described, may be used as a standard with a time-constant not exceeding 1×10^{-9} H/Ω in magnitude, for values between 10 Ω and 1 kΩ; a resistor of 100 Ω is likely to have a time-constant very close to zero.

ACKNOWLEDGEMENTS

The work described above has been carried out as part of the research programme of the National Physical Laboratory, and this paper is published by permission of the Director of the Laboratory.

REFERENCES

(1) ARNOLD, A. H. M. *J. Instn Elect. Engrs*, (II), **100**, p. 319 (1953).
(2) ASTBURY, N. F. *J. Instn Elect. Engrs*, **76**, p. 389 (1935).
(3) LYNCH, A. C., RAYNER, G. H., and FORD, L. H. *J. Sci. Instrum.*, **35**, p. 36 (1958).
(4) RAYNER, G. H., and FORD, L. H. *J. Sci. Instrum.*, **34**, p. 190 (1957).
(5) HARTSHORN, L. *Proc. Phys. Soc. (London)*, **39**, p. 377 (1927).

Bonding optical components to metal mounts

By K. H. SPRING, M.Sc.,* Fighting Vehicles Research and Development Establishment, Chertsey, Surrey

[*Paper first received* 24 *October*, 1957, *and in final form* 3 *January*, 1958]

Various methods of bonding optical components to metal mounts, using synthetic resin adhesives, are described. In some cases a rubber interlayer is necessary to maintain resilience and prevent strain in the glass. A sandwich-type silicone rubber interlayer may be used to maintain resilience at temperature extremes. The tensile strength and shock resistance of the various types of bond are discussed, and a laboratory shock-tester suitable for small specimens is described.

Optical components such as prisms are usually held in position by small metal clips around their edges, sometimes with thin layers of cork to prevent strain or damage to the glass. This method of attachment is satisfactory for, say, hand-held binoculars, but is less so for the larger optical components in instruments which are likely to receive more severe shock, such as those mounted on military vehicles liable to be attacked by gunfire. The inertia of the component, in relation to the small area over which it is effectively held, may then cause it to break off and render the instrument unusable, perhaps at a critical time. The military ideal would be for all the optical instruments in a vehicle to remain usable for as long as the vehicle itself were fightable. A considerable advance towards this ideal has become possible in recent years owing to the introduction of synthetic resins which permit an optical component to be bonded to its mount over the whole common base area.

STANDARD TECHNIQUE

A technique for bonding, which has now become almost standard, was evolved mainly by the Admiralty Gunnery Establishment. The optical element is bonded to a steel plate using a rubber interlayer. Nilo 48 (by Henry Wiggin and Co. Ltd.), an alloy steel, is used to minimize differential expansion between steel and glass, and Gaco synthetic rubber (by G. Angus and Co.), which satisfactorily withstands the necessary bond-curing temperature, is used as a stress-relieving layer. Rubber of a thickness of $\frac{1}{64}$ in. and Shore hardness of 75° were found to give the most satisfactory results. The glass, steel and rubber are thoroughly cleaned with alcohol and the rubber is baked for four hours at 140° C, hanging from clips in an oven. All the components are then brought to a temperature of about 100–120° C—slowly, of course, in the case of large glass elements. The mating surfaces of glass and steel, and both sides of the rubber, are coated with a thin layer of Araldite type 1 (hot setting) cement (by Aero Research Ltd.). They are brought together under light pressure, taking care that as few air bubbles as possible remain. The assembly, usually held in a jig, is then baked for eight hours at 140° C, the lowest temperature at which satisfactory curing takes place. Considerable thought is usually needed to design a jig which holds the components with the necessary accuracy, but which does not strain the glass at any stage in the temperature cycle. Bonds produced in this manner have a tensile strength at room temperature of about 0·5–0·7 t/in.^{2}, i.e. of the same order as glass itself.

BONDING OF LARGE AREAS

Most prisms are sufficiently rigid to withstand distortion even when under strain, but this is not always true of large, comparatively thin, plates such as mirrors, for which the standard technique just described is unsuitable.

Front aluminized flats, $4 \times 2 \times \frac{3}{8}$ in. thick, were examined on the interferometer before and after being bonded on to steel plates with $\frac{1}{64}$ in. rubber interlayers. In most cases there was a slight change in fringe pattern. Much more serious distortion of the glass occurred, however, when the

* Now at Royal Aircraft Establishment, Farnborough, Hants.

Nilo steel plates were themselves attached to their supporting framework. This was so even when great care was exercised in flattening the steel plates, and in using a three-point support with spherical washers and seatings. Tests were therefore carried out with thicker interlayers, and Gaco rubber $\frac{1}{8}$ in. thick and of 75° Shore hardness was used. It was thought that with this thickness of rubber small distortions of the steel backing plate would not be transmitted to the glass plate.

To investigate this point, a glass plate 4 × 2 in. was bonded over its whole area, using a $\frac{1}{8}$ in. interlayer, to a steel plate 12 × 3 in. Provision was made for bending the steel plate longitudinally into a circular arc, the curvature of which could be increased smoothly from zero in either sense, concave or convex. Measurements of the curvature of both the steel and glass plates were obtained from observations with two autocollimators, as shown schematically in Fig. 1.

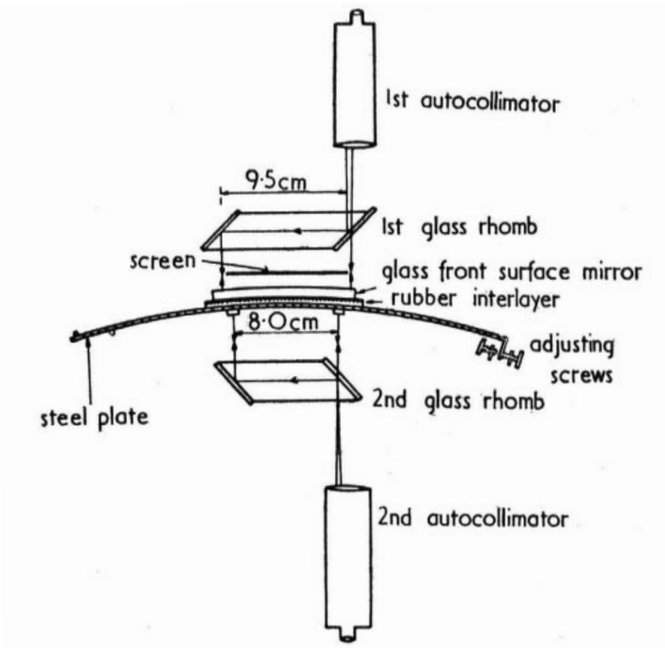

Fig. 1. Arrangement for determining curvatures of steel and glass plates. The curvature of the steel plate is greatly exaggerated

Interferograms of the glass plate are shown in Fig. 2 for five different conditions of bending of the steel plate. It will be observed that in the nominally unstrained state (*a*) the glass is slightly convex and becomes flatter on making the steel plate concave (*d* and *e*). From measurements of the fringe positions it is possible to deduce the average curvature of the glass plate under the five conditions, and these results are shown in Fig. 3.

Fig. 3 also gives the autocollimator results which are plotted to show the relation between the curvature of the glass plate and that of the steel plate. There is fairly close agreement between the slopes for the two sets of results, one of which is related to the average bending of the glass and the other to the difference between the ends. The glass must therefore have been bent almost into a circular arc. The interferograms show the smaller transverse curvature to be expected from elasticity theory. The autocollimator results pass through the origin, since only changes in curvature can be measured in this way.

It is apparent that, even for very small deflexions, the relation between the curvature of the glass and that of the steel is linear, the ratio of the two being 0·435. This means that a glass plate bonded in this manner will faithfully follow on a reduced scale the deflexions of the backing plate, the scaling factor depending, of course, on the thickness and elasticity of the glass and the rubber interlayer.

As a result of this investigation, the methods of support shown in Fig. 4 were designed for large plates. The front

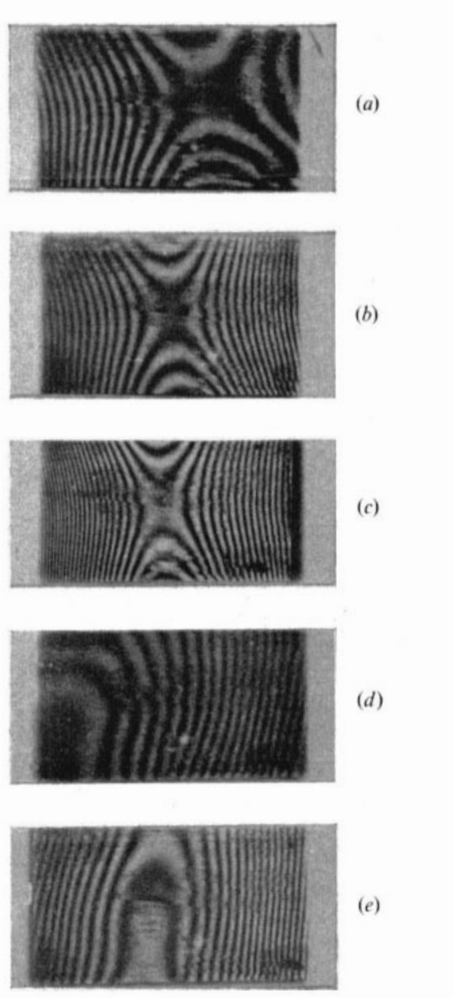

Fig. 2. Interferograms of stressed glass plate

(*a*) Steel plate unstrained.
(*b*) Steel plate 1 min. convex.
(*c*) Steel plate 2 min. convex.
(*d*) Steel plate 1 min. concave.
(*e*) Steel plate 2 min. concave.

surface reflector shown in (*a*) is bonded by a form of geometric line and point attachment and the semi-reflector in (*b*) is bonded along the edges. Both plates when mounted were found to be adequately free from strain, and they were also satisfactory as regards optical stability and shock resistance.

EXPERIMENTS WITH ARALDITE ADHESIVES

As part of a general investigation into strain-free joints, bonding tests have been made with several types of Araldite adhesive. Tensile strength tests were made using glass specimens $1\frac{1}{8}$ in. diameter (1 in.^{2} area) bonded between steel arms of the same diameters, and shaped to fit an Avery tensile-test machine. These tests have been carried out over a range of temperatures. A laboratory shock-tester, described later, has been constructed to permit investigation of the behaviour under shock of small bonded specimens.

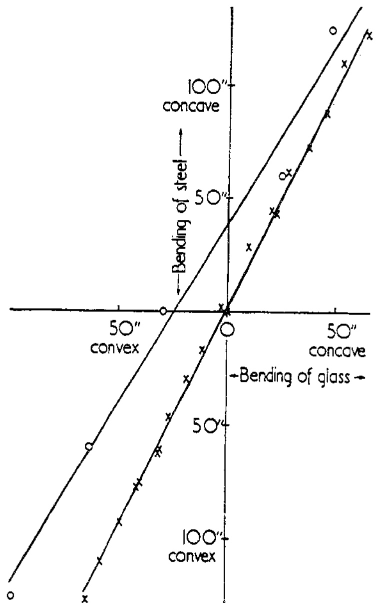

Fig. 3. Curvature of glass plate in relation to that of steel plate

○ = interferometer results; × = autocollimator results. Ratio on graph: glass/steel = 103/200. Base for glass = 9·5 cm. Base for steel = 8·0 cm. Actual ratio of curvatures:

$$\frac{\text{glass}}{\text{steel}} = \frac{103}{200} \times \frac{8 \cdot 0}{9 \cdot 5} = 0 \cdot 435$$

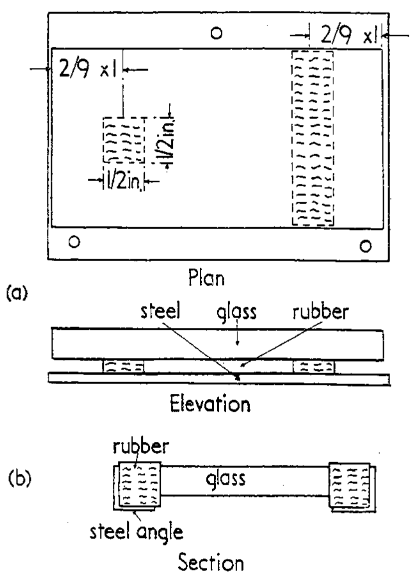

Fig. 4. Strain-free mounting of large glass plates

(*a*) Front surface reflector.
(*b*) Semi-reflector.

It would be a great convenience if a cold-setting adhesive could be used for bonding, as this would simplify procedure, and also reduce the risk of fracturing glassware from heat. Unfortunately, for Service applications the strength of the cold-setting adhesives falls off at high temperatures, but this may not be important for some uses.

Room-temperature tests with cold-setting Araldite 101 gave metal-glass tensile strengths of 0·80 t/in.^{2}, and with Araldite D, which is a later introduction, about 0·25 t/in.^{2} Type D, however, loses less strength when hot. There was no significant difference in strength between joints made with polished glass and those with fine-ground glass. A slight increase in strength is obtained if the joints are baked at about 80° C for an hour, after cold setting, but they are relatively very weak during this phase.

At room temperature, with both type 101 and type D Araldite, failure of the joints sometimes occurred by failure of the glass, and examination of the type of fracture indicated that the glass was under strain. It was therefore decided to investigate the effects of Gaco rubber inserts in cold-setting glass-metal bonds. It was found that the highest strength was obtained when the rubber was first cleaned with acetone (or ethyl acetate) and baked for four hours (or left for twenty-four hours to dry out). Less satisfactory results were obtained if the rubber were crazed by acid pickling, with the intention of presenting a greater surface area. This may have been because, despite care in cleaning and baking, the rubber surface was still contaminated.

With Araldite 101 the tensile strength at room temperature of these rubber-glass-metal joints was about 0·2 t/in.^{2}, failure occurring at the rubber surface, and with type D about 0·1 t/in.^{2} These figures show that the rubber insert reduces the tensile strength by a considerable factor and the resulting strength is too low for many applications. The increased resilience may, however, offset the loss of strength under shock conditions. In addition to the loss of strength at room temperature, the effects of high and low temperatures have also to be considered. A similar loss of strength factor occurs with hot-setting Araldite (type 1). The mean strength of metal-metal joints is 5·1 t/in.^{2}, whereas that with a rubber insert is 0·5–0·7 t/in.^{2} (Glass cannot be used as the strength of the bond greatly exceeds the tensile strength of glass.)

Glass-metal joints made with cold-setting Araldite 102, to which about one-fifth by weight of powdered Gaco rubber had been added, gave strain-free joints, with a room temperature strength of 0·2 t/in.^{2} A similar strength was attained with Araldite 15, with a rubber interlayer. This adhesive was mixed and applied cold, allowed to dry out and then cured hot, as for Araldite type 1.

The tensile strength of various types of Araldite-bonded joint over the Service temperature range of −40 to +60° C is shown in Table 1. "Type 1" refers to glass-Gaco rubber-metal joints made with hot-setting Araldite, type 1. Such joints show increasingly high strength below 0° C, owing to progressive freezing of the rubber. The high strength is, however, offset by the smaller resilience. "Type 101" in the table refers to glass-metal joints (without rubber interlayer) made with cold-setting Araldite 101, and "type D" to similar joints made with cold-setting Araldite D.

Table 1. *Strength of Araldite-bonded joints*

Temperature (°C)	Tensile strength (t/in.²) Type I	Type 101	Type D
−40	1·8	0·8*	0·25*
−20	1·3	1·8	0·25*
0	0·75	1·2	0·25*
20	0·48	0·80	0·25*
40	0·40	0·40	0·20
60	0·40	0·12	0·20

* Denotes glass failure.

TESTS WITH "FLEXIBLE" ARALDITE

Towards the end of 1953 an experimental flexible form of Araldite was announced by Messrs. Aero Research Ltd. to be available for evaluation. The adhesive, No. 33/896, consists of three components, *A*, *B* and *C*, the proportions of *A* to *C* being kept constant, whilst that of *B* may be changed to vary the flexibility.

Initially, three mixtures were prepared, those having the maximum and minimum flexibility recommended by the manufacturers, and an intermediate mix. Subsequently a fourth mix was made and Table 2 shows the mixtures used, together with the mean tensile strength of glass-steel joints at various temperatures. Finely divided aluminium powder—as used in aluminium paint—was added to all the mixes to increase their viscosity when hot. This in turn increased the thickness of the adhesive layer, which was thought to be desirable to give greater stress relief in the joints, rubber inserts not being used. Curing was effected in all cases by baking at 100° C for three hours.

Table 2. *Flexible Araldite*

Flexibility	Proportions (by weight) A	B	C	Al	Tensile strength (t/in².) −35° C	18° C	60° C
Minimum	100	50	6	10		1·8	1·5
	100	65	6	10	1·2	1·8	0·7
Intermediate	100	75	6	10		1·6	0·33
Maximum	100	100	6	10		1·0	0·13

As expected, flexibility is gained at the expense of strength, particularly at higher temperatures. The 100 : 65 : 6 (or 17 : 11 : 1) mix was thought to have adequate strength at all temperatures, as all joint failures occurred by at least partial rupture of the glass. Interferometric investigations showed that prisms cemented direct to Nilo plates with this mix showed little more strain than corresponding prisms bonded with a Gaco rubber insert and Araldite type 1.

Using aluminium powder as a filler the adhesive thickness was found to be about 0·004 in. Subsequently, powdered glass or silica has been substituted for the aluminium and with the mixture now used, 17*A* : 11*B* : 1*C* : 1·5 silica by weight, virtually strain-free glass-metal joints are obtained with a room temperature strength of about 2·1 t/in.² Firing trials have shown that at normal temperatures the shock-resistance of such joints is comparable with that of those made by the standard technique with Araldite type 1.

Glass-to-metal bonding with flexible Araldite is much less exacting than with Araldite type 1 as no rubber interlayer is used. Thus the usual steps of cleaning, drying, baking and coating of the rubber are eliminated. The curing process is also much shorter—three hours at 100° C compared with eight hours at 140° C. Since the glass does not have to be removed from the oven at 100° C for coating with adhesive, and the curing is at a lower temperature, the risk of fracture during processing is greatly reduced. For these reasons, much use has recently been made of flexible Araldite in the construction of prototype and other optical instruments.

TESTS WITH SILICONES

For Service use an optical instrument should be as resistant to shock as possible at temperature extremes as well as at normal temperatures. It was known that Gaco rubber lost its resilience progressively below 0° C and also during baking at temperatures above 150° C, although this is, of course, well above the highest temperature experienced in use. It was thought that silicones, as a general class of materials, deserved investigation because of their well-known property of tolerating temperature extremes.

When the investigation was started available information indicated that, whereas natural or the usual synthetic rubbers could not be bonded to glass, silicone rubber probably could be. It was also thought that Araldite-type adhesives would not adhere satisfactorily to silicone rubber. These two indications suggested that direct bonding of glass to metal with a silicone resin or rubber would be the most hopeful approach and some tests were made in conjunction with Messrs. Midland Silicones Ltd.

Tensile test specimens of glass steel bond were made with two different types of resin. In each case all surfaces were coated with resin, air-dried, assembled and then cured by placing in an oven which was raised to 200° C in two hours, and held at this temperature for a further two hours before cooling slowly. The mean tensile strength of joints made with resin MS993 was 0·33 t/in.² at 18° C, but for resin F.3044 was only 0·02 t/in.²

Some prisms and tensile test specimens were bonded by direct vulcanization of a silicone rubber layer (Silastomer 6–128) between the glass and steel. The parts were first dipped in primer MS602, air-dried and then steam vulcanized for five minutes at 25 lb/in.², followed by curing in an oven at 125° C for two hours. The glass parts were brought slowly up to temperature before vulcanization. The resulting tensile strength was only 0·04 t/in.² and the rubber layer was too soft and thick to ensure optical stability. Even so, such prisms stood up fairly well to firing trials, the low tensile strength being offset by the increased resilience.

It was appreciated that the maximum strength of bond between the Silastomer and glass or steel could only be developed by a combination of high pressure and temperature, but it did not seem advisable to exceed materially the values already used because of the risk of fracturing optical components. Tests confirmed that the tensile strength of bonds made with Silastomer and Araldite type 1 was very low—about 0·04 t/in.² It was therefore thought that the most hopeful method would be to prepare a three-ply sandwich of silicone rubber between steel plates, and to bond this between an optical component and its base, using, say, flexible Araldite. In this way it was hoped that the maximum bond strength could be obtained and the hardness and thickness of the Silastomer more closely controlled.

Initially a 4 in. square sheet was made, comprising two $\frac{1}{64}$ in. steel plates bonded with $\frac{3}{32}$ in. Silastomer 80 of about 50° Shore hardness. From this sheet were cut interlayers for tensile- and shock-testing, and for two prism assemblies for firing trials. The tensile strength appeared to depend on the region of the sheet from which the sample was cut, but was between 0·1 and 0·3 t/in.² As discussed in the next section, the results of the firing and shock-testing trials were very satisfactory, and showed that the silicone sandwich had a substantial advantage over other methods. For these tests, flexible Araldite was used for bonding the sandwich to the glass and steel. Still better shock resistance may be obtained by bonding with Araldite type 1, using a very thin metal layer in the sandwich to prevent straining the glass.

Before the tests were undertaken, it was hoped that a fairly large sandwich could be made, from which individual requirements could be cut. However, it is now clear that small "tailor-made" sandwiches can be vulcanized more satisfactorily than large areas.

SHOCK TESTING

The resistance to shock of optical assemblies is usually studied in firing trials. The severity of attack is increased gradually by altering the calibre, velocity and angle of attack of the projectile which is fired at a structure to which the assembly is bolted. During the course of the experimental work already described the need was felt for a simple laboratory apparatus for shock testing, to supplement the results obtained from tensile tests, which give little direct information concerning resilience, and from firing trials, which are expensive and cumbersome.

The apparatus shown in Fig. 5 was designed and built for he purpose. It consists essentially of three parts, a "bomb"

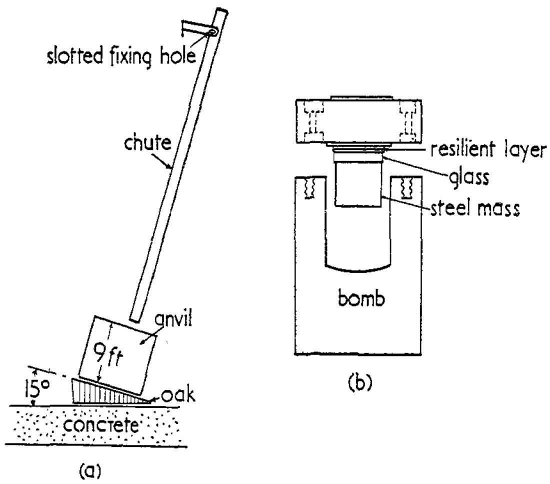

Fig. 5. Laboratory shock tester

(*a*) Chute and anvil (not to scale).
(*b*) Bomb, cap and assembly ($\times\frac{1}{2}$).

containing the assembly under test, a chute which guides the bomb during fall, and an anvil on which the bomb is suddenly brought to rest. The bomb is a steel cylinder, 3 in. in diameter and 4 in. long, with a cavity in one end. A steel cap, on to which a test assembly can be bonded, closes the end and is held in position with six screws. The total weight is about 9 lb. The chute is of machined 3 in. angle iron about 9 ft high and is inclined at 15° to the vertical. The anvil is a block of steel, of 230 lb mass supported on a 15° oak wedge, which in turn is supported by a mass concrete floor. Adjustments are provided on the chute so that its axis may be exactly normal to the striking face of the anvil; after sliding down and striking the anvil, the bomb then rebounds up the chute. Resilient material is arranged around the anvil so that no further damage is done after the primary shock. The height of drop is raised successively in steps of about 10% until failure occurs, which is readily detected by shaking the bomb.

A bonded joint can be subjected to a sudden load in either tension or compression, according to whether the bomb is dropped with the test assembly inverted or upright. The former method normally gives lower heights of failure and is mostly used. The load on a bond may be increased by adding an inertial mass of steel. Remembering that the density of steel is about three times that of glass, it is easy to calculate the thickness of steel required to simulate any given optical component.

Table 3 shows the height of failure of various types of optical bond on the shock tester, for shocks in tension. As a rough basis for comparison, the type of attack found necessary in firing trials to induce failure is also shown.

Table 3. *Comparison of shock resistance*

Type of assembly	*Adhesive*	*Height of failure, shock tester (ft)*	*Corresponding failure, firing trial*
$\frac{1}{4}$ in. glass 1 in. steel	Flexible Araldite	1–2	2 pr. 30–60° 2000 f/s
$\frac{1}{4}$ in. glass 1 in. steel Gaco interlayer	Araldite type 1	1–2	2 pr. 30–60° 2000 f/s or 6 pr. 60° 1600 f/s
1 in. steel, direct to cap	Araldite type 1	3	
$\frac{1}{4}$ in. glass 1 in. steel 3-ply silicone sandwich	Flexible Araldite	$4\frac{1}{2}$	17 pr. 60° 2500 f/s
$\frac{1}{4}$ in. glass 1 in. steel 3-ply silicone sandwich	Araldite type 1	6	

CONCLUSIONS

Glass-to-metal bonds of the highest strength are obtained with Araldite type 1 used in conjunction with a rubber stress-relieving layer. Flexible Araldite (used without a rubber interlayer) produces bonds of comparable strength, except at temperature extremes, using a technique which is less exacting than that for Araldite type 1. Bonds produced with the various forms of cold-setting Araldite introduce strain into all but the smallest glass components at normal temperatures and are of low strength at high temperatures. Interlayers of silicone rubber, suitable sandwiched, promise to maintain the strength and resilience of glass-to-metal bonds at temperature extremes. Special measures must be taken to prevent large, comparatively thin, components from being distorted when mounted.

ACKNOWLEDGEMENTS

The work described in this paper was carried out at the Fighting Vehicles Research and Development Establishment, and the author is indebted to his colleagues there for many useful discussions and ideas. Some aspects of the work are still being pursued. The paper is reproduced with the permission of the Controller of Her Majesty's Stationery Office, and Crown copyright is reserved.