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THE LIFE AND RELIABILITY OF VALVES

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In recent years there has been a substantial increase in the use of electronic equipment. Not only have telecommunications developed enormously, but new fields of application have been opened up. Typical examples are industrial measurement and control equipment, electronic computers and many new kinds of navigational aids for ships and aircraft. A modern airliner, with radar, may have as many as 500 valves in its equipment. Moreover, the military use of electronic equipment has expanded on a vast scale. American publications mention figures like 2000 electronic valves in a large bomber and 10 000 on board a battle-ship.

As a result of the rapidly increasing use of electronic valves in industrial equipment, aircraft and etc., far more attention is being paid to the reliability of these components than ever before, particularly in view of the often serious consequences of a valve failure in complex equipment. In the following article new definitions are given for the related concepts "reliability" and "life" A description follows of the measures adopted in the factory, and of those which the user can adopt, to improve the reliability and life of valves.

Orginally, the electronic valve was used predominantly in the field of broadcasting, later extended to include television. While both these applications are still expanding, there has been in recent years an enormous increase in the use of valves in other fields, here referred to quite generally as "professional" applications. These may be classified under four main headings: carrier-telephony, electronic computers, industrial measurement and control equipment, and mobile transmitters and receivers. Several modern "Special Quality" valves for these applications are shown in *fig. 1.*

Owing to the serious consequences that may arise from the failure of a valve in professional equipment, the conventional requirements — for example with regard to the mutual conductance, power dissipation, suitability for wide-band amplification, etc. are no longer adequate. It is evident that valves used for professional equipment should satisfy the additional requirement of reliability, for the equipment should be ready for operation at all times and there must be no risk of sudden failures. Other properties that may be important are long life, shock resistance and narrow tolerances in electrical characteristics, although they may not all be equally necessary in every application. For instance, long life and constant electrical characteristics are required of valves used in computers and in telephone repeater amplifiers, but ruggedness is not so necessary, for in this equipment the valves are not subjected to mechanical vibrations or shocks. On the other hand, the valves used in aircraft transmitters and receivers must be able to withstand severe vibrations and shock, but some variation in characteristics is usually to be tolerated, and life also presents no problems where the equipment is in operation only for short periods a day.

The terms "reliability" and "life"

It is necessary in the first place to define the terms "reliability" and "life". To do this, we postulate an electronic apparatus equipped with a large number S_0 (e.g. 1000) of new valves, all of the same type, and which at a given moment is switched on for a long period of operation. Each valve failure is recorded, so that the number of original valves still functioning (S) can be seen at any instant (t). If S/S_0 is plotted, on a logarithmic scale, as a function of t, a curve is obtained similar to those shown in *fig. 2*, which have all been taken from publications on the subject [1][2][3][4][5].

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[1]) N. W. Lewis, Post Office Electr. Engr's J. **41**, Part I, 10-12, 1948.
[2]) D. K. Gannet, Bell Labs. Record **18**, 378-382, 1940.
[3]) C. R. Knight, A.I.E.E. Conf. Electron tubes for instrumentation and industrial use, Philadelphia, March 1948.
[4]) Eleanor M. MacElwee, Sylvania Technologist **3**, 16-20, April 1950.
[5]) K. Rodenhuis and W. Sparbier, Elektron. Rundschau **9**, 22-25, Jan. 1955 and 72-74, Febr. 1955.

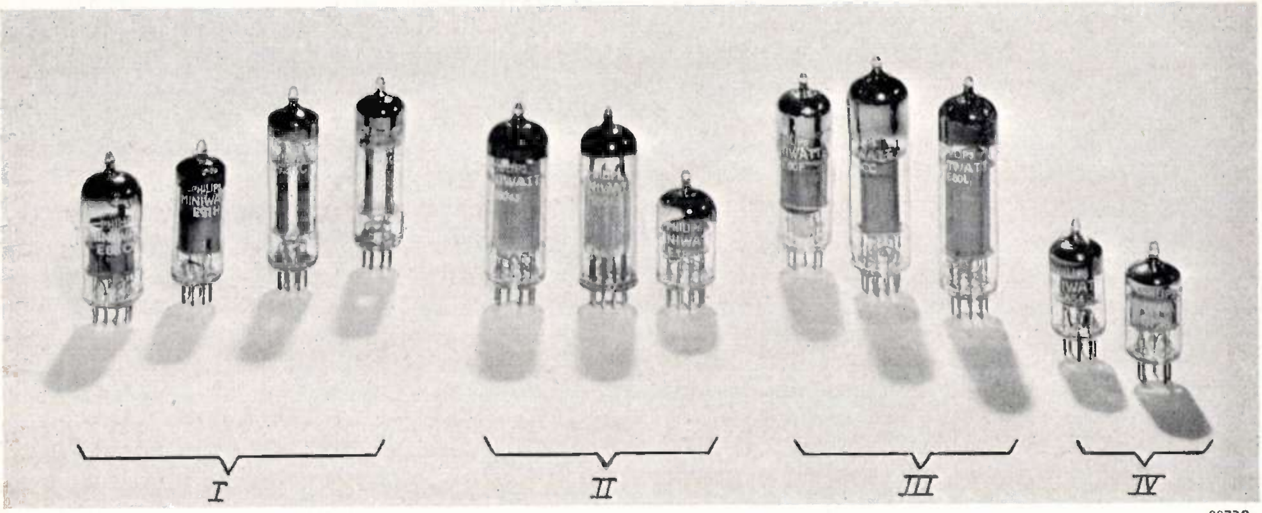

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Fig. 1. Some modern "Special Quality" valves for professional equipment.
Group I. Valves for electronic computers (great reliability, long life (also when operated cut-off), narrow spread in characteristics affecting switching functions): E 80 CC, E 91 H, E 92CC, E 90 CC.
Group II. Valves for telephone repeater amplifiers (great reliability, long life, narrow tolerances in amplifying, characteristics): 18045, 18042, E 180 F.
Group III. Valves for control and metering equipment (same characteristics as in group II but also shock-proof): E 80 F, E 80 CC, E 80 L.
Group IV. Valves for mobile radio stations (great reliability, shock-proof): 5654, 5726.

Curve *1* found by Lewis [1]) is noteworthy; it is almost a straight line, having the equation:

$$S/S_0 = e^{-Pt}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where P is a constant. From this simple expression certain interesting conclusions may be drawn. For example, the number of valve failures per unit time, i.e. $-dS/dt$, is $PS_0\,e^{-Pt} = PS$. Consequently, the percentage failures per unit time (the "failure rate", analogous to the death rate of a population), i.e. $-100\,(dS/dt)/S$, is equal to the constant $100\,P$ and is therefore independent of time.

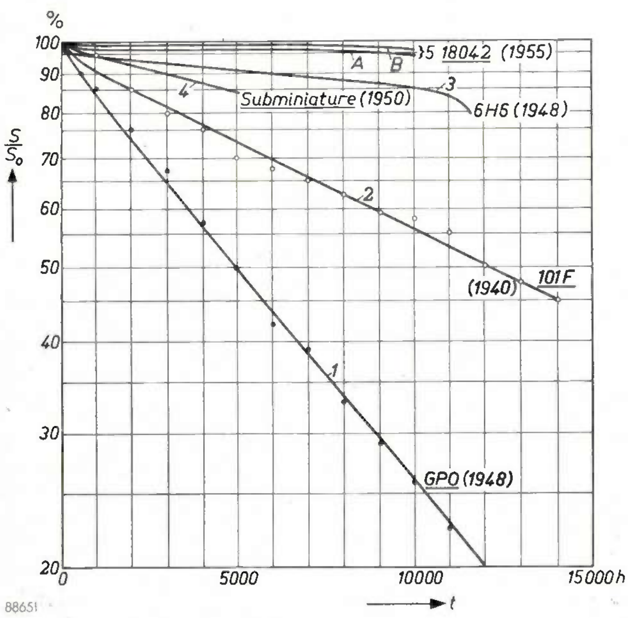

Fig. 2. The percentage S/S_0, on logarithmic scale, as a function of time t, for life tests on various types of valve. The curves *1* . . . *5* have been taken from published sources [1]) . . .[5]); the valve type and the year of publication of the curves are given in each case. The data for curves 5*A* and *B* were obtained from a test made with the cooperation of the Netherlands Post Office.

In the case of curve *1*, the average life L_m of the group is found from the equation:

$$L_m = \frac{1}{S_0}\int_0^\infty S_0\,e^{-Pt}\,dt = \frac{1}{P}. \quad . \quad . \quad . \quad (2)$$

For curve *1*, $P = 0.135 \times 10^{-3}$ per hour (failure rate 13.5% per 1000 h) and therefore $L_m = 1000/0.135 = 7500$ h.

At a time $t = L_m$, the number of survivors is:

$$S_{L_m} = S_0\,e^{-1} = 0.368\,S_0,$$

in other words, 36.8% of the original number are still in operation. At a time $t = 2\,L_m$, the number of survivors is $S_{2L_m} = S_0\,e^{-2}$, and so on: in each period L_m the percentage survivors decreases by a factor e. This means that the valves that have already been in operation for thousands of hours are in no respect to be distinguished from brand-new valves, and that there is therefore no point in replacing them. Obviously, this holds good only for a straight line, such as curve *1* in fig. 2.

Lewis [1]) has pointed out that a straight line is only to be expected where completely random conditions prevail. It cannot therefore be taken as representative of the normal case. The type of curve that should be regarded as normal is, in our opinion, curve *3*, given by Knight [3]). This shows a sharp drop during the first few hundred hours, followed by a long, fairly straight portion with a slight slope, which finally falls steeply again after many thousands of hours. The form of this curve may be explained as follows. In the beginning, some valves show the effects of manufacturing faults not detected in the factory, such as bad welds or near short-circuits between electrodes. After these valves have been removed, there will be merely an occasional "random" failure, until finally certain kinds of predictable defects become prevalent, defects arising from gradual physical and chemical processes in and near the cathode, such as declining emission and diminishing insulation resistance beween electrodes.

A curve of this form (*3*, fig. 2) yields the following information.

1) In the straight central portion of the curve the valves behave more or less in accordance with the exponential law (eq. 1).
2) The higher failure rate during the first 100 to 1000 hours means that valves that have been in operation for several hundred hours are more reliable than new valves.
3) Just past the straight portion, where the failure rate increases, it is advisable (unless certain precautions have been taken, which will be discussed later) to replace all survivors by new valves.

As regards the latter point we shall define the end of a valve's "useful life" (L_p) as *the moment at which the failure rate begins to increase (fig. 3).* This moment depends, of course, not only on the quality of the valve but also on the circuit, since the permissible deviations that may occur in certain valve characteristics are determined by the particular function of the valve in the circuit. Two important valve-characteristics in this respect are mutual conductance and grid current. To give a typical objective criterion: a valve is regarded as unserviceable when its mutual conductance has dropped to 70% of the nominal value, or when its grid current (under specific conditions) has risen to 1 μA. Other criteria may be chosen for valves used in special equipment, for example in electronic computers.

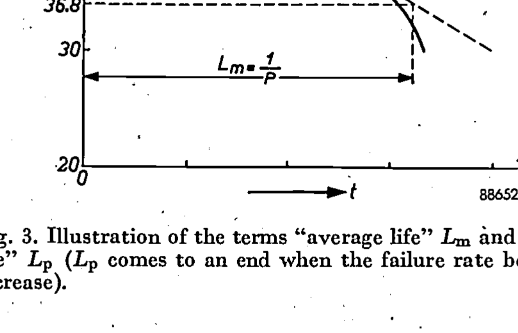

Fig. 3. Illustration of the terms "average life" L_m and "useful life" L_p (L_p comes to an end when the failure rate begins to increase).

Other definitions of "life" have been given by Eleonor MacElwee [4]), who regards it as the time after which 80% of the valves are still functioning, and by Gannet [2]), who takes the average life according to (2) as the life of a valve. Gannet's definition is useful for exponential characteristics (straight lines in fig. 2) but for more representative curves, such as *3*, it gives a result of little practical value. According to MacElwee's definition a "life of 5000 hours" represents in fact a failure rate of about 4% per 1000 h. The present authors prefer to relate the failure rate to reliability rather than to life (see below).

During a practical life test the failure rate (except at the beginning) is constant and relatively low. *This* failure rate mainly determines the frequency of the troubles arising from valve breakdowns. We shall regard the reciprocal value of this failure rate as a measure of *reliability;* the flatter the curve the greater the reliability.

The behaviour of a valve of great reliability is exemplified by curves *5A* and *5B* in fig. 2, both of which apply to a type 18042 pentode, used in telephone repeaters. The two curves refer to different applications. Curve *5A* was plotted from data recorded during a test on a circuit highly sensitive to insulation defects in valves. In this case, each valve was signalled as a failure, via a relay, as soon as its insulation resistance fell to 1 MΩ. Curve *5B* applies to the same type of valve under the same load conditions, but employed in an ordinary AF amplifier where a drop in insulation resistance to 1 MΩ could do no harm. In the right portion, curve *5A* has a slope of 0.5% per 1000 h and curve *5B* a slope of 0.25% per 1000 h. The curves still showed no tendency to bend over even at 10 000 hours.

It is believed that these figures do not represent the utmost that can be reached. It may be expected that with further experience it will be possible to reduce the failure rate of Special Quality valves to about 0.1%, a figure that should represent a reliability sufficient for practically all purposes.

A distinction may be made between the sudden and the gradual failure of a valve. A sudden failure without previous warning may be due to a broken connection, short-circuiting, or a cracked envelope.

A gradual failure implies, for example, slowly declining emission (associated with a drop in mutual conductance and in output power), deteriorating insulation, rising grid current, etc. Gradually failing valves in an equipment can be detected beforehand by regular measurements, and serious breakdowns can be avoided by replacing such valves in good time. The advantage of this "preventive maintenance" as against replacement en bloc is that the valves are replaced only as the need arises. The disadvantage — particularly where the plant concerned is equipped with large numbers of valves — is that it may entail putting the equipment partly or wholly out of operation during the measurements. Methods have been devised, however, which allow the equipment to remain in operation during inspection. For this purpose the working conditions of the valve are deliberately worsened, so that any shortcoming can be more readily detected. In a telephone repeater, for example, the test can take the form of decreasing the heater voltage or increasing the resistance in the grid circuit and then measuring the effect on the anode current; this can be done without taking the valve out of its socket or interrupting its operation. In electronic computers so-called "marginal checking" methods are used, in which it is ascertained by how much the amplitude or repetition frequency of control pulses can be varied before the computer begins to make mistakes.

Efficient preventive maintenance not only forestalls breakdowns but effects considerable economies, since it enables the valves to be used up to the end of their individual lives.

Both types of failures, gradual and sudden, will now be dealt with in turn. A discussion then follows of the contacts between valve and valve holder, electrical tolerances, ruggedness and quality control.

Gradual failures

Cathode phenomena

Most valves have an indirectly heated oxide cathode, which consists of a nickel tube coated with a mixture of crystals of BaO and SrO (and sometimes CaO). A tungsten wire inside the nickel tube heats the cathode to a temperature of 750 to 800 °C [6]). The saturation emission of such cathodes lies between 2.5 and 25 A/cm^2.

A high emission is dependent on the oxide mixture having a low work function, and this is the case only when a small fraction of Ba atoms are present in the oxide mixture (of the order of 0.01%) not combined with oxygen. Free Ba atoms may orignate in two ways:

a) Reaction of the BaO with reducing agents in the nickel. These are minute impurities in the cathode nickel that constitute less than 1% of the total weight but affect the emission properties to a very large extent.

b) Electrolysis of the oxide layer by the cathode current passing through it.

During operation, however, certain processes take place in the valve that tend to decrease the quantity of free barium. If the free barium is removed faster than it is produced the result will be a gradual decline in emission. The processes are of two kinds, physical (evaporation) and chemical ("poisoning").

Poisoning may be due to residual gas. Even with efficient pumping and getter action, a residual pressure of about 10^{-7} mm of mercury remains in the valve. The number of gas molecules in the valve is then 10^{-10} less than at atmospheric pressure, but there are still 3×10^9 per cm^3. Moreover, gas may also be given off gradually by the electrodes and the glass envelope. The gas molecules inevitably come into contact with the cathode — positive ions are in fact attracted by it — and some of these molecules and ions combine with the free barium.

Cathode poisoning may also due to another cause. Various adsorbed compounds — including evaporation products from the cathode — lie at the surface of electrodes, glass and mica. Electron bombardment releases some of these materials: of those reaching the cathode some combine with the free barium.

Another process occurring in the cathode, and which may lead to a valve failure, concerns the nature of the reducing agents in the cathode nickel. In the course of time the reducing agents react with the cathode coating at the boundary between the nickel tube and the coating. One reaction product may be a gradually thickening interface layer of barium orthosilicate (Ba_2SiO_4), which has a high resistance. The hotter the cathode, and the lower the current, the more rapidly the layer grows. This interface resistance effectively adds a resistor in the cathode lead shunted by a capacitance of the order of 10 000 pF; this not only reduces the cathode current but introduces negative feedback, causing a drop in gain, particularly at the lower frequencies [7]).

[6]) See for example, R. Loosjes and H. J. Vink, Philips tech. Rev. 11, 271-272, 1949/50.

[7]) From the extensive literature on this subject we may mention: A. S. Eisenstein, The leaky-condenser oxide cathode interface, J. appl. Phys. 22, 138-148, 1951, and M. R. Child, The growth and properties of cathode interface layers in receiving valves, Post Office Electr. Engr's J. 44, 176-178, 1951/52.

The behaviour of these different processes as a function of cathode temperature is very important. At temperatures of 50° to 100 °C below normal, the cathode is much more susceptible to poisoning. The reason is that the supply of free barium to the cathode surface is slowed down at low temperatures, as are diffusion processes in general, and also that certain reactions then take place between barium and other elements that do not occur at normal working temperatures. At higher temperatures, however, evaporation is more pronounced and the interface layer grows faster. There is therefore an optimum cathode temperature, which can be lower the more succesfully cathode poisoning has been combated.

To obtain the best results certain precautions should be taken by the valve manufacturer as well as by the equipment designer (the valve user). We shall first consider the manufacturing side.

a) To reduce *poisoning effects* the configuration of electrodes and screens should be such that no electrons can impinge on glass or mica. The components, moreover, should be kept scrupulously clean, requiring special procedures for cleaning and assembly, such as degreasing, boiling in distilled water, degassing by annealing in vacuum before assembly. Dust-free assembly, long pumping schedules and the use of high-quality getters are also necessary.

b) The *cathode temperature rating* should be as low as possible without increasing too much the susceptibility to poisoning. (There must, of course, be some safety margin to allow for heater voltage fluctuations.)

c) To combat *interface effects*, "passive" nickel should be used for the cathode tube, i.e. nickel containing approximately 0.03% Mg and not more than 0.01% Si (ordinary nickel contains up to about 0.1% Si). It takes longer with passive nickel to activate the cathode, but after 10 000 hours operation at normal cathode temperature there is still no measurable interface resistance.

The equipment designer, or user, can do a great deal to increase the useful life of a valve by observing the following precautions:

a) *Heater voltage*. As a general rule the heater voltage should never be allowed to deviate from the nominal value by more than $\pm 5\%$. (For this reason, the heaters should not, where it can be avoided, be fed in series.) Where the heater voltage has been stabilized to within 1%, however, the valve can quite permissibly be run at, say, 5% (in some cases even at 10%) below the nominal value.

b) *Bulb temperature*. To minimize the release of gas from the glass the bulb temperature should not be allowed to exceed 170 °C at the hottest point. In this connection, the use of screening cans round the valves calls for some care.

c) *Anode and screen-grid dissipation*. High dissipation causes over-heating of the anode or screen-grid, or both, and also raises the temperature of the cathode, entailing the risk of gas formation and barium evaporation. With regard to poisoning it makes a difference whether a given dissipation is produced by a high voltage and a low current or by a low voltage and a high current. Poisoning effects are more pronounced at high than at low voltages, probably because the compounds adsorbed at the surfaces of anode and screen grid are more readily broken down by high-energy electrons into substances harmful to the cathode. It follows, therefore, that low dissipation at low voltage is advantageous; the permissible cathode current may quite be high.

Insulation faults, grid emission and ion current

Material evaporating from the cathode gives rise to faulty insulation by forming a conducting film on the mica spacers and the glass base of the valve. Deposits formed on the control grid can lead to grid emission. This cause of gradual failure may be remedied by using passive cathode material and by keeping the cathode temperature as low as possible and the control grid cool. The insulation over the surface of the mica spacers can be considerably improved by a coating of magnesium oxide.

When the grid is negative, positive ions in the valve cause some grid current to flow. In a well-manufactured valve with an efficient getter, however, so few positive ions reach the first grid per second that the measured grid current is only 10^{-8} to 10^{-9} A, of which a considerable fraction in any case arises from another cause, namely that the electrodes exposed to electron bombardment emit small quantities of soft X-rays, which release photo-electrons from the control grid. Genuine "ionic currents" (of the order of 1 μA) are found only in valves with an air leak or with an inefficient getter. Both these defects are abnormal and can only be due to undetected manufacturing errors.

The manufacturer can prevent the occurrence of such defects in delivered valves by first keeping them in storage for a month and then checking for the presence of gas current. A very efficient method of checking for air leaks is to apply the *argon test*. If a valve is leaky, a good getter will absorb all constituents of the intruding air except the argon (about 1%). The argon test consists in storing the valves for, say, twenty-four hours in a container filled with argon at atmospheric pressure; after this time the presence of a leak can easily be ascertained by measuring the grid current. In this way, storage for one day is equivalent to a shelf life of 100 days.

The equipment designer can often reduce the effects of imperfect insulation and grid emission by keeping the control-grid resistance as low as possible.

Sudden failures

Sudden failures may be due to broken connections (e.g. a bad weld), short-circuiting between two electrodes, glass cracks and heater-cathode short-circuits.

Broken connections

Practically all open connections in valves occur at or near welds. A reliable welding technique (spot welding) is therefore essential in the manufacture of valves. Non-destructive testing of every individual weld is obviously impracticable, but a generally high standard of welds can be obtained if the following rules are observed:

1) The valve designer should ensure that all welded connections are clearly visible and easily accessible, and that only readily weldable materials are used.
2) The welding equipment should yield a completely reproducible result.
3) Sampling tests on the quality of welds should be carried out at regular intervals.

The second point requires some elucidation. The quality of a spot weld depends on many factors, the most important being the pressure on the weld, the no-load voltage on the transformer secondary, the impedance of the whole secondary circuit, the phase at the moment the current is switched on, the time of the current cycle, the nature of the materials to be welded, the shape and surface of the electrodes, the mass of the moving parts and the atmosphere in which the joint is made. In a modern spot welder (*fig. 4*) all variables are accurately controlled. The optimum pressure for the usual welds is pre-adjusted to a fixed value found experimentally. The secondary voltages for each individual weld are specified in a table; in general, two or three voltages suffice. The operator places the parts to be welded in the appropriate position between the electrodes and starts the weld by depressing a pedal, after which the process is entirely automatic and free of the human element. The transformer primary current flows through two thyratrons in anti-parallel, which open and close the power circuit at the required times. The phase of the initiating current is fixed and entirely independent of the operator. The weld is terminated automatically, usually after one complete cycle of the mains voltage. (One cycle is normally sufficient, but in some cases several cycles may be required, which are here obtained by means of a control circuit using cold cathode valves.) The welding electrodes, made of a copper alloy, are exchanged at regular intervals, the old ones being reshaped on a special milling machine. A stream of a mixture of hydrogen and nitrogen is played on the weld to prevent oxidation. The mass of the moving arm is small, so that its inertia causes no significant variation of the electrode pressure as the materials compress during the welding operation. All these measures ensure reproducible welds of a consistently high quality.

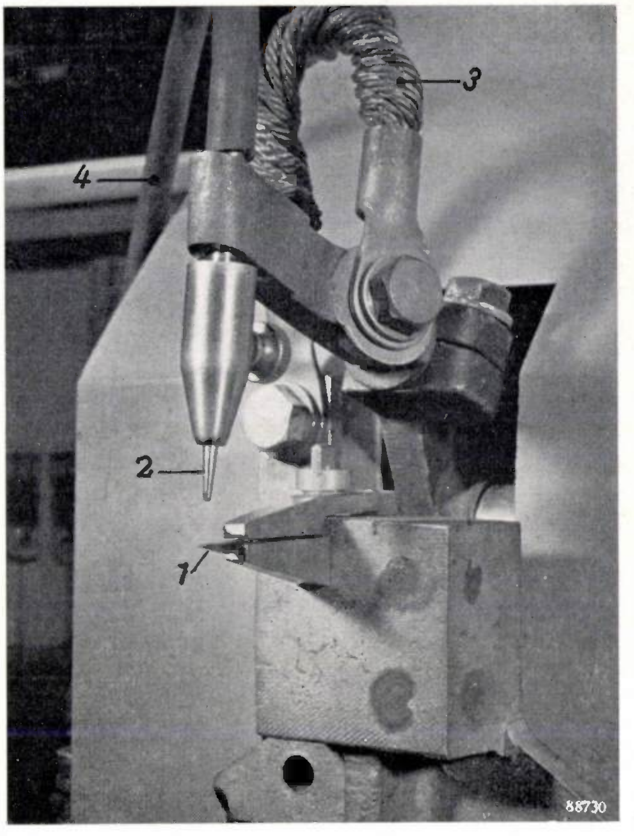

Fig. 4. Spot-welder. *1* fixed electrode, *2* moving electrode, *3* current supply cable, *4* hose through which a stream of a reducing mixture of H_2 and N_2 is played on the weld.

Short-circuits

Short circuits due to direct contact between two electrodes (which may be only 100 μ or even 50 μ apart) are easy to detect during production and are therefore extremely rare in the finished product. A much more difficult problem is the prevention of partial short-circuits or conducting paths arising from foreign particles in the valve. "Short-circuits" of this nature may show values of resistance varying from 10^7 to 1 ohm. Moreover, they may only be intermittent, which makes them very difficult to detect.

These particles originate in many ways. In the first place they may be present in the air as dust, and therefore the air supply to the assembly shop is always filtered. The formation of dust in the assembly shop itself is reduced by using materials that give off little dust for walls, ceiling, benches, curtains, etc. Floors and benches should be repeatedly wiped down with wet cloths. Well-polished linoleum is a good dust-trap. The parts are assembled and welded under dust covers, screened off at the front by nylon curtains as shown in *fig. 5a* and *b*.

The components themselves, of course, must also be free of dust. They are therefore produced under conditions that are as dust-free as possible, after which they are subjected to washing and stoving processes before being conveyed, suitably packed, to the assembly shop. Only glass, metal or plastics can be used as packing material. For the conveyance and storage of grids, for example, a metal packing has been developed in which the grids can remain during the washing and stoving processes.

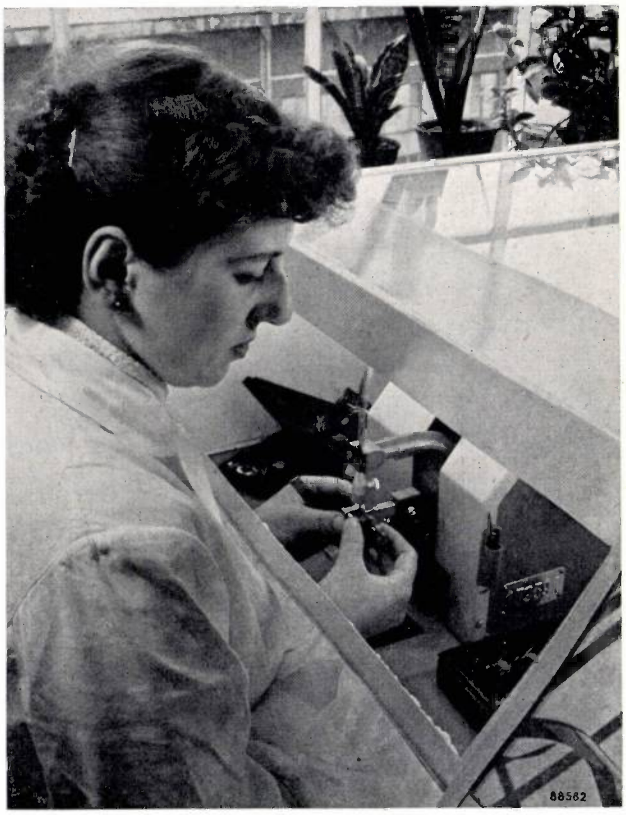

Fig. 5*b*. Spot-welding the electrode system of an amplifier valve.

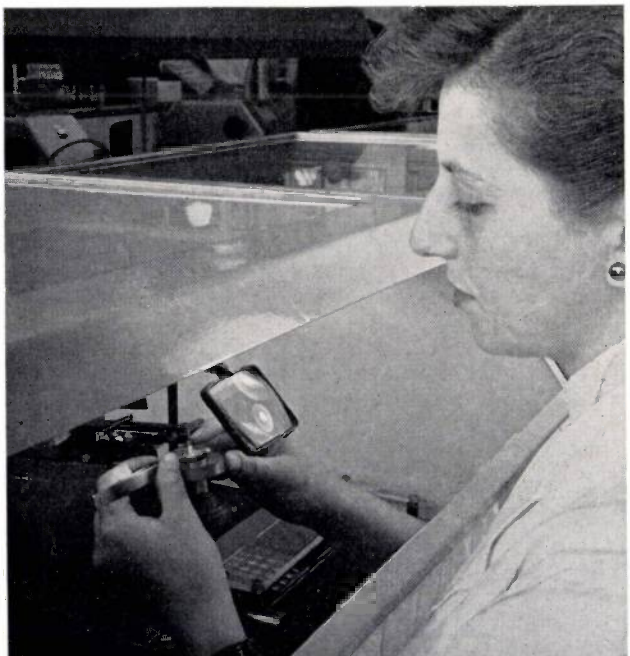

Fig. 5*a*. Assembling the electrode system of an amplifier valve. This operation, like that in fig. 5*b*, is carried out under a transparent dust-cover. The operator's hands enter the dust-cover through slits in a nylon curtain, which produces no dust itself.

Finally there are the particles introduced during production: metal particles may fly off during welding, the coating of the cathode may be chipped and bits may flake off the mica spacers (mica particles become conductive in the long run under a coating of cathode material). Sputtered metal particles point to faulty adjustment of the welding machine, and chipped cathode material indicates a lack of care in the manufacture of the cathode. Formation of mica particles can be reduced by using a new form of spacer, which flakes much less than the old type (*fig. 6a* and *b*).

In spite of all these measures, the quality of a valve is still to some extent dependent upon the girl at the assembly bench. It is not enough to provide her with the best tools and to simplify and reduce the fatigue of the operations she has to perform. It is equally necessary to ensure that her working environment is fresh, clean and orderly as befits the quality expected of the product. What is more, the operatives should understand the importance of their work; this should be explained to them during their training period. Last but not least, the results are considerably influenced by the wage policy. In our opinion the best method is to pay a piece-rate in combination with a system of bonuses based on the quality of the work performed.

The quality is expressed in so many marks out of ten, the marks being given, in accordance with a fixed schedule, after making a number of sample tests.

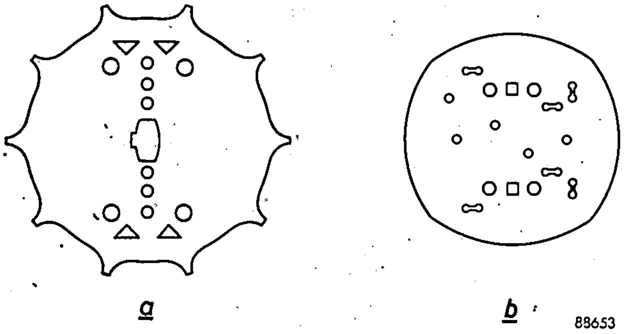

Fig. 6. Old form (*a*) and new form (*b*) of mica spacers. The new form reduces the incidence of flaking and chipping.

Glass defects

After the electrodes have been mounted on metal rods, which are fused into a glass base, the glass base is sealed into the envelope. This is done in an automatic sealing machine, which must be checked constantly on its performance in order to prevent the occurrence of glass strains which might ultimately lead to cracks and hence to sudden failures. The variables here are the gas jets, the intensity and height of which depend upon the composition and pressure of the gas, and the glass, which is not a perfectly constant product. Each production run is preceded by the sealing in of a number of dummies, which are inspected for glass strain with the aid of a polariscope [8]), and for the form of the seal by making a cross-section. After the machine has been adjusted for optimum sealing, the production run is started. Every hour samples are taken: after cooling, the sample valves are immersed in boiling water and a metal cone of prescribed form is pressed between the pins; they are then plunged directly into cold water. The occurrence of cracks gives indications of how the machine should be readjusted. After exhausting, all valves are immersed for a moment in boiling water. This test should result in no rejects; a reject is a sign that the sealing machine needs readjustment.

Heater-cathode short-circuits

One type of failure that is due to a gradual physico-chemical process and yet occurs suddenly, without any warning, is the breakdown of the insulation between heater and cathode [9]). The nickel tube of an indirectly heated cathode is heated to a temperature of 750-800 °C by a tungsten (usually helical) filament, which itself has a temperature of about 1100 °C (*fig. 7a*). The only material that has been found suitable at this temperature to insulate the heater from the cathode, while preserving adequate adhesion and flexibility, is alumina (Al_2O_3). The tungsten is coated with alumina by spraying or by electrophoresis [10]), and afterwards sintered at a high temperature.

In most cases the heater-cathode insulation does not have to satisfy very stringent requirements. For example, in a high-frequency amplifier, with the heaters connected in parallel, the potential difference between the cathodes and the middle of the heater is only a few volts, viz. the voltage drop over the cathode resistor. It is quite another matter, however, in circuits where the heaters are connected in series or where the cathode is used as an output electrode and is at a high potential with respect to earth. There is then a danger that the insulation will ultimately break down owing to gradual electrolysis of the alumina at those points where it makes direct contact with the cathode nickel. When the heater is positive with respect to the cathode (the other polarity will be considered presently) negative oxygen ions are drawn to the heater where they cause oxidation. The tungsten oxide thus formed dissolves in the alumina, producing an aluminium tungstate (fig. 7*b*). The resistance of this compound is much lower than that of alumina. After a time determined by the voltage V_{kf} and the temperature of the heater the insulation between

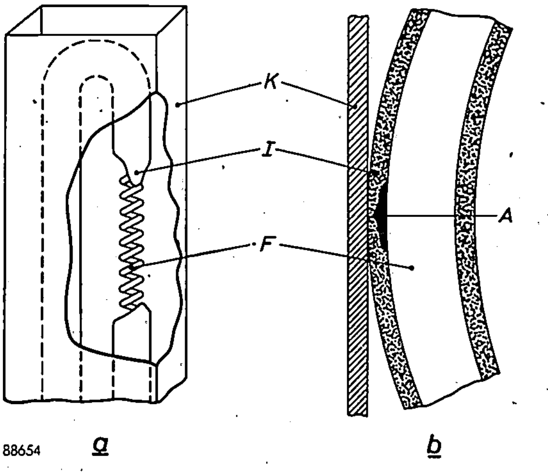

Fig. 7. *a*) Indirectly heated oxide cathode. *K* nickel cathode tube, *F* tungsten heater, surrounded by an insulating layer of alumina *I*.
b) If the heater is positive with respect to the cathode, a conducting layer of an aluminium tungstate (*A*) forms in the alumina coating at the points where the latter touches the cathode nickel, which may lead to a heater-cathode short-circuit. (Drawings not to scale.)

8) Philips tech. Rev. **9**, 277-284, 1947/48; **14**, 290, 1952/53.
9) This phenomenon has been investigated by P. G. van Zanten and P. N. Kuiper of the Physico-chemical Laboratory, Electronic valve factory, Eindhoven.
10) S. A. Troelstra, Philips tech. Rev. **12**, 293-303, 1950/51.

the cathode and a point of the heater will suddenly break down, possibly resulting in a complete short-circuit. If the impedance in the heater-cathode circuit is low, the short may lead to the fusing of the heater.

Fig. 8 shows the relationship between V_{kf} (heater positive) and the time t in which 1% of a batch of valves develop heater-cathode shorts, with the heater voltage as parameter. (The values are for guidance only, having been obtained by extrapolation of accelerated tests carried out at higher voltages and temperatures.) The figure shows clearly how the life of a valve is shortened by raising V_{kf} and how this is influenced by the heater voltage. It can be seen that V_{kf} should not exceed 100 V if a life of 10 000 hours is required.

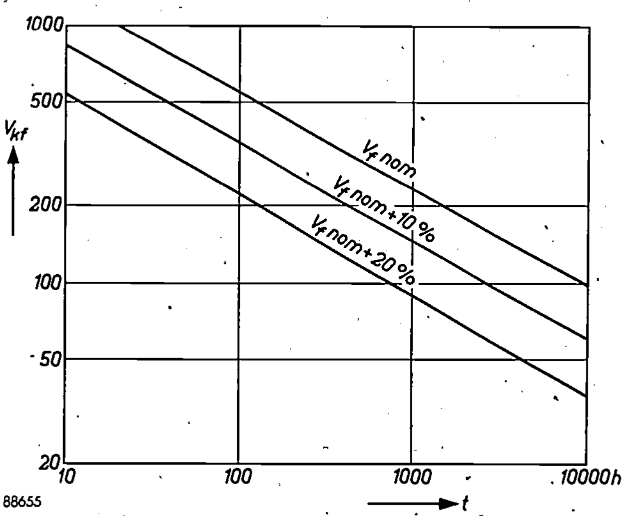

Fig. 8. Potential V_{kf} (heater positive with respect to cathode) as a function of the time t in which 1% of the valves show heater-cathode short-circuits, at nominal heater voltage $V_{f\,nom}$ (heater temperature 1080 °C) and at 10% and 20% higher heater voltages. Provisional curves only, obtained by extrapolation of accelerated tests.)

The situation is less serious if the cathode is positive with respect to the heater. In this case it is the nickel that is oxidized, but since nickel is not so readily oxidized as tungsten, the process takes much longer (about ten times longer). This means, however, that to obtain the same life as with the other polarity the value of V_{kf} may only be about twice that of the former case.

To counteract this phenomenon the manufacturer can try to prevent contact taking place between the cathode and the heater insulation touching the inside of the cathode, or at least to allow contact only via a long insulation path. This is done for instance in booster diodes for television receivers, in which peak voltages of many thousands of volts occur between cathode and heater. However, the method is only practicable for large cathodes, and has the drawback of requiring a higher heater temperature, which tends to make heaters brittle. In many Philips valves for professional use the method adopted for smaller cathodes is to coat not only the tungsten but also the inside of the cathode tube with a layer of alumina. This has two advantages:

a) The temperature of the inside coating is lower than the coating on the tungsten, which offers a greater safeguard against breakdowns.
b) The heat transfer is improved by the higher radiation absorption factor of alumina compared with nickel, which means that the heater temperature can be lowered.

It has been found that valves with cathodes treated in this way (types E80CC and E80L are examples) function 5 to 10 times longer before insulation breakdowns occur between heater and cathode, or that, for the same life, V_{kf} can be appreciably higher.

Insulation breakdown due to electrolysis currents as described above is in no way connected with the leakage currents, often much larger, that may flow between heater and cathode. Such currents may be due to emission phenomena (e.g. the presence of BaO on the tungsten or on the inside of the cathode) or to ionic conduction arising from impurities (e.g. sodium) in the alumina coating.

The contacts between valve and valve holder

The quality of base pins and socket contacts, by which a valve is connected with the circuit, has a very important bearing on the quality and reliability of the whole. An investigation conducted by Morrell [11]) of the British General Post Office demonstrated that changes in level (even interruptions) and noise in long-distance telephone communications are due in large measure to bad contacts, including base-pin contacts. Morrell concludes that the only answer is to solder the valves into the circuit.

In our opinion this drastic step is acceptable only where the life of the other circuit elements is of the same order as the valve life, or shorter. Usually, however, equipment life is many times longer than the average life of the valves, so that the replacement of soldered-in valves would create a serious maintenance problem. On the whole, new valves and new valve-holders make excellent contact; the contact deteriorates in the course of time owing to corrosion. Only precious metals maintain stable contact under corrosive conditions, a fact which has been proved by the excellent results obtained from a series of extensive tests car-

[11]) F. O. Morell, paper read before the London branch of the Institution of Post Office Electrical Engineers, 5 April 1948.

ried out, under very adverse conditions, with gold-plated pins and socket contacts. The majority of Philips "Special Quality" valves are now equipped with gold-plated base pins.

Spread in characteristics

Discrepancies in electrical characteristics between valves of the same type are attributable to differences in the dimensions or clearances of electrodes, in the work function of the control grid and in cathode emissivity.

Pentode type 18042 will serve to illustrate the effect of dimensional variations on the electrical characteristics. This valve has clearances of 120 μ between cathode and first grid and 310 μ between the first and second grids. The following table shows the change in grid voltage V_{g1} and mutual conductance S at 10 mA anode current (screen-grid potential 120 V) for 1μ variations of various electrode dimensions.

	Change in V_{g1} mV/μ	Change in S (mA/V)/μ
Cathode diameter	10	0.06
Grid 1 diameter	1.5	0.06
Grid 1 pitch	90	—
Grid 1 wire diam.	115	—
Grid 2 diameter	5	—

It is evident that special measures are needed in the manufacture of this type of valve in order to satisfy the specification, say, that V_{g1} should not vary by more than ±330 mV from the nominal value (as required for the pentode 18042). It calls, among other things, for extremely narrow tolerances in the diameter and tensile strength of the wire for the first grid, and for the utmost accuracy in the cathode diameter (the grid pitch can be set precisely relatively easily).

The work function of the first grid in a new valve may fluctuate initially, but will settle down if the valve is allowed to burn in for 48 hours. The work function depends largely upon the extent to which evaporation products from the cathode have become deposited upon the grid surface, that is to say it depends on the cathode temperature. The grid is more susceptible to poisoning than the cathode since it does not itself produce free barium but can only receive it from the cathode. The aim of the 48 hour ageing period is therefore to allow the surface of the grid to reach its normal working condition, after which there will be no appreciable change in the work function.

In discussing electrical tolerances, mention should be made of a new grid construction, evolved elsewhere [12]). Until quite recently, grids were almost invariably made as shown in *fig. 9a*. Molybdenum grid wire is wound helically around two "backbones" made of nickel, copper-clad wire or a similar material, in which grooves are cut to hold the wire turns in place, the grooves being closed under pressure after winding is completed. The grid wire itself, whose turns may be oval or round in form, have not only an electrical function but also a mechanical function, in that, together with two mica spacers, they determine the spacing between the backbones. In the new construction [12]), illustrated in fig. 9*b*, the grid

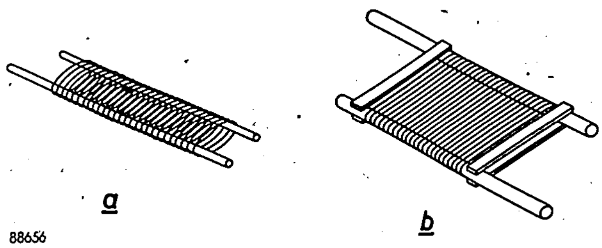

Fig. 9. A grid of normal construction (*a*) and a modern "frame grid" (*b*).

wires have a purely electrical function. The mechanical function is fulfilled by a sturdy frame consisting of two molybdenum rods connected, with the right separation by four spot-welded molybdenum strips. Very thin tungsten wire (e.g. 7.5 μ) is wound tightly around the frame, the winding tension corresponding to about 60% of the tensile strength of the wire. The wire is fixed to the frame with gold solder or with molten glass powder. The thickness of these frame grids, that is to say the clearance between the turns on opposite sides of the frame, is wholly determined by the thickness of the molybdenum rods, which can be manufactured within a precision of 5 μ.

In conjunction with measures to reduce the tolerance in the dimensions of the cathode and the mica spacers, the use of a frame grid allows valves to be made with a cathode-grid clearance of 50 μ, that is, half the clearance that can be reached satisfactorily with normal grids. Several types of Philips valves have already been fitted with frame grids (e.g. E180F and E88CC, shown in fig. 1) and other types will follow in the near future.

Shock and vibration resistance

The enormous increase in the use of electronic equipment in aircraft has made it essential to make valves that can withstand severe vibrations and shock.

[12]) G. T. Ford, Bell Labs, Record 27, 59-61, 1949. E. J. Walsh, ibid. 28, 165-167, 1950. G. T. Ford and E. J. Walsh, Bell Syst. tech. J. 30, 1103-1128, 1951.

If there is the slightest play between the mica spacer and the glass envelope, or between the mica and a component which it holds in place, the mica will begin to wear as soon as the valve is exposed to vibrations and this will tend to increase the amount of play. The first of several harmful consequences will be increased microphonic noise. In an advanced stage the play may cause shorts between two or more electrodes. Moreover, the mica may release gas, and mica flakes may come in contact with the cathode and poison its surface. Mechanical fatigue may lead to rupture, particularly of welds, filament and cathode connecting strip.

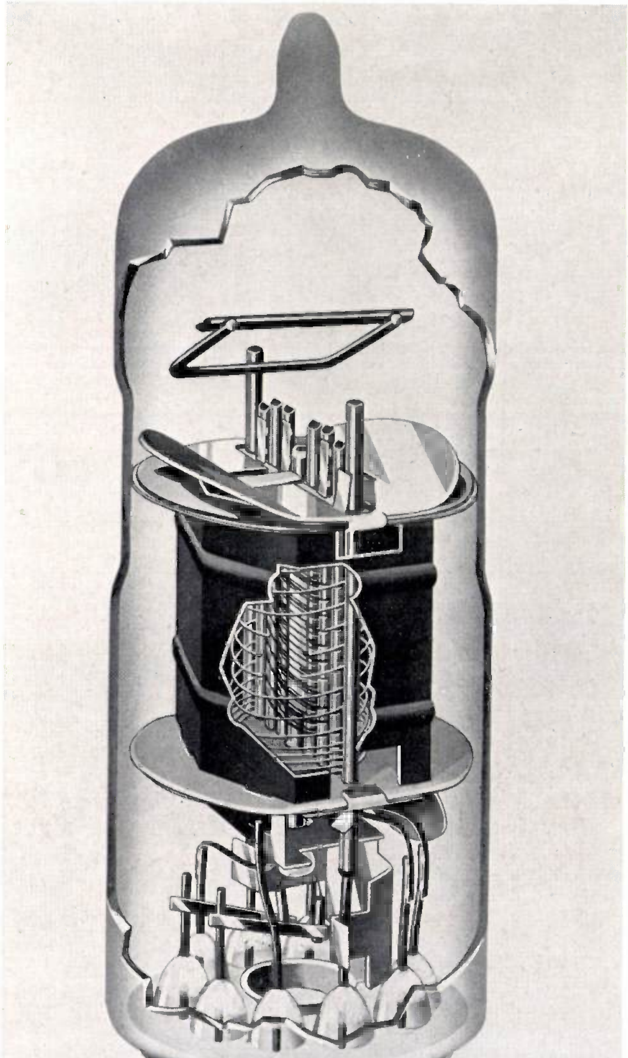

Fig. 10. Type E80F pentode, fitted with mica spacers as in fig. 6*b*. The upper spacer fits tightly in a constricted region of the envelope.

To improve a valve's ability to withstand adverse mechanical conditions it is first of all necessary to restrict the forces acting on the components. This is done by using the lightest possible components and by avoiding mechanical resonances under 200 c/s, and preferably under 1000 c/s. The toothed mica spacers formerly in general use (fig. 6*a*) are liable to break off at the teeth under vibration (especially in large valves) which gives rise to play and to flaking mica. The new form of spacer illustrated in fig. 6*b* is a substantial improvement. An especially good fit is obtained by very accurately narrowing the bulb at the height of the spacer to an inner diameter about 0.1 to 0.2 mm smaller than the largest diameter of the spacer. *Fig. 10* shows the interior of a valve in which this method has been employed. Mechanical fatigue of the heater can be prevented by restricting the movement of this element inside the cathode tube. The cathode connector can be safeguarded against rupture by giving it a large bend.

Various methods have been devised for testing valves under adverse mechanical conditions. The American military specifications, which are used as standard for Philips valves, prescribe a vibration test lasting in total 96 hours, divided into three equal periods of 32 hours, during each of which the acceleration force is applied in one of the three main axes of the valve. The specified repetition frequency is 25 c/s and the peak acceleration 2.5 g (g being the acceleration due to gravity), and the amplitude 1 mm. The American specifications also lay down a shock test consisting of five shocks of 500 g, each lasting 1 millisecond, and applied in the direction of each of the axes; for the longitudinal axis five blows are given in the one direction and five in the opposite direction. This test is carried out on a machine of American design. (*fig. 11*).

The valves are considered to have passed these tests when they are still in working order and when their electrical characteristics still fulfil certain requirements. As the tests are, in a sense, of a destructive nature, they can only be carried out by sampling. The American military specifications therefore lay down sampling plans [13]) which are based on an "acceptable quality level" of 6.5% rejects for the vibration test and 20% for the shock test. The figures indicate that valves which have satisfied these specifications should not be exposed in practice to vibrations and shocks of the same magnitude as during the tests, as otherwise the failure rate would be very high.

[13]) For a general treatment of sample testing and sampling inspection plans, see Philips tech. Rev. **11**, 176-182, 260-270 and 362-370, 1949/50.

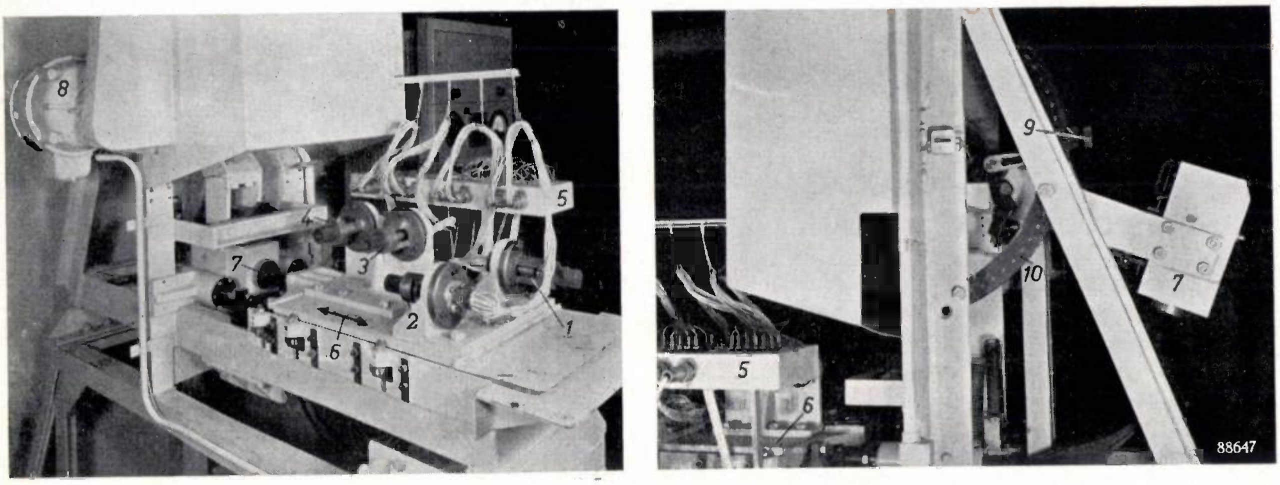

Fig. 11. Two views of a machine for shock-testing valves in accordance with American military specifications. *1, 2, 3*, and *4* are valve bases mounted facing different directions, connected to the supply rack *5*, and fixed rigidly to a carriage *6* which can slide in the directions indicated by arrows. A hammer *7*, driven by a motor *8*, strikes the carriage after a fall from a height adjusted by screw *9* along a scale *10*. After 5 consecutive blows the positions of the valves are changed until they have passed through all four positions *1 . . . 4*. They are then removed and inspected for damage.

Quality control

In the manufacture of "Special Quality" valves, the methods of quality control play a very important part. Some examples have already been mentioned in connection with assembly work and glass strains. However, these methods start as far back as in the manufacture of components, where samples are tested on their most important properties. After pumping and "screening" (cathode activation and stabilization), the valves are tested for short-circuits, open connections, crackling, etc., and certain of their electrical characteristics are measured. They are then subjected for five minutes to a vibration test in order to detect the presence of loose particles, and this is followed by a 48 hours' ageing period to stabilize the electrical characteristics, which constitutes a short life test on every valve produced. Rejects occurring during this period give valuable indications concerning the reliability of the valves. After ageing, all valves are tested on their more important characteristics, such as emission, mutual conductance and anode current and examined again for crackling and insulation. Each week's production is stored separately. From each batch several samples are taken, some being subjected to measurements on capacitances, grid emission, noise, microphony, etc. and others to a life test of 500 hours.

The results of these sample tests determine whether the week's production is suitable for delivery. Before dispatch, the valves are tested once again on their principal characteristics in order to ascertain whether they have suffered during storage.

Conclusion

The purpose of this article has been to give some idea of the problems confronting the manufacturer of special quality valves for professional equipment, and also to indicate how the valves can be employed to best advantage in electronic equipment. As stated, a failure rate of 0.5% per thousand hours with a useful life of 10000 hours does not mean that endeavours to improve the reliability of these valves are at an end. Much work undoubtedly remains to be done before the failure rate can be reduced to 0.1% per 1000 hours. The equipment designer can help in reaching this goal by making available the extensive practical data at his disposal; close cooperation in this respect between valve manufacturer and valve user can do a great deal to improve the quality of this class of valves.

Summary. The greatly increased use of valves for professional equipment has focussed the attention of manufacturers and users alike on the reliability and life of these components. The authors define "reliability" as the reciprocal of the failure rate, i.e. the percentage failures in a batch of valves after 1000 hours operation. They regard the end of a valve's useful life as the moment at which the failure rate begins to increase. A useful life of 10000 hours and a failure rate of 0.5% per 1000 hours have already been reached with "Special Quality" type valves; it is hoped to be able to reduce the failure rate to 0.1% per 1000 hours.

Valve failures may be either gradual or sudden. The causes of both categories of failure are discussed separately and a description is given of the measures taken in recent years to reduce the incidence of valve defects. The spread of characteristics and shock and vibration resistance are also discussed. In conclusion the desirability of close cooperation between valve manufacturer and valve user is underlined.