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RADIO SECTION

A STUDY OF SOME OF THE PROPERTIES OF MATERIALS AFFECTING VALVE RELIABILITY

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SUMMARY

Attention is given to the study of those properties of materials which determine the failure of electronic valves from mechanical causes. The fracture behaviour, together with the time-dependence or fatigue behaviour, of glass, metal and mica is discussed. The influence of (*a*) continuously applied static stresses partly residing within the valves and partly applied externally, (*b*) continuously applied cyclic stresses, and (*c*) transient shock stresses on fracture behaviour, is described. The approximate time dependence of the probability of static-fatigue fracture is established empirically. This relationship permits the prediction of the probability of static-fatigue fracture.

The concept of safe amplitude under vibration is applied to the observed fatigue fractures, and the design and manufacturing features which determine the most dangerous stress amplitudes under vibration are explained. It is shown that static-fatigue fractures, which are the primary cause of mechanical failure in early life, and vibration-fatigue fractures, which generally appear later in life, may be reduced in numbers to a level which is insignificant in comparison with valve failures from other causes.

(1) INTRODUCTION

The reliability standard required of electronic valves for Service equipments has been defined by Hunt.[1] In an equipment embodying 100 or more valves where the probability of failure has to be kept down to about 1%, the probability of valve failure would have to be about one part in 10^4. This figure includes only catastrophic faults, mechanical and electrical, and applies during a certain limited period of time, if necessary for only 100 hours. For longer-term use and including serious, although not necessarily catastrophic, changes in valve characteristic, a probability of failure of one part in 10^2 during 1 000 hours has been proposed. In this case, the conditions, especially those of mechanical vibration, were not expected to be unduly onerous.

The causes of valve failure may be classified under three headings:

(*a*) Fracture in materials comprising the valve, e.g. fracture of envelope with consequent catastrophic failure, or in mica spacers under vibration leading to serious deterioration of electrical properties and eventually to short-circuits or component fractures.

(*b*) Gradual deterioration of electrical characteristic, e.g. loss of cathode emission owing to poisoning.

(*c*) Insufficient appreciation, during design and manufacture, of some of the required electrical characteristics. This applies especially to noise and microphony in specific applications.

The industry development programme, planned to Service requirements, first emphasized (*a*), the catastrophic form of failure, and indeed it was impossible in the presence of failure due to mica fracture to appreciate clearly the magnitude of the problems (*b*) and (*c*). The first part of the programme is substantially complete: a probability of failure of 1 part in 10^5 or 10^6 should be capable of achievement, especially with that form of fracture primarily responsible for the familiar early-life failures. With vibration fatigue, which is responsible for the mechanical failure in later life, the concept of safe amplitude stress is explained together with some examples of design and manufacturing technology which can lead to virtual freedom from vibration-fatigue fracture.

In studies of static-fatigue fracture the relationship between the probability of fracture and time was established empirically. This relationship has been applied to special-quality valves, and a field probability of failure of one part in 10^5 or 10^6 was predicted. No opportunity has yet arisen to compare this with an observed figure, and therefore confidence in this relationship can only come from an understanding of the physics of fracture behaviour.

Having defined the task, the Service authorities specified certain commonly used all-glass miniature radio-valve types for study. Trials were arranged in selected aircraft in order to assist in establishing the relationship between design, together with manufacturing technology, and flight experience. Frequent reference will be made to these flight trials. Although all valves submitted for flight trial were superior to their prototypes as regards mica fatigue resistance, they contained different stages in the evolution of envelope technology, welding technology and the like.

The paper, in fact, represents an addition to the knowledge of static- and vibration-fatigue fracture in radio valves.

(2) MAIN TYPES OF FRACTURE

For a full survey reference should be made to the paper by Orowan.[2]

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(2.1) Atomic Configuration of Glass and Metal

In order better to explain the fracture behaviour of glass and metal it is necessary to refer briefly to the atomic configuration of these two materials.

The atomic configuration of metals follows a regular geometrical pattern which is not infinite in extent, and a polycrystalline metal is composed of a number of grains, in each of which there is regular geometrical form. Between adjacent grains there are differences in the angles of orientation of the crystal planes, and as a consequence the metal atoms lying in the intergranular boundary are distorted from the regular geometrical pattern. A polycrystalline metal, therefore, contains two textural elements—crystal grains having nearly perfect geometrical arrangement of atoms, and boundary layers in which the atoms are disordered.

The atomic configuration of glass does not have the regularity of that of metals. In Fig. 1 the tetrahedral structure of soda glass is reproduced in 2-dimensional form. The structure is regular in so far as each silicon atom is surrounded by four oxygen atoms, but the distance between pairs of atoms is variable and as a consequence there is no extensive geometrical pattern. This disordered pattern is infinite in extent and a piece of glass contains this one textural element only.

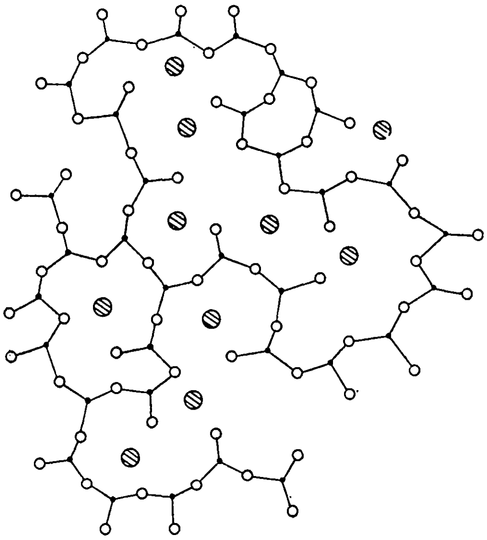

Fig. 1.—Diagrammatic representation of the structure of glass.

● Silicon.
○ Oxygen.
▨ Sodium.

(2.2) Ductile Fracture

The known property of ductility in metals is explained by the ability of adjacent layers of atoms to glide over one another on the application of a suitable stress. The ability to glide is a consequence of the regular geometrical pattern which permits the glide of one layer of atoms over another by small discrete steps of approximately one interatomic distance. On completing each small displacement the metal regains its normal regular atomic structure. (This is a very crude picture, and a more correct explanation of the behaviour is to be found in the recent theory of dislocations in metals.) Glide in a metal grain leads to considerable plastic distortion before fracture occurs. This form of fracture is ductile.

(2.3) Brittle Fracture

With disordered atomic structures, glide of atomic planes over one another is no longer possible, and in such cases fracture is not preceded by plastic distortion. This form of fracture is brittle.

(2.4) Vibration-Fatigue Fracture

Under cyclic stressing plastic deformation occurs, eventually leading to fracture. This is therefore a form of ductile fracture, and it will be discussed later.

(2.5) Forms of Fracture likely to be found in Radio Valves

Ductile fracture, being preceded by considerable plastic deformation, requires the continued application of the breaking stress. An externally applied static stress is not sustained over a long period. A static stress residing in a part of the structure as a result of manufacture is immediately released or reduced in magnitude on plastic deformation of that part of the structure. Therefore, because of the absence of a sustained static stress, either externally or internally applied, ductile fracture has not been observed. Vibration fatigue can occur, and some factors determining the behaviour will be discussed later.

There can be sustained static forces leading to brittle fracture in the disordered atomic structure of glass and of the intergranular boundaries of metals. Brittle fracture is responsible for the familiar early-life mechanical failures, and for this reason it is proposed to discuss it fully and with special reference to glass, with which this property is most commonly associated.

(3) FRACTURE BEHAVIOUR OF GLASS

(3.1) Tensile Strength of Glass

Two properties of the tensile strength of glass are important. First, it is a small fraction, perhaps as small as one-hundredth, of that which would be expected from a consideration of the molecular cohesive forces. Secondly, it depends upon the duration of the breaking force.

The cause of the discrepancy between the molecular cohesive strength and the observed tensile strength has been proposed by Griffiths.[3] He assumed it was due to the presence of very small cracks or other flaws on the surface of the glass around which a stress concentration developed on the application of stress. Fig. 2 represents the cross-section of a crack, and the lines represent stress trajectories. The stress multiplication is given by

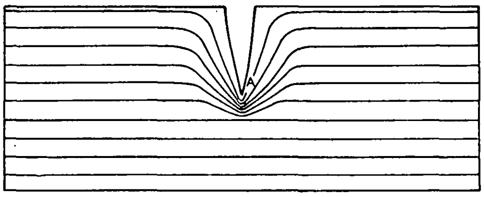

Fig. 2.—Stress concentration of a Griffith-type crack.

$$\sigma_m = 2\sigma\left(\frac{d}{\rho}\right)^{\frac{1}{2}}$$

where σ_m = Maximum stress at the point A.
σ = Mean applied stress.
d = Depth of the crack.
ρ = Radius of curvature at the tip of the crack.

Although σ may be small, σ_m is so increased that over a microscopically small area near the tip of the crack it may be as large as the molecular cohesive forces. The crack will lengthen and lead to fracture if for a small increase in its depth d the external forces are sufficient to provide an increase both of the elastic energy around the crack and of the surface energy.

From energy considerations, therefore, it has been shown that the mean applied stress leading to fracture is

$$\sigma = \left(\frac{2\alpha E}{\pi d}\right)^{\frac{1}{2}}$$

where α = Specific surface energy.
E = Young's modulus.

As to the second property, much experimental work has been reported—that of Holland and Turner,[4] and Preston,[5] for example. The experimental results are exemplified in Fig. 3,

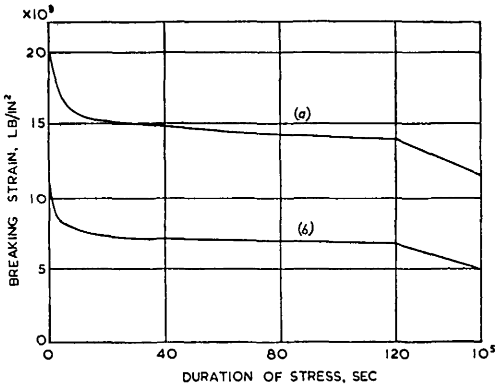

Fig. 3.—Breaking-strain/stress relationship for disannealed Pyrex.

(*a*) Dry.
(*b*) Scratched, wet.

A change in scale of the time co-ordinate occurs at 120 sec.

which is a graph of breaking stress against duration of stress. It will be noticed that the fracture behaviour differs according to environmental conditions. An explanation of this behaviour has been proposed by Orowan,[6] who attributed it to a reduction in the surface energy of glass in the presence of moist air. Let α_v be the surface energy in a perfect vacuum, and α_w the surface energy in the presence of moisture, α_v being larger than α_w. If a crack has an initial depth d and a stress σ has been applied, which lies between $(2\alpha_w E/\pi d)^{\frac{1}{2}}$ and $(2\alpha_v E/\pi d)^{\frac{1}{2}}$, the crack will extend and continue to extend at such a rate as to enable the moisture film to travel forward with the new surface as it is being formed. Eventually the depth reaches a value giving sufficient stress multiplication to propagate the crack as if under vacuum. From this point propagation is almost instantaneous and fracture complete.

Therefore, the time dependence of the tensile strength of glass can be ascribed to the finite rate of diffusion of the adsorbed moisture film within the crack.

(3.2) Distribution of Stress within a Valve Envelope

The experimental work mentioned earlier has been concerned with the study of simple specimens with simple known applied stresses. The radio-valve envelope is not a simple structure, nor is a simple known stress applied to it. One difficulty which arises in an attempt to estimate residual stresses comes from an effect which has been described by Preston,[7] and which may be called the "notch effect." It may be studied by reference to Fig. 4, which represents a possible cross-section of a portion of the glass envelope. Let a tensile stress exist on the inner surface, the presence of which will result in a tendency for the surface to bow, i.e. for ϕ to increase. This tendency will increase the tensile stress at the notch tip and at the same time produce a compressive stress on the outer surface. It was shown that the additional strain at the notch is approximately equal to $\phi/\pi r$, where ϕ is the notch angle and r is the radius of curvature at the apex of the notch.

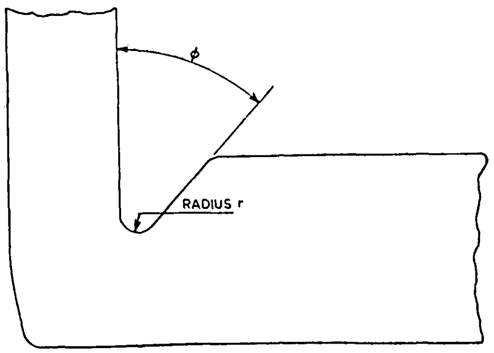

Fig. 4.—Section of the foot of the valve envelope.

In a group of envelopes the most dangerous tensile stress is statistically distributed about a mean value. In the absence of the notch effect, it will probably have a symmetrical distribution, and in the presence of the notch effect (which will itself have a statistical distribution) it will probably have a skew distribution, since when r is small the additional stress is large. The static stress is permanent and arises, for example, from imperfect matching of the components making up the envelope.

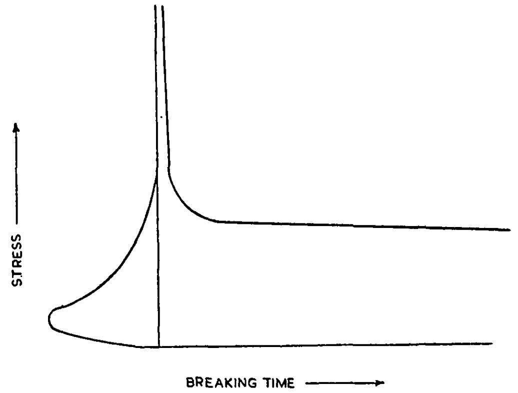

Fig. 5.—Distribution of glass failures.

In Fig. 5 the two relationships of tensile-strength/time and (distribution of stress)/(number of individuals) are combined. From these two curves it can be seen that individuals having stress levels above the knee of the strength/time curve fail early in life, while those below the knee survive indefinitely.

(3.3) Probability of Envelope Fracture as a Function of Time

(3.3.1) Normal Product.

The life of an envelope is made up of a period of manufacture, a period of storage and a period of use in the final equipment. In establishing a relationship between failure rate and time, it is necessary throughout to preserve in each individual a substantially constant stress level. Since the stress is partly applied externally from the socket, the manufacturing data covers the period of cathode activation and electrical test but does not include the prior processes of sealing and exhaust. During storage each valve was plugged into a socket-like fixture in which they were delivered to the user.

The data summarized in the first row of Table 1 have been collected from normal miniature-valve production and the field returns from general use.

Only the total loss is available from the figures obtained during manufacture and in field. The storage loss totalled $1\cdot5\%$, but daily observations were made and a breakdown of the figures is reproduced in Fig. 6, which is plotted on a logarithmic scale

Table 1

Envelope Fracture

	Fracture during manufacture	Time	Fracture during storage	Time	Fracture in the field	Time
	%	days	%	days	%	days
Normal product	2	1	1·5	15	0·3	100
Special quality	0·3	1	0·06	15	0·0	100

and gives a relationship between percentage failures per day and time. An approximately linear relationship is obtained.

(3.3.2) Special-Quality Valves.

In the development of special-quality valves, envelope improvements were achieved by methods to be described later. The results presented are of the first small quantities of valves, i.e. about 10 000, for which the manufacturing and storage losses are given in Table 1. Two observations only were made; the first of the total manufacturing loss, but still excluding losses to the exhaust process, and the second of the total storage loss.

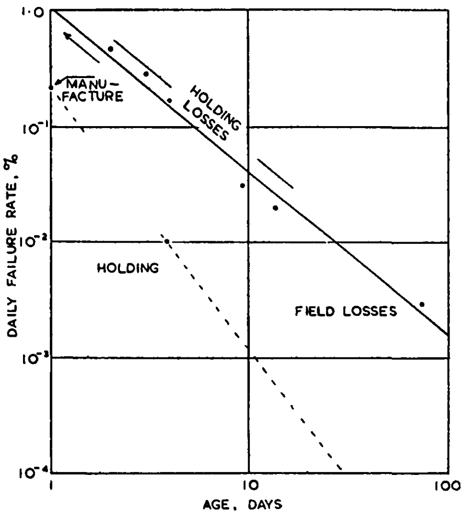

Fig. 6.—Glass-failure rate.
—— Normal production.
---- Special-quality production.

A linear relationship has been assumed in Fig. 6. The manufacturing point has been fairly well established, and the slope has been calculated to result in a total storage loss, over 15 days, of 0·06%.

(3.4) Prediction of Field Failures

The equations for the straight lines of Fig. 6 are:

$$\log_{10} F = -1{\cdot}25 \log_{10} t - 0{\cdot}25 \text{ (for normal quality)} \quad (1)$$

$$\log_{10} F = -2{\cdot}28 \log_{10} t - 0{\cdot}67 \text{ (for special quality)} \quad (2)$$

where F = Rate of failure, percentage per day.
t = Time, days.

By extrapolation the total number of failures between the 100th and 1 000th days may be determined. Now the total number of failures in normal production is 0·3%, and the total number of failures in special-quality production is 0·0005%. The total number of failures of special-quality valves in the first three years following three months' storage is about one part in 10^5 or 10^6. In the first 100 hours after storage of one month it is of the same order.

(4) STATIC-FATIGUE FRACTURE IN METAL COMPONENTS

(4.1) Probability of Weld Fracture as a Function of Time

Having explained the time dependence or fatigue behaviour of brittle fracture in glass, let us assume that a similar behaviour occurs in the brittle fracture of metal. In the development of special-quality valves, each was inspected for weld fracture at various stages in its life. Fractures were occasionally found at welded joints, presumably because in the interface the atomic layers are disordered. Records were made at a time when the fatigue behaviour was not fully appreciated, and the time intervals are only approximate. Four sets of figures have been recorded:

(*a*) *Assembly loss.*—Each completed assembly, or mount, was inspected for weld fracture before being passed on to the sealing and exhaust stage. Each mount was inspected within one day of the weld having been made.

(*b*) *Testing loss.*—Within one further day the processes of sealing, exhaust, cathode activation and electrical tests were completed.

(*c*) *Storage loss.*—The valves were stored for about four months before installation in equipment. In the example quoted, only a portion of the total number manufactured were actually installed in equipment.

(*d*) *Flight loss.*—At the time of compiling the Table the valves had been in the equipment on flight trial for about eight months.

In Table 2 figures are given applying to the weld which gave the most trouble in development.

The failure rate, in percentage per day, has been plotted against time on logarithmic scale in Fig. 7. A straight line may be drawn through the points.

The linear relationship has not been rigorously established and a more carefully planned experiment should be performed, but the welding technique which gave rise to these figures was considered so unsatisfactory that an alternative was quickly sought. The new method gave weld losses which are also

Table 2

Weld Fracture

	Old welding technique (Mark I)				New technique (Mark II)		
	Number of failures	Total number of welds	Duration of process	Failures	Number of failures	Total number of welds	Duration of process
			days	% per day			days
Assembly ..	120	3 000	1	4·0	0	500	1
Testing ..	19	3 000	1	0·6	1	500	1
Storage ..	3	500	120	0·005	0	500	14
Field ..	0	500	240	0·000	Not yet available		

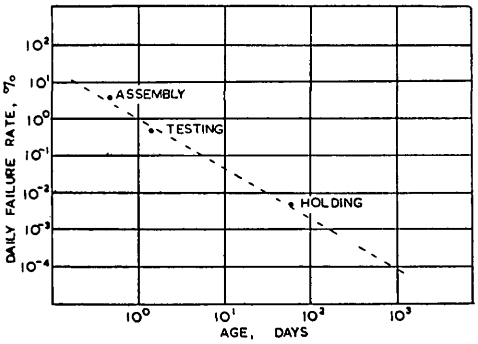

Fig. 7.—Weld-failure rate.

summarized in Table 2. There are so few fractures that it is impossible to establish the fatigue behaviour.

(4.2) Possible Mechanisms of Static-Fatigue Fracture at Welds

(4.2.1) Crack Propagation of the Griffiths type.

Crack propagation of the Griffiths type requires permanent static stress, stress multiplication at the tip of a flaw, and an impurity in the flaw reducing the surface energy of the pure metal.

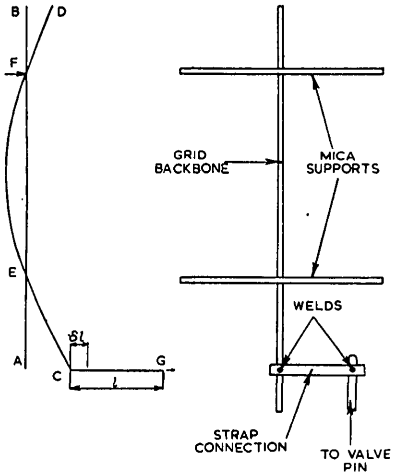

Fig. 8.—Tensile stress in cathode strap.

Fig. 8 is a sketch of the structure to which the weld was made. The fractures recorded in Table 2 occurred at the join between connector and grid support rod. The material of the connector was nickel and the grid support rod was of copper. Heat generated at the weld, which must be raised to a temperature of about 1 500° C, is partly conducted into the connector, which will then expand. If its subsequent contraction on cooling to room temperature is constrained, the connector will be in a state of extension. Also, if the zone of contact between the two members is not completely fused and contains oxide inclusion, impurity-filled flaws are present. Fig. 9 shows this possibility. The metal oxide has a low cohesive strength, and therefore stress trajectories across the boundary pass entirely through the metal with multiplication at the tips of the flaws.

(4.2.2) Viscous Fracture in Grain Boundaries.

It is often considered that the state of disorder in the grain boundary may approach complete disorder, corresponding to the metal in liquid form. The boundary will then show the viscous behaviour characteristic of liquids, and if the interface of Fig. 9 has viscous properties, a shear stress applied to the interface will cause one metal to slide over the other, leading eventually to fracture. Since the rate of viscous slide depends on the shear-stress level, a time-dependence of fracture must again be expected. It is generally accepted that viscous slide between adjacent grains is found only at high temperatures.

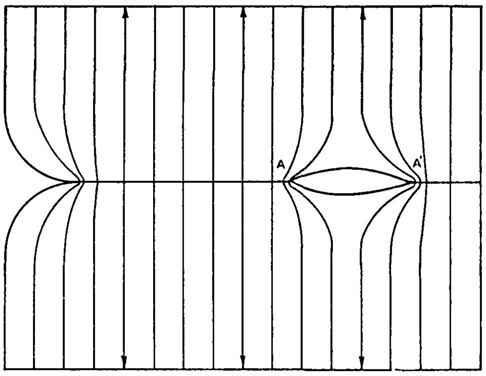

Fig. 9.—Metal interface with oxide inclusion.

The two forms of brittle fracture, both showing a time dependence of fracture, have been described. One can apply at low temperatures and the other only at very high temperatures. The possibility of an intermediate form at intermediate temperatures may also exist.

(4.2.3) Estimate of the Contraction Force at the Weld.

In Fig. 8 the connector CG has contracted and bent the side rod DFEC. From a consideration of the moments of the forces about the point E, and substituting typical component dimensions and a mean rise in temperature of 100° C, the connector is found to be extended by about 10 microns and the force residing in the connector is 100 grammes weight. The peak force on a grid, due to its own mass and the fact that it is vibrating at an acceleration of 6*g*, is 0·5 gramme weight.

The permanent static stress is likely to be so much greater than the permanent cyclic stress that the fatigue behaviour is not affected by the flight conditions. In fact, a reduction in the static stress during flight is expected because of the rise in temperature of the grid connector. A shock acceleration of 500*g* on the grid mass produces a force of 40 grammes weight, which is of the same order as the contraction force. Since it may last only for some milliseconds, the effect of such a force will be negligible in comparison with that of the permanent stress.

(4.3) Prediction of Fracture Failures in the Field

If the straight line of Fig. 7 is extrapolated the probability of failure in the flight trial referred to in Table 2 is about one part in 5 000. Actually no failures were observed among 500 valves. This cannot be said to support the extrapolation, but it adds support to the probability that the field conditions of vibration do not substantially affect the probability of fracture due to static fatigue. In larger-scale manufacture of the valve, from which the preceding example has been taken, records have been kept of the total number of weld-fatigue fractures appearing during manufacture and storage. The incidence of fracture is a few-tenths of 1 % during the process of manufacture and about 0·5 % during the period of storage. If a straight-line relationship is again assumed, this quality is capable of giving a probability of failure similar to that which was established in the discussion on glass, i.e. a probability of one part in 10^5 or 10^6 in a period of three years after three months' storage.

(5) VIBRATION-FATIGUE BEHAVIOUR OF METALS

(5.1) Concept of Safe Amplitude

One of the principal laws of mechanical fatigue under cyclic stressing is that of the existence of safe amplitudes.[2] If the logarithm of the stress amplitude is plotted as a function of the logarithm of the number of cycles after which fracture occurs, the resulting curve usually has the shape of Fig. 10.

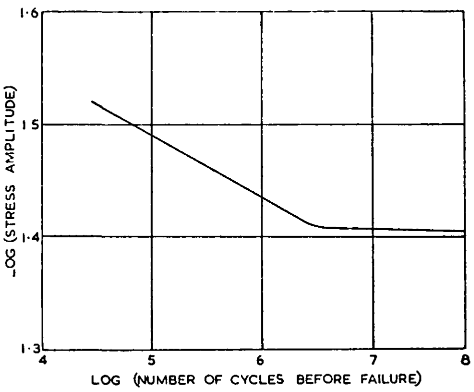

Fig. 10.—Mechanical fatigue under cyclic stressing.

Bragg[8] proposed an explanation for the existence of the safe amplitude of strain. There is little knowledge either of the stress or strain amplitudes under field conditions, but nevertheless it is useful here to reproduce briefly Bragg's argument.

The grain and grain-boundary structure of polycrystalline metals have previously been mentioned. These grains, as the result of cold working such as drawing, break down into a number of much smaller crystal fragments with slightly different orientations, although according to X-ray studies there seems to be a limit to the crystallite size-reduction process. Bragg assumed a simple cubic fragment of linear dimension t in a material whose interatomic distance is s, and established that to produce plastic shear the shear angle must be at least equal to $s/2t$. If the shear angle is less than $s/2t$ the shear strain is elastic and the material returns to its normal state on removing the shear stress. If each cycle of stress produces plastic shear, the continued application of the oscillatory stresses will eventually produce fracture.

Wood[9] has determined values for the lower limiting size of the crystallites for a number of metals. These are as follows:

Iron: $3\cdot2 \times 10^{-5}$ cm
Molybdenum: $2\cdot2 \times 10^{-5}$ cm
Nickel: $1\cdot2 \times 10^{-5}$ cm
Silver: $0\cdot8 \times 10^{-5}$ cm
Gold: $0\cdot7 \times 10^{-5}$ cm
Tungsten: Unknown: it is assumed to be about 2×10^{-5} cm

Let $s = 4 \times 10^{-8}$ cm. Then the safe shear strains are as follows:

Copper and nickel: 2×10^{-3} radn
Molybdenum: 1×10^{-3} radn
Tungsten: 1×10^{-3} radn

(5.2) Application to Radio Valves

For a grid support rod supported in the mica spacer at a point 30 mm from the glass base, an angle of 2×10^{-3} radn is equivalent to a movement of 60 microns at the top spacer, assuming the movement to be a simple shear. This loose fit of the rod in the spacer can easily be prevented, and indeed it is necessary to do so in order to avoid microphonic effects.

With coiled heaters it is necessary to have a certain looseness of fitting to allow for insertion into the cathode and for expansion on heating without damage to the insulating layer. A clearance of 50 microns between the heater and cathode is usually required, and in a typical coil such a clearance would give a shear angle of $0\cdot5 \times 10^{-3}$ radn. This calculation is crude in assuming the shear to be simple, i.e. only at right-angles to the wire axis and constant along the wire, but it does make clear that, without due care in design, heater fracture could result from severe vibration.

(5.3) Results of Flight Trials

In Section 6 the behaviour of mica under vibration conditions will be considered, but an improperly designed valve will have poor resistance to cyclic stressing, the effect of which is to enlarge mica-spacer holes and to loosen the components supported in the mica spacer. The shear strain of individual components is thus increased. From studies of field returns on normal valves it has been observed that a high rate of heater fracture, and in one specific case as many as one-quarter of the total failures, always coincided with severe mica-fatigue wear. An important design feature of the special-quality valve is a very much improved mica-fatigue resistance, and we must therefore draw upon field experience of special-quality valves for information on fatigue failures not in the presence of mica wear. Of the several valve types undergoing flight trials in Service equipment, only one has disclosed fatigue failures. The number of failures observed and the times at which failure was reported is given in Table 3.

Table 3

FATIGUE FRACTURES ON FIELD TRIAL

Cathode connector		Heaters
Old welding technique, 800 valves	New welding technique, 400 valves	1 200 valves
1 at 78 flying hours 2 at 131 flying hours 2 at 165 flying hours 2 at 236 flying hours 1 at 284 flying hours	Nil in about 300 flying hours	1 at 274 flying hours

In one group the cathode connector had a flaw from a bad welding technique, while the other group was free from this flaw. The significance of the flaw on fatigue behaviour was not clear in laboratory fatigue tests, but in the flight trial significant differences were seen. In a flight period of about 300 h, a number of failures occurred in the cathode connector of the group which contained the flaw but none in the group not containing the flaw. One heater fracture occurred after 274 h.

The frequency of stress-cycling during flight is about 100 c/s, so that about 10^7 cycles of stress have been applied before the appearance of the first fracture. If it is assumed that the vibration-fatigue curve (Fig. 10) applies to the materials in question, the stress level in the worst valve seems to be just at, or just below, the knee of the fatigue curve. A comparatively small reduction in the worst stress level would then be sufficient to avoid fatigue fracture. The avoidance of the cathode-connector flaw together with its stress multiplication must have achieved this, and in flaw-free valves no fracture has yet been observed.

The appearance of one heater fracture in 1 200 valves after 274 flying hours suggests that the amplitude of the stresses is a little too high. A small reduction in amplitude, either by a reduction in the severity of use or else by a reduction of the looseness of fitting in the cathode, would probably be sufficient to postpone the onset of fatigue fracture indefinitely.

(5.4) Comparison with Laboratory Tests

The laboratory vibration test is of 72 hours' duration at 170 cycles and 6g peak acceleration. The relationship between laboratory test results of the valves to which Table 3 refers may be summarized briefly as follows:

(*a*) The heater fractures on laboratory tests were 2% in 72 h. The heater fractures on field trial were one in 1 200 at 274 h. The laboratory test would seem to be more severe than the field trial, and it gives a stress distribution extending to a point just above the knee of the fatigue curve.

(*b*) No cathode-connector failures were observed within 72 h, although a longer period of vibration gave some. It seems that the more severe condition of test does not appreciably increase the number of connector fractures.

(*c*) Apart from mechanical vibration, cyclic stresses come about from heater switching. In the laboratory test the heaters were switched off and on every 5 min, and therefore more frequently than is likely in the field. In spite of this, the laboratory failures in the cathode connectors did not appear earlier. It may therefore be assumed that the mechanical vibration is more serious. As for the heater, it is unlikely that simple expansion or contraction along the length of the cathode increases the shear angle.

(6) VIBRATION-FATIGUE FRACTURE IN MICA SPACERS

(6.1) Properties of Mica

Mica is categorized by a very easy cleavage plane in a single direction and by a high degree of flexibility and toughness in the thin flakes. In the course of experiments on thermal conductivities, Wood[10] concluded that the laminated structure is not infinitely extensive but that there is a limited size to which the unit cell may be multiplied before the appearance of flaws. In other words, a sheet of mica is composed of a very large number of plate-like crystallites.

The properties of toughness and flexibility are very important for radio valves. For example, apart from spacing the individual electrodes, suitably designed mica sheet permits a spring-like retention of the structure in the valve envelope. High stresses can exist in the mica sheets without leading to fracture.

(6.2) The Effect of Externally Applied Forces

The effect of externally applied forces should be considered under two headings:

(6.2.1) The Effect of Shock Forces.

It is possible for an externally applied shock to result in an extension of the cleavage of the laminae comprising the mica sheet. The effect of this extension is never to bring about mechanical failure in a valve but possibly to result in some evolution of gas and a slight effect on cathode emission. However, it is not difficult to "ruggedize" the structure so as to prevent cleavage during shock.

(6.2.2) The Effect of Cyclic Stressing.

The effect of cyclic stressing is much more important than the effect of shock forces. For example, under vibration a large grid support rod held loosely in a mica hole hammers against the edge of the mica, bringing about fracture, which takes the form of the release of tiny plates of mica and a gradual enlargement of a mica hole. The effects are not immediately catastrophic and the symptoms in increasing order of severity are:

Effect	Symptom
Microphony	First slight enlargement of mica hole.
Inter-electrode insulation	Intermittent effects due to mica particles lying between the electrodes or across the insulating surfaces.
Cathode emission ..	Cathode poisoning due to gas released by fragments on contact with the hot cathode, or from the freshly exposed cleavage planes.
Eventually catastrophic failures	As the electrodes become loose in the mica spacers the shear angles increase. Heater failures may then occur. Still more severe mica wear produces fracture in other components or connectors.

With components lying loosely in the mica holes the rate of mica fracture depends on the mass of the component, the looseness of fitting and the vibration conditions, since these determine the total amount of energy transferred to the mica edge on impact with the component. If the operational vibration conditions are known, therefore, it is not difficult to design the valve to have a sufficiently light mass and tightness of fitting to prevent fatigue failure. Alternatively, it may sometimes be convenient to attach the components firmly to the mica.

(6.3) Field Experience on Mica-Fatigue Fracture

(6.3.1) Normal Valves.

In general, the old normal valve designs were not capable of surviving conditions of severe vibration. Reject valves returned from use by the Services frequently showed that as many as four-fifths of the valves had severe mica wear.

(6.3.2) Special-Quality Valves.

Some thousands of valves having improved fatigue resistance have now undergone flight trials over hundreds of hours. A number of failures for various reasons have occurred, but in none of these defective valves has any trace of mica-fatigue fracture been found. The effects of fatigue wear on electrical characteristics have been previously outlined. The less serious consequences, i.e. noise, microphony and emission deterioration, may be caused by effects other than mica fracture. On flight trials it would seem that the proportion of characteristic faults attributable to mica fracture is very small in comparison with that attributable to other causes.

(7) IMPROVEMENTS IN MANUFACTURING TECHNOLOGY

(7.1) Glass

(7.1.1) Origin of Fracture.

Fracture in the all-glass miniature envelope almost always occurs at one of four regions (see Fig. 11). These are:

(*a*) The joint between the nickel pin and the glass (site A).
(*b*) The inner surface at the corner (site B).
(*c*) In a diameter of the cylindrical bulb (site C).
(*d*) At the seal-off tip (site D).

Each of these will be discussed in turn.

(*a*) Because of the difference in the coefficients of thermal expansion of the nickel electrode and the glass, a state of strain exists at the junction and the stress is usually released by local fracture of the glass at this point. Since the stress is local the

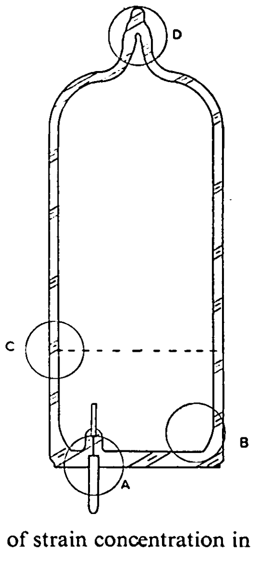

Fig. 11.—Points of strain concentration in a valve envelope.

fracture will not be propagated, except in the event of an external tensile stress being applied at the tip of the crack. To prevent the appearance of such a stress it is normal practice in the fabrication of the miniature envelope to introduce a permanent compressive stress in the outer surface of the wafer base. The application of a tensile stress, e.g. when the envelope is socketed, may only reduce the level of compressive stress but still leave it generally compressive.

(*b*) On introducing the permanent compressive stress in the outer surface of the base, a permanent tensile stress appears in the inner surface. This can be dangerous if excessive and especially if there is an appreciable additional notch stress at the corner. The notch effect must be kept low, and consistently low, by having a large and consistent radius of curvature at the corner. This is achieved while the glass is still soft on the sealing-in machine by blowing out the soft glass against a graphite roller applied to the outer surface.

(*c*) Because of the need to introduce the compressive stress in the base, which is done by applying a jet of cold air to the hot glass surface, the envelope is not annealed or cooled slowly and uniformly. Therefore, after the sealing operation a band of strain appears in a diameter of the bulb (zone C of Fig. 11). The stress level may be limited by not allowing this zone to cool too quickly after the application of the air jet.

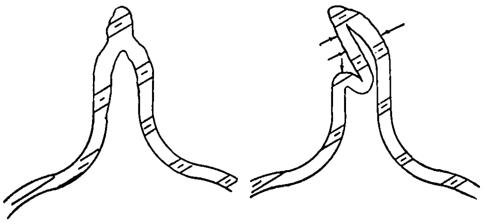

Fig. 12.—Valve-envelope pip illustrating re-entrant surfaces.

(*d*) In Fig. 12 two forms of seal-off tip are shown—the desirable form and the undesirable form. In both of these there is a notch on the inner surface, while in the undesirable form there is one also on the outer surface. The closing of the exhaust stem while under vacuum makes it impossible to avoid the inner notch. Nevertheless this inner notch is never a source of fracture, and it is assumed that this is because the external stresses apply pressure to the outer surface (see arrow directions in Fig. 12). Such forces introduce a compressive stress at the apex of the inner notch, which is not dangerous, and a tensile stress at the apex of the outer notch, which is dangerous. To avoid the external notch a thick-walled pumping stem or else a pre-constricted stem should be used.

(7.1.2) Manufacturing Controls.

The following stress levels are controlled by regular measurement on a projection strain viewer as manufacture proceeds:

Ring stress.
Compressive stress on the outer surface of base.
Tensile stress on the inner surface of base.

The notch additional stresses cannot be measured easily except in so far as the manufacturing and storage losses give an indication, but this information is not available in time to provide for the proper control of the manufacturing process. It is therefore customary to make use of an overload test for notch effects. This has been designed to introduce tensile stress on the outer surface in the vicinity of the pins, and it is done by inserting a truncated cone of metal into the circle of pins and bending them outwards. The whole is then immersed in boiling water, when the temperature gradient in the wall of the bulb introduces tensile stress on the inner surface of the valve near zone B of Fig. 11. The raising of these tensile-stress levels in the vicinity of external and internal notches increases the probability of failure. The severity of the test is adjusted to give a small number of failures in a sample of the product, so that in an already established process it is possible from a knowledge of total defectives in the sample to determine whether or not the process is still under control.

(7.2) Weld Technology

(7.2.1) Reduction of Stress Levels.

The residual stresses in connector members may be minimized in three possible ways:

(*a*) Annealing.
(*b*) Loose fitting in mica spacers.
(*c*) Design connector to be thin and arc-like in form, so that on contraction it takes up a smaller arc.

While (*a*) is impracticable the extent to which (*b*) and (*c*) may be developed depends on the requirements of microphony, ruggedness, thermal condition and lead inductance. The one case where such a thin arc-formed connector may be used with advantage is to the cathode tube.

(7.2.2) Reduction of Notch Effects.

In the resistance-welding technique, universally used in radio-valve manufacture, the two elements to be joined are brought into contact and a current is passed across the contact area. The contact resistance at the area permits the accumulation of heat there, leading to local melting and fusion between the two elements. Such a technique works best when the two elements to be joined together have similar melting points, similar masses and dimensions, and low thermal conductivity.

Unless the dimensions are unfavourable, nickel and iron have suitable melting points and sufficiently low thermal conductivity to allow reliable welding. On account of its high thermal conductivity, copper is difficult. Heat generated at the contact is conducted away rapidly so that local melting and fusion becomes more difficult. The weld from which the information derived in Table 2 was obtained was actually to the copper side-rod of a control grid. This difficult weld, combined with a connector having apparently a high residual stress, gave the high fracture rate reported.

In this particular case a brazing technique has been developed in which a third element is sandwiched between the two elements to be joined. The sandwich element must have a lower melting point than copper, and present practice is to use a copper-silver alloy having a melting point of 780° C. A further feature of the technique is that the braze-weld is done in an inert atmosphere, permitting the sandwich material to flow over the surfaces of the elements being joined, thus increasing the area over which the joint is made and diminishing the notch effect.

(8) CONCLUSION

Mechanical failures may be classified in two categories:

(*a*) *Static-Fatigue Fracture.*—This form of fracture, occurring in envelopes and at welded joints, is the result primarily of permanent static stresses and partly of externally applied static stresses. In normal Service applications with vibrations incorporating accelerations of a small multiple of *g* and low-level shock, static-fatigue fractures are substantially independent of the conditions of usage. The probability of static-fatigue fracture diminishes with time, and techniques are now available by which it may be possible to predict roughly the probability of this form of fracture and to expect that it should be as low as one part in 10^5 in a period of three years after suitable storage.

This probability is so low that it will be some time before it is confirmed in practice.

(*b*) *Vibration-Fatigue Fracture.*—An understanding of vibration-fatigue fracture can be obtained from a study of the curve in Fig. 10. This explains the concept of safe amplitude below which it never occurs, but above which fractures will occur. On normal-quality valves used under severe Service conditions, the stress amplitude is just not quite safe. Reduction in this stress amplitude by a comparatively small amount (and the measures in manufacture which may lead to this reduction have been explained) will bring about the postponement of fatigue fracture almost indefinitely. The responsibility of the user also in bringing about what may appear to be quite modest reductions in vibration amplitude, and the possible large gains which may be so achieved in vibration-fatigue fracture, will also be clear. Fracture of mica spacers from vibration fatigue does not lead to catastrophic failure. The gradual changes in valve characteristic which may occur as a result of mica wear are similar to those which may occur for other non-mechanical reasons. Again, the evidence is that deterioration of electrical characteristic in special-quality valves under the severe Service conditions from mica wear is now insignificant in comparison with the deterioration from other causes.

To achieve the target outlined in the Introduction, work must continue on overcoming failures due to gradual physical processes, e.g. evaporation of volatile material affecting inter-electrode leakage, slow contamination of the cathode, breakdown of insulation between heater and cathode, and the building up of interface resistance. These problems are occupying the attention of many research and development laboratories, and many advances have been made and described in the literature. With this must be coupled the need to study more closely the requirements of individual applications of a general-purpose valve.

(9) ACKNOWLEDGMENTS

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(10) REFERENCES

(1) Hunt, G. L.: "A Survey of Quality and Reliability Standards in Electronic Valves for Service Equipment," *Journal of the British Institution of Radio Engineers*, 1951, **11**, p. 519.

(2) Orowan, E.: "Fracture and Strength of Solids," *Reports on Progress in Physics*, 1948–9, **12**, p. 185.

(3) Grifiths, A. A.: "The Phenomena of Rupture and Flow in Solids," *Transactions of the Royal Society*, 1920, **10**, p. 163.

(4) Holland, A. J., and Turner, W. E. S.: "Effect of Sustained Loading on the Braking Strength of Sheet Glass," *Journal of the Society of Glass Technology*, 1940, **2**, p. 47.

(5) Preston, F. W.: "The Mechanical Properties of Glass," *Journal of Applied Physics*, 1942, **10**, p. 623.

(6) Orowan, E.: "The Fatigue of Glass under Stress," *Nature*, 1944, **154**, p. 341.

(7) Preston, F. W.: "Stresses in Bottles or Jars from Differences in Outside and Inside Temperatures," *Journal of the American Ceramic Society*, 1940, **5**, p. 119.

(8) Bragg, L.: "Theory of the Strength of Metals," *Nature*, 1942, **149**, p. 511.

(9) Wood, W. A.: "Lower Limiting Crystallite Size and Internal Strains in Cold Worked Metals," *Proceedings of the Royal Society*, A, 1939, **172**, p. 231.

(10) Wood, W. A.: "Temperature Variation of Thermal Conductivity and X-ray Structure of Micas," *ibid.*, 1937, **163**, p. 189.

DISCUSSION BEFORE THE RADIO SECTION, 10TH MARCH, 1954

Dr. G. H. Metson: About three years ago we had an interesting and useful discussion on the reliability of valves,* and I believe that at that meeting reliability was defined as the failure of so many valves in a certain time under the full electrical rating and some mechanical stress or load. It would have been helpful if the author could have given a hard and fast definition of reliability, i.e. a definite number of valves failing in so many hundred hours under the full electrical rating and under a clearly defined mechanical load.

We used to regard Griffith cracks in glass as of no practical importance until we found microscopic cracks on the surface of the glass bulbs of our repeater valves. We have tried to investigate them by observation under a microscope and by ill-treatment. However, we have not succeeded in getting cracks to develop under the action of locally applied heat, tapping or scratching. Has the author any comments to make on the likelihood of failure with such valves?

It might be possible to eliminate welds as mechanical fixings entirely in reliable valves. A valve has been designed at the Post Office Engineering Department in which there are no welds as mechanical fixings. The general principle is simple. One member is set upon another, and they are secured mechanically by a sort of claw action. The whole structure can be assembled without a welding machine, and it is hoped that it will be satisfactory mechanically. The weld is used only to reduce electrical noise and produce good conductivity.

Can the author suggest any precautions to avoid mica dust? At present we use very close-fitting components in the mica so that there is no rattling or banging of the components, and we never use mica "ears" scraping on the glass envelope. These are, however, only common-sense precautions.

We have considered using artificial mica in valves, but the task of developing it is considerable, and I do not think that it can be undertaken easily by a single firm. However, if we combined together we might make a case for overcoming the difficulty. Of course, mica is a rather vital strategic material, which is why the Germans developed it during the 1939–45 War.

I consider that the author should have dealt with the subject of tungsten embrittlement. If we break open a valve and take out the tungsten heater we may find that it is ductile and strong. However, with the next valve it may fall to pieces, and if it is placed between two glass plates which are squeezed together, it may be reduced to a fine, hard powder. We have tried to make our own heaters, but so far without much success. On taking a roll of tungsten wire we found that it differed in strength at different parts of its length; it varied from roll to roll, and we feel that the whole position is very unsatisfactory. The probability of heater breakage increases rapidly if it is run hot under vibration, and I feel that there is much room for improvement in the general reliability of the tungsten heater.

The relatively new problem of heater-cathode breakdown is mentioned. We all know that it does occur, but I do not think that we have been quite conscious of the widespread nature of the breakdown and the conditions under which it occurs. During the past 18 months a great deal of work has been done on heater-cathode insulation breakdown, and a good deal of information has been gained about it. In general, the insulation resistance

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* Discussion on "How Reliable is a Radio Valve?" *Proceedings I.E.E.*, 1951, 98, Part III, p. 207.