C of 1/4 in. x 1/8 in. Rubber Strip - In Inert Atmosphere

It is clear from the above results that there should be very ample factors of safety as regards load, time and temperature with a rubber bond medium provided that the potential bond strengths are realised in practice. The difficulties in achieving this are primarily due to the large scale, and many procedures which work infallibly in the laboratory tests either give bad results or cannot be carried out at all when scaled up to a 12 ft diameter and a 20 ton weight. These matters will be discussed later, however at the present moment it is important to realise that there is ample possibility of failing to achieve the desired results in practice and a means of testing the finished product is very much to be desired. In this respect the rubber strip medium has particular advantages over other alternatives. The first two advantages arise from the low bond-strength requirement. Thus a 73 p.s.i. test over the whole disc area adds up to a total load of 490 tons which is much easier to provide than the higher loads required to test other media. Secondly, the possibility of damage should the bond fail under test is proportionately reduced. Thirdly, the relatively large deflections of the bond medium make it possible to measure the effective elastic modulus and to observe its variation radially and circumferentially. The use of spaced strip permits large test loads to be applied uniformly over the disc area by means of gas pressure introduced into the spaces between the strips. Furthermore, the simultaneous effect of the gas pressure acting on the sides of the rubber strips gives an enhanced test of both rubber and bond which does not occur with other media. This arises because the rubber deforms as shown in Figure 9, giving rise to very large shear strain at the rubber corners, with an increased disc area for vertical gas load and a decreased rubber area to withstand it.

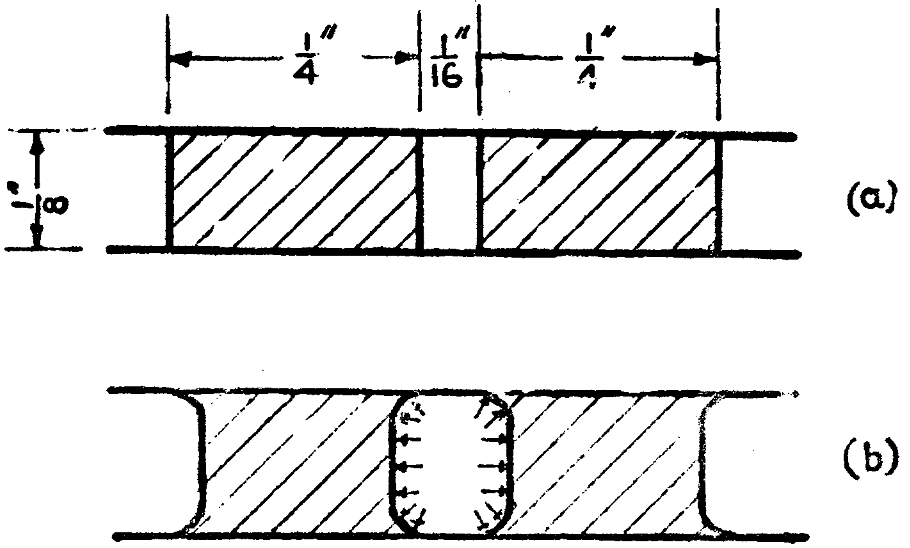

Figure 9. Deformation of Rubber Strip with Gas Pressure Test

The bond will also experience large shear stress concentrations at the rubber corners and tensile stress concentration towards the centres of the rubber strips. It was found by means of small scale tests that a gas pressure of 600 p.s.i. in the 1/16 in. gaps between 1/4 in. wide rubber strips was sufficient to destroy the rubber in a matter of minutes at 70°C. The rubber always failed near a bonded face presumably due to the shear concentration at the corners. With a more rigid medium this gas pressure would only have tested the bond and strip to a tensile load of 150 p.s.i. Tests done at 300 p.s.i. nitrogen pressure gave an initial (after about 30 minutes) extension of about 20% (0.025 in.) and a life of about 12 days at 70°C. On the basis of these tests a gas pressure of 250 p.s.i. applied for 30 minutes at 70°C was adopted as an adequate acceptance test for the finished homopolar rotors provided that the bond deflection was reasonably uniform and less than 20%.

A feature of this form of test is that in the event of initial or subsequent failure of an area of the rubber to bond to one of the discs the gas pressure could also operate on a substantially increased area of the disc and a very sensitive indication of fault would be obtained. This, in association with the typical non-linear behaviour of rubber in tension at high stress, would mean that the existence of a defectively bonded area to one side of the rotor would show up very noticeably as an unbalanced deflection.

In addition to the above advantages of rubber as a bond medium there are a number of minor advantages which are worthy of mention. These have considerable effect on the application procedure. Firstly, the rubber can be quickly ground to an accurate thickness by pulling the strip between a grinding wheel and a table. Secondly, if both sides are so ground the surfaces are cleaned in the same operations. This is a great convenience as meticulously clean surfaces are always required for the bonding resin. Thirdly, because of the low operating pressures required during bonding more rigid media would be required to be flat as well as uniform in thickness. With rubber strips only the thickness has to be accurate. Fourthly, the straightness of the strip is not important with rubber as it can be pushed into any position and held there easily. Rigid strips would be required to be straight so that uniform gaps could be produced between them. Fifthly, rubber is light and easily handled and stored in the form of coils or long strips. By nailing to wood battens on a light frame a complete sheet of bonding medium can be prefabricated and manipulated quickly and easily. A few taut piano wires give all the support necessary to prevent excessive sag. Sixthly, small pieces of grit or other foreign matter will embed in the rubber at a low pressure. With a more rigid medium greater cleanliness would be required in order that the bonded joints could be closed accurately with the low pressure available.

Only one real disadvantage has been found with the use of rubber and that is the necessity to 'cyclize' the surface, i. e., to prepare it for adhesion with epoxy resin. This is done by wetting the surface with concentrated sulphuric acid for a short while then washing with fresh water. The procedure for treating both sides of the two miles of rubber strip required for cementing the two rotors took a considerable time to evolve and a number of difficulties were experienced before a rapid and satisfactory technique was developed. The details of this will be discussed later.

CHOICE OF ADHESIVE

The adhesive which was finally employed for the rotor bonding was Epikote type VIII, a viscous hot setting epoxy resin marketed by the Shell Chemical Co., and specially formulated to meet USAF specification Mil-A-8331 calling for good creep strength at a temperature of 180°F. The hardener employed was type A with 6 parts hardener to 100 resin by weight and the curing temperature was 70°C. At this temperature a three hour cure will develop a bond strength to steel of 2 to 3 tons per sq. in. and a bond strength to rubber consistently greater than the rubber strength. At the same time the temperature is not high enough to cause serious rubber oxidation during cementing operations. Before adopting this particular resin various others, especially of the room-temperature curing variety, were considered and tested, as also was the possibility of vulcanizing the rubber directly to the steel discs or to intermediate metal plates. The last mentioned process would eliminate the cyclizing requirement but introduces other problems as regards tolerance, space, resin squeeze out, etc. and these finally led to its rejection. Attempts to vulcanize to brass plated steel at 'low pressures' of 30 p. s. i. yielded very poor results and it was clear that with the available pressures of 3 p. s. i. this would never be practicable in a single operation over a rotor area.

Experiments with a variety of cold setting epoxy resins failed to inculcate the required degree of confidence either when bonding to rubber or to steel. Some resins appeared inordinately sensitive to atmospheric humidity and surface cleanliness and all gave unaccountable failures at one time or another. It was not until the adoption of Epikote VIII and a 70°C cure that complete consistency of performance was obtained. Even then for reliable adhesion to cyclized rubber it was found desirable to preheat the components to 70°C before applying the resins. This procedure was adopted very reluctantly because of the anticipated difficulties of application arising from the large scale of the rotors. Initially it had been accepted as highly desirable for the rotor bonding to be carried out in a procedure called 'B staging', i.e., bonding and partial curve at room temperature followed some time later by hot curing to achieve the maximum bond properties. If the latter hot cure is carried out slowly bond stresses due to thermal gradients can be kept below the instantaneous bond strengths and no damage will be done. This process was carried out successfully on small scale tests and was worked up successively through a 15 in. to a 30 in. diameter scale test before being found faulty. In this latter test the rubber mat was stuck to one disc for three weeks before being given a hot cure and this bond failed under test at a load less than 200 p.s.i. Subsequent investigation showed that with cyclized rubber the actual rate of heating after a bond is made has an important bearing on the final bond strength, whereas with steel to steel bonds the final temperature alone is significant. Other experience with Epikote VIII resin bonding to itself led to results somewhat similar to those for rubber and it is now accepted as a rule that with adhesion to non-metals any delay in initiating a hot cure after closing a bond should be avoided, and if this is not possible, it should be the subject of a test which simulates the exact thermal cycle and other conditions contemplated. The safest working procedure is undoubtedly to have all components hot before applying the resin and to keep them hot until the cure is complete. This raises many problems of application since at 70°C the resin pot life is reduced from hours to minutes and at the same time the ease of application to the steel surfaces is impaired by the temperature and by the physical presence of ovens. These problems led to the decision to apply the resin in the form of a prefabricated flat sheet carried on a light framework, which could be slid between the two steel discs in a matter of seconds. As a medium for carrying the resin various thin glass, cotton and nylon fabrics were investigated with the final adoption of a 0.007in. thick cotton voile. This was found to incorporate to a good degree all the properties required in practice, i.e. good window size, large enough to allow free resin movement and not to weaken the bond and yet small enough to trap and hold the resin well; good strength, sufficient to withstand the resin drag during coating, and yet small enough not to induce peel-type failure in the bond; relative inelasticity due to the simple weave, thus avoiding lateral contraction when stretched longitudinally; freedom from contaminants that weaken the resin; low cost and good availability. A sheet width of 35 in. with selvedge removed was adopted and a completed resin sheet comprises four parallel adjacent strips of impregnated cloth nailed between wooden battens on a light square frame.

In general the problems met in carrying out the rotor cementing fell into two classes. Those inherent in any method and those arising from the use of heat. In the former class are the problems of handling the 20 ton discs, i.e. supporting, cleaning and turning over as well as raising and lowering quickly and smoothly without tilt, rotation or sideways movement. In this class also are problems relating to the accuracies of the surfaces, the rubber thickness, width and spacing, and the resin sheet thickness and flatness. In the second class are the problems of heating the discs and avoiding or allowing for deviations from flatness due to thermal gradients set up by transient and steady state heating and cooling processes. Of the latter processes, cooling by air convection, the chilling effect of the resin sheet, the thermal capacities of the oven and lagging and the resin exotherm during cure are all significant. The first class of problems is aggravated by the necessity to work within time limits set by the hot and cold resin pot lives and the need to limit rubber oxidation. In addition to problems specifically relating to the cementing operation the necessity to seal against NaK ingress and nitrogen escape and the need to ensure good electrical insulation in the bond space and outside it, where the NaK is thrown about, gave rise to additional problems.

It is not possible to do more here than comment briefly in turn on the above problems. The actual sequence of operations carried out involved the sticking of the prefabricated rubber mat to the underneath surface of the top disc of a pair followed by the sticking together of the two at a later date. Similar problems of application would be experienced in any other sequence. In the first sticking operation the rubber mat is supported elastically by resting on a 1/8 in. thick polyurethane foam layer covering the top surface of the bottom disc. The resin sheet is placed over the rubber mat and the top disc lowered on to it. The weight of the top disc is taken entirely by the rubber and the purpose of the plastic foam is to ensure that every part of the rubber mat is pressed into the resin sheet with a pressure of 3 p.s.i. It is not necessary at this stage to have the two discs accurately concentric or to otherwise control tilt, rotation or spacing. After cure the operation is repeated with the resin sheet resting on the top surface of the bottom disc, and with the top disc lowered on to it and allowed to sink down, as the resin squeezes out, until stopped by a ring of supports at the periphery of the discs. This support is necessary so that the discs will be accurately parallel to each other in the final condition. If the full weight of the top disc is taken on the ring of supports the disc will bow at the centre under its own weight by an amount of 0.002 in. If the lower disc likewise rests on a ring of supports at its outer edge it will also bow by the same amount and the two discs will be exactly parallel. This argument however pre-supposes that the supports are all identical and are registering on accurately plane surfaces, a condition which cannot be realised. With imperfect supports the load distributions will be non-uniform and dissimilar bending of the discs can occur, likewise the equilibrium condition may be unstable. In principle the use of a three point support for each disc instead of a ring of supports could ensure identical and stable disc shapes, however it is very difficult to lower the top disc on to three points without causing an initial tilt about a line through two of the supports. Such a tilt would cause excess resin squeeze out over an area and in order to finally rest on the three points the top disc would have to withdraw at this region thereby opening the bond. This difficulty applies to the use of any finite number of supports on the periphery of the bonded area, however in practice 24 supports is quite satisfactory. This method calls for accurately ground supports and the best accuracy in machining the surface on which the supports register. Clearly an equal number of supports is required for the bottom disc and these should be as far as possible, immediately below the other set. In order to compensate for floor movements under natural causes and under the disc loading which changes from zero to 40 tons, an elastic floor support was adopted, consisting of 3 in. squares of half-inch thick rubber sandwiched between steel plates and proportioned to compress linearly by an amount of 0.080 in. under the weight of the two discs.

For cleaning the disc surfaces for bonding solvent-degreasing was followed by sanding with flexible pad disc sanders and the procedure adopted was to just eliminate the turning marks. With experienced operators this did not impair surface flatness by as much as 0.001 in. The use of solvents alone has never been found to give consistent results.

For the first sticking operation the top disc of a pair was turned over, cleaned and turned back. The cleaning operation occupied two to three man days and each turning operation occupied an hour. The freshly sanded surface was covered with fresh brown paper overlapped and taped together and around the edge so that the surface could not be contaminated during turning over and subsequent handling. Cleaning was always done at the last possible moment.

Lifting of the top disc was done with a 30 ton overhead crane in low gear using a special tackle engaging a circumferential slot round the edge of the centre hole. For lowering on to the resin the crane motion was not sufficiently slow or smooth, nor could the crane hook be used, as its free and loaded hanging positions were not coincident. Instead a pair of 6 in. diameter hydraulic rams were welded at the top to plates which fitted over the ends of the crane hook hinge-pin and at the bottom to the ends of a rigid T piece which engaged with the disc centre-hole tackle. Thus lifting operations and lowering to within 1 in. of the final position were always controlled by the crane motor, but final lowering was executed slowly and smoothly by releasing oil from the two hydraulic cylinders.

Tilt control was satisfactorily achieved by putting a weight on the top disc at a suitable position to make the disc hang freely in a horizontal position. Rotation control was achieved by means of a pair of vertical 1 in. diameter steel guide pins rigidly attached to the floor at points along a diameter and passing through holes in plates attached to bars cemented to the sides of the top disc. This was essential to control the tendency of the wire ropes to untwist when loaded.

Approximate disc centering was achieved by the same rotation-control pins over most of the lift, which was about 12 in. During the bottom 1/2 in. of movement however, very accurate centering was achieved with the aid of spring loaded guides at each of four points. Each guide had a short flat vertical surface which was pressed against the top outside edge of the bottom disc and acted as a guide down which the bottom outside edge of the top disc could slide. Two of the guides, 90° apart, were spring loaded with a force of 100 lb and the opposing guides were loaded to half this. The guides had a tapered lead-in and were spring-loaded to avoid damage when first met by the top disc. Friction with the guide surfaces damped any sway oscillations within a few seconds and the more strongly loaded pair of guides determined the relative disc centering. To allow for azimuthal and vertical variations in radius of each disc a detailed centering survey was carried out at an earlier stage and the relations for optimum centering established at the above four points of the circumference. The more heavily loaded side guides were adjusted by means of shims to produce this relationship.

The main requirement for accuracy of surface for the steel discs is introduced by resin squeeze-out problems. In order to allow for variation of the inter-disc gap it is necessary to have excess resin and to leave spaces to which the surplus can flow. These spaces should be close together so that flow of resin will be complete before it becomes too viscous. The spaces themselves will reduce the area for adhesion and should thus be kept small, on the other hand they must be large enough for the squeezed-out resins not to join up or to otherwise impair the elastic properties of the joint. In Figure 10 resin squeeze-out into a crack between rubber strips is shown. In 10(b) the squeeze-out is large and the resin streams meet and push each other against the rubber sides. The effect of this is to interfere with the elastic behaviour of the rubber in compression and in shear transverse to the strips. If the rubber sides were cyclized the resin would stick to them and would thus interfere with the behaviour of the rubber in tension and in shear along the strips. In order to eliminate the latter possibilities the rubber sides are not cyclized.

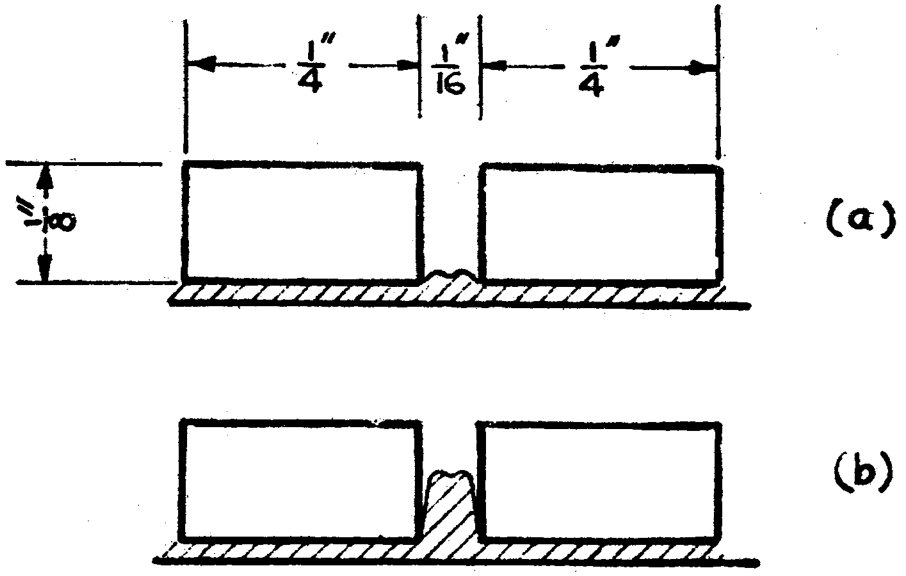

Figure 10. Squeeze Out of Resin in Gaps

As a result of the above consideration a gap of 1/16 in. was adopted between the 1/4 in. rubber strips. This represents an immediate loss of strength of 20%, however it allows reasonable tolerances on rubber width, thickness and spacing, steel flatness and resin thickness. The tolerances which were adopted were as follows: rubber width ± 0.005 in., rubber thickness ± 0.001 in., rubber spacing ± 0.005 in., steel to steel gap ± 0.002 in., resin thickness ± 0.001 in. (twice). The tolerances achieved in practice were determined as a result of hundreds of measurements of each item and in every case well over 90% of the measurements lay within the chosen range. If the thickness tolerances all added up an overall figure of ± 0.005 in. would be obtained and the minimum excess resin would need to be greater than 0.010 in., i.e. the mean height of resin in the worst gaps would amount to more than 0.050 in. It is not possible to measure the final resin height, however a check on the gap between the bottom face of the rubber and the top face of the bottom disc was carried out on each pair of discs shortly before the final sticking operations were carried out. This measurement incorporated all the tolerances except those of the final resin sheet. The range of readings obtained was ± 0.0035 in. and ± 0.0032 in. for the first and second rotors respectively. These readings are obtained by preparing a test-cast frame consisting of 20 narrow strips of Epikote VIII, sandwiched between 0.0005 in. thick Mylar film which was nailed to a square frame. The top disc of a pair was raised, the frame was pushed through the gap and the disc lowered again on to its stops. The discs were at 70°C and after two hours the test cast was removed and the Mylar-resin sandwiches measured by a micrometer at the points of a 20 by 20 grid. This technique was used at several stages in the procedure and was found to give very consistent results, provided that the discs were hot.

The resin-sheet thicknesses adopted for sticking the rubber mat to the top and bottom discs were respectively 0.0105 in. and 0.0170 in. The former is the minimum thickness found satisfactory by test and the latter is that required to cope with the overall tolerances with a safety margin of 0.002 in. over the worst case. This margin is required to cover the resin-sheet tolerance and gap variations due to disc bowing under the various thermal disturbances. The second resin-sheet thickness and the inter-disc stops were chosen so that the average resin thickness after the top disc had settled on its stops would be 0.0115 in. This was estimated to result in most of the disc weight being finally taken by its stops; a result which was borne out in practice.

Under the above conditions the maximum heights of resin in the squeeze-out gaps would be expected to be 5 x 0.002 in. = 0.010 in. and 5 x 0.009 in. = 0.045 in., at the top and bottom respectively. In order to determine the loss of shear strength the mean squeeze-out height at the outside edge of the disc is required. With the first pair of discs this is 5 x 0.004 in. = 0.020 in. at the bottom and with the second 5 x 0.006 in. = 0.030 in. Thus in the latter case the total height is 0.040 in. and the resultant shear modulus transverse to the rubber strip could conceivably be raised in the ratio 120/80. The effect of this would be to raise the transverse shear stress about 17% above the mean. The resultant effect when combined with the 20% reduction of adhesive area would raise the peripheral shear stress occasioned by a 5 million ampere short circuit from 100 p.s.i. to a maximum of about 146 p.s.i. transverse to some the rubber strips.

A small thermal distortion of the steel disc during the cementing operation will not aggravate the tolerance problem arising from resin squeeze-out since the latter is only serious near the periphery at which region the gap is accurately defined by stops. However it will introduce other difficulties if it is not stable. Of these the most important is the possible withdrawal of a disc surface after resin squeeze-out is complete. At some stage in the cure the resin will be too viscous to be sucked back into an increasing gap and will not have an adhesive and cohesive strength sufficient to prevent the gap from changing. It is necessary to know what thermal distortions can occur in practice and what changes can be made in the resin-filled gap without fear of impairing the ultimate bond.

Because it is easy to achieve a good degree of circular symmetry and radial uniformity the only thermal distortion which can concern us is a simple bow of one disc relative to the other. This can be caused by inadequate oven lagging which allows heat to flow out at the horizontal faces and thus establishes a vertical temperature gradient with consequent spherical bow. The lagging which was used consisted of a 4 in. thickness of Stramit strawboard on all outside faces and this cut the rate of fall of temperature to 0.27°C per hour representing a total loss of 1.3 kW. The thermal gradient produced by this heat loss causes the discs to bow towards each other at the centre by a total amount of 0.0008 in. With this lagging it is possible to overrun the temperature by a couple of degrees, accurately balance the two disc temperatures, switch off the oven power and leave for eight or more hours before cementing. Thus the thermal conditions will be very uniform and stable except for the disturbances introduced by the cementing procedures. The first of these disturbances is due to the in rush of cold air when the discs are separated and the subsequent convection loss. This was found by experiment to cause the discs to bow apart by an amount of 0.0023 in. if they were separated by 12 in. for a period of 10 minutes. After reclosing the gap the bow diminished with a time constant of about 9 minutes. A similar impulsive bow is caused by the cooling action of the resin mat and was estimated to have a magnitude of 0.0012 in. for a resin sheet thickness of 0.017 in. The combined effect of these two disturbances, i.e. 0.0035 in., exceeds the safety margin of 0.002 in. in resin sheet thickness, as discussed already, however the recovery time-constant of 9 minutes is sufficiently short in relation to the rate of cure of the resin to ensure that much of the bow will have vanished before the resin is stiff enough to prevent further squeeze-out. Because of the flexibility of the steel discs when considered in relation to the small tolerances and the resin flow-pressure-time characteristics it is difficult to define a set of conditions which must be adhered to in order to ensure satisfactory resin contact over the complete disc area. One danger to be avoided is that the pressure available will not be able to complete the resin squeeze-out at places where it is required to be large, thus distorting the two discs and preventing contact with resin at some of the other points. Another danger is that a disc with a relaxing thermal bow and meeting with too much resistance to flow by the resin will 'sit' on the resin over one area and complete the relaxation of its bow by withdrawing other areas from contact with the resin. The latter is avoided by designing for much of the weight of the top disc to end up on rigid stops at its outside edge in which case, since the above thermal bows relax by moving the disc centres in towards each other, the outer regions cannot separate unless the force causing the bow is sufficiently great to lift the disc edge off the stops, i.e. to support the full 20 tons weight. The above bows could not do this.

In arriving at an understanding of the conditions necessary to ensure successful cementing over the whole disc area a variety of small scale tests was carried out with different loads pressing 1/4 in. wide strips into two-hour-old resin sheets which had been applied to a hot surface for different intervals of time. The resulting final resin thickness was measured in each case and plotted against pressure for each interval of time. The choice of resin sheet thickness and inter-disc stop height as mentioned previously were then chosen by referring the mean and lower extreme values of the gap, as measured, to the curve for a 10 minute time interval and checking that the corresponding pressures did not exceed 1 and 3 p.s.i. respectively. On this basis the upper limits which were adopted for the operating times during a final cementing operation were 10 and 5 minutes respectively for the time of opening of the disc gap (12 in.) and the time that the resin sheet is on the bottom disc surface before the full weight of the top disc is released by the crane. In the final cementing operations it was found possible to greatly improve on these target figures and in fact with the first pair of discs the respective times achieved were 2 and 1.25 minutes and with the second pair of discs 1.25 and 0.75 minutes. In both cases the peripheral stops received over 90% of the disc weight within another two minutes.

A further thermal disturbance which was examined and proved to be marginal is that produced by the resin exotherm. This was measured calorimetrically in a number of tests covering the range of conditions anticipated and a rate of energy release of about 1 calorie per gram per minute was obtained, commencing after 10 minutes and lasting for about 50 minutes. For a full resin sheet this represents a power input into each disc of about 170 watts and the resultant bowing together of the discs would be about 0.0003 in.

DISC OVENS

The ovens for the discs consisted of 4 in. thick discs of Stramit strawboard beneath the bottom disc and above the top disc. These carried the heater elements consisting of 1 in. wide aluminium foil cemented to the face of the Stramit with an epoxy varnish. The outside edges of the discs were insulated by 4 in. thick Stramit sheet bent round the periphery (with the aid of numerous cuts) and held by steel banding. The Stramit was obtained as 12 ft by 4 ft by 2 in. thick sheets and each disc was cut from a composite 12 ft. sq sheet made up by gluing and skew nailing the sheets (with wooden nails). The bottom disc sat on the floor and had a ring of holes through which passed steel pillars from the 24 rubber floor supports. The bottom disc was 1 in. away from the aluminium foil heater and was heated by radiation and convection. The top disc was heated by radiation only from a similar element 1 in. above it. The surrounding Stramit walls consisted of 2 in. thicknesses banded to each disc and a single 2 in. thickness embracing both. This latter was removed during the actual cementing operations.

Each rubber mat consisted of 424 strips of rubber each 13 ft long and having a total length of just over one mile. The strip was knifed continuously in 1/4 in. widths from 13 ft by 2 ft rubber sheet of 1/8 in. thickness stuck to a wooden drum with a circumference of 13 ft. The identity of each sheet and strip position in it was retained to the end of the project by drawing one or more parallel adjacent slant lines across the sheet with crayon before knifing. This facilitated the detection and removal of defective strips and the systematic dispersal of each batch uniformly over the sheet area with suitable alternation of strip ends and faces so that a homogeneous mat would be achieved despite the non detection of a faulty batch. After knifing, the strips of a batch were laid side by side on edge and the slant-line code transferred to the cut edge with a water and acid proof paint. The strips were then joined end for end with scarfed joints and rubber solution to make continuous lengths of 30 or more strips. These lengths were ground in turn to a uniform thickness by never less than four passes under a grinding wheel. The rubber sheets were specified to be 'uniform' and with a thickness tolerance of ± 0.005 in., however thicknesses ranging from 0.125 in. to 0.150 in. were finally accepted. The sheets frequently had waves in which the extreme upper and lower limits appeared close together, an effect which is probably caused by buckling the plies as they are run together. The waves always appeared on only one surface of the sheet, so the practice was adopted of grinding the wavy side first and not touching the other face until the waves had disappeared. If this was not done the effect of grinding was to produce matching surface waves on each side of the rubber thus giving a uniform thickness but a wavy strip which could in some cases require sticking pressure in excess of 3 p.s.i. to flatten out. The final grinding pass on the second face of each length was always carried out slowly with very little tension in the strip in order to achieve the 0.120 in. ± 0.001 in. final accuracy. The rubber lengths were pulled over a flat table by hand with a convenient arrangement of guide walls and rollers as shown in Figure 11. The direction of motion was against the wheel. The operation was carried out without lubricant and a nylon brush and suitable air blasts were arranged to remove the swarf, leaving a clean strip. The grinding machine was a standard workshop grinder and it was found necessary to protect its bearings by enclosing wherever possible in thin polythene sheet. Despite the large amounts of rubber to be removed the grinding process was carried out quite quickly and it was found possible to process a mile of rubber in a fortnight with very close inspection at all stages. The ease and accuracy of grinding is largely due to using a fairly hard rubber. A tolerance of ± 0.0005 in. could quite easily have been achieved. The complete supply was found to have Shore hardness figures ranging from 77 to 85 with most of the rubber lying in half this range. The extremes represent a variation of intrinsic strip elasticity of ± 15%. The grinding process gives a clean smooth surface which allows a very short cyclizing time to be employed. This in itself was a great asset as alternative methods of surface cleaning were found to be dirty, tedious and destructive of accuracy.

The acid treatment was carried out in the equipment shown in Figure 12 by passing the continuous rubber lengths around the top of a 3 in. diameter polystyrene wheel which dipped at the bottom into a concentrated sulphuric acid bath. The strip then travelled a distance of about 18 in. before entering a large water bath. Under the water surface it passed between a pair of glass fibre pads arranged to wipe off air bubbles and ensure the uniform washing of the surface. It then passed under a roller and

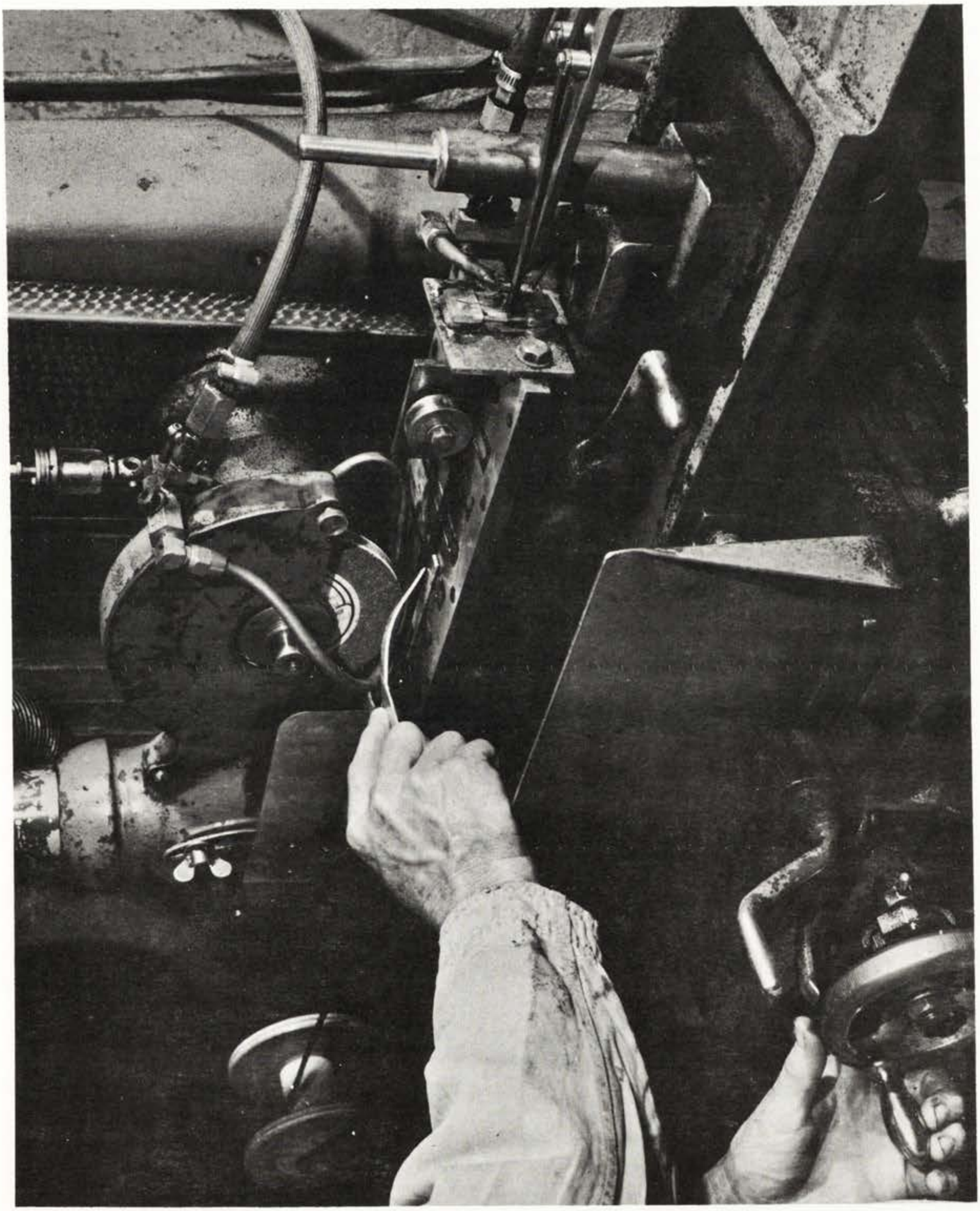

Figure 11. Rubber Grinding Set Up

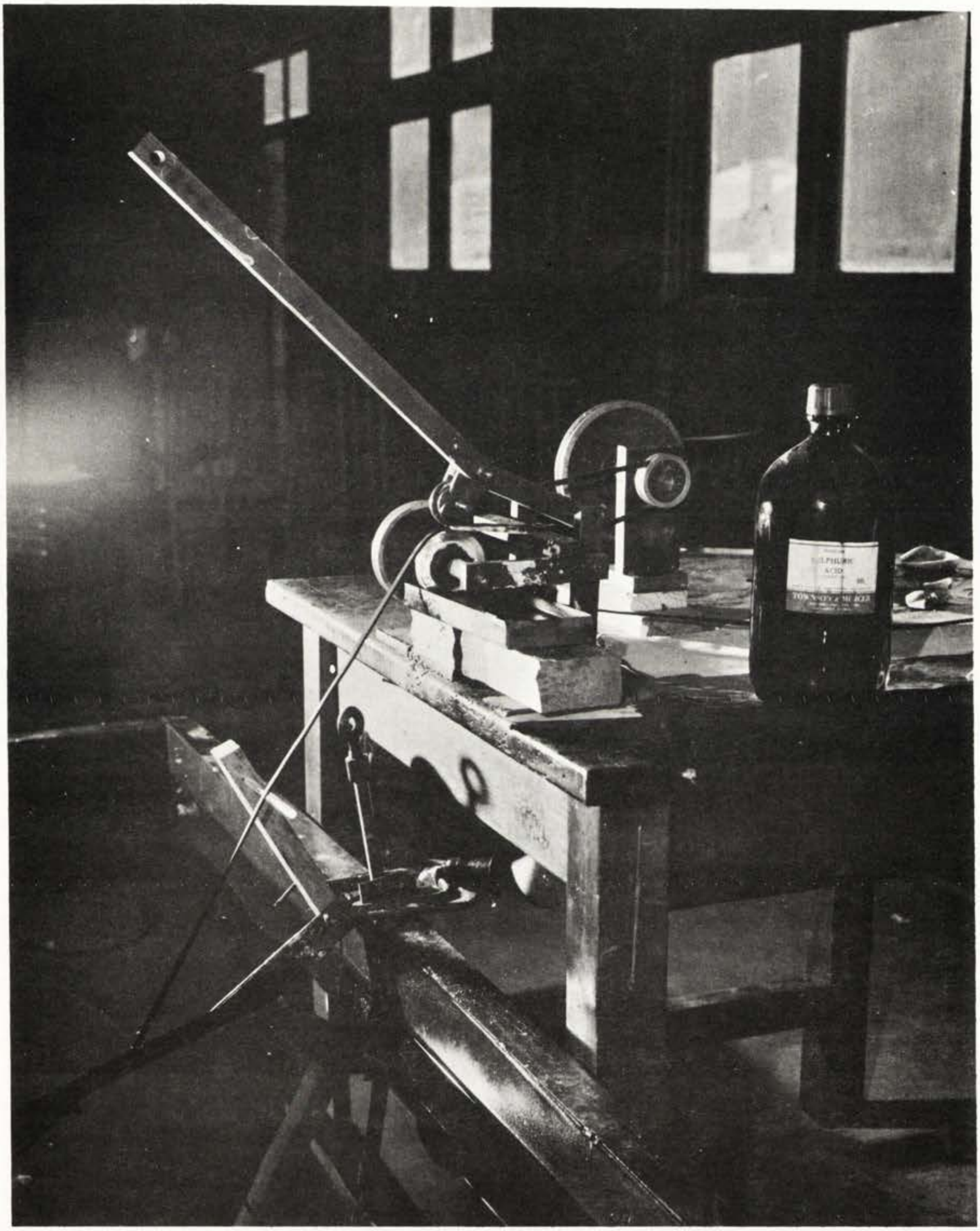

Figure 12. Rubber Aciding Set Up

up out of the water on to a large rotating basket frame for draining and drying by a large fan. The polystyrene roller was 1/4 in. wide and had two circumferential grooves turned in the surface. The rubber was guided centrally on to the roller and the degree of dip into the acid bath adjusted in relation to the rate of movement so that a supply of acid was carried to the top adequate to wet the contacting rubber face and not the sides. The purpose of the circumferential grooves is to prevent the acid from pulling by the influence of surface tension towards the strip centre when it leaves the roller thereby starving the edges of acid. In order to obtain reliable fast processing it was found desirable to scrape the rubber strip over a 1/4 in. diameter glass rod fixed at a point half way between the roller and the water. This has the effect of redistributing the adhering acid so that it firstly rewets the whole surface and then pulls by surface tension to cover the previously starved regions over the grooves. The rate of movement of the rubber was about 1 ft per second so every part of the rubber surface experienced a thick acid film for at least 0.75 second. This is a tremendous reduction over the normally specified cyclizing time of 5 minutes and was only adopted after extensive bonding tests at steady loads of 450 p.s.i. and temperatures up to 100°C. Quality control of each processed strip was checked with such tests. The rubber was pulled through the equipment by manually cranking the receiving basket frame and in order to achieve a non-jerky movement a simple flywheel was coupled to the aciding wheel. Each rubber strip was passed twice through the equipment, once for each side, with drying in between sides. After the final process the rubber was thoroughly washed in running water in the bath in order to eliminate the last trace of acid. The lengths were subsequently cut at the scarfed joins, clamped individually on edge on a table and lightly sanded on the sides to remove small traces of acid action extending round the corners. The strips were then laid out in the required order and directions on a number of wooden planks and nailed at each end for storage and subsequent handling.

PREPARATION OF RUBBER MAT

The rubber mat was prepared by nailing each strip of rubber to two lengths of wood attached to opposite sides of a light rigid square frame constructed from duralumin channel. The strips were laid across the bottom steel disc (and temporary corner tables) without tension and were accurately positioned and cross laced to preserve the 1/16 in. gap throughout the subsequent handling. The cross lacing was achieved by sticking nichrome tapes 1/32 in. wide by 0.004 in. thick transversely across the top surface of the rubber. The tapes were coated all over with a thickness of about 0.0005 in. of a thin epoxy resin (Araldite type D) by pulling vertically downwards through a narrow crack loaded with resin on its top side. Before applying the tape to the rubber a suitable electric current was passed through it to partially cure the resin to a tack free state so that it could be laid down, positioned and pressed down without wetting the rubber surface. When ready for sticking, a current of 1.3 amps was passed through the tape for several minutes and produced a bond which is as strong as the rubber. In order to position the rubber strips a long double comb was prepared by bolting a set of accurately milled steel combs to each side of a long 4 in. x 1/2 in. steel bar. This was positioned along each nichrome tape in turn so that continuous combs engaged every rubber gap and held the

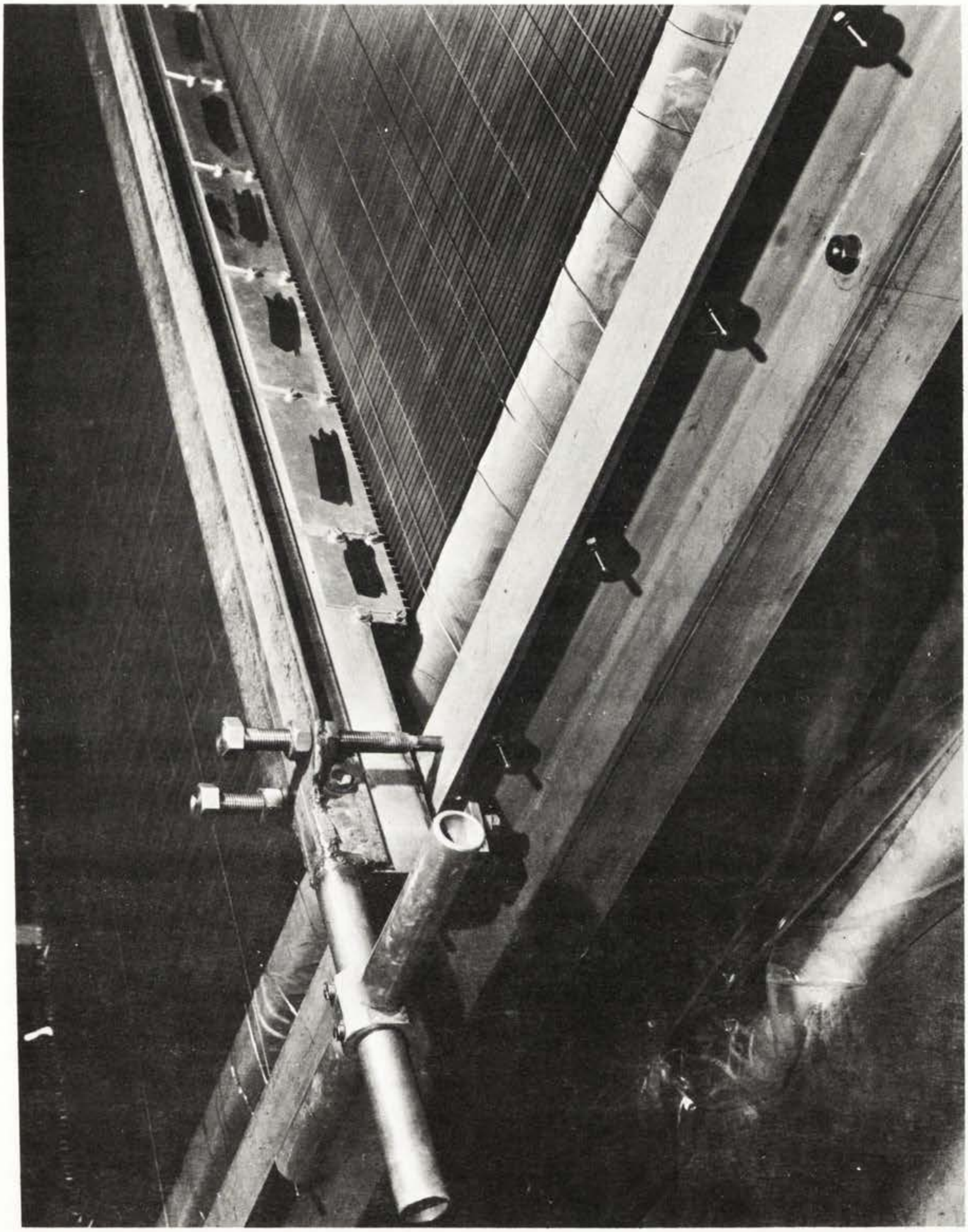

Figure 13. Rubber Mat During Cross-Lacing

Figure 14. Coating Cotton Voile with Resin

Figure 14 shows a resin sheet being prepared by pulling the cotton voile from a roll vertically downwards through the crack in the floor of a resin filled hopper. The cross section of the hopper is shown in Figure 15.

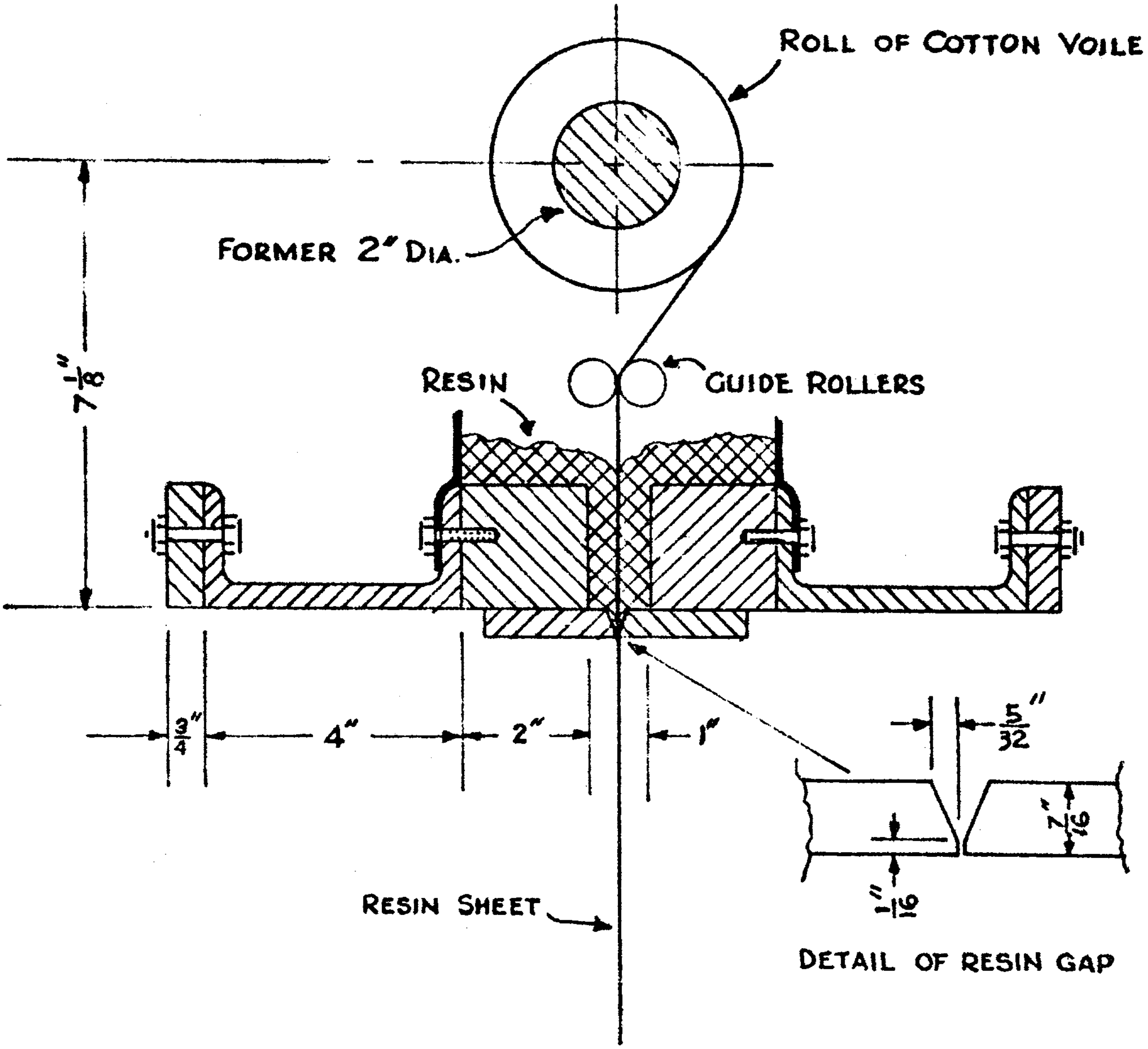

Figure 15. Cross Section of Resin Sheet Hopper

Without the reinforcement of the two channel sections bolted along the sides the resin crack was found to open by 0.006 in. due to bending of the side supports. This is caused by the substantial pressure developed in the resin at the base of the hopper, which produces a force equal to about 300 lb on each side. This pressure is caused by the viscous drag of the resin on the cloth and the force required to pull it through at a suitable rate of about 2-1/2 ft per minute was about 120 lb. With this rate of cloth movement a single length takes 5 minutes and the total cloth pulling time is 20 minutes. Because of the pressure in the hopper the resin penetrates the voile very thoroughly and there is no loss of bond strength due to the presence of the cloth. The resin crack widths adopted for preparation of the first and second resin sheets of each rotor pair were ~~0.130~~ 0.0130 in. and 0.0230 in. respectively, giving overall resin sheet thickness of 0.0105 in. and 0.017 in. respectively. With the second sheet the thickness tolerance achieved was checked after completion of the operation and it was found that thicknesses at each end of a cloth length and across the width all lay within the limits 0.017 in. ± 0.001 in. and over 90% of the readings lay within 0.017 in. ± 0.0005 in. These figures are consistent with a general rule found to hold for any shape of scraper used for spreading thin viscous resin films on a flat surface. The resultant resin thickness is 60% of the mechanical gap used to make it. This holds over a wide range of speeds of operation and shapes of scraper from round rods to sharp knife edges. If one were to assume a uniform rate of viscous shear across the forming gap the figure to be expected would be 50% instead of 60%. With the very plausible assumption of a higher than average shear at the restricted area of the scraper the 60% figure is not surprising. The accuracy of the figure is the surprising feature. Applying the method to the 0.013 in. and 0.023 in. gaps we obtain 0.007 in. + 0.6 (0.013 in. - 0.007 in.) = 0.0106 in. and 0.007 + 0.6 x (0.023 in. - 0.007 in.) = 0.0166 in. respectively in very good agreement with the measured mean figures of 0.0105 in. and 0.017 in.

After the pulling of each length of voile clamps were attached to facilitate cutting and transfer to the correct position on the resin frame. Pulling was done by two men on a floor 17 ft below. Attachment to the frame was by nailing on thin wooden cover strips. The preparation of a complete resin sheet took 50 minutes starting with a full resin hopper. Allowing for an initial resin mixing time of 20 to 25 minutes the time from commencement of resin mixing to the completion of the resin sheet in general occupied 70 to 75 minutes. Subsequent operations on the resin sheet involved: lowering to a horizontal position and locating on slides ready for rapid and accurate movement into position between the steel discs, cutting four windows for the accurate centering devices to pass through and applying small resin-cloth patches to cover gaps between cloth lengths at the positions where the rubber gas seals cross them.

In the horizontal position the resin sheet was supported against sag by tensioned piano wires attached to the frame at 12 in. spacing. These had the secondary effect of flattening the sheet, thereby removing any curling and buckling tendencies and allowing rapid movement and lowering into final position without cloth sway. It must be remembered that with this highly tacky resin the cloth strips must not touch themselves or anything else even momentarily.

The time of preparation of a resin-sheet from starting to mix the first resin until the sheet was ready to slide into the gap between the discs was just over 1-1/2 hours. During the final cementing operation a total of 10 kilograms of resin was mixed and of this, 7-1/2 kilograms was transferred to the cloth. Mixing was done in 2 kilogram batches using a simple paddle in a variable speed power drill.

After the fabrication of a resin sheet was completed subsequent cementing operation took two minutes or less to finish. The top disc together with its oven was lifted off its temporary stops and raised 1 in. to allow them to be removed. It was then lifted another 11 in. and the resin frame was slid into position, centering firmly and accurately at the same time. The frame was then cranked down on top of the bottom disc with the aid of four jacks and the top disc was moved down with it by means of the crane motor. The top disc was stopped about half an inch above the resin while the piano wires which had previously supported the sag of the cloth were cut and pulled out. The disc was then lowered finally by means of the hydraulic tackle. Figure 16 shows one of the resin frames being pushed into the gap.

With the cementing of the first face of each pair of discs there are very few possibilities of failure and these can be checked by observation and test after the resin has cured. The weight of the top disc is taken completely by the resin sheet and barring defective materials the cementing should suceed at every point. After cure the resin sheet was trimmed away and the ring of wood banded to the bottom disc was removed. The top disc was removed and the lacing tapes peeled off. The disc was then lifted on to some large concrete blocks with the rubber supported over a large area by several inches thickness of Stramit as a cushion. It was held at 70°C by its own oven and by wrapping around with aluminised sisalkraft to prevent heat loss from below. Several 1 in. square steel blocks were then cemented to the under surface of the rubber and pulled off after cure by levers loaded with lead weights which were increased every hour in steps corresponding to 75 p.s.i. This was continued until each block broke away, in most cases in a few minutes after reaching a load of 625 p.s.i. In this way the cleanliness of the top disc, and the resin and rubber quality were checked. With the cementing of the second face the problems of resin flow and thermal distortion arise and means of checking the closure of the joint are desirable. In order to observe the extent of load transfer to the stops each of them was fitted with a pair of resistance wire strain gauges transforming them into small load cells. The stops are ground steel rectangles approximately 7/8 in. high and are located in a 3/4 in. deep undercut ring at the outside edge of the bottom disc. This undercut ring is designed to help throw off NaK droplets, serves to protect the outside edge of the 1/8 in. gap from damage and in general improves the efficiency of insulation at this vulnerable point. The 24 stops were wired in series in groups of three and connected to a bridge arranged so that load readings could be quickly read in sequence. It is difficult to achieve accuracy of load and rapid response with these stops because of the thermal disturbances during the cementing operation. This includes also the effect of the resin sheet which is interposed between the top of the stops and the registering surface of the top disc. Nevertheless enough evidence was obtained to show that about 90% of the weight of the top disc was taken by the stops within a few minutes. Load was balanced uniformly round the disc and increased monotonically showing that there was no evidence of retraction at any point. In addition to the evidence from the load on the stops five clock gauges were arranged to operate through the gaps between resin strips and indicate changes in the inter-disc gap at the periphery and at the centre hole. In all cases the outside clocks were within 0.001 in. of their final readings in a few seconds and within 0.0005 in. in 1 minute. The centre clock was within 0.002 in. of its final reading in a few seconds and within 0.0005 in. in 12 minutes. The clocks

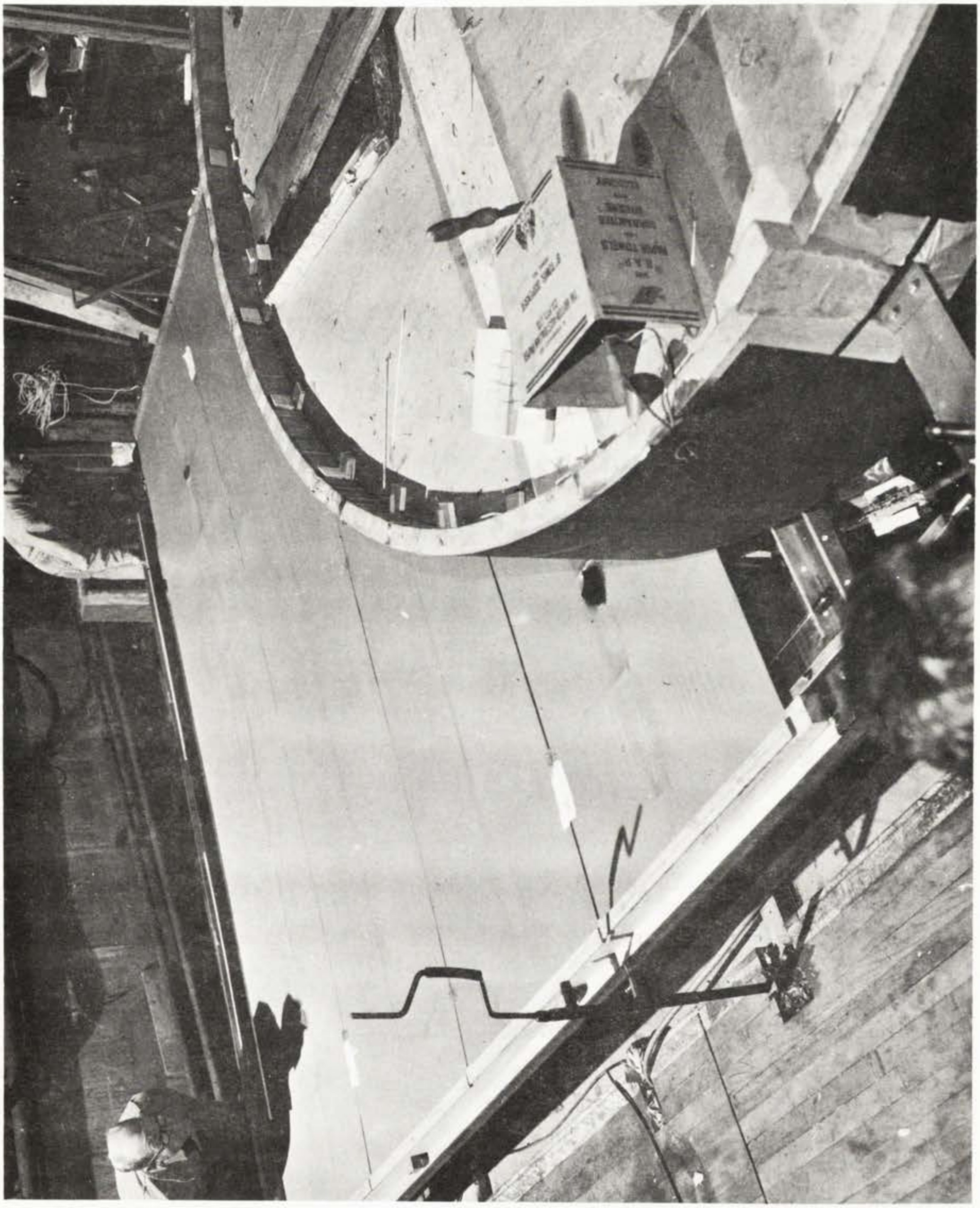

Figure 16. Resin Sheet Being Pushed Between Steel Discs

indicated a final bow apart of 0.0006 in. at the disc centres, suggesting a residual resin pressure at this point of less than 1 p.s.i. The evidence of all of these measurements combines to suggest that the operation proceeded as expected and that resin was satisfactorily met over the majority of the area. At this point it should be mentioned that two escape vents for air were drilled in the steel, bypassing the outer rubber sealing ring. Without these vents it would be possible for trapped air to prevent the satisfactory settling of the surfaces into the resin. The same vents were used for subsequent gas filling of the cracks between the rubbers.

FINAL TESTS

Each completed rotor was subjected to a gas pressure test as already described. The test was carried out at 70°C using nitrogen and the pressure was raised in steps over a period of 1-1/2 to 2 hours to a value of 280 p.s.i. Neither rotor gave evidence of excessive deflection or unbalance during this test. At a maximum deflection of 0.017 in. the first rotor (bottom) showed a difference of 0.0005 in. between clock gauges. For the second rotor (top) the difference was 0.002 in. with a deflection of 0.020 in. Both of these figures are regarded as satisfactory.

The electrical insulation of the two completed rotors was checked with a 500 volt Megger. No reading was obtained indicating an insulation resistance of at least 200 megohms.

CONCLUSIONS

It is possible to conclude from the above discussion that, considering all relevant factors, the cementing of two steel discs to form a composite rotor in the manner described, is at least as good a method as any other which has been proposed, as regards strength and economy of space. It is necessary however to emphasise the very great expenditure in time and manpower required to investigate and carry out the operation successfully. Only a fraction of the detail has been covered in this account and almost nothing of the great number of alternatives which were considered and decided against at every point in the procedure. The development of the various aspects of the technique occupied two years and the detailed application to the two rotors took five and three months respectively of intense activity from a team of three men. This is a large investment for one item, but the experience gained is already paying off in many other ways as the intrusion of plastics techniques into everyday workshop procedures is steadily progressing.

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